A Health Monitoring System Using Multiple Non-Contact ECG Sensors for Automotive Drivers

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***Abstract* — Health and alert-level monitoring of automotive driver is very important to reduce the number of vehicle accidents and associated fatalities. The proposed work focuses on the development of a reliable and low-cost health monitoring system for automotive drivers. It is based on non-contact electrocardiogram (ECG) principle. Multiple signal acquisition ECG electrodes are placed on the seat and seat-belt of the automotive. The signals from the different electrodes are interfaced to simple analog and digital signal processing units through a switching logic. The frequency domain-based digital processing and the switching logic ensures that best quality ECG signal is selected for heart rate (HR) estimation. A prototype of the proposed system is build and tested on several volunteers. These tests show that the accuracy is 2 bpm. Additional tests to determine the system performance in various conditions was conducted and results reported.**

***Keywords* — Automotive Instrumentation; Integrated Sensor system; Non-Contact Electrocardiogram; Health Monitoring System, Fast Fourier Transform; Heart Rate Variability; Internet of Things; Analog Signal Conditioning**

I. Introduction

Sensors form an integral part of any instrumentation system. In a typical scenario, the signal provided by the sensor is suitably processed to obtain a good-quality estimate of the desired measurand. However, in many applications, the information provided by a single sensor may not give a reliable or accurate estimate of the measurand. In such cases, multiple numbers of same sensors or multiple types of sensors are usually employed, and the ensuing output signals are processed together to obtain reliable and meaningful information. This multi-sensor concept has been successfully employed in instrumentation system design for many respective applications, such as vehicle collision avoidance system [1], driver attention alert system [2], etc. It is equally important to reliably process and transmit the information from individual sensors to a central computational unit.

Human health monitoring is an important application where multi-sensor based data acquisition and processing is extremely crucial [3], [4]. Such sensing solutions could be used in bio-medical point-care-clinics, automotive industry, and harsh industrial work conditions. In this paper, we focus on design and development of a multi-Electrocardiogram (ECG) sensor and signal acquisition system for non-intrusive health monitoring of passengers of automotive vehicles.

Non-intrusive, compact sensor modalities for health monitoring of humans in an automotive is need of the hour, given the large number of accidents occurring due to human fatigue or health related issues of automotive users (especially, drivers) [5]-[6]. Different sensing solutions for the development of driver fatigue/health monitors have been reported. Common solutions include the usage of: (a) camera/Infra-Red sensors and image processing algorithms [7], (b) Photoplethysmographic (PPG) sensors on wrist/finger/ear [8], [9], (c) Electroencephalography (EEG) head cap [10]. The above methods are either complex in nature [7] or require direct optical contact with skin [8], [9] or large number of electrodes [10] or require special processing stages for harsh (unclean) automotive environments [7]. Principle of non-contact capacitive ECG is simple alternative, which is well suited for health monitoring [11], [12]. The basic utility of this technique for realizing health monitors in vehicles is shown in [11], [12]. These sensors can acquire bio-signals even when the electrodes are placed outside the cloth fabric. In [11], non-contact ECG electrodes have been integrated into the steering wheel of a vehicle. This scheme however, will not work well when driver removes one hand from the wheel (e. g., during gear-shifting). Other interesting technique of using ECG electrodes on the vehicle seat [12] may give unreliable results for different posture and/or size of passengers. Based on the above facts, it can be concluded that there is a need of reliable non-contact ECG sensor solutions for health monitoring in automotive. Such solutions should give good results, regardless of posture/size of the drivers and additionally possess alert automation and wireless transmission capabilities.

In the proposed work, we aim to realize non-contact ECG based health monitor using novel ECG electrode configurations on the seat-belt and the seat of the automotive. Outputs of these multiple electrodes are processed by simple and low-cost analog signal conditioner and digital signal processing unit to render a reliable real-time health monitor with aforementioned merits. The system has the intelligence to automatically switch between sensor electrodes and select the best configuration and obtain the best possible signal (the one with highest signal-to noise-ratio) from a person. The on-board micro-controller uses the user's ECG data to estimate Heart Rate (HR) and HR Variability (HRV) of the subject and generates audio alert signals in case of any abnormal change in HRV. The system also transmits of real

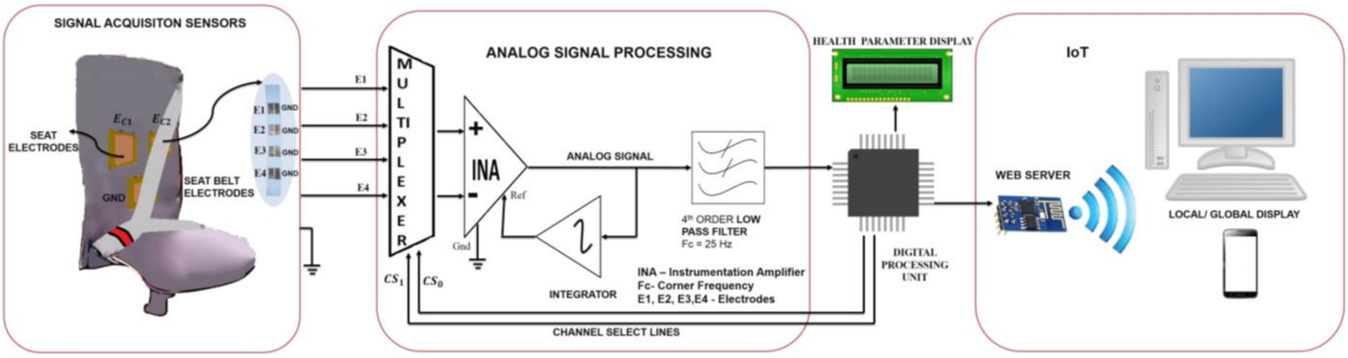


Fig. 1. System Architecture of the Proposed Model

time data to a remote server where the data-logs of driver are maintained and analyzed. This can be used to generate necessary help action during emergency. The next section explains the architecture and working of the proposed system. Complete system has been implemented and detailed experimentation has been performed. This is described in Section III of the paper.

II. System Architecture

The architecture of the proposed system is shown in Fig. 1. The system consists of four main parts, (a) Signal acquisition sensors, comprising novel configuration of ECG electrodes, (b) Analog Electronic Circuit, (c) Signal-processing in Digital Domain, (d) Wireless signal transmission. The individual parts are depicted in Fig. 2 and described in the below sub-sections.

A. Signal Acquisition Sensors and Their Configuration

Non-contact ECG electrodes is placed on seat belt and seat of the automotive. Four sets of ECG acquisition electrodes are placed on the seat-belt and one is placed on the seat. Signals from these electrodes are given to signal processing stages and processed to realize a robust ECG-based health monitor. Electrode configurations are explained below.

(i) Seat Belt Electrodes: Four sensing electrodes, namely E1, E2, E3 and E4 are embedded on the seat-belt as shown in Fig. 1 and Fig. 3. Ground electrodes GND is placed close-by to each of the sensing electrodes (see Fig. 3). The presence of adjacent GND electrodes helps to reduce the effects of common mode noise. The sensing electrodes and their respective grounds form one pair of electrodes and each pair are placed at equal intervals in the seat-belt. This multi-sensor configuration can be used to provide reliable signals for people of different height and other features. In the present work, the electrode pairs that give the best ECG signal for a given volunteer will be selected and processed to render a reliable HR monitor. The electrode combinations used for selection in this work are E1 and E3, E2 and E4, E1 and E4 and E2 and E3. This means that one of the above combinations will be selected to get the best-quality ECG signal.

(ii) Chair: As indicated in Fig. 3, three electrodes (E_{C1}, E_{C2} and GND) are placed on the back-rest of the chair. E_{C1} and E_{C2} are the sensing electrodes, while GND is the ground electrode. These electrodes are placed such that they will, most probably, be in contact with the back of the human. This pair of electrodes is used as the one of the input signals (others are from the seat-belt) to the selector logic.

B. Signal Conditioning Circuit

The signal coming from the electrodes are first made to pass through a Multiplexer IC. Here, CD4052B is used as a multiplexer IC which contains two 4X1 multiplexers. Both the multiplexers have common selector pins, hence both of them gets the same channel selected simultaneously. Hence for a 4 electrode configuration, we use various combinations of electrode and get various differential signal input combinations. The selected signal is amplified by passing it through an Instrumentation amplifier (IA). IA used is INA129P whose gain is set to 50 using an appropriate gain resistor. By passing the signal through an amplifier, it also amplifies the noise along with the required signal, hence it is passed through a filter stage in order to eliminate the noisy part of it. It also uses an integrator

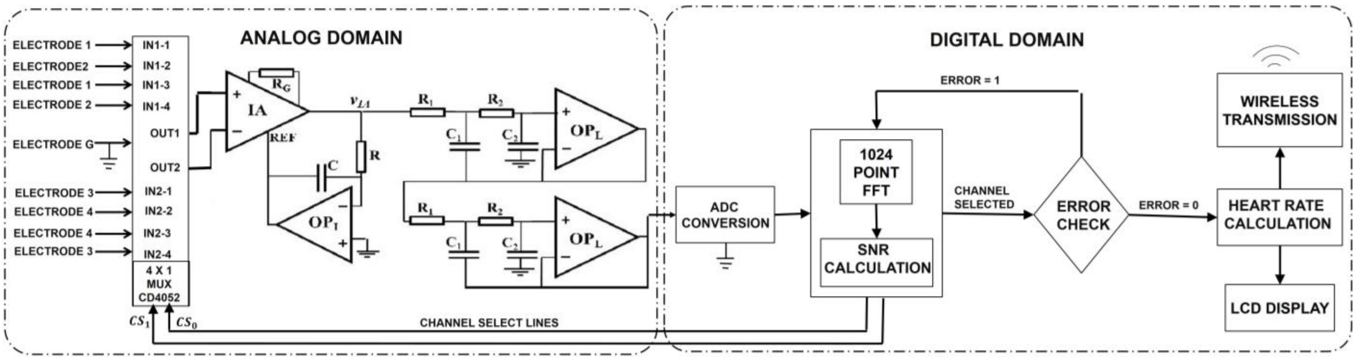
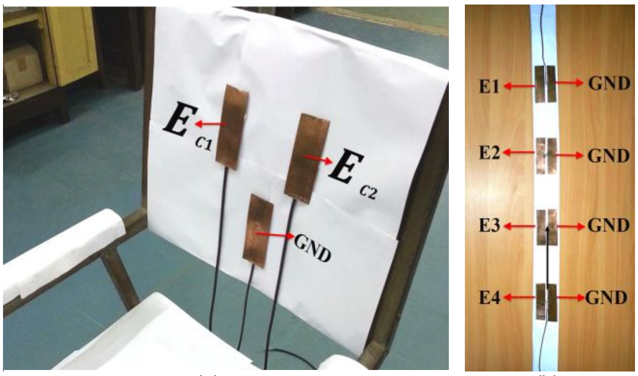


Fig. 2. Detailed Hardware and Software Flow Diagram



(a) (b)

Fig. 3 a) Chair and (b) Seat Belt sensor electrode configuration

part which is used to filter out the motion artifacts from the signal. A 4th order Low pass filter of Sallen Key topology which is implemented to clear and smoothen the signal by removing the Common Mode Noise (which 50Hz noise in our experiments). The filter works quite well in removing the Common Mode Noise for thin cloth layers but with increase in cloth thickness the SNR decreases considerably. The final output signal is fed into a level shifter configuration comprising of summing opamp and voltage clipping circuit using diode, resistor and biasing DC voltage. The level shifted output signal is fed into ADC pin of the microcontroller.

C. Signal Processing

The real time signal processing is performed on ARM Cortex M4+ microcontroller having hardware Floating Point Unit (FPU) and 12-bit ADC module. As from fig. 1, the Channel Select (CS) lines (CS_1 and CS_0) which are directly controlled by the microcontroller using 2 I/O pins enabling 4 sets of different electrode configurations as shown in Fig. 3(b) namely (a) CS_1= 0 & CS_0 = 0 selects E1-E3 (b) CS_1= 0 & CS_0 = 1 selects E2-E4 (c) CS_1= 1 & CS_0 = 0 selects E1-E4 (d) CS_1= 1 & CS_0 = 1 selects E2-E3. Later, E2-E3 configuration was replaced with chair electrodes (E_{C1}- E_{C2} as indicated in Fig. 3(a)) for integration with chair. At the time of startup, the system goes into CS mode where it switches from one channel to another in 5.12 sec time interval. It takes 1024 data samples at the sampling rate of 200 and evaluates SNR (as indicated in Fig. 2) which is the ratio between fundamental frequency and 50Hz noise signal. The calculated SNR values are stored and compared between different channels and corresponding channel with highest SNR is selected. During the CS mode, mean and standard deviation (SD) of the input signal is also evaluated so as to take care of situations when there is no signal (opamps are saturated) or when signal is completely noise.

As represented in Fig. 1 and 2, the analog signal from the selected channel enters into the processing block where 1024 data samples are collected with a sampling rate of 100. Fast Fourier Transform (FFT) is performed on acquired input data sample from which the fundamental component is selected from the HR interval window (40-150 bpm). The frequency domain analysis of the signal ensures a good HR estimation even when SNR is very low i.e. noise signal dominates over the ECG signal. The error check block (as indicated in Fig. 2) constantly monitors the SNR, mean and SD of the input signal and compares with the previously stored SNR values. The processing block automatically switches to CS Mode when the selected channel starts giving bad quality ECG signal due to the motion of the driver. The Digital Signal Processing (DSP) was performed on STM32F4Discovery Board by ST Microelectronics using CMSIS Library provided by ARM. After HR calculation, the estimated HR and the data samples are sent to the Wireless Signal Transmission block.

D. Wireless Signal Transmission (IoT)

The proposed system was integrated with ESP8266 Wi-Fi module. It consists of an inbuilt TCP-IP stack which enables it to communicate with the internet based protocols. In the initial prototyping phase, the module was configured as a local webserver which starts publishing data on a particular assigned port. The ECG data rate was kept to be 100 samples per second which can be increased depending on the required resolution of

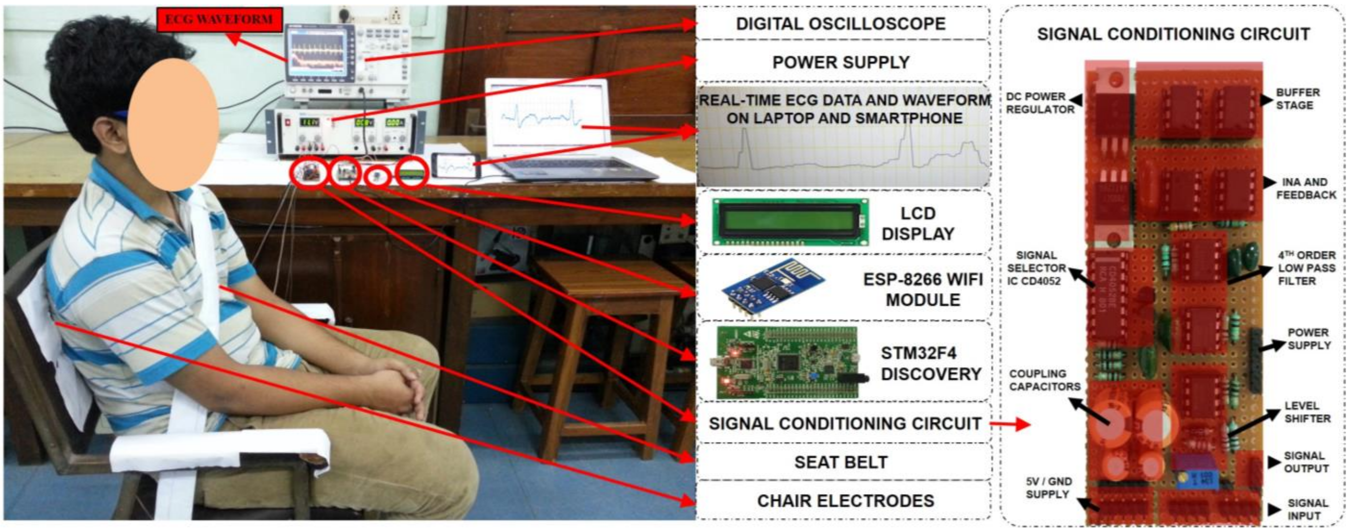
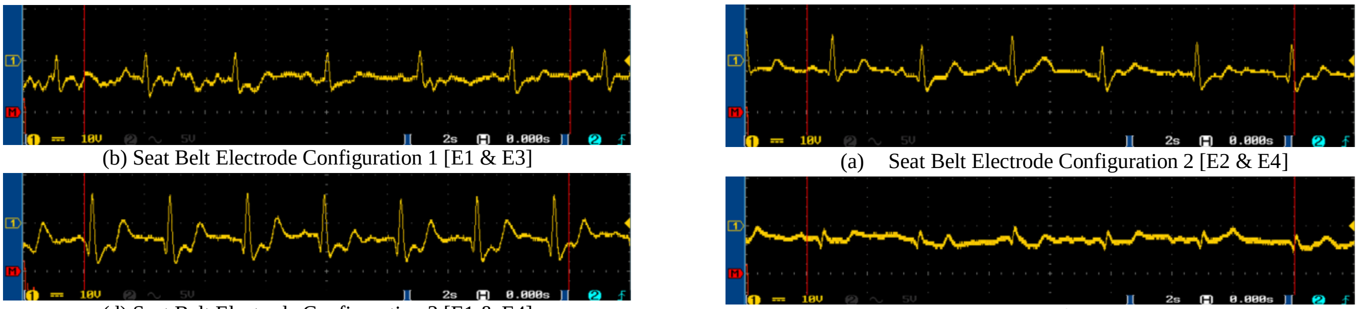


Fig. 4. Experimental Setup of the whole Prototype



(b) Seat Belt Electrode Configuration 1 [E1 & E3]

(a) Seat Belt Electrode Configuration 2 [E2 & E4]

(d) Seat Belt Electrode Configuration 3 [E1 & E4]

(c) Seat Belt Electrode Configuration 4 [E2 & E3]

Fig. 5. ECG Signals from different electrode configurations captured on Digital Oscilloscope of the developed scheme. The signal of best quality is selected for Heart Rate Estimation.

data. Further, the published data can be displayed or processed on any computer connected to the local server. The system can easily be extended to a remote server enabling access of the data globally. Extra security measures needs to be taken care during the design of a large interconnected system.

III. Experimental Results

A laboratory prototype of the proposed system has been built and tested. The non-contact ECG electrodes were placed in the appropriate locations as shown in Fig. 1. The electrodes were fabricated from low-cost copper sheets of dimension 8cmX3cmX0.1mm. The choice of copper electrodes makes the system cost-effective. It can be replaced by Ag-AgCl electrodes to achieve better performance. The signal conditioning and digital processing units were implemented using the components mentioned in Section II. Different tests were conducted on the prototype developed. Details of these tests are given in the forth-coming sub-sections.

A. Basic Performance Tests

The basic functionality of the developed system was first tested on a volunteer (by manual switch positioning). The ECG signals observed from different electrodes are shown in Fig. 5(a)-(d). These figures show that the system has the capability to give good quality signals. Later, automatic switching logic was implement. The transient switching waveforms observed on power-on of the system is shown in Fig. 6. It can be seen form Fig. 6 that system switches between different electrode combinations (channel 1 to 4) and selects the best signal (channel-3 for this specific case) for further processing. Note that channel 1 (i.e. signal from E2 & E4 is not able to give proper ECG signal for this specific case. This might be due to

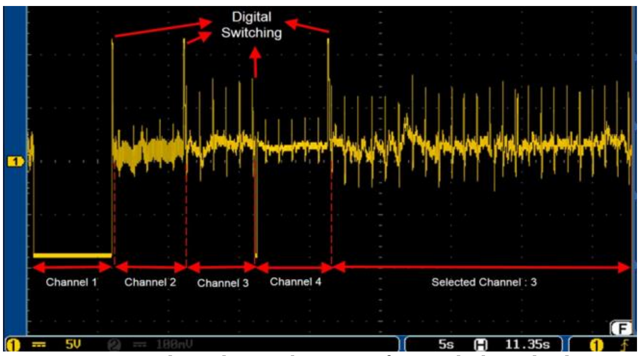


Fig. 6. ECG Electrode Switching Waveform and Channel Selection

the seating posture or loss of contact between his cloth and electrode of channel 1. The accuracy of the system for heart rate estimation was then verified. Tests were conducted on 5 volunteers for this purpose. Currently, test results and system performance are reported using an initial laboratory prototype of our proposed model. Test results are reported on male volunteers. More elaborate tests as well as test-results on female volunteers will be done, once the final prototype is ready. During the above tests, the reference value of HR was estimated simultaneously using a standard pulse meter [16] as well as using R-R peak internal measurements of the ECG waves obtained. Results obtained from the above tests are summarized in Table 1. In table 1, 'X' denotes the case where the developed system is not able to get ECG signal and estimate HR. Hence, it can be inferred from Table 1 that the developed system is able to determine HR from most electrode combinations. Table 1 also shows that the accuracy is around 2 beats per minute.

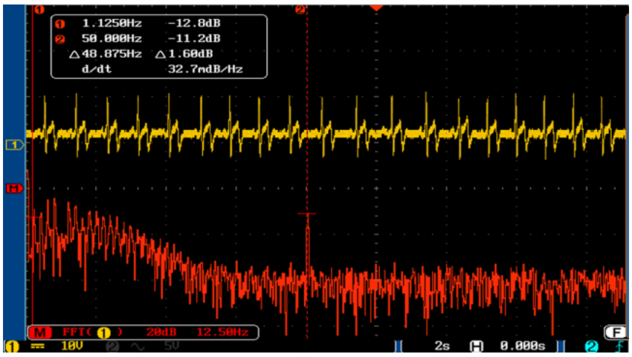
B. Effect of Cloth Thickness on Acquired ECG Signals

In actual scenario, the vehicle drivers can wear cloths of different thickness. Hence, some tests were conducted to find the effect of various cloth thickness on the system performance. In

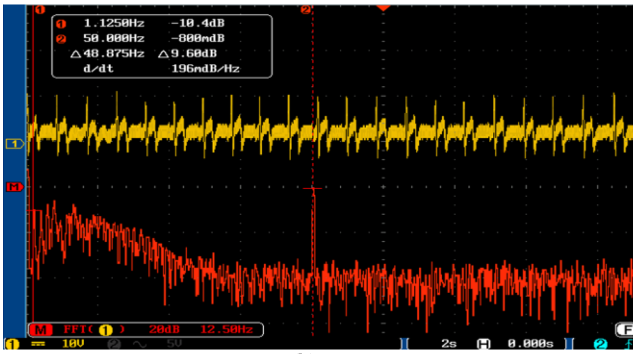
TABLE I. Heart Rate estimation Results with different electrode Configurations

Volunteer (Age, cloth thickness [in mm])	**Electrode Config.**	**Heart Rate (in BPM)**		
		Reference Pulse meter	***R-R Peak Interval***	***Developed System***
A (21, 0.85)	1	X	X	X
	2	88	86	87
	3	87	88	87
	4	X	X	X
B (20, 0.38)	1	111	108	111
	2	111	110	110
	3	107	108	109
	4	112	112	111
C (20, 0.47)	1	80	81	82
	2	94	95	93
	3	93	X	93
	4	88	90	87
D (27, 0.70)	1	64	63	64
	2	X	X	X
	3	63	63	64
	4	69	70	70
E (21, 0.29)	1	76	80	78
	2	76	78	76
	3	92	93	93
	4	76	77	77

X: HR could not be calculated due to no ECG signal/ Noisy data



(a)



(b)

Fig. 7. ECG waveforms and common mode (50Hz) when cloth of thickness (a) 0.34mm (b) 0.68mm is present between the human body and electrode. There is an increase in Common Mode Noise with the variation in Cloth thickness.

the experiment, the volunteer was requested to wear cloth (same material) of different thickness. Test results obtained are given in Fig. 7 and Fig. 8. It can be seen from Fig.7 (a) and (b) that the common mode noise (50Hz noise is most prominent contributor in our laboratory prototype) increases with the increase in cloth thickness. Signal-to-Noise (SNR) of the acquired signals are calculated and plotted in Fig. 8. SNR can be seen to decrease with cloth thickness. Hence, in practice the effect of SMPS noise in an automotive will also increase with increase in thickness of cloth fabric. It was observed during the tests that the SNR was considerably dependent on cloth material (e.g. low for synthetic clothes and high for cotton clothes). SNR was high for moist environments as well.

C. Developed System as Fatigue Monitor

The efficacy of the developed system as a fatigue monitor was tested. The volunteer was solicited to take a short nap during this experiment. Heart rate was monitored throughout

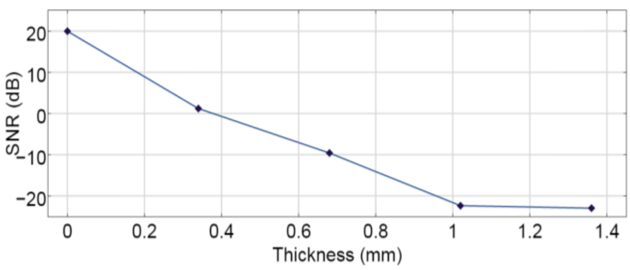


Fig. 8. SNR Variation due to change in thickness of cloth

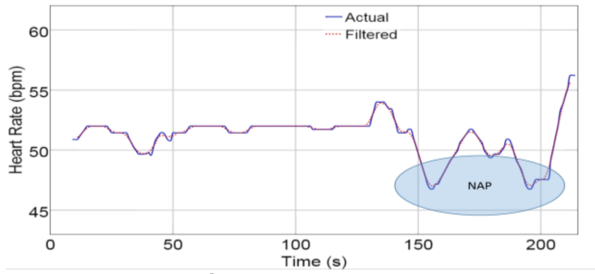


Fig. 9. Nap Test on a Volunteer

the experiment. HR remained almost constant about a mean value when the person is in normal state. It decreased significantly when the volunteer was drowsy (nap). Hence, HRV can be monitored to ascertain driver fatigue and raise an suitable audio alarm.

IV. CONCLUSIONS

The proposed work was successful in developing an integrated system for real-time health monitoring for all the passengers of an automobile which includes driver as well. It intelligently switch between different channels (sensor electrodes) so as to acquire the best signal out of the given channels. The sampled ECG data was successfully sent to a central web server which could be used by a doctor for health monitoring or central authorities for providing immediate response in case of any emergency. Future, the system can also be integrated with the steering wheel of automobile where PPG, ECG base techniques etc. can also be incorporated for making it more robust.

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