A Robust and Non-Invasive Heart-Rate Monitoring System

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Abstract- A non-invasive method for detecting the Heart Rate (HR) and the variation in the HR that aids in providing continuous, safe and effective monitoring of drowsiness of an automotive driver or a power tool operator is presented in this paper. HR is detected using an appropriately located photoplethysmograph (PPG) sensor. A simple but reliable detection scheme is developed to accurately measure HR from the PPG signal. The scheme produces a quasi-digital signal, enabling easy interface to a digital system. This signal is independent of base-line and peak-to-peak variations that are present in consecutive cycles of a PPG signal. A prototype sensor and detection circuit has been built and tested. A suitable virtual instrument has been developed, which acquires and process the signals from the detection unit to obtain the HR and its variability. Tests have been conducted on volunteers to observe HR variation between awake and drowsy conditions. A consistent trend of reduction in HR was observed as the subject changes the state from awake to sleep, which may be used as one of the parameters to monitor drowsiness. Tests were also performed, using suitably developed sensors, to check the reliability of the scheme while driving a vehicle. It recorded the HR data accurately while driving.

I.   Introduction

Heart rate (HR) and its variability are widely employed for monitoring of patient health [1]. Different principles are employed to develop HR monitoring systems. Phonocardiogram (PCG) based systems [2], [3] are non-invasive, and require only a single probe, which can be placed near the heart, for its operation. However, the output of a PCG based sensor will be contaminated by noise from other parts of the body as well as external environment [4], and therefore, complex signal conditioning schemes may be required to obtain a good PCG signal. An accurate indication of HR can be extracted from Electrocardiogram (ECG) signal. But, conventional ECG based HR monitors' are generally expensive, and require multiple electrodes and connecting wires, which may not be well suited for many real-time scenarios. Different schemes (e. g. using capacitance technique [5], accelerometer [6], [7] etc.) are being proposed to develop an ECG HR monitor that overcomes these limitations. Information about HR can be estimated, with relative ease, using Photoplethysmography (PPG) signal [8]. HR and its variability, which can be obtained from a PPG signal, is reported to exhibit good correlation with that obtained from an ECG signal [9]. The compact nature and the ease of positioning of PPG sensors make them a good candidate for estimation of HR. In this work, we develop a reliable and robust PPG based HR monitoring system using a new and simple signal conditioning scheme. Latter ensures that the motion artefacts and peak-to-peak variations present in PPG sensor output have negligible effect on the performance of the HR system. In
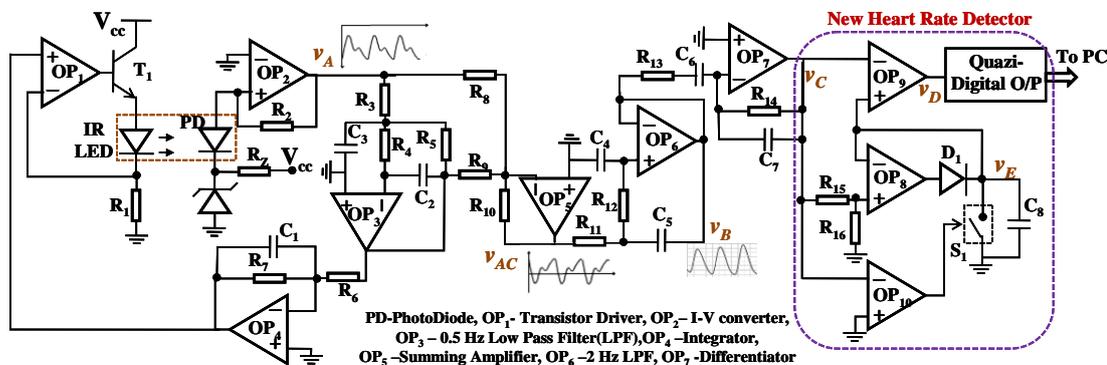

Figure 1. Schematic of proposed signal conditioning circuit employed to estimate the heart rate. Quasi-digital output of this circuit is independent of most of the unwanted parameters in the raw PPG signal, and can be easily interfaced to a digital system. Waveforms at cardinal points of the circuit are also shown.

addition, an applicability of proposed system as an instrument, which is capable of providing continuous, safe and effective monitoring of HR, and hence its possible application to monitor drowsiness, is presented. The details of the proposed scheme, prototype sensor unit and results obtained are reported below.

II. Proposed Sensor and Heart Rate Detection Unit

The circuit diagram of the proposed scheme is shown in Figure 1. The basic PPG sensor, shown in Figure 1, has an Infra-Red (IR) transmitter, which illuminates a specific part of a human body, and a photodiode employed in photoconductive mode. The photodiode converts the reflected IR light from the body to an equivalent current. This current is then converted to a voltage, v_A employing a I-to-V converter (built using opamp OP_2 in Figure 1). The signal v_A is the raw PPG signal, whose DC level of v_A varies with the texture of the skin and thickness of the finger (or the part being illuminated) of the subject under test. Different DC levels of v_A can affect the quality of HR measurements, and is hence normalized by employing a feedback network [10], consisting of the opamps OP_1-OP_4 and the transistor T_1. Information of HR is present in the ac part, v_{AC} of the signal v_A. v_{AC} is extracted with the help of a low-pass filter (LPF) of corner frequency 0.5 Hz and a summing amplifier. The opamp OP_3 implements the LPF, and OP_5 realizes the summing amplifier. Power-line frequency interferences present in v_{AC} are filtered with a LPF (OP_6) of cut-off frequency 2 Hz (the fundamental component of PPG alone is extracted using this LPF). The resulting signal, v_B is shown in Figure 1.
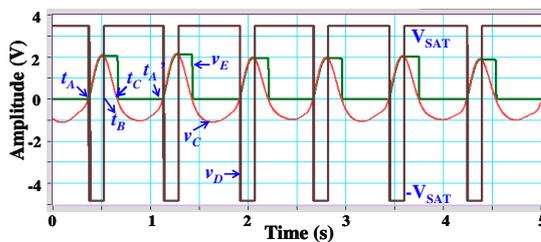

Figure 2. Waveforms at the important nodes of the proposed Heart Rate (HR) detector circuit shown in Figure 1. Output v_D is a quasi-digital pulse, whose time period gives a measure of HR.
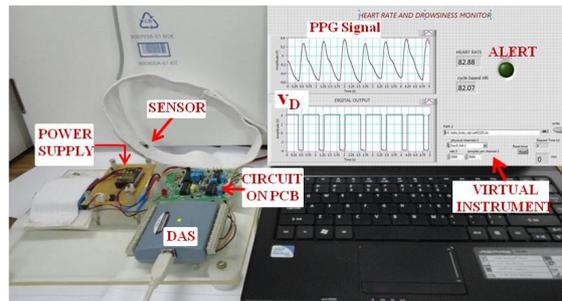

Figure 3. Integrated setup of the proposed HR detection system. A virtual instrument developed in LABVIEW is used to digitally process the signal v_D to obtain an estimate of HR and % HRV.

The Heart-Rate (HR) can be estimated by measuring the time period of v_B (or v_A). Equivalently, HR is reciprocal of the time interval (T) between two consecutive instances at which v_B crosses zero from a negative to a positive value. v_B is given to a differentiator circuit (realised using OP_7) to attenuate the effect of base-line artefacts. Output of OP_7 (v_C) will be maximum at the low-to-high zero crossings of v_B. A typical plot of v_C is shown in Figure 2. Hence, HR can be found by measuring the time T between two successive positive peaks of the signal, v_C. This task is accomplished using a new HR detector circuit, shown in Figure 1.

The HR detector circuit consists of a resistive divider (R_{15}, R_{16}), a precision half-wave rectifier, implemented using the opamp OP_8, a charge-storage capacitor, C_8, a switch S_1, and two comparators (OP_9 and OP_{10}) as in Figure 1. Signal v_C is given to a resistive network, which applies $0.99v_C$ ($=v_i$) at the input of OP_8. Let us now consider the time instant t_A marked in Figure 2 (for ease of explanation). At this instant t_A, v_C becomes greater than zero, and hence, the output (say, v_F) of OP_{10} will be at negative saturation (-V_{SAT} in Figure 2). v_F controls the operation of the switch S_1. When $v_F = $ -V_{SAT}, S_1 will be open, and as v_F becomes V_{SAT}, S_1 will be closed. Thus, for t > t_A, S_1 will be open, and hence, capacitor C_8 will charge, through the super-diode circuit (opamp OP_8), to the peak value of v_i. This charging process takes place until t = t_B as in Figure 2. The voltage waveform across the capacitor is shown by the signal v_E in Figure 2. At t = t_B, v_C starts to decrease from its positive peak as in Figure 2 and soon, v_C will become less than v_E. This causes v_D to become +V_{SAT} (refer Figure 2). The state change of the other signal, v_F ($v_F \rightarrow$ +V_{SAT}) occurs at the instant, t_C when $v_C < 0$. This closes the switch S_1, and thus v_E discharges to zero (refer Figure 2). S_1 will be opened again at the next instant when v_C becomes greater than 0, i. e., at t = t_A' in Figure 2. Hence, C_8 can charge towards the next positive peak as shown in Figure 2. From Figure 2, we can also see that every positive peak of v_C is detected and transformed into the positive rising edge of quasi-digital pulse, v_D. An important feature of this circuit is that its output, v_D is independent of the peak-to-peak variations in adjacent cycles of v_C or base-line variations of v_A. As the proposed circuit produces a quasi-digital output, v_D, HR can be easily obtained by measuring the time interval between two rising/falling edges of v_D using a microcontroller or any other digital system. A major part of the circuit in Figure 1 could be alternatively implemented by a digital signal processor. Latter, however will require the use of complex digital

filters and a dedicated analog-to-digital converter. Analog implementation, shown in Figure 1, will be less expensive, and for practical applications, it can be easily packaged as a compact integrated chip.

A. Experimental Setup and Results

A prototype of the sensor unit and the proposed HR detection circuit has been developed as shown in Figure 3. An IR transmitter OP240, operating at a wavelength of about 900 nm, and IR receiver module, BPW34 was used to build the sensor unit shown in Figure 3. Commercially available ICs were used to realise the HR detection unit. TL064 ICs were used to realise the opamps OP_1-OP_8. The comparators OP_9 and OP_{10} were implemented using LM311. SL100 was used as the transistor T_1, while CD4052 was used to realise the switch S_1. The output of the detection circuit is interfaced to a Data Acquisition System (DAS). The acquired signals are processed by a Virtual Instrument (VI), developed in LABVIEW, which calculates HR using the quasi-digital output of the detector circuit and computes the moving average (HR_M) of the HR data. Tests were performed on a few volunteers to check the accuracy of HR detection and results obtained are shown in Table 1. From Table 1, we can infer that the measured HR matched closely with the reference HR, with a tolerance of ± 2 beats, during resting period.

Table 1. Heart Rate measured for different volunteers

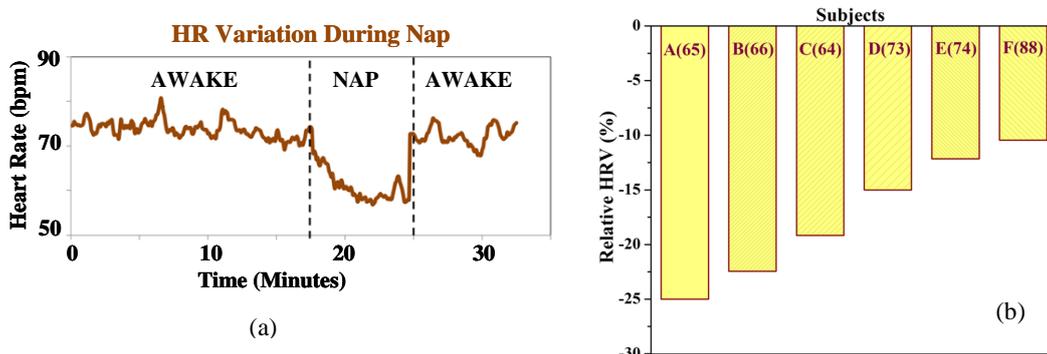| Subject (Age)	Reference HR (bpm)	Measured HR (bpm)	Difference (bpm)
A (24)	65	64	1
B (22)	67	65	2
C (34)	64	63	1
D (30)	77	75	2
E (28)	74	73	-1
F (26)	88	86	2
G (1)	100	98	2

Figure 4. (a) Heart Rate Variation (HRV) measured for a subject during his power nap. (b) Bar diagram showing relative percentage of HRV for different subjects with their resting heart rate mentioned in brackets.

The developed VI was also programmed for possible detection of drowsiness of a subject, based on the difference between the current HR_M and the resting HR_M. In order to test this, volunteers, fitted with the sensor unit, were asked to take micro-naps. A typical HR variation (HRV) observed in a volunteer during his nap is shown in Figure 4 (a). It can be seen that HR decreases during nap, noticeably. Relative HRVs and resting HR_M obtained for few subjects is plotted in Figure 4 (b). It can be seen from Figure 4 (b) that HRV changes between -25% to -10%, for the subjects under test. Also, the % HRV decreases with resting HR_M.
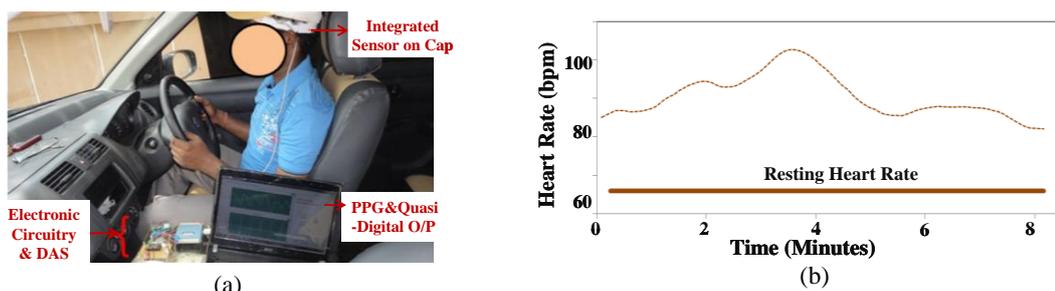

Figure 5. Experimental test set-up in a car (b) Heart rate variation of the subject obtained during driving.

Tests were also conducted to assess the stability of the PPG signal and variation of HR during driving. The sensor was positioned on the forehead of the car-driver (using a suitable cap) as in Figure 5 (a). Several trials were conducted by driving the vehicle at different speeds and through rough roads to ascertain the reliability of the scheme. Even though there were large variations in base-line and peak-to-peak of the PPG signal, the detector circuit helps to correctly capture the HR data. HR of the subject during the trial was found to be always higher than the resting HR (for the subject tested) as can be seen in Figure 5 (b). Similar tests were conducted on a subject driving a motor-cycle. Estimated HR of the subject on a bike trial is shown in Figure 6. In this case also, same trend of HR was observed.
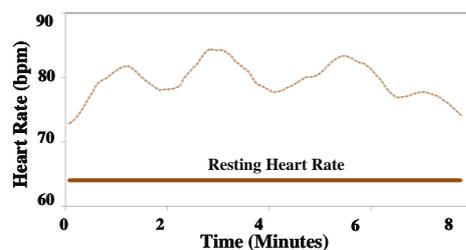

Figure 6 Heart rate variation of the subject while driving a motor cycle, recorded using the developed system.

III. Conclusions

A new, non-invasive and reliable photoplethysmograph (PPG) based heart rate (HR) monitoring system is reported in the paper. The proposed HR detection unit ensures that unwanted parameters that may be present in the raw PPG signal will not have much effect on the HR estimated by the scheme. A prototype PPG sensor has been built, and the HR detection unit has been realized in a PCB. Output of the detection unit was suitably processed by a digital instrument to compute and display the HR. Tests conducted on a few human subjects revealed the efficacy of proposed scheme as an accurate HR monitor. Further, the utility of the proposed scheme as a device capable of detecting human drowsiness is presented. Vehicle trials, conducted on the developed prototype, further verified the robustness of proposed scheme.

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