A Real-Time Heart-Rate Monitor Using Non-Contact Electrocardiogram for Automotive Drivers

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Abstract— **A large number of vehicle accidents and its associated human fatalities occur throughout the world due to drowsiness or health-related issues of the driver. Such mis-happenings can be reduced by integrating a driver-health monitor into the automotive. Different techniques such as camera-based image processing, photoplethysmograph, electroencephalograph, etc. have been employed to develop driver-state monitors. They use either multiple electrodes or require direct optical contact with the human body or need complex signal conditioning algorithms. In this paper, we develop a basic framework in the direction of developing a simple real-time heart-rate (HR) monitoring system using non-contact capacitive electrocardiograph (ECG). The system uses of an electrode structure which can be integrated within a steering wheel and simple, low-cost signal processing blocks. The system efficiency is verified through extensive testing on a number of volunteers in multiple scenarios and multiple electrode configurations with respect to the steering wheel. These tests show that the proposed system gives good quality ECG signals and estimates HR with good accuracy. The capability of the system as a reliable drowsiness monitor is also tested and encouraging results are obtained.**

Keywords-Drowsiness Detection, Heart Rate Monitor, Non-Contact Electrocardiogram, Automotive Electronics, Biomedical Instrumentation, Steering Wheel

I. Introduction

Rise in population and increase in production of vehicles have led to a drastic increase of drivers of different age groups coming to roads. A driver's health and state of mind are two very critical factors in ensuring the safety of driver as well as other people who are accompanying the driver or are nearby. One of the major causes of road accidents are heart diseases and drowsiness/fatigue which is a result of sleep disorders, excessive workload and lack of mental rest [1], [2]. Numerous research works [3]-[8] have reported new multiple assistive methods of providing a (beforehand) safety alarm to the driver before he/she loses control of the vehicle.

The most widely employed and studied technique for estimating driver behavior is based on image processing schemes [3]-[5]. These schemes rely on physical changes in behavior of the driver such as eye blinking [3], eye gaze [4], and head nodding [5], and yawning. The major problem associated with these vision based techniques is that it needs to incorporate complex signal processing stages to suppress parameters like harsh environmental conditions, driver movements and the driving conditions. Bio-signals like PPG, ECG, EEG are widely employed for health monitoring [9]-[11]. Low-cost products [9]-[12] based on the above bio-signals are reported. Some papers have also demonstrated the capability of these signals for drowsiness/health monitoring in an automotive [6]-[8]. However, PPG based systems [6] require direct optical contact with the body of the driver, which can be very cumbersome. Lee [7] has reported the use of PPG sensors in conjunction with camera based techniques for drowsiness detection. EEG systems [8] require a multi-electrode cap which needs to be placed on driver's head as well as complex signal processing stages.

Non-contact capacitive ECG principle [13], [14] provides alternatively simple systems for Heart Rate (HR) monitors. However, some of these works [13] require the electrodes to be placed on the seats of the driver. It poses lots of challenges in real world implementation as the strength of the signal varies with the height of the electrode and the driver. Hence, there is a need of a simple, but robust system which can be easily integrated on any vehicle.

The paper proposes a development of real-time heart rate monitoring system for automotive drivers. The proposed system uses a simple and easy-to-integrate configuration for non-contact ECG signal acquisition on a steering wheel, followed by simple analog front-end and HR estimators for estimation of HR and its variability. The similar sensor configuration can also be used in the case of two-wheelers. The sensors are such a way placed that the ground electrodes are placed near the sensing electrodes (rather than at right leg). Apart from that, the system uses a 32-bit processor for the digital processing of the sampled analog data. The choice of the components for the system was made in accordance to system portability. For evaluating the performance of the whole system, ARM Cortex M4 Microcontroller with Floating Point Unit was used to perform digital processing of the acquired signal. Next section explains the principle of operation of the

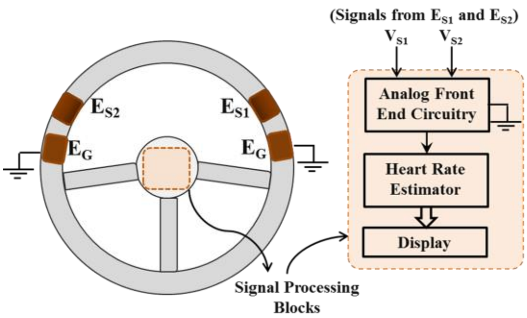


Fig. 1. Conceptual schematic of the proposed system. E_{S1}, E_{S2}- Sensing Electrodes, E_G – Ground Electrode. Signals from E_{S1} and E_{S2} are processed further to obtain a good quality ECG and Heart rate indication. Possible position of signal processing block is indicated.

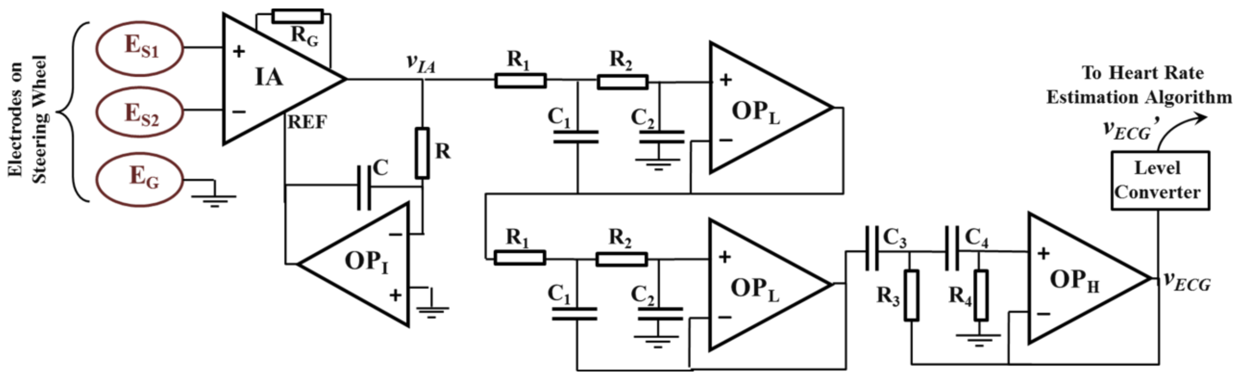


Fig. 2. Circuit Diagram of analog front-end used to obtain quality ECG from the raw signals from the electrodes.

proposed system. This is followed by Section III, which describes the experimental set-up and detailed test-results obtained with the prototype of the developed system.

II. System Description

A simple block schematic of the proposed steering wheel based heart monitor is depicted in Fig. 1. As in Fig. 1, the system comprises the following main parts (i) electrodes (E_{S1}, E_{S2}, E_G) on the steering wheel, (ii) analog front-end electronics, (iii) heart rate estimation unit and display. Optimum location for placement of the signal processing stages (i. e., parts (ii) and (iii)) are shown in Fig. 1. The principle of operation of these parts is described below.

A. Signal Acquistion Electrodes

As shown in Fig. 1 and Fig. 2, two suitably positioned electrodes E_{S1} and E_{S2} are employed to acquire the ECG signal. Ground electrodes (E_G) are placed in close proximity to these sensing electrodes. When a vehicle driver places his hand on the electrode-setup (touching all of the electrodes E_{S1}, E_{S2}, E_G) of the steering wheel, a feeble voltage signal will be observed at the electrode E_{S1} with-respect-to E_{S2}. This difference signal (say, V_{S1}-V_{S2}) gives raw Lead 1 ECG signal and is processed further by the signal processing blocks. This electrode arrangement possesses two distinct advantages (1) Low interference coupling [15] from power sources (50/60 Hz), (2) Ease of integration with the steering wheel when compared to conventional Lead 1 ECG system which requires one electrode to be placed at the right leg. We have developed two different sensor configurations which implement the above arrangement. Details of these developed configurations will be explained in a later section. Next sub-section explains about the signal conditioning scheme employed to obtain a clean ECG signal from the output of the raw electrodes.

B. Analog Front End Electronics

The circuit diagram of the analog circuit employed is shown in Fig. 2. The signals (i. e., V_{S1}, V_{S2}) from the sensing electrodes are first passed through a high gain instrumentation amplifier IA as shown in Fig. 2. Output of IA (node v_{IA} in Fig. 2) is a single-ended raw ECG signal. This signal, apart from the desired bio signal, contains many undesired components such as base line shifts due to motion artifacts, respiratory artifacts, power line interferences, etc.

Base line of the signal v_{IA} is stabilized with the help of an integrator, realized using the opamp OP_I (see Fig. 2). The output of OP_I will be the negative (say, V_{BIA}) of the DC level of v_{IA}. This DC voltage V_{BIA} is added with the signal v_{IA} using the reference pin of IA. This corrective loop ensures that v_{IA} will be almost independent of base line wandering effects.

Further, the dominant power line interferences are attenuated by using a fourth-order low-pass filter (LPF) of cut-off frequency 30 Hz. This filter is implemented using two cascaded second-order Sallen Key LPF (vide, the opamps OP_L in Fig. 2). Respiratory artifacts of low magnitude are then suppressed using a second-order high-pass filter, realized using the opamp OP_H. The output (v_{ECG}) of OP_H will predominately consist of desired frequency components. This voltage, v_{ECG} is appropriately scaled down using a passive voltage scaling circuit (built using resistors, diodes and voltage references) so that the final analog ECG signal output, v_{ECG}' is compatible with the microcontroller used for computation of heart rate.

C. Heart Rate Computation Unit

Heart Rate computational block described below accepts analog ECG signal from the signal conditioning circuit described in the above section and processes and estimates HR. At first, the ECG signal is sampled at 100 Hz. The initial display of heart rate requires acquiring of signal for 10.24 s.

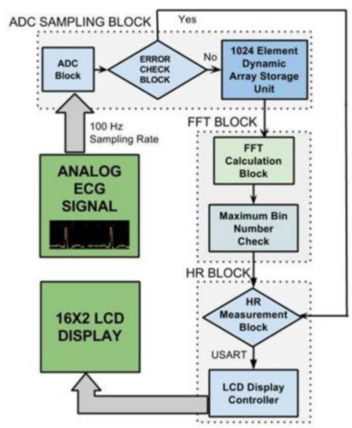


Fig. 3. Block Diagram of the algorithm employed for heart rate estimation. Algorithm has been implemented and tested in real time with the acquired ECG signals and accurate results obtained.

(a) (b)

Fig. 4. Photograph of the developed electrodes on the steering wheel. Two different configurations are shown in (a) and (b). Configuration (A) is more compact while (B) offers more flexibility to the driver for placing his/her hand.

Later, 100 new readings are added to the existing data set while simultaneously removing earlier readings for every newly added data.

Signal sampling and processing is interrupt driven which ensures real time digital signal processing (DSP). The sampling time (10ms) is controlled by Timer Interrupt which triggers the Analog to Digital (ADC) Interrupt. Before signal sampling, a start pointer is marked which is used for error checking of the extracted signal so as to avoid wrong HR calculation. Wrong HR calculation will happen in a situation when the user has not placed his/her hand on the electrodes properly which will result in erroneous ECG signal. After every 1 s interval, 100 new data samples gets added which are then passed through Error Check Block (ECB). If there is no error (indicated in Fig. 3 by 'No') found in the acquired data, it passes the stored data in data set to a 1-D array. In case of an error, ECU gives information to HR Measurement Block (indicated in Fig.3) not to update the HR value. When the input signal is error-free, a 1024 point FFT is evaluated by FFT block. For the calculation of FFT, the DSP library of Cortex Microcontroller Software Interface Standard (CMSIS) software package was used.

Magnitude of the real and the complex part is taken to evaluate the magnitude of the bin number. The bin number having maximum amplitude in the set HR range (40 – 150 beats) is evaluated by the FFT Block. The third block (HR Block) takes the maximum bin number and evaluates the HR. It also acts as a secondary error check by using the delta HR (difference between current and previous HRs). The following formula is applied to evaluate the heart rate.

$$Heart\ Rate[HR] = \frac{Sample\ Rate \times 60}{No.of\ FFT\ Points} \times Max\{HR\ Bin\ Range\} \quad (1)$$

According to a previous work [16], the general average variation in HR is 10.97 beats-per-minute (bpm) with a standard deviation of 10.849 bpm. Hence, in order to remove any faulty HR measurement occurred due to noise (which was not detected by the ECB) present in the input signal, a cutoff criteria was set for displaying the instantaneous HR. In short, if the current HR varied from the previous HR by 20 beats, then the measured reading was not taken into consideration. Apart from displaying instantaneous HR, the previous 3 HR readings were used to display an average HR. The averaging of instantaneous HR's gives a more smooth and accurate HR data because it depends on many previous HR readings. Details of the experimental set-up and results obtained are discussed next.

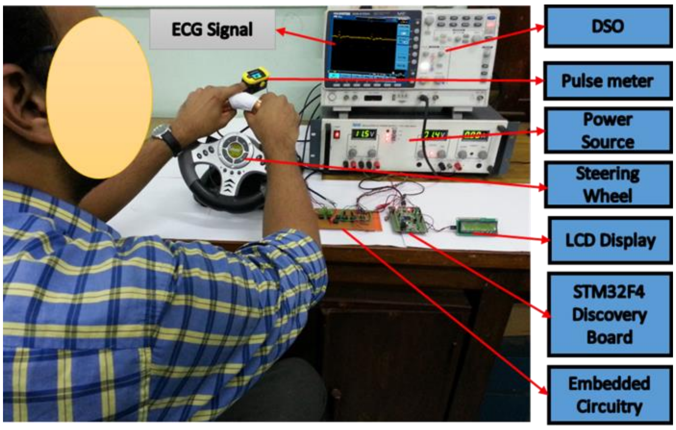


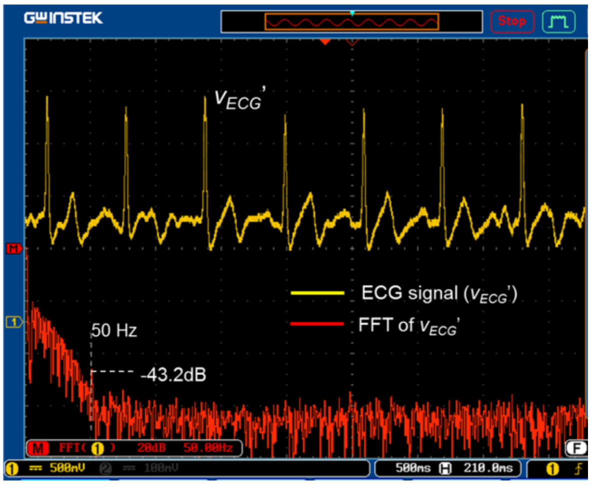
Fig. 5. Snapshot of the complete laboratory experimental setup. The discrete signal conditioning blocks shown in figure can be miniaturized and embedded within the wheel.

III. EXPERIMENTAL SETUP, RESULTS AND DISCUSSION

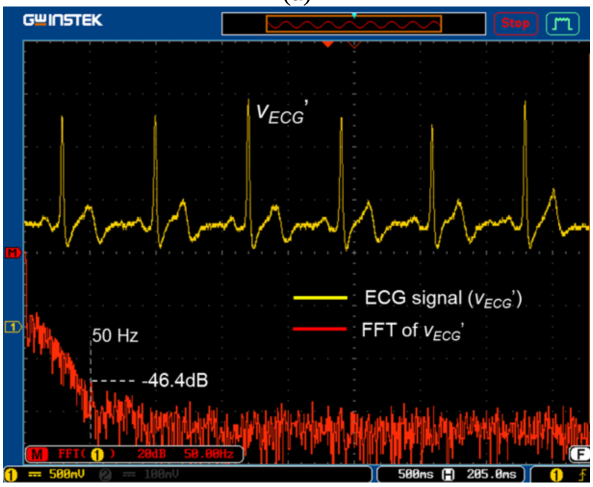
A. Prototype Experimental Setup

A prototype of the proposed system was developed, using readily available and low cost components to ascertain its performance. A model of the steering wheel was used in this test phase. Two different sensor electrode configurations were mounted/placed on the wheel as shown in Fig. 4(a) and Fig. 4(b). The principle of operation of both configurations are same as described in Section II and either one of these configurations can be employed to acquire heart signals. In sensor configuration A, sensing electrodes E_{S1} and E_{S2} and their ground electrodes are placed close by as in Fig. 1. This offers a compact sensor solution to the automobiles. In sensor configuration B, as shown in Fig. 4(b), sensing electrodes are placed on the outer circumference of the wheel while ground electrode is placed on the inner circumference. This configuration allows more flexibility as the vehicle driver can place his hand on any portion of the (wide arc) of electrodes E_{S1} and E_{S2} (see Fig. 4(b)). The electrodes in these sensor arrangements were fabricated using Copper (Cu) strips of 0.2 mm thickness.

The developed electrode configurations were tested with a prototype of signal conditioning circuit and heart rate computation unit. A snapshot of the complete system of sensor has been shown in Fig. 5. The instrumentation amplifier of the circuit has been implemented using high precision INA129 from Texas Instruments (TI) Inc., while the filter circuits and integrator OP_I realized using low offset and high precision OP07 (from TI Inc.). The HR computation unit utilizes STM32F4 Discovery board for ST Microelectronics [17]. The development board uses ARM Cortex M4 which is a 32-bit Microcontroller having hardware FPU. The hardware FPU makes it very suitable for Real Time Signal Processing. For displaying the HR in this prototype, a low cost 16X2 character LCD is used which uses Hitachi HD44780 LCD controller. In the prototype setup, developed electronic ICs are outside of the steering wheel. The entire signal processing chain can be suitably embedded inside the steering wheel (at the center).



(a)



(b)

Fig. 6. Results obtained on testing the electrode structure (on steering wheel) with analog front-end for (a) Sensor Configuration A (b) Sensor Configuration B.

B. *Basic Results and Discussion*

The signals from the output of the electronic circuit were observed on Digital Oscilloscope (DSO) model GDS-2000A Series from GwInstek. The ChoiceMMed Pulse Oximeter [11] was placed on the finger for reference HR measurements (measured HR calculated from the developed system) were displayed on the character LCD.

Volunteer tests were conducted by requesting a human volunteer to place his hand on the electrodes on the wheel and the waveforms were simultaneously observed on the DSO. The waveforms observed with a volunteer using sensor configurations A and B are shown in Fig. 6 (a) and (b), respectively. It can be inferred that relevant morphological features of ECG signal is distinct in the plots.

In practice, some insulator material (e.g. fabric) might be present between the electrodes and the human hand. Tests have been conducted to estimate the quality of the signal as well as system performance on such scenarios. For this purpose, volunteers were requested to place hands on steering wheel, which was covered with cloth of 2mm thickness. It was

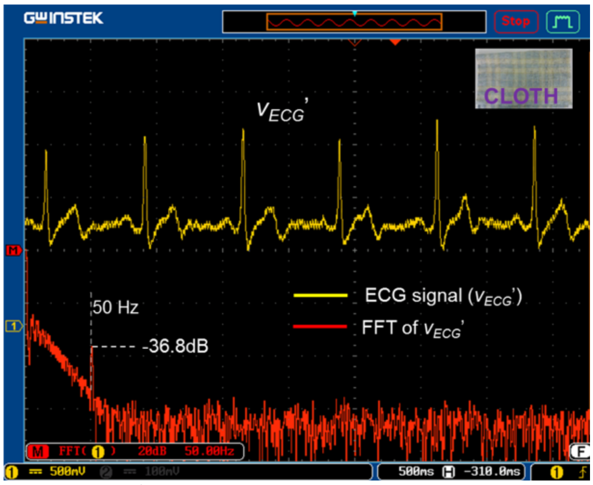


Fig. 7. ECG waveforms obtained when a volunteer placed his hand on the steering wheel electrode-setup, covered with a cloth of 2mm thickness.

observed that the 50 Hz noise in the signal increased with the increase in thickness of the cloth. As can be inferred from Fig. 7, the noise has increased, but the pattern of ECG can still be seen clearly in the plots (such 50Hz of noise will be present in automobiles as well [18]).

C. *Extensive Tests with Human Volunteers*

Next, tests were conducted on numerous volunteers to check the accuracy of HR estimation method of the developed system. Bare hand was placed on the electrodes (palms are in direct contact with the electrodes). The HR results of the developed system and the reference monitor [11] was simultaneously monitored and noted and tabulated in Table 1.

Table: 1 Measured heart rate vs. reference measurements (when hand is in direct contact with electrodes on steering wheel)

Volunteer(Age)	Heart Rate (bpm) estimated:		
	Developed System	R-R Method	Pulse Meter
A(47)	76	75	75
B(20)	70	70	69
C(28)	70	71	71
D(35)	70	70	70
E(41)	87	87	87
F(25)	93	94	94
G(23)	70	70	71
H(21)	82	82	83

Table: 2 Measured heart rate vs. Reference when an insulating layer (fabric) is present between the palm and steering wheel.

Volunteer(Age)	Heart Rate (bpm) estimated		
	Developed System	R-R Method	Pulse Meter
A(47)	76	78	78
B(20)	70	72	71
C(28)	76	77	77
D(35)	76	74	75
E(41)	87	87	88
F(25)	87	88	88
G(23)	70	71	69
H(21)	82	83	83

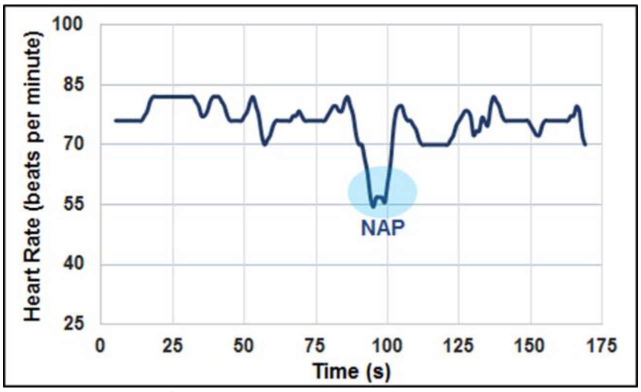


Fig. 8. Variation of heart rate recorded when volunteer took a short nap.

The readings of the system were seen to match closely with that of reference meter. Accuracy of reference meter is around ± 2 beats. Hence, to further verify the performance of the algorithm and system, we computed average R-R interval measurements on the acquired ECG data. This information is also shown Table 1. The developed HR monitor output corroborates with the R-R interval measured result as well.

Similar tests were done on the steering wheel covered with cloth of thickness 2mm and the results are shown in Table 2. Again, the HR estimated by the system is in agreement with reference measurement. The developed method uses frequency domain analysis and hence still works well (even though the signal-to-noise ratio has reduced as in Fig. 5) for this case. These tests show the efficiency of the developed system as an accurate HR monitoring system.

The aforementioned test results demonstrated the utility of the developed system for ECG acquisition as well as HR estimation. Further, tests were done to find the variability on HR (of the proposed system) when driver becomes drowsy and to emulate the driver, a volunteer (with palms placed on electrodes) was requested to take a short nap. The system continuously recorded HR during this testing period. Nature of variation of HR, recorded by the system, is plotted and shown in Fig. 8. As can be seen from Fig. 8, there is a significant decrease in HR during the nap period. This decrease in HR can be easily used to detect driver fatigue and can be used to alert the driver (e. g., in form of an audio signal). The system can also be designed to send the data to a central server (using suitable transmission protocols) where necessary monitoring and action can be taken by concerned authorities. It was also observed that sweaty hands increased the relative amplitudes of the peaks of the observed signal. The HR estimation yielded satisfactory results in this case as well (system is not much dependent on amplitude changes). However, care should be taken so as to ensure that changes in amplitude of the signals will not saturate/affect the analog front-end circuits and processor used. Extensive characterization of the system performance will be done to ascertain the effect of sweat, hand movement and other non-idealities in future.

IV. Conclusions

A simple and reliable real time heart rate monitoring system suitable for automotive drivers was designed and developed. The developed system employed the principle of non-contact ECG on a steering wheel. The system used a simple analog signal conditioning circuit and a digital computation unit to give a real time HR monitoring. Two different sensor prototypes were developed (based on the same principle) and tested with numerous volunteers. The developed system produced good quality ECG signals even when the subject held the steering wheel through an insulator (cloth). Error in HR estimated, in comparison with standard HR measuring methods was within the admissible limits. This suggests that the developed system can be successfully incorporated in vehicles to ensure the safety of automotive drivers.

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