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Accurate Speed Measurement Methodologies for Formula One Cars

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Abstract - *There are several methods of speed measurement for F1 applications. In this paper, two measurement systems realized for this aim, a GPS-based and a contact-less sensor based one, are presented. The theoretical disadvantages and practical risks for each solution are described. Particular attention is focused on the solution based on contact-less optical speed sensor, currently considered the best way to satisfy the requirements of the very harsh racing environment. The first results of laboratory experiments carried out using such sensor, show possible short-term improvements.*

Keywords – *F1, GPS, contact-less speed sensor, IMU, INS.*

I. INTRODUCTION

NOWDAYS, several alternatives exist to estimate the vehicle velocity. The ground speed sensors can provide potentially important inputs to advanced vehicle control systems, including instrumentation, navigation, braking, traction and steering. These subsystems require true speed measurements independent of wheel slip or skid, often under extreme conditions. Unfortunately, F1 cars can't use the Anti-lock Braking System (ABS), because it is forbidden by the FIA (Federation Internationale de l'Automobile) regulations, and the resultant locking of the wheels during hard braking increases the difference between wheels speed, measured by traditional accelerometers, and the true ground speed. However, the speed measurement accuracy, in the racing context, is fundamental for the performance monitoring and for the strategy management. A typical application is the split time computation/comparison (Fig.1). F1 is a typical application where high precision is required and where the basic environmental specifications usually considered for automotive industry sensors (temperature range, vibration, speed range, etc) are not appropriate. The next Sections focus on two speed measurement systems realized to be installed on Ferrari F1 racing cars. The first one is based on Global Positioning System (GPS), by tracking the car position versus time. The second one is based on contact-less sensing of speed. Each Section gives an overview of the specific solution considering F1 car compatibility issues, like robustness, installation, safety, delay, dimensions, weight, Electromagnetic Interference (EMI). The last Section is dedicated to contact-less optical speed sensor that is actually used on the Ferrari 248F1 to compute a real time ground speed value.

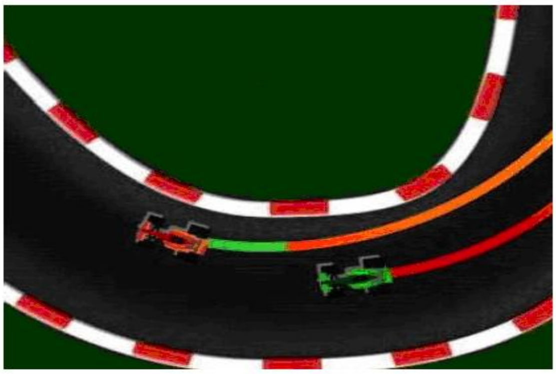

Fig. 1 Performance monitoring by speed information.

II. GLOBAL POSITIONING SYSTEM

A. *F1 GPS receiver*

In order to track the car position during the races, a GPS receiving system has been designed and developed.
The system core is an L1/L2 receiver with 24 channels "all in view" parallel tracking and 20 Hz raw data and position output rate has been adopted. A system for voltage and temperature monitoring and reporting has been added,.
This receiver with dual-frequency capabilities makes the following possible:

- Longer baselines in differential positioning mode, due to the reduction of atmospheric errors.
- Faster resolution of carrier-phase ambiguities when performing RTK (Real Time Kinematics) positioning.
- Enhanced positioning precision due to the additional measurements [1-3].

Specific enclosures offer protection against environmental conditions and radio frequency interference. In fact, there are several transceivers on an F1 car, necessary to exchange information with the pit equipment about position monitoring, timing control, accident condition, and so on. As they should be used in race conditions the enclosures provide also a shock and vibration-resistant housing.

An RF section performs the translation from the incoming RF signal to an IF signal usable by the digital section. The RF section can reject a high level of potential interference (e.g. cellular phone, telemetry of others teams, TV sub-harmonic signals, and FIA transmission service). The digital section of the receiver, receives a down-converted, amplified GPS signal which is digitized and processed to obtain a GPS solution (position, velocity and time).

An RS-232 interface can be used to communicate with a host computing unit for configuration and transmission of logs .

Normally the boot needs about 10 s but this is not a big problem considering the time interval between launch procedure on starting grid and race start.

B. Antenna design

The GPS antenna must be installed on car in order to have direct visibility of the sky. If this is not possible (e.g. GPS temperature range incompatible with temperatures in some areas near of engine) a Kevlar circular cover can be applied, provided that it is wide enough to leave to the antenna a minimum 170° cone visibility of the sky. In this manner each satellite above the horizon can be tracked without obstruction. Multipath signal reception is one of the most plaguing problems that detracts from accuracy potential of GPS pseudo range differential positioning systems [2,4]. Each track (The World Championship includes 18 tracks) has different multipath conditions but in every case both the direct and reflected signals are present at the antenna and the multipath signals have lower amplitude than the direct signal. Obstruction of direct path signal is very common in city track (e.g. Gran Prix of Monaco) environments where many tall buildings block the line of sight to the satellites. If the GPS receiver is in a valley with nearby hills, mountains and heavy vegetation (e.g. Monza track), signal obstruction and attenuation are also very common. A few options exist by which GPS users may reduce the level of multipath reception. Some of them are:

- *Antenna site selection* - it's important to place the antenna as far as possible from obvious reflective objects, especially reflective objects above the antenna's radiation pattern horizon. GPS antenna has been mounted on the roll-hoop (higher point behind the driver seat) in Kevlar housing. Water bodies are extremely good reflectors. Because of the short wavelengths at GPS frequencies, even small ponds and water puddles can be a strong source of multipath reception, especially for low angle satellites. However, during the rainy sessions monitored until now the increase of multipath error has been negligible.
- *Special antenna design* – quadrifilar helix antennas and other similar vertically high profile antennas tend to have high radiation gain patterns at the horizon. The antennas used during the carried out tests incorporate some form of left hand circular polarization (LHCP) rejection.
- *Ground plane options* - one of the roles of the antenna ground plane is to create a stabilizing artificial environment that becomes a part of the antenna structure and its resultant radiation pattern. The designed and realized antenna, thanks to its soft boundary, prevents the wave from propagating along the surface of the ground plane and thereby reducing the edge diffraction effects.

C. Results of the first experimental evaluation

The GPS tracking system has been mounted on car in several tests in order to satisfy the most of racing requirements. The receiver was placed laterally to driver seat, as close as possible to the car's center of gravity. This placement is good relatively to vibration and temperature levels. As demonstrated in the several test sessions, the biggest disadvantages of this solution are two, precisely:

- *Electromagnetic Interference* – the noise introduced by other transmission devices mounted on the car can be removed thanks to a notch filter. In fact, when there are not other cars on the track the EMI problem is negligible. On other hand it's no simple to eliminate the interference caused by competitor cars, especially if they are near on the system isn't shielded.
- *Coverage* – this is a serious limit of GPS in racing context! It respects very hard accuracy resolution standard (less of 0.001 km/h with differential mode) but the coverage is necessary during all lap and on all 18 tracks of the World Championship. In order to collect useful data and so to estimate a correct position are necessary at least 4 available satellites. Unfortunately, only few circuits resulted to be totally covered.

If GPS alone cannot continuously give the position of a vehicle, other navigation aids are necessary. Future work will concentrate on coupling of GPS and an inertial platform. In practice, when the first device can't return a good velocity estimate, the second one replaces it.

D. A new perspective: integrating GPS and INS

Integration of GPS and Inertial Navigation System (INS) is a moderately affordable and economic solution where highly accurate position and altitude information is required. INS measurement provides angular rate and acceleration with respect to the body frame. It generates high short-term accuracy but the measurement can be noisy. The general approach to integrate GPS and INS information is via Kalman filtering technique which is defined as to minimize the mean square errors of both systems [5-7]. In addition,

GPS/INS integration by using Kalman filter improves the performances
and robustness of the system by providing a state estimate during GPS signal loss.
In order to implement such integration, an Inertial Measurement Unit (IMU) has been selected. This device utilizes the triaxial gyros to track dynamic orientation of car and triaxial DC accelerometers along with triaxial magnetometers to track static orientation. Full temperature compensation is provided for all nine orthogonal sensors (three per axis) to insure performance over a wide operating temperature range. The IMU can output orientation information in three different forms: Quaternion, Euler angles and 3x3 rotation matrixes. The rotation matrix is expressed as follows:

$$M = \begin{bmatrix} m11 & m12 & m13 \\ m21 & m22 & m23 \\ m31 & m32 & m33 \end{bmatrix} \equiv RotationMatrix \qquad (1)$$

where M satisfies the vector equation

$$VL = M \cdot VE \ , \qquad (2)$$

VE is a vector expressed in the earth-fixed coordinate system and VL is the same vector expressed in the IMU local coordinate system.
Euler angles consist of pitch, roll and yaw or equivalently elevation, bank and heading. They can be obtained from the rotation matrix coefficients as follows:

$$\begin{aligned} \theta &= \arcsin(-m13) \equiv Pitch \\ \phi &= \arctan(m23/m33) \equiv Roll \\ \psi &= \arctan(m12/m11) \equiv Yaw \end{aligned} \qquad (3)$$

The most of accurate integrations between GPS and INS are implemented in aerospace applications. Actually it isn't possible to transfer aerospace technology to F1 car due to dimensions and weight (≈ 2 kg) of IMU. Next efforts will be focused on this goal.

III. SPEED MEASUREMENT WITH CONTACT-LESS SENSOR

A. *Optical contact-less measurement of speed*

A valid alternative to tachometer is certainly an optical sensor. In traditional speed measurement systems that use this kind of sensor, basically, the velocity is obtained by measuring the time delay between two signals. This delay is inversely proportional to the velocity, ideally [8-10]. The measuring head, mounted under the chassis, faces the road surface. It contains two optical sub-systems to scan the track. The asphalt is illuminated by a solid-state infra-red light matrix source (Fig.2). This light is reflected and converted into electric signal by a photo-detector located in same head. They only blur the sharp scanning slits. Therefore, vertical distance variations of the measuring head due to suspensions loading or due to wear in the wheels have no influence on the time delay between the two signals and consequently on the measurement accuracy. Using the road as a reference surface for the optical system assures that there is a continuous stream of signals which can be used for delay estimation. Only interruptions at road shunts or rapid color changes of asphalt, for example, cause short-time gaps in signal. Therefore the processor can produce a continuous stream of velocity measurements computed from these signals.
Applying the maximum likelihood principle for the estimation of the time delay D between two stochastic signals disturbed by additive noise gives an estimator, which yields the generalized cross-correlation function [9].
This estimator can be realized in an open-loop or a closed-loop structure; the first one computes the cross-correlation function:

$$R_{xx}\left(D-\hat{D}\right) = \frac{1}{T}\int_0^T X_1\left(t-D\right)X_2\left(t-\hat{D}\right)dt \qquad (4)$$

For a set of values of the trial parameter $\hat{D}_1,\ldots,\hat{D}_n$. The value of $\hat{D}_k$ for which R_{xx} function is maximal is the most likely estimate. The observation time T must be chosen as a trade-off between two requirements. On the one hand, T should be as large as possible in order to minimize the variance of the estimate which is roughly proportional to $1/\sqrt{T}$. On the other hand, T must be chosen sufficiently small to prevent a spreading of the peak in the correlation function caused by delay variations during the observation time.
Since the derivate of the delay D with respect to time is inversely proportional to square velocity:

$$D = \frac{Ldv}{V^2 dt} \qquad (5)$$

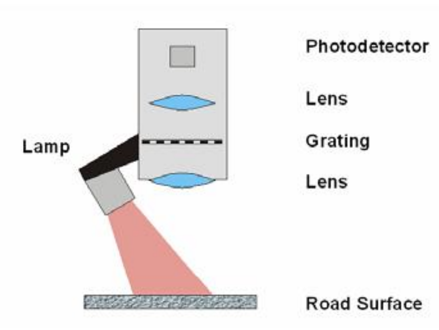

Fig. 2. Scheme of the optical sensor.

where L is the distance between the sensors and the largest values of D are found for low velocities.
The maximum allowable delay variation is:

$$|\Delta D|_{\max} = |\Delta|_{\max} \cdot T_e \,. \tag{6}$$

From (6) the observation time T_e can be determined.

The performance of the measurement system should be regarded under two different aspects: (i) the uncertainty when continuous signals are provided and (ii) the reaction on signal interruptions.
The variance of the estimate is a suitable performance measure under stationary conditions. It can be determined, for a given observation time T_e, from the second derivate of the cross-correlation function of the optimally pre-filtered signal taken at the location of the true delay. Thus, the cross-correlation function should have a sharp peak in order to yield a good estimate. In the case of optical signal generation this is accomplished by taking scanning slits that are narrow with respect to the distance L of the two sensors. The most of uncertainty is caused by:

- non-identical analog signal path;
- analog to digital signal conversion;
- discrete approximation of the estimate algorithm.

Typical problem with an optical device is its sensitivity to smudging. Suitable precautions, such as aero-dynamical shaping of the sensor box and air jets to prevent the penetration of dirt are unavoidable in a racing application.

B. *Experimental sensor*

The optical sensor used during the tests provides highly accurate measurement of distance, speed and acceleration, tire slip angle, drift angle and yaw angle. It uses proven optical correlation technology to ensure the most accurate signal representation. A high-intensity light source illuminates the test surface, which is optically detected by the sensor via two-phase optical grating system (Fig.3).

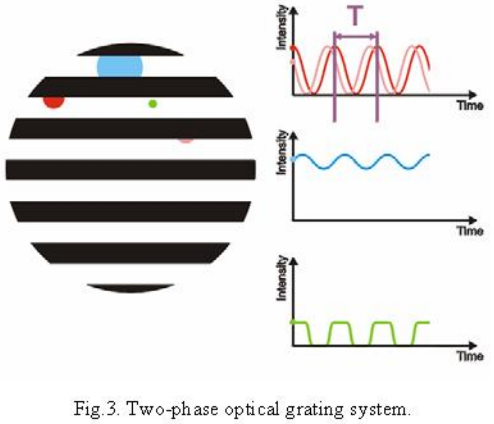

Fig.3. Two-phase optical grating system.

The sensor consists of a light source, imaging optics, and a photo-detector array. An optical spatial filter is formed by combining the alternate elements of the array in two groups and taking their difference electronically.
When there is a relative movement between the surface and the sensor, the spatial filter selectively interferes with the particular spatial frequency component in the projected surface pattern, resulting in a time-varying signal.
The frequency of such time variations is proportional to the speed and can be measured in terms of pulse count or time period. Precisely:

$$dx = (g \cdot N)/M \tag{7}$$

where x represents the distance, g is the optical displacement, N is the number of pulses and M is called magnification factor.
To represent the value of speed v it is possible to use the next formalization:

$$v = (g \cdot f)/M \tag{8}$$

Figure 4 represents a model of head sensor and it underlines the optical steps to obtain the output signal which is the sum of all individual texture points in field of view.
The output of device can be defined *two-axis speed* because the grating type is two-dimensional (Fig.5). Fig.6 represents the frontal section of grate. The movement is calculated from right (red arrow) and left (blue arrow) components, using Pythagoras/trigonometry rules. The specific measured data (traveled distance, speed, angle, etc.) is made available to the CAN-Interface (Controller Area Network) of the sensor system.
The sensor should be aligned parallel to the direction of car travel so that there is no horizontal offset angle. In F1 application it also very important to consider factors such as suspension pitching, vibration, dust or water spray when choosing a mounting location and housing for sensor. The performance of device depends on some track characteristics, like aquaplaning and color of asphalt.

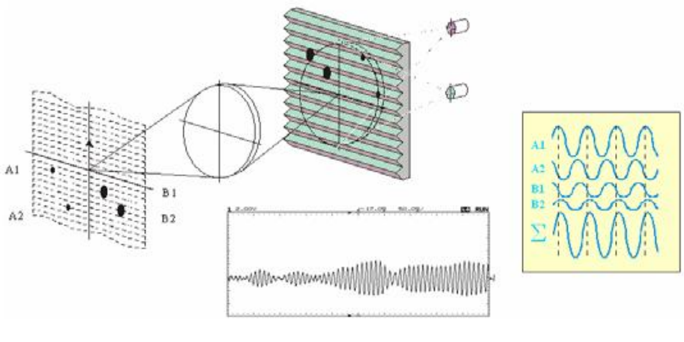

Fig.4. Optical head sensor scheme.

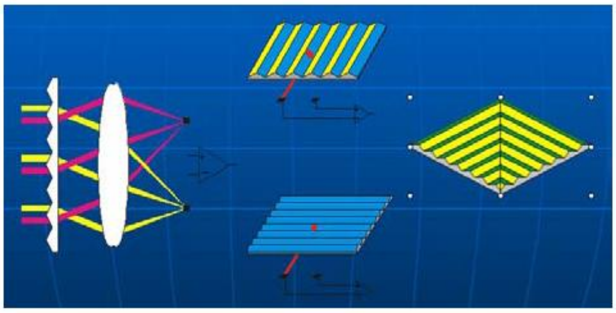

Fig.5. Two-dimensional grating.

Fig.6. Front section of the grating system.

On wet surface the reflected light on optical sensor can reach 40% but if the water level is lower of 10 mm there isn't risk of anomalies.

The sensor should be mounted on a rigid location, far from engine vibration. Suspension pitching effects can be removed by post-processing to smooth the data; it's possible to regulate the filtering entity to find the best trade-off between quality of signal (Signal to Noise Ratio - SNR) and the delay introduced by processing.

C. *Experimental filtering strategy*

The digital filtering system of the optical sensor system is programmable. More in detail it's possible to set a number of filter taps from 4 to 512 in steps of 4 (1 tap $\approx$ 1ms). To modify the kind of filtering is sufficient to write some dedicated setting registers by means of an RS-232 interface. Intuitively a greater filtering time increases the SNR, but increases the introduced delay, too. On the other hand, reducing the number of taps the delay will reduce proportionally, but the SNR improvement will decrease.

It's not sufficient a qualitative evaluation of phenomena to find the exact number of filter taps which returns the best trade-off that minimize delay and noise at same time. The optimal number of taps has been selected experimentally. A measurement set up consisting of (i) two optical sensor heads, (ii) two optical sensor controllers, and (iii) a power supply unit has been realized. It has been used to measure the velocity of a belt simulator, as in Fig.7. Both sensors have been mounted in same position, with lens on front of electric belt at about 20 cm distance.

The first one is programmed with max filter action (512 ms) and it is called *reference sensor* because it doesn't change the filter taps number during all measurements. The second optical head is called *test sensor* because before of each measurement its filter taps number decreases of 50% (512, 256, 8, 4). At each step the belt speed has been measured for 90s (30s per three repetitions) using a sampling frequency of 1 kHz. The function of the belt device is to simulate the car movement on the road; precisely, it can simulate low speed motion (max. 34 km/h) of car on straight segment of a track perfectly plane. The presence of bends and slopes in this experiment has not been considered.

The purpose of the logging system is to reproduce the F1 car ECU (Electronic Control Unit), CAN and telemetry acquisition software. Each measurement step consists of several increase-decrease cycles of the belt speed. As above mentioned on the belt simulator are mounted two optical sensors to log the misalignment between reference device and test device.

Figure 8 represents a plot of the belt velocity measured simultaneously by two identical sensors with different filtering set-ups. The device with the shorter filter returns a poor quality signal, while sensor with the longer ones generates a very low noise output.

In order to determine quantitatively the best trade-off between the filter length and its smoothing action, a statistical analysis has been carried out to study the speed measurement accuracy starting from the mean and the standard deviation of the speed measures. Some self-made Matlab® functions have been used for this aim. By analyzing the results obtained for each filter length and the latency of each filter, the 32 tap filtering solution resulted to be the

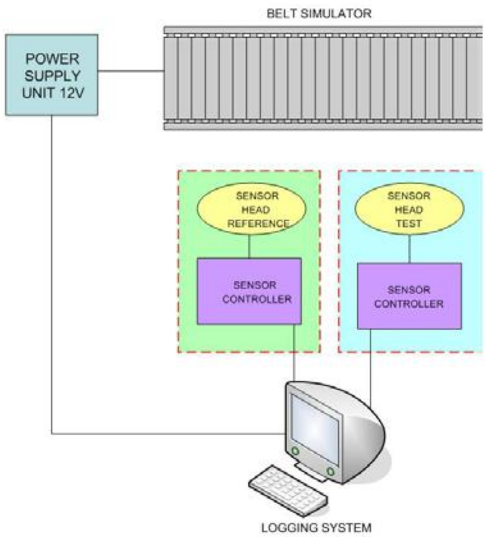

Fig.7. Block scheme of the calibration bench.

most appropriate approach to have an accurate speed estimate value, in hard work conditions and with similar delay ($\approx$ 10 ms) respect to traditional speed estimation algorithm, based on wheels accelerometers.
Like GPS device, the optical sensor should be coupled to an inertial platform for the same reasons. A future effort can be oriented to study the potential benefits by complementary use of both systems.

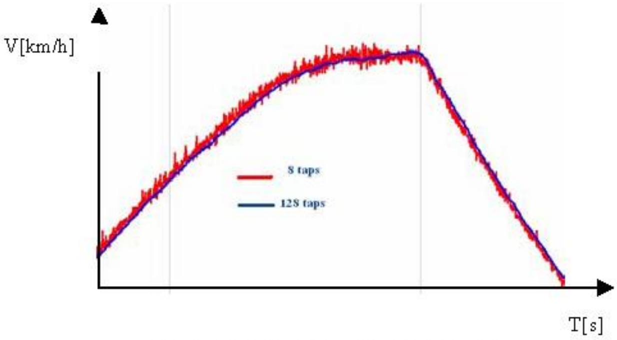

Fig.8. Belt velocity with different filters.

IV. CONCLUSIONS

Two different methods for measuring F1 car velocity with high accuracy have been implemented compared: GPS and contact-less speed measurement.
GPS can reach an excellent accuracy level and its install/maintenance management is relatively simple. its disadvantages should be dampen down by implementing a GPS-IMU integrate system. Currently test and race sessions are On other hand, two obstacles currently persist for racing use: EMI (caused by competitors team transmission system) and satellites coverage discontinuities (i.e. caused by a presence of bridges on track). GPS solution is not abandoned because focused on assuring reliability of contact-less optical sensors for measuring the car speed. The laboratory goes on to improve signal processing performance. The combination of a precise optical system and digital signal processing could yield a speed measurement system of very high precision and reliability. It's possible to have an optimal matching with the race specifications by regulating conveniently the filtering asset. The accuracy of the adopted device is about 1%. The small variations that could be experienced depend on several factors, the most important are: color/water level of surface and software set up.

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