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IFAC-PapersOnLine 49-15 (2016) 139–144

Tire-Ground Forces Estimation in a 4-Wheel Vehicle Using a Delayed Interconnected Cascade-Observer Structure [★]

Rafael A. Cordeiro [*] **Alessandro C. Victorino** [**]
Paulo A. V. Ferreira [*] **Ely C. de Paiva** [***]
Samuel S. Bueno [****]

[*] *School of Electrical and Computer Engineering, University of Campinas, Campinas, Brazil (e-mails: rcordeir@dt.fee.unicamp.br, valente@dt.fee.unicamp.br).*
[**] *Heudiasyc Lab, UMR CNRS 7253, Université de Technologie de Compiègne, Compiègne, France (e-mail: Alessandro.Victorino@utc.fr)*
[***] *School of Mechanical Engineering, University of Campinas, Campinas, Brazil (e-mail: elypaiva@fem.unicamp.br)*
[****] *Division of Robotics and Computer Vision, Center for Information Technology Renato Archer, Campinas, Brazil (e-mail:samuel.bueno@cti.gov.br)*

Abstract: The knowledge of tire-ground interaction forces is interesting for intelligent vehicles. However, tire forces transducers are expensive and not suitable for ordinary passengers cars. An alternative is to estimate these forces using common sensors. This paper presents an estimator structure capable of reconstructing tire-ground interaction forces in all directions. A delayed interconnected cascade-observer structure is proposed to eliminate mutual dependence between estimators. Observers are developed based on nonlinear vehicle dynamic models with the Extended Kalman Filter algorithm. The estimator is validated with experimental results. The results are also compared with an existent estimator of the literature.

Keywords: Tire-ground forces estimation, State observers, Kalman Filters, Vehicle dynamics, Intelligent vehicles

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NOMENCLATURE

Index $_i$:	$<$ 1 (front) | 2 (rear) $>$
Index $_j$:	$<$ 1 (left) | 2 (right) $>$
$F_{x_{ij}}$,$F_{y_{ij}}$,$F_{z_{ij}}$:	Long., lat. and vert. tire force
m:	Vehicle mass
g:	Gravitational acceleration
u,v,w:	Long., lat. and vert. linear speed
p,q,r:	Roll, pitch and yaw rate
ϕ, θ:	Roll and pitch angle
m:	Vehicle mass
J_{xx},J_{yy},J_{zz}:	Principal inertia in each axis
L_i:	Distance from CG to front/rear.
E :	Distance from CG to lateral
k_s,c_s:	Suspension stiffness and damper coeff.
δ_{ij} :	Tire steering angle
α_{ij},σ_{ij}:	Slip angle and slip rate
$C_{\alpha_{ij}}$,$C_{\sigma_{ij}}$:	Cornering and longitudinal stiffness
$\rho_{x_{ij}}$,$\rho_{y_{ij}}$:	Long. and Lat. relaxation lengths
Ω_{ij}:	Wheel spin speed
$r_{w_{ij}}$:	Tire radius
$h_{z_{ij}}$:	Suspension length
T_S:	Sample time

1. INTRODUCTION

There have always been a strong seek for new technologies in the automobile industry. In a recent past, the automobile technology aimed to improve the so called “hardware” of vehicles. New engines, chassis, dampers, electronics, *etc.* are developed to increase stability, security and comfort.

Nowadays, the new technologies have been sought at the “software” level. More and more intelligent systems have been applied in vehicles worldwide. At this context, there are two main research: The Advanced Driver Assistance Systems (ADAS) and the Autonomous Vehicle (AV) systems.

In ADAS, the main goal is to aid human drivers under unsafe conditions. The ADAS can work indirectly, providing warnings and advises for drivers, or directly, taking control of accelerator, brakes or even steering to increase safety. The most known ADAS are ABS (Anti-lock Braking Systems) and ESC (Electronic Stability Control).

Differently, AV systems aim to overlap the human driver, controlling the entire vehicle. Excluding the driver, the control system could make decisions to increase safety, reduce traffic and even reduce gas emissions. The most well-known project is the Google Autonomous Car, that has been exhaustively tested at USA streets.

[★] The authors acknowledge the grants: Ph.D. FAPESP (2014/06610-8), BEPE FAPESP (2014/27240-4) and Regular FAPESP Project VERDE (2014/02672-9). This work was carried out within the framework of the Equipex ROBOTEX (Reference ANR-10-EQPX-44-01) Heudiasyc Laboratory UMR CNRS UTC 7253.

10.1016/j.ifacol.2016.07.722

To be able to make precise decisions, both ADAS and AV systems need to be fed with information related to driving activity. Therefore, they should be able to sense the vehicle dynamic and/or environment conditions.

There is a huge number of sensors that could be used to provide essential information for ADAS and AVs: accelerometer, gyrometer, video camera, laser, gps, *etc.* are some of the sensors commonly used. However, there are some variables that are difficult to be measured. Furthermore, some sensors are expensive which denies their use in ordinary passengers car.

One of the most difficult information to be measured are the tire-ground interaction forces. In ADAS, for example, these forces can be used to predict rollover situations (Bouton et al., 2008), allowing the system to warn, or even to act in the vehicle to avoid the hazard. For AVs, tire-ground forces are more important in off-road vehicles, where terrain irregularities and slippery conditions results in forces variation, leading to instability.

To obtain tire forces information, but avoiding expensive sensors, estimators have been developed. Works like (Ray, 1997), (M'sirdi et al., 2005), and (Doumiati et al., 2011) presents estimators for measure these forces, however most of them do not treat longitudinal force estimation, or use sensors that are not suitable for ordinary vehicles.

This paper presents a tire-ground forces estimator able to reconstruct forces in all directions using inexpensive sensors applied in common vehicles. Firstly, the estimator structure is presented in Section 2. Following up, dynamic vehicle models are developed to be used in the synthesis of observers. Section 4 introduces the algorithm of the observers used in the cascade structure. The validation of the estimator is presented in Section 5, where real experimental data are used. Finally, the authors present their final conclusions.

2. OBSERVER STRUCTURE

Vertical, lateral and longitudinal tire forces are strongly coupled. Lateral and longitudinal tire forces are friction forces over the tire, therefore, they are directly related to vertical forces. In addiction, they are also indirectly coupled since they depend on vehicle dynamics (speeds and accelerations).

These dependencies interfere on the observability of the estimators. Doumiati et al. (2011) proposed a cascade-observer to overcome this problem, where the vertical forces are estimated firstly and, then, the estimated vertical forces are used as inputs to the lateral forces observer.

To decouple the forces estimators, random walk models were proposed, which are used for linear dynamics of the vehicle in the vertical forces estimator, and for longitudinal driven axle force ($F_{x_1} = F_{x_{11}} + F_{x_{12}}$) in the lateral forces estimator. Also, The longitudinal force at each driven tire is proportional to the vertical forces distribution at the axle and null at non-driven wheels.

The present work intends to enhance the observer response by eliminating random walk models. For such, a cascade-observer with one-sample delayed interconnections is proposed, as shown in Fig. 1.

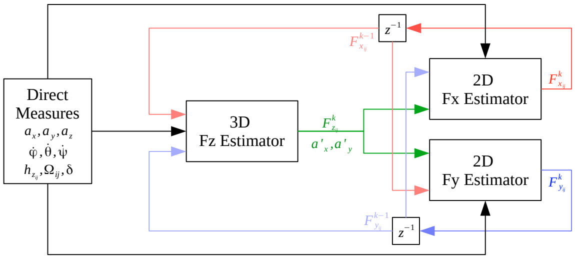

Fig. 1. Cascade-observer structure with delayed interconnections.

The vertical forces observer receives as input the steering angle command and, also, the estimated lateral and longitudinal forces provided by the others observers in the cascade structure. However, the lateral and longitudinal estimators depends on the vertical tire forces. To solve the mutual dependency problem at the vertical estimator, the lateral and longitudinal forces input are delayed by one sample, i.e. the forces in time k are approximated by the same forces at time $k-1$. This time delay is an acceptable approximation since tire force dynamics are normally slow. Moreover, the need of initial conditions can be overcome since at $k = 0$ the vehicle is normally in a rest mode, where lateral and longitudinal forces are expected to be null.

3. OBSERVERS STATE-SPACE MODEL

The estimators showed in Fig. 1 are state-space observers. The nonlinear state-space model used by each observer is presented in the following subsections.

3.1 Vertical state-space model

To estimate vertical forces, a 3D vehicle model is considered. This model is inspired on the one presented by the authors in (Cordeiro et al., 2013). The vehicle is considered as a planar body with four independent suspension (spring-damper systems), which are considered always vertical to the vehicle.

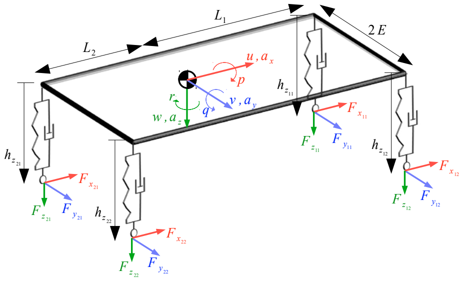

Fig. 2. Proposed 3D model for the vertical estimator.

The proposed model representation is shown in Fig 2. Dynamic analysis are made using Euler-Newton equation, resulting in:

$$\dot{u} = vr - wq - g\sin\theta + 1/m \sum F'_{x_{ij}} \tag{1}$$

$$\dot{v} = wp - ur + g\sin\phi\cos\theta + 1/m \sum F'_{y_{ij}} \tag{2}$$

$$\dot{w} = uq - vp + g\cos\phi\cos\theta + 1/m \sum F_{z_{ij}} \tag{3}$$