Low-Cost Sensor for Vehicle Speed Based on Sliding Mode Observer

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Abstract— **This paper presents a new robust observer methodology based on sliding mode for estimation of vehicle velocity. The paper addresses the design and implementation issues of such observer which is based on the measurement by a standard sensor in many of the new cars. This is the encoders which are mounted in the ABS system. They provide a low angular resolution position measurement. The estimate has been validated experimentally using an instrumented vehicle by different sensors. The actual results show effectiveness and robustness of the proposed method**

Keywords- ***Vehicle dynamics; Sliding Mode Observer; Robust Observers; Vehicle Velocity; Estimation; Encoder.***

I. Introduction

One of the main challenges in vehicle design is to improve safety and comfort of vehicle passengers by using active control. More and more new actives safety systems are developed and installed on the vehicles for monitoring and the controlling in real-time of the dynamic stability (EBS, ABS, ESP,…) [1,2,3]. Many of these systems have in common the vehicle velocity. However, this is rarely the directly measured and must be inferred from other measures, such as wheel speed, yaw rate and acceleration measurements.

In general, the vehicle velocity (longitudinal) is obtained by fusion of the data from all rotation wheel velocities and longitudinal acceleration sensors. The estimation must be very accurate, as a basis for the wheel slip calculation. Two methods for estimating and replacing the vehicle speed, the Kalman filter and the fuzzy estimator are considered in [4]. The earlier works on observers for estimation of vehicle velocity are mainly based on linear or nonlinear techniques [5]. An extended Kalman-filter is used for estimating vehicle velocity and tire forces in [6].

In this paper, a robust observer is considered in the objective of an on line estimation using the super-twisting based on robust exact observer [7] for estimation of velocities.

This proposed super-twisting algorithm combines the merits of:

i) make the velocity observation without filtering;

i)) provide, in a finite time, the convergence to the exact value of derivative.

This paper is organized as follows: Section 2 provides the description of the vehicle and modeling. The design of the second order sliding mode observer is presented in section 3. Some experimental results on the observation using the proposed method statements are given in Section 4. Finally, some remarks and perspectives are given in a concluding section.

II. Vehicle Model

The modeling of the vehicle have been extensively studied by many researchers [8,9,10,11]. The type of used model is defined by the purpose of the intended application. This type of system is complex and composed of many nonlinear coupled subsystems: wheels, engine and braking system, suspension, steering, more inward and embedded electronics.

The vehicle dynamics depend largely on the road profile and tire forces which are nonlinear functions of wheel slip, slip angles and depend on some factors such as tire wear, pressure, normal load and tire road interface properties [12,13].

The vehicle moves in space and describes the following six movements as shown in Fig.1:

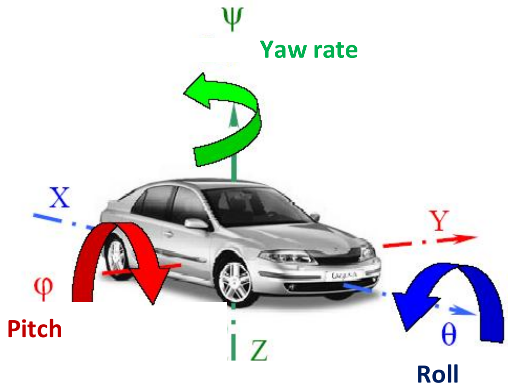

Figure 1: The different movements of the vehicle

The vehicle body receives an excitations external forces and moments following the three axes:

- Longitudinal, lateral and vertical.

These come from interaction of the wheels and road, from perturbations (wind for example), gravity and vehicle drive line. This kind of systems is complex and nonlinear composed with many coupled subsystems: wheels, motor and system of braking, suspensions, steering, more and more inboard and imbedded electronics.

The dynamic equations can be reduced, in case where we assume that motion is normal driving in a normal strait road, to translations and rotations of the body, and wheels plus suspension motions [14,15,16]. For translations we find often in literature:

$$\begin{cases} m\dot{v}_x = \sum F_x \\ m\dot{v}_y = \sum F_y \\ m\dot{v}_z = \sum F_z \end{cases} \qquad (1)$$

Where m is the total mass of the vehicle and $v = [v_x \quad v_y \quad v_z]^T$ describe the vehicle velocities along x, y, z.

In the left hand side of this approximate model are the forces $\sum F_x$, $\sum F_y$ and $\sum F_z$ applied in directions of x, y and z and the balance of the moments ($\sum M_x$, $\sum M_y$, $\sum M_z$), give rotations following the three directions *x, y* and *z*, is given by:

$$J\begin{bmatrix} \ddot{\theta} \\ \ddot{\varphi} \\ \ddot{\psi} \end{bmatrix} = \begin{bmatrix} \sum M_x \\ \sum M_x \\ \sum M_z \end{bmatrix} \qquad (2)$$

The wheel angular motions can be written:

$$\begin{aligned} \dot{\omega}_{fl} &= \frac{1}{I_\omega}\left(C_{fl} - R_\omega F_{xfl}\right) \\ \dot{\omega}_{fr} &= \frac{1}{I_\omega}\left(C_{fr} - R_\omega F_{xfr}\right) \\ \dot{\omega}_{rl} &= \frac{1}{I_\omega}\left(C_{rl} - R_\omega F_{xrl}\right) \\ \dot{\omega}_{rr} &= \frac{1}{I_\omega}\left(C_{rr} - R_\omega F_{xrr}\right) \end{aligned} \qquad (3)$$

With ω_f and ω_r are the rotation velocities of the front and rear wheel, C_{mi} is the motor couple applied at wheel i and T_i is the braking couple applied at wheel i.

Let r_1 be the distance between the center of gravity and the front axis and r_2 the distance between the center of gravity and the rear axis.

The complete model is difficult to use in control applications.

The most part of applications deal with simplified and partial models and this has advantages and many disadvantages.

In this paper, we present new method which is not based on any model to estimate the speed of the vehicle. In addition, it's cheap and simple to implement.

We consider that only the rotational angles of the wheels are measured. These measures are already integrated in the ABS system. Moreover, the estimate method can be used to detect a failure on the speed sensor if there has one in the vehicle (diagnostic by observer).

III. OBSERVER DESIGN

In this section, we will use a Robust Differentiation Estimator (RDE) [17,18] to deduce our estimations. Consider a smooth dynamics function $S(x) \in R$.

The system containing this variable may be closed by some possibly dynamical discontinuous feedback where the control task may be to keep the output $S(x(t)) = 0$.

Then provided that successive total time derivatives $s, \dot{s}, \ddot{s}, \dddot{s} \ldots\ldots s^{(r-1)}$ are continuous functions of the closed system state space variables, and the t-sliding point set is non-empty and consist locally of Filippov trajectories.

$$s, = \dot{s} = \ddot{s} = \dddot{s} \ldots\ldots = s^{(r-1)} = 0$$

is non-empty and consists locally of Filippov trajectories. The motion on set [19,20] is called r-sliding mode (rth-order sliding mode) [21].

The Levant observer [22,23] will produce estimates of the successive derivatives. High Order Sliding Modes (HOSM) presents even better robust performance than traditional first order sliding modes.

HOSM dynamics converge toward the origin of surface coordinates in a finite time, always that the order of the sliding controller is equal or bigger than the sum of the relative degrees of the plant and the actuator.

Let the input signal *f(t)* be a measurable function and it consist of base signal having a derivative with Lipschitz's constant C > 0.
In order to differentiate the input signal, consider the auxiliary equation $\dot{x} = u$. The structure of the differentiator is illustrated in Fig. 2, the idea is to consider the following sliding surface which represents the difference between x and f(t) :

$$s = x - f(t) \qquad (4)$$

By differentiating s, we have

$$\dot{s} = u - \dot{f}(t). \qquad (5)$$

The super twisting algorithm defines the control law u as the following:

$$u = u_1 - \lambda |s|^{\frac{1}{2}} \operatorname{sgn}(s), \qquad (6)$$

$$\text{with} \quad \dot{u}_1 = \omega \operatorname{sgn}(s) \qquad (7)$$

where λ, $\omega > 0$ Here u is the output of the differentiator. The corresponding sufficient condition for finite time convergence is [16]:

$$\omega > C$$

$$\lambda^2 \geq 4C \frac{\omega + C}{\omega - C}$$

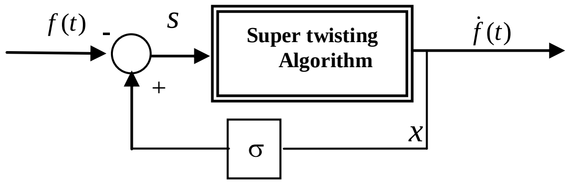

Fig. 2. Structure of the differentiator

In this section, we develop a robust second order differentiator to build up an estimation scheme allowing us to identify the vehicle parameters.

The robust differentiation observer is used for estimation of the velocities and accelerations of the wheels. The wheels angular positions and the one of the vehicle body are assumed available for measurements. The previous robust estimator is useful for retrieval of the corresponding velocities and accelerations.

The convergence of these estimates is guaranteed in finite time t_0. The estimations will be produced in two steps, as cascaded observers and estimator, reconstruction of information and system states step by step.

This approach allows us to avoid the observability problems dealing with inappropriate use of the complete modelling equations. For vehicle systems it is very hard to build up a complete and appropriate model for global observation of all the system states in one step.

Thus in our work, we avoid this problem by means of use of simple and cascaded models suitable for robust observers design. The first step produces estimations of velocities. In the second step we calculate the averaged value of this speed to reconstruct the vehicle velocity.

EXPERIMENTAL RESULTS

Some experimental results to validate the proposed estimators are presented in this section. The proposed algorithm is developed and applied to a vehicle to demonstrate the effectiveness of this method.

To examine the performances of the proposed procedures to estimate the vehicle velocity, several trials have been done with a vehicle.

The Peugeot 406 vehicle of the LCPC (Laboratoire Central des Ponts et Chaussées) is equipped with several different sensors as given in Fig.3. The measurements have been acquired with the vehicle rolling trials at several speeds.

Figure 3. Vehicle used for experiments

Figure 4 shows the measured and estimated wheel velocity. The figure points out the good convergence to the actual vehicle velocity estimation.

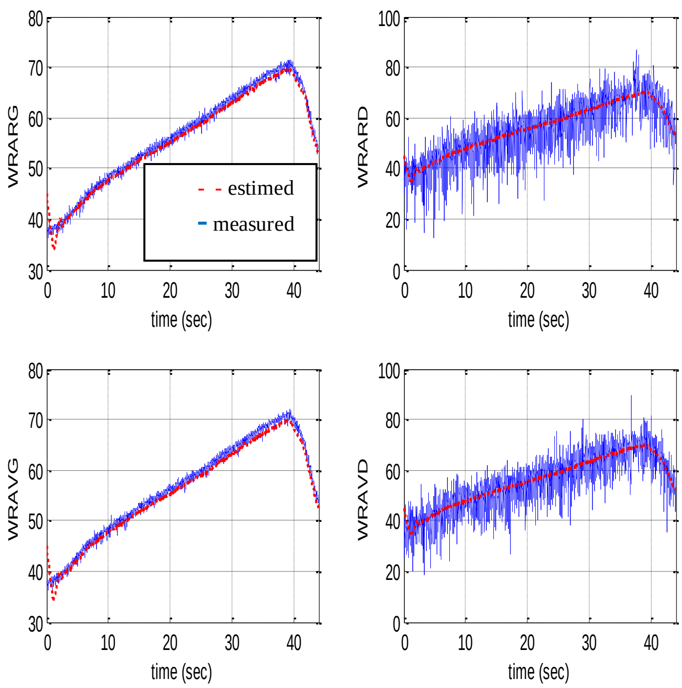

Figure 4. The four wheel rotational velocities

We remark that the results provided by our observer are better than filtered derivatives of the sensor measurements.

A good reconstruction of angular velocity enables the estimation of the longitudinal vehicle velocity. Figure 5 presents both the measured velocity and the estimated one.

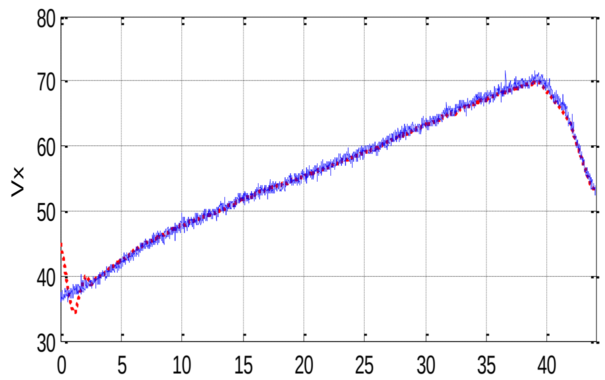

Figure 5. The vehicle velocity

Another test for variable speed is given as shown in Fig. 6 which shows the comparison between the measured angular speeds covered by each of the wheels with those estimated.

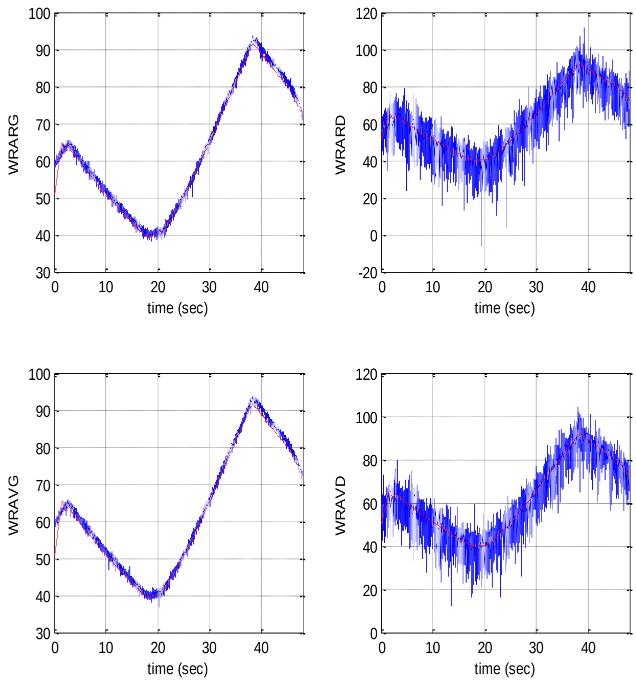

Figure 6. Comparison of the four wheel rotational velocities

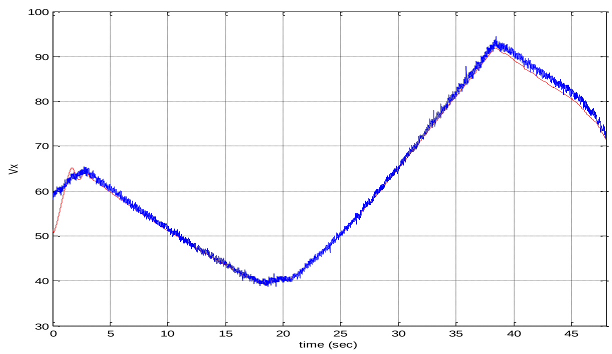

Figure 5. The vehicle velocity

With this test, we see that we can estimate the speed of the vehicle at low cost. This estimate can be used to make the diagnosis method is based on an observer's bench. It may be used in the control systems of the vehicle stability.

CONCLUSION

In this paper, a robust differentiator has been developed using HOSM observers and used to estimate the angular velocities and then reconstruct the longitudinal vehicle velocity. Experimental data have been acquired with use of a Peugeot 406 vehicle (in collaboration with the LCPC) and used to show the design procedure and the merits of the proposed estimator.

In addition, it can be integrated in the vehicles without requirement of extra sensors. The actual results prove effectiveness and robustness of the proposed method. In our further investigations the estimations produced on line will be used to define a predictive control to enhance the safety. Indeed, this estimate will enable us to compare in real time the value measured by the sensor and the estimated. When a sensor fault is detected and the difference it will allow us to detect the fault.

REFERENCES

[1] S. Zhen, H. Tang, Z. Han and Y. Zhan, "Controller design for vehicle stability enhancement" Control Engineering Practice 14 (2006) 1413-1421.

[2] H.Lee and M.Tomizuka. Adaptative vehicle traction force control for intelligent vehicle highway systems (IVHSs) IEEE Trans. On Industrial Electronics, V 50 N 1 February 2003.

[3] D.I. Livingston, J.E. Brown. Physics of the Slipping Wheel,II : Slip under Both Travtive and Lateral Forces. Rubber chemistry and technology, V 43, N 2, 1970.

[4] V. Zanten A.T, R. Erhardt and G. Pfaff. "VDC, the vehicle dynamics control system of Bosch" SAE Tehnical Paper 950759.

[5] S. Drakunov, U. Ozguner, P. Dix and B. Ashrafi. ABS control using optimum search via sliding modes. IEEE Trans. Control Systems Technology, V 3, pp 79-85, March 1995.

[6] U. Kiencken, L. Nielsen. Automotive Control Systems. Springer, Berlin, 2000.

[7] L. Imsland and all ”Vehicle velocity estimation using non linear observers” In journal automatice v42 (2006) 20091-2103.

[8] Laura Ray. Nonlinear state and tire force estimation for advanced vehicle control. IEEE T on control systems technology, V3, N1, pp117-124, march 1995.

[9] K. Yi, K. Hedrick and S. C. Lee. Estimation of Tire Road Friction Using Observers Based Identifiers. Vehicle System Dynamics, 31, pp. 233-261, 1999.

[10] Gentiane Venture. Identification des paramètres dynamiques d’une voiture. Thèse de Doctorat de l’Ecole Polytechnique de l’Université de Nantes, IRCCyN. Nantes novembre 2003

[11] P.J.T. Venhovens and K. Nab, ”Vehicle dynamics estimation using Kalman filters”, Vehicle system dynamics, vol 32, pp.171-184, 1999.

[12] Christopher R. Carlson. Estimation With Applications for Au- tomobile Dead Reckoning and Control. PhD thesis, University of STANDFOR 2003.

[13] R. Ramirez-Mendoza. Sur la modélisation et la commande des véhicules automobiles. PHD thesis Institut National Polytechnique de Grenoble, Laboratoire d Automatique de Grenoble 1997.

[14] S. Mammar, L. Nouvelière, N.K. M’Sirdi. Contrôle intégré d’un Véhicule en Automatisation Basse Vitesse. CIFA2000, Lille

[15] A. Rabhi. Estimation de la dynamique d’un véhicule en interaction avec son environnement. . PHD thesis Université de Versailles, 2005.

[16] N. K. M'Sirdi, A. Rabhi, N. Zbiri, Y. Delanne VRIM: Vehicle Road Interaction Modelling for Estimation of Contact Forces, 3rd Int Colloquium Tyre Models For Vehicle Dynamics Analysis, Vienna, Austria, 2004.

[17] A. Rabhi, N.K. M'sirdi, M. Ouladsine Robust Estimation of Tyre Road Frictions and Contact Forces, Integrated Modeling and Analysis in Applied Control and Automation, Marseille 2005.

[18] A. Rabhi, N. K. M’Sirdi,A. Naamane and B. Jaballah, Estimation of Contact Forces and Road Profile using High Order Sliding Modes, Int. J. Accounting, Auditing and Performance Evaluation

[19] L. Fridman, A. Levant. Higher Order Sliding Modes. Marcel Dekker, 2002.

[20] A. Levant. Robust exact differentiation via sliding mode technique. Journal Automatica, Vol 34, pp379-384, 1998.

[21] Levant, A. Higher-order sliding modes, differentiation and output-feedback control, International Journal of Control, 2003, Vol.76, pp.924-941

[22] V. Utkin, J. Guldner, J. Shi, Sliding Mode Control in Electro-mechanical Systems, London, UK:Taylor & Francis; 1999

[23] J. Davila and L. Fridman. “Observation and Identification of Mechanical Systems via Second Order Sliding Modes”, 8th. In-ternational Workshop on Variable Structure Systems,September 2004, Espana.