Distributed Sensor for Steering Wheel Grip Force Measurement in Driver Fatigue Detection

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***Abstract*—This paper presents a low-cost and simple distributed force sensor that is particularly suitable for measuring grip force and hand position on a steering wheel. The sensor can be used in automotive active safety systems that aim at detecting driver's fatigue, which is a major issue to prevent road accidents. The key point of our approach is to design a chain of sensor units, each of them provided with some intelligence and general purpose capabilities, so that it can serve as platform for integrating different kinds of sensors into the steering wheel. A proof-of-concept demonstration of the distributed sensor consisting of 16 units based on capacitive sensing elements has been realised and preliminary results are presented.**

I. Introduction

Today, it is well recognised that driver fatigue is a contributing factor in a large number of road accidents. Thus, developing intelligent systems for assessing driver's vigilance level is becoming a central issue in the field of active safety research [1]. Such systems are based on the assumption that the occurrence of fatigue or drowsiness can be related to measurable changes in driver's state and behaviour. A crucial point is therefore the way those changes are revealed, that is, the methods employed to detect driver's fatigue must be reliable, as well as non-intrusive [2], [3], [4].

The approaches presented in the related literature can be grouped into two major classes according to the source of the data used. On the one hand, there are methods based on signals from the driver. These include physiological parameters, such as electroencephalogram, electrocardiogram, electromyogram and skin conductivity [5], whose measure usually requires electrodes to be applied to the driver. Other driver-related signals are eye movement, head position, and facial expression, which can be acquired using cameras and computer-vision [3]. On the other hand, the vehicle's behaviour including its speed, lateral position and distance from the vehicle in front is monitored [6].

In general, driver-related data reveal a stronger correlation to the driver's vigilance level than vehicle-related ones, which suffer from a larger sensitivity to external parameters, such as road and traffic conditions. On the contrary, the measure of driver-related signals usually results more difficult and invasive. However, a promising approach can be found in considering the data available at the interface between driver and vehicle, i.e., the steering wheel and the pedals, which may provide direct information about driver's state and can easier be acquired [4]. In particular, the grip force that a driver applies to the steering wheel has been used in driver's hypovigilance detection systems [4], [7], [8]. It is important to notice that the effectiveness of such systems can significantly be improved through the fusion of different kinds of data [8].

Although several promising methodologies for driver fatigue detection have been proposed in literature, much work still needs to be done in the research of effective solutions to their practical implementation. The aim of this paper is to describe a low-cost distributed intelligent sensor, which can easily be integrated into a commercial steering wheel for real-time grip force measurement. Moreover, the proposed sensor is also able to provide information about the position of the hands on the steering wheel and it can be connected to an on-board ECU (Electronic Control Unit) by means of a simple digital interface. As a result, the grip force data is integrated into the information data flow of the car active safety system, which can use the sensor also to measure driver's response to noninvasive stimulus that it generates to test driver's vigilance level.

II. Steering wheel distributed sensor

The key point of our approach is to integrate a distributed sensor network into the steering wheel, as sketched in Fig. 1. Each unit of the distributed sensor network embeds a tiny microcontroller, which is in charge of reading the actual sensing element and transmitting the local data over the sensor chain. In addition, it is possible to cascade an almost arbitrary number of units through a simple interface made up of 4 wires, which comprise power supply, clock, and a bidirectional data signal. This solution offers significant advantages as compared to having a set of dumb sensing elements along with a centralised acquisition module, as proposed in [4] in which 17 groups of 3 sensors (polyvinylidene fluoride film, piezoresistive, and temperature sensors) are used. Obviously, adopting a distributed sensor network approach, the wire harness of the overall sensor and its integration into the steering wheel is dramatically simplified [9]. Moreover, the

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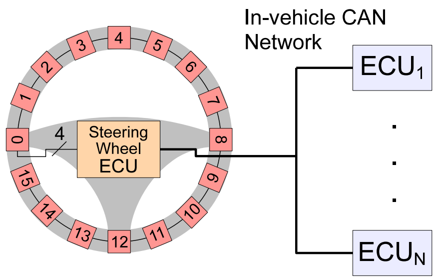

Fig. 1. Steering wheel distributed sensor.

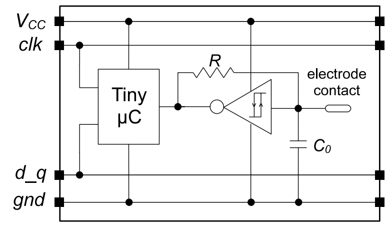

Fig. 2. Basic schematic of the sensor unit.

small additional cost due to the presence of a microcontroller in each unit is comparable with the cost of the analogue multiplexer required in the centralised approach [4], whose complexity also increases with the number of units utilised.

Fig. 1 shows a possible application scenario of the distributed sensor network, in which 16 units are cascaded, so that a good spatial resolution is obtained. In the considered scenario, the first element of the sensor chain is connected to the nearest CAN (Controller Area Network) node, i.e., the *Steering Wheel* ECU. We notice that the In-Vehicle CAN network seems to be the ideal infrastructure for sharing data relevant to driver's fatigue detection, which can be performed by either the *Steering Wheel* ECU, or another ECU specifically devoted to active safety. In this way, some valuable data, such as steering angle and torque, which are already available from the Servo Steering ECU, can be exploited by detection algorithms without the need of additional hardware.

As far as the sensor network management is concerned, each unit owns a unique address, which is assigned to it during the configuration phase. The *Steering Wheel* ECU can retrieve the data related to a given unit by issuing the reading command together with the unit address. It is also possible to broadcast a command, which does not require a reply, using a general address, so that the command is handled by all the units at the same time. This is useful for triggering the acquisition of the sensing elements by all the units simultaneously. In addition, the broadband address can be used during the configuration phase to set the address of the unit that is selected forcing the reading of its sensing element to a particular value, outside the range of values that are measured during the operating phase.

In this work, we focused our efforts on the measure of the grip force applied to the steering wheel. As sensing element we investigated the possibility of using the capacitor that is introduced by the presence of the hands, whose value can change with the pressure applied to the steering wheel. The sensing capacitor is inserted in a free running oscillator, whose frequency can easily be measured by the microcontroller.

III. Unit Design

As mentioned above, the basic idea is to provide each unit with some intelligence, i.e., a very low-cost 8-bit microcontroller, which can manage the communication over the network, as well as the measure of the actual sensing element. Thus, the sensor unit designed is flexible and assuming that is provided with the proper front-end and A/D conversion electronics, it can acquire different kinds of sensors, such as capacitive and piezoresistive force ones, as well as NTC resistors for temperature measure. The capacitive approach here adopted is very interesting because of its extremely low-cost and very compact geometrical layout, parameters that are of crucial importance in this application.

A. Hardware

The principle schematic of the sensor unit is depicted in Fig. 2. The sensing circuit consists of a simple relaxation oscillator, realised with a CMOS Schmitt trigger inverter, whose period is proportional to the product of the resistance and capacitance connected to the inverter. The capacitance comprises a fixed term C_0 and a variable one that is introduced through the electrode contact. Consequently, the oscillation frequency can be related to the the external capacitance, whose value can be made to vary with the pressure applied by hands to the steering wheel. The oscillator output is routed to the input of the TIMER/COUNTER peripheral embedded in the microcontroller, which implements a frequency meter, that is, it counts the number of oscillation cycles within a given time integration window.

To reduce as much as possible the number of on-board components, the microcontroller clock with 1 MHz frequency is one of the interface signals (clk). As a result, it is possible to avoid the bulky crystal component for stable and accurate clock generation needed to handle the frequency measure and the communication protocol, which cannot be achieved by the microcontroller internal RC oscillator. The communication protocol is based on an UART (Universal Asynchronous Receiver Transmitter)-compatible serial link employing only a bidirectional data signal (d_q), which is connected to an I/O pin of the microcontroller that can trigger an external interrupt. Normally, this pin is configured as input, so that the *Steering Wheel* ECU can drive the d_q line to issue a command to the sensor chain. Once the ECU has sent the command, it releases the data line, which can be used by the addressed sensor unit to transmit the command reply (e.g. the measured data). The other two wires (V_{CC}, gnd) of the sensor interface, which is replicated to both sides of each sensor board to facilitate the building up of the chain, carry the power supply.

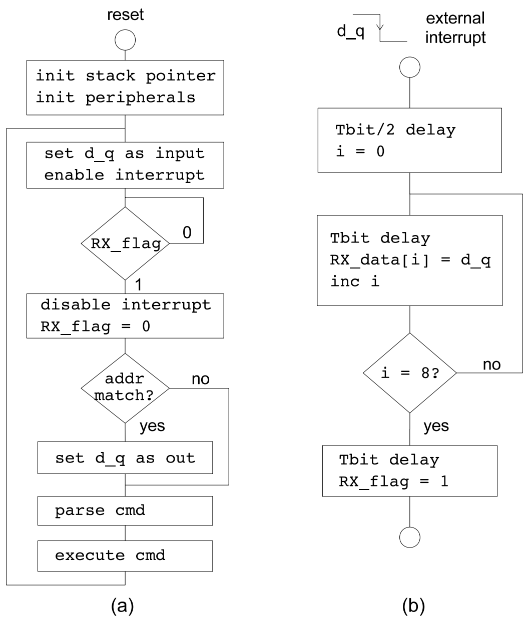

Fig. 3. Flow diagram: (a) main loop (b) external interrupt service routine.

B. Firmware

As our aim was to use a tiny microcontroller with limited program memory size (1 KB for the microcontroller used in this work), the firmware has been developed using the microcontroller assembly language. This choice can further be motivated by observing that the microcontroller has to perform low-level tasks with stringent time requirements, which can easier be coded using assembly than a higher level language. The size of the written code is 388 B, i.e., roughly 38% of the available memory. This means that further functions for acquiring other sensors can be mapped into the same microcontroller.

The basic flow diagram of the microcontroller firmware is reported in Fig. 3. Following the reset, some initialisation steps are carried out before entering a wait loop until the reception of a command via the serial link is completed (see Fig. 3.a). This happens within the external interrupt service routine, as shown in Fig. 3.b. In fact, the routine execution is triggered by the falling edge of the transmitted data start bit. After that, the following 8 b coding the command type (3 b) and the unit address (5 b, i.e., 31 unit addresses, plus 1 general address) form the received data (*RX_data*). Then, a further bit time (T_{bit}) delay to wait for stop bit reception is inserted into the service routine before returning to the main loop, which starts to process the new command, as it founds the *RX_flag* set.

Firstly, the address contained in *RX_data* is compared with the unit internal address and if they match, the microcontroller pin connected to d_q is configured as output, as the unit is going to use the shared communication line to transmit the command reply. It is important to notice that the processing of the command is performed synchronously by all the units. In this way, we can avoid that the command reply is interpreted

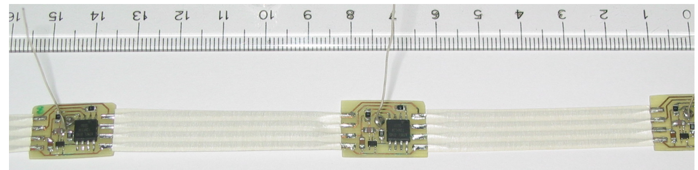

Fig. 4. Photograph of the sensor chain.

as a new command by an unselected unit because interrupts are disabled during command processing. As a consequence, raw data can be transmitted with the advantage that the communication protocol is very simple. When a command is issued with a general address, no match occurs and all the units process the command with d_q set as input, as no reply is expected in this case.

IV. Implementation and Test

The sensor unit board has been realised and 16 units have been chained together. A photograph of a portion of the sensor chain is reported in Fig. 4, which shows that each unit is connected only to its neighbouring ones. The PCB area of a single unit is 20x14 mm^2 and the spacing between consecutive units is around 75 mm. The sensor chain has been assembled on a commercial steering wheel (with a 380 mm diameter) adopting for the sensing electrodes the structure sketched in Fig. 5, which has been specifically designed for this work. In the absence of driver's hands, the only capacitance added to C_0 is the capacitance C_e between sensing and *gnd* electrodes. On the contrary, the presence of the driver's hand introduces three additional capacitors, i.e., C_{he} between hand and sensing electrode, C_h between hand and *gnd* electrode, and C_b that is the driver capacitance towards *gnd*. The values of the first two capacitors depend on the grip force, so that the frequency of the oscillator is related to the presence of the hand and to its grip force to the steering wheel. The on-board components R and C_0, as well as the integration window of the frequency meter, can be tailored to the above electrode parameters to increase sensor sensitivity.

The implemented distributed sensor has been tested connecting it to a PC through an interface board that generates the 1 MHz clock and acts as a bridge between the sensor chain and the PC serial port. Before assembling the chain on the steering wheel, each unit has been configured with a unique address. As that phase can be carried out by broadcast commands only, the selection of the unit being configured is

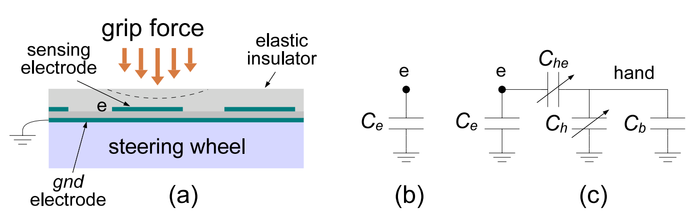

Fig. 5. (a) Capacitive sensing element. (b) and (c) Electrical models in the absence and presence of the driver's hand respectively.

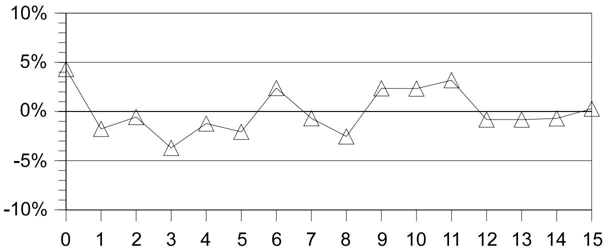

Fig. 6. Relative frequency mismatch of the 16 units when no force is applied.

achieved by connecting its sensing electrode to *gnd*, so that it is the only unit in the chain with the oscillator stopped. Then, only the microcontroller that reads a frequency equal to zero will accept the configuration command and set its address.

Once the chain has been configured and assembled on the steering wheel, the performance of the sensor has been evaluated querying the sensor readings from a LabVIEW application running on the PC with 10 Hz rate. First of all, no force was applied to characterise the uniformity of the chain and the results are reported in Fig. 6, which shows a good repeatability from unit to unit. Then, the response of the sensor to a grip force was investigated. It was found that the frequency reading of the unit corresponding to the steering wheel sector where the hand is positioned decreases as expected and up to 40% when the maximum force is applied. This is a very encouraging result and proves that the proposed sensor can be used to monitor grip force in driver's fatigue detection systems.

V. Conclusion

The design of a distributed sensor for noninvasive monitoring of fatigue-related parameters present at the driver-vehicle interface formed by the steering wheel has been presented. The sensor is low-cost, general-purpose and it can easily be embedded in a commercial steering wheel. Preliminary experimental results show that the distributed sensor is fully functional and that using a very simple capacitive sensing element it is possible to reliably detect the hand position on the steering wheel, together with some information about the related grip force. We expect to integrate the sensor into a driving simulator and to complement the grip force data with other relevant data, such as steering angle and torque and vehicle speed and position, which are available through the simulator CAN network. The ultimate goal is to develop a reliable fatigue detection system based on a nonintrusive measure of driver and vehicle parameters.

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