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Technical note

# On-line model-based wheel speed filtering for geometrical error compensation☆

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ABSTRACT

Wheel speed measurements provided by incremental encoders in road vehicles are usually affected by a significant periodic noise. Unavoidable geometrical or misalignment errors in the structure of the encoder are here regarded as possible causes of the measurement disturbance. Such disturbances are commonly rejected using simple solutions, like low-pass or notch filters. However, such methods may not be adequate in some applications, as the signal information is canceled jointly with the disturbances, thus jeopardizing the overall system performance. This paper presents an online filtering procedure, based on the geometrical model of the sensor and recursive constrained least squares estimation, aimed at rejecting only the periodic noise. Such a procedure will result into a speed measurement processing that is most suited for advanced vehicle applications. Experimental data are used to show the effectiveness of the proposed approach considering two different vehicles: a bicycle - where the proposed method is shown to be effective for cycling cadence estimation - and a sport car - where the speed variable is of primary importance, e.g., for braking and stability control.

## 1. Introduction

In modern road vehicles, one of the most widely used sensor for measuring the speed of the wheels is the discrete incremental encoder. The working principle is simple: a circular element with several *lines* allocated on it jointly rotates with the wheel, while a *detector* mounted on the vehicle's frame is able to reveal the passage of each *line*.

Among all the available technologies, magnetic encoders are generally preferred for automotive applications, mainly due to their compactness and robustness (see [13]). The wide impact of encoders in the automotive industry has been acknowledged in many contributions, see, e.g., the survey in [4].

In a magnetic encoder, permanent magnets assembled on a rigid disk (the so-called *magnetic wheel*) represent the *lines* and rotate with the wheel, while a Hall sensor (fixed on the vehicle chassis) acts as *detector* and transforms the magnetic field perturbed by the magnets into a voltage signal correlated with the original speed (which is then digitalized obtaining a square wave). An estimation problem then arises: the reconstruction of the wheel speed from a sequences of pulses identified by state changes of the digital square wave.

Speed reconstruction strategies have been extensively studied in the signal processing literature (see, *e.g.*, [6,8,12], where it has been shown that the performance of each algorithm strongly depends on the considered ranges of speed and acceleration.

However, almost all the methods can be seen as refinements of two basic techniques, both relying on a known (usually equispaced) geometrical allocation of the magnets along the circumference of the magnetic wheel: the *lines per period* algorithm, where the number of pulses within a fixed time interval defines the corresponding covered angle, and the *fixed position* algorithm that computes the time interval between two consecutive pulses. With modern electronics, the time span defined by pulse detection events can be computed very accurately, thus the fixed position strategy is usually preferred, in order to have a higher-resolution speed measurement.

Nevertheless, the experimental analysis in [2] reveals the presence of a periodic noise affecting the reconstructed wheel speed, when the fixed position algorithm is employed. In particular, it is shown that the most significant harmonics of the noise arise at multiples of the fundamental rotational frequency of the wheel. The analysis of Panzani et al. [9] shows that such a noise could be attributed to the fact that the center of the encoder and the wheel rotation axis do not coincide.

The magnitude of such disturbances is usually large and has to be reduced, especially if the wheel speed measurement is employed for safety-critical applications like braking or traction control.

Generally, the information processing is directly performed in the control stage, depending on the particular application considered. It is

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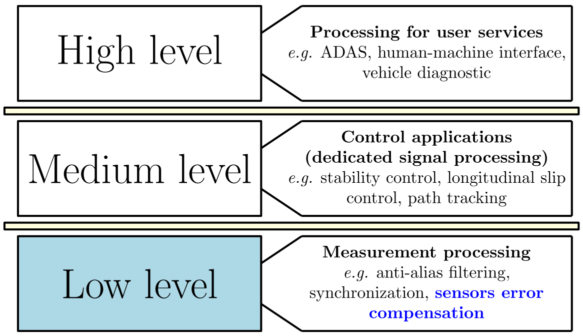


**Fig. 1.** Signal processing levels in vehicles.

possible to rank this procedures among the *medium level* of the signal processing in vehicles, as depicted in Fig. 1. For example, the authors of Panzani et al. [9] show that adaptive notch filtering of the periodic disturbances should be preferred in the traction control framework (with respect to simpler low-pass filtering), as the latter might introduce critical phase delay and remove some of the relevant features of the signal.

In the proposed classification of Fig. 1, a *high level* processing can also be highlighted, which is more oriented to the treatment of information to provide to the user (see, e.g., driver-assistance systems). The strategy described in this paper is instead placed at the *low level*: it is a model based filtering strategy that intervenes in the computation of the rotational speed from the incremental encoder raw signals. It is indeed true that, when the signal application is known (e.g. it is the measured output of a certain control loop), the filtering of the signal can be further improved by taking such a knowledge into account, using more complex filters. This is however out of the scopes of this paper, whose aim is more general.

The proposed filtering approach follows the line introduced in [5,10] , where the main assumption is that the periodic disturbance is due to the non-ideal equispacing of the magnets on the magnetic wheel. The main idea is to estimate these geometrical errors (first characterized in [11]) and to compensate them in the fixed position strategy.

The novel contribution of this paper is to show that the approach in [10] is shown to be equivalent to a constrained least squares problem and to propose an online implementation of the algorithm. The main advantage of the proposed strategy with respect to commonly used filters like notch filters is that the periodic noise can be removed without compromising the information content of the wheel speed signal. Moreover, regarding the implementation, since the method is based on recursive constrained least squares, it is shown to be simple and computationally efficient.

In order to certify the above statement, a bicycle application serves as the first case-study. The irregular nature of the pedalling (see [1]) causes an oscillating torque whose frequency reveals the cycling cadence. This oscillation is rigidly transmitted to the rear wheel and it is contained in the speed measurement although it is not clearly visible from the raw signal (which is affected by the periodic noise). The filtering strategy reduces the effect of the disturbance while preserving the pedalling oscillation for a following cadence estimation via frequency tracking [3]. A comparison with the notch filter concludes this case-study.

The filtering procedure is then applied to a sport car, which represents a second case-study to assess the general applicability of the proposed strategy. Compared to the bicycle application, this second example allows one to show the effectiveness of the approach on a more demanding vehicle, with larger ranges of speed and acceleration.

The paper is structured as follows. The algorithm and the implementation notes are provided in Section 2. The effectiveness of the proposed strategy is experimentally illustrated in Section 3, where a bicycle case study, including a comparison with notch filtering, as well as a sport car case study are analyzed in detail. The paper is ended by some concluding remarks.

## 2. The filtering method

Consider a magnetic encoder with $L$ magnets in a North/South ($N$/$S$) layout. The analog voltage signal provided by the Hall sensor is digitalized by exploiting a 0 $V$ threshold: if the voltage is positive (*i.e.*, if a $N$-oriented magnet is exposed to the sensor), the digital output is 1; as soon as a $S$-oriented magnet faces the sensor, the digital output becomes 0. It is here assumed that both rising and falling edges of this digital square wave count as a pulse.

Without loss of generality, the delays of the Hall sensors as well as the quantization error in the measurement of the time between two pulses are here supposed to be negligible, and the rotational speed is assumed to be $\omega(t) > 0$, $\forall t$ (changes of the rotation direction are not contemplated). Notice that, under the above assumptions, $L$ pulses occur per each revolution.

The basic version of the fixed position algorithm relies on two additional assumptions: (i) the magnets are equispaced and (ii) they are identical. Therefore, in the time interval defined by two consecutive pulses, the magnetic wheel (jointly with the vehicle's wheel) covers a constant angular distance equal to

$$\alpha_{\text{nom}} = \frac{2\pi}{L}. \tag{1}$$

The speed measurement is updated when a new pulse is observed: this approach is usually referred to as *event based sampling*. If $t_{i,\,k}$ indicates the instant of occurrence of the $i$th-pulse out of $L$ total events expected for the $k$th revolution and $\Delta t_{i,k} = t_{i,k} - t_{i-1,k}$ is the elapsed time from the previous event, the computation of the value of the speed reads

$$\omega^{\text{b}}(t_{i,k}) = \omega^{\text{b}}_{i,k} := \frac{\alpha_{\text{nom}}}{\Delta t_{i,k}}. \tag{2}$$

Such algorithm holds for all types of encoder, provided that any rotating part (*e.g.* the magnetic wheel) can be modelled as a disk partitioned by *lines* (*e.g.* magnets) into $L$ equal circular sector of width $\alpha_{\text{nom}}$.

According to Persson [10], when the magnets are not exactly equispaced, the fixed point algorithm yields a biased result, since the width of the circular sectors is no longer constant but equal to $\alpha_{\text{nom}}$. Similar errors could be induced by different reasons, *e.g.* if the axis of the Hall sensor is not effectively perpendicular to the plane of the magnetic wheel (which actually cannot be perfectly planar) or if the encoder center and the rotation axis of the vehicle's wheel do not coincide (see [9]).

In Fig. 2, a graphical representation of a realistic setting is shown: the $i$th sector (*i.e.* the portion spanned in the time interval

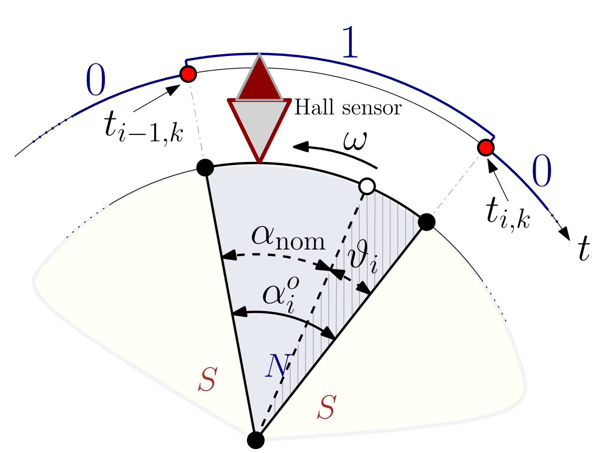


**Fig. 2.** A scheme of the magnetic encoder, assuming that the $i$th sector refers to a $N$-oriented magnet.