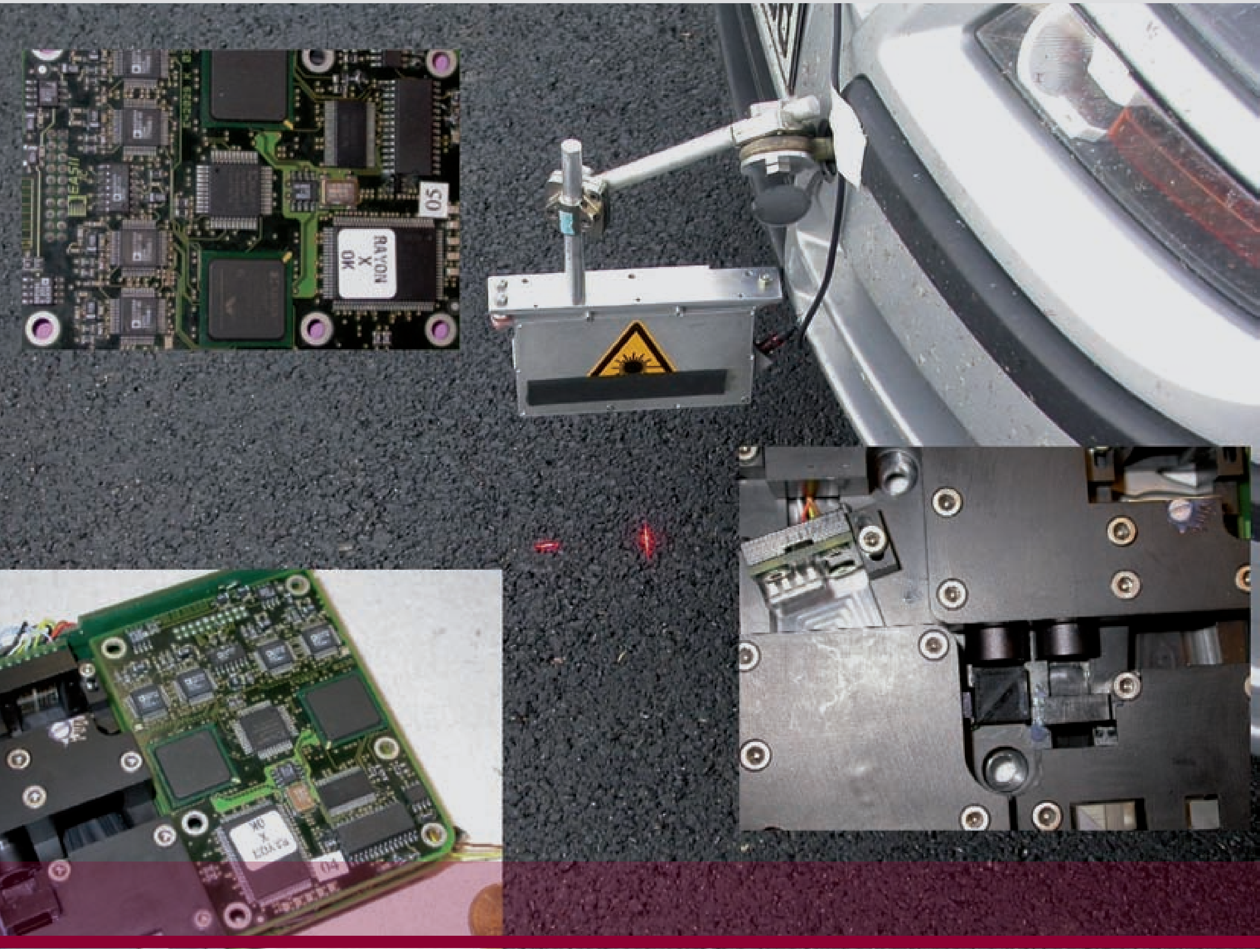

High-Performance Speed Sensor for Formula 1 Applications

The Laboratoire d'Electronique et de Technologies de l'Information (LETI), Grenoble, France, in cooperation with Michelin Technology Centre has developed a high-performance speed sensor prototype dedicated to tests in Formula 1 (F1) car races. The challenge was to obtain a highly accurate and real-time sensor that is able to operate on wet surfaces and to calculate both the speed and the slip angle. An optical solution based on a correlation principle was adopted. Three prototypes have been developed and tested.

1 Principles and General Description

The sensor basically uses the physical proprieties of point scatterers moving under the car during its displacement. Sampled laser images of the surface are taken by photodiode arrays. An autocorrelation function is computed giving accurate speed and slip angle estimations of the vehicle. This approach is well known in printing or textile industries, where control of speed is essential in assembly lines [1]. The sensor is designed to work with velocity ranges from 2 km/h to 400 km/h. Slip angles from -10 ° to +10 ° can be calculated. The various experiments have shown that this field covers the major part of F1 longitudinal and transversal dynamics. The size of the sensor facilitates rapid mounting on the car, which can be on the keel for racing cars or anywhere on the chassis. Data are transmitted to a PC in real time via a CAN bus. **Figure 1** illustrates the sensor mounted on a Formula 3000 car.

2 System Configuration

The block sensor is essentially composed of two laser diodes that emit elliptical beam shapes. They illuminate the ground on the longitudinal axis of the car. The length *B* separating the two spots is constant and constitutes a determinant parameter of the system. Two linear photodiode arrays collect the reflected light beams on the ground. The first one – the front photodiode array – is mounted on the longitudinal axis, whereas the second one – the rear photodiode array – is arranged orthogonally to the direction of motion. Basically, the correlation is performed between a point scatterer that is illuminated alternatively by the two laser beams. If the slip angle is different from zero, the diode where the signal is maximum is shifted from a distance ΔD from the centre of the rear photodiode. The time τ that elapses before peak correlation is detected between the rear and front images. The speed and the slip angle are basically given by Eq. (1) and Eq. (2):

$$Speed = \frac{B}{\tau.\cos(sip\ angle)} \qquad \text{Eq. (1)}$$

$$\tan(Slip\ angle) = \frac{\Delta D}{B}. \qquad \text{Eq. (2)}$$

Figure 2 illustrates this general configuration.

The sampling period of the ground inherited from the linear photodiode array is a determinant parameter that will impact directly on the accuracy of the system. The choice was made to drive the acquisition frequency of diodes so that the ground sampling remains constant during the displacement of the vehicle. For that reason, the algorithmic concept includes a control loop that adjusts the sampling frequency according to the speed estimation. When the speed of the vehicle is too low, only two spaced pixels from the front photodiodes array are used and a correlation between their recordings is computed. Thus, only the longitudinal speed is measured in this case. Finally, the

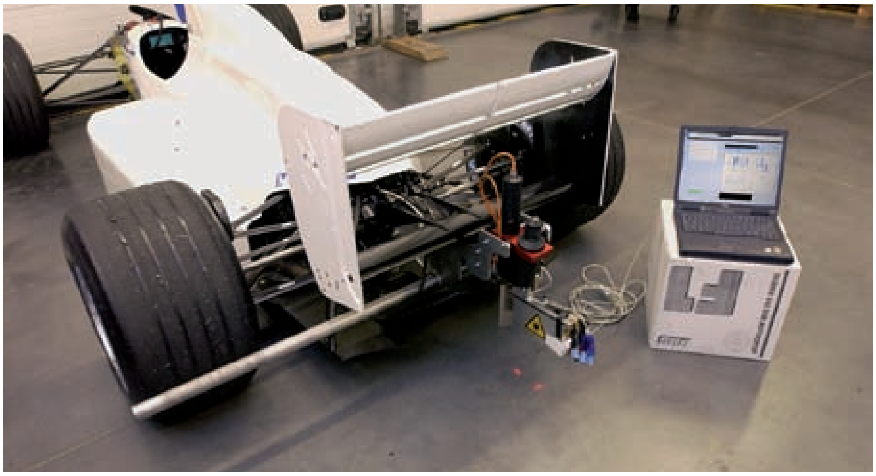

Figure 1: Speed sensor mounted on a F 3000

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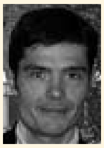

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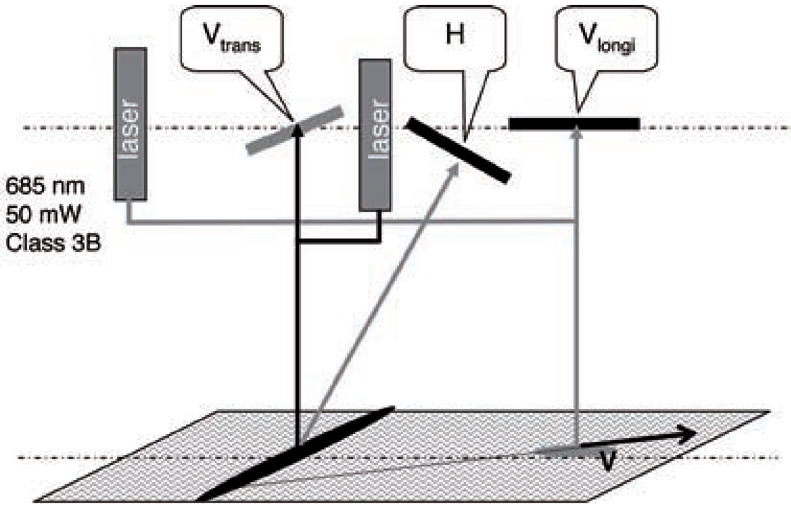

Figure 2: General principles of the speed sensor

Table 1: The two working modes of the VF1 sensor

	Speed estimation	Slip angle estimation
Lower speed mode [2 km/h– 42 km/h]	Estimated on front photodiode	Not estimated
High speed mode [40 km/h – 400 km/h]	Estimated between front and back photodiodes arrays	Estimated between front and back photodiodes arrays

system offers the operating modes shown in **Table 1**, which are automatically adapted depending on the speed estimation. In order to take into account optical growth beam variations caused by the movements of the car, the height of the sensor is continuously computed using a triangulation process, thus requiring another specific linear photodiode array. The result of this calculation is directly entered into the algorithmic loop of correlation. Ground height measurement is useful for users in controlling the movements of the car.

When working on wet ground, specular reflections from water have to be avoided. The first solution is to use a specific inclination of the laser beams. For example, **Figure 3** shows that an orientation of 3 ° in both directions is not sufficient to run on wet ground, whereas 8 ° of orientation in both directions is efficient. Therefore, a precise design of the laser trajectories is necessary. The second solution is to apply specific pre-processing in order to reduce spurious peaks. The principle is to pass the signal received on each pixel through a filter based on information provided by an analysis of its histogram. Thanks to these techniques, the VF1 sensor offers good functionality not only on wet ground but also on ice or snow.

3 Choice of Components

Most of the basic components of this development are available off the shelf, which means that further optimisation is probably possible if a specific design is performed. With regard to optical block issues, two class IIIB laser diodes are used in order to ensure sufficient ground illumination. The other optical elements are mainly composed of filters and cylinder lenses that are used to shape linear laser beams on the ground. Spherical doublet lenses then ensure good focusing on linear photodiode arrays. Signals from the laser are digitalized by a 10-bit A/D converter at a sampling rate of 2.5 MHz. The data are sent to reconfigurable computing devices based on two Field Programmable Gate Arrays (FPGAs) – Xilinx Virtex 2. The following output parameters are finally calculated at a frequency of 100 Hz: height measurement, longitudinal speed and slip angle. The stream of data is then transmitted through a high-speed CAN bus. The power consumption of the device is about 10 W.

4 Testing and Results

The prototype has been set up and tested with a dedicated tool able to simulate high speed and slip angle variations. After a calibration phase, the prototype was successfully used in real conditions on racing car circuits. More than 50 trials have been performed since 2003. These measurements have made it possible to significantly improve the sensor performance and to validate its use under a wide variety of conditions, including driving on wet and moist

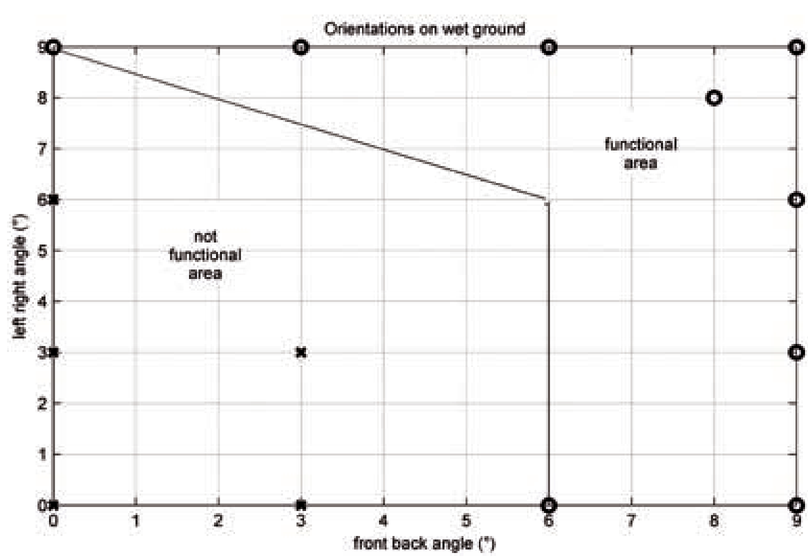

Figure 3: Area of operation on wet soil

Table 2: Performance of the VF1 sensor

Sensor parameters	Low speed mode speed	High speed mode Speed Slip angle	High speed mode Speed Slip angle	Height
Range	2-42 km/h	40-400 km/h	-10° +10°	130-220 mm
Error Mean Max	0.1 % – 0.4 km/h 0.3 % – 1.1 km/h	0.2 % – 0.8 km/h 0.4 % – 1.6 km/h	0.04° 0.13°	0.4 mm 0.7 mm
Linearity	0.3 % – 1.1 km/h	0.7 % – 2.7 km/h	–	–
Resolution	<0.02 % < 0.06 km/h	< 0.02 % < 0.06 km/h	< 0.1°	< 0.3 mm
Noise (rms)	0.01 km/h/√Hz	0.01 km/h/√Hz	0.01°/√Hz	0.01 mm/√Hz
Noise (pp) (B = 50 Hz)	0.3 km/h	0.3 km/h	0.09°	0.09 mm

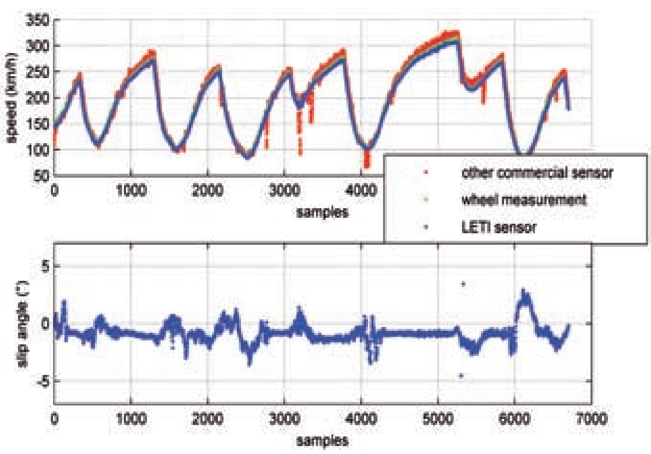

Figure 4: Speed and slip angle recordings on dry ground

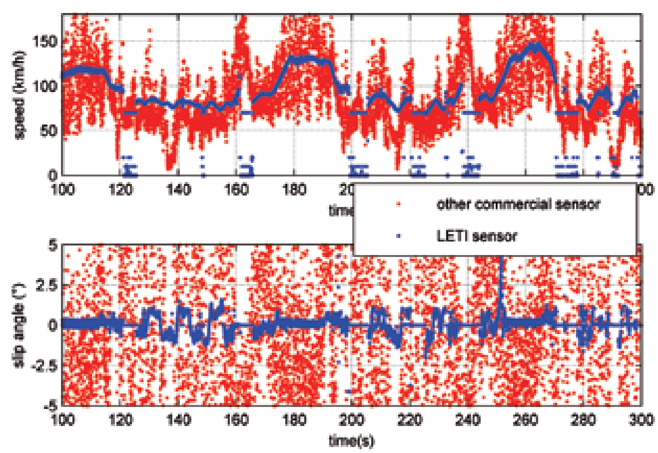

Figure 5: Speed and slip angle recordings on wet ground

surfaces. A commercial optical sensor was used as a reference for real trials on circuits. The results demonstrated a high degree of similarity on dry ground, **Figure 4**, and better robustness on wet ground, **Figure 5**. It is assumed that these results prove the engineering maturity of this prototype. The total amount of collected data can be used to calculate the performance of the sensor. **Table 2** shows the main characteristics of the sensor. As the physical principle of this sensor is based on ground characteristics, the measurement can also be used to study and compare different soils. Some experiments were conducted over many asphalts and surfaces such as ice and snow, as well as grassy and stony ground. Basic optical signals of some pixels were acquired over several tens of centimetres during a run. Analysis of the statistical distribution of the samples and the frequency contents of the signals show differences between surfaces. For example, the kurtosis parameter, which corresponds to a measurement of the relative flatness of a real distribution of a random variable compared to a normal distribution, delivers the results given in **Table 3**. It could be used to characterise ground surfaces. This kind of information may help to adapt the racing car parameters to asphalt and inform the racing driver of the conditions.

Table 3: Results of the kurtosis characterisation for several ground surfaces

Grounds	Kurtosis
Dark and smooth asphalt	18
Clearly asphalt with some small stones	21
Clearly asphalt with many small stones	25
Track ground with grass	8
Stony track	5
Dark wet asphalt	40
Clearly wet asphalt	33
Snow	2
Ice	13

5 Conclusion

It goes without saying that slip angle and accurate speed measurements are decisive for car races or even for improving new dynamic systems and controls. The VF1 sensor prototype has demonstrated its effectiveness for accurate speed measurement. In particular, the most innovative function is the ability to operate on wet surfaces, which often remains a key challenge for non-contact speed sensors. Furthermore, the system has full real-time functionality, which is another advantage if processed data are likely to be used by another embedded system.

The simplicity of the global architecture – an electronic board and optical parts – offers a lower cost implementation. Additionally, power consumption and packaging can also be reduced, thus making the use of this device very simple. The objectives of the next studies are to exploit the possibilities of the 2D image sensor and to add external sensors, for example accelerometers, to extend the number of measured parameters of the movement of the car.

Reference

[1] Sabater J. : Vélocimètre laser par corrélation. In : J. Optics (1980), vol. 11, no 4, pp 225-229