A Driver's Physiological Monitoring System Based on a Wearable PPG Sensor and a Smartphone

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Abstract. In the course of driving, sudden disease outbreak often cause traffic accidents. In this study, we designed a wearable photoplethysmography (PPG) sensor module based on a Programmable System on Chip (PSoC). It transmits PPG signal to a smartphone via Bluetooth. On the smartphone, a heart rate (HR) detection algorithm is implemented. When the abnormal HR is detected, the smartphone will use the sound and vibration to warn the driver. At the same time, physiological data and GPS location are also be transmitted to the remote server (remote health care center) via the 3G mobile network, so that the staff on the center can monitor the newest information and understand the driver's driving status. In order to reduce motion artifact, LED and silicon photodiode are put into the separate magnetic ring and use the transmission method to measure PPG signal on earlobe. The results show the difference in heart beats between the ECG method and our method there is 0 in all driving behaviors test. It shows this new PPG sensor can prevent motion artifact effectively in driver's physiological monitoring.

Keywords: Physiological monitoring system, PSoC, smartphone, PPG, wearable sensor.

1 Introduction

In the course of driving, sudden disease outbreak often cause traffic accidents. In the past studies, many people measure physiological signals in the car such as ECG, EMG and respiratory signal [1]. However, these methods need to hang on many physiological measurement sensors and wires on the body so that the drivers may feel inconvenient and even affect their driving behaviors.

In 2009, Jonannes Schumm et al integrated the ECG measurement system into the backrest of the airplane seat [2]. As this ECG system is unobtrusively integrated into the seat, it does not disturb the user, but it is sensitive to body movements and is only capable of measuring the ECG while the user is leaning on the back. In 2010, Heung-Sub Shin et al present the car driver's condition monitoring system that designed by

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using ECG and PPG sensors to obtain physiological signals on the steering wheel [3]. These methods use non-wearable sensor which are convenient for measuring on driving, but it ignores the driver's driving behavior. If the driver can't always hold the steering wheel, then the physiological signals can't be measured. In 2007, Lei Wang et al design the earpiece PPG sensor [4]. The device is encapsulated with multiple LEDs and photodiodes based on a reflective PPG design. The ear measuring method is more suitable than previous measurement, just like the Bluetooth headset, but the motion artifact is still the most serious problem. In 2010, Ming-Zher et al also use wireless earpiece to measure PPG signal on the earlobe [5] and reduce motion artifact to get higher accuracy by adaptive noise cancellation [6], but the elimination of noise are also limited.

Recently, smartphones are very popular and have great computing capability and communication capability. Moreover, most of the drivers are used to wear a Bluetooth headset on the road. If the physiological sensors can be built into the wireless headset and use the smartphone to process the data, then the size of the measuring device and wires on the body will be greatly reduced. Although there are many ways to measure physiological signals for drivers, but the most devices can't real-time alert the driver to rest or emergency contact a remote server when the driver's physiological signals are abnormal. Therefore, this study designed a wearable PPG sensor module based on a PSoC and can transmit signals to a smartphone by Bluetooth. In order to reduce motion artifact, the physiological sensors are put into the magnetic ring and are used to measure the PPG on the earlobe. When the abnormal physiological signals are detected, the smartphone will generate a feedback to alert user. It is expected to reduce traffic accident when the abnormal physiological signals occur.

2 System Description

In this study, we develop a wearable real-time physiological monitoring system based on the smartphone. This system consists of three parts, including a wearable sensor module, a smartphone and the remote server. Fig. 1 shows the system block diagram. The sensor module can be worn on the earlobe. It includes an optical sensor which uses transmission method for PPG measurement, a three-axis accelerometer (G-sensor) and a PSoC. The signal acquisition and analog circuits are designed by PSoC. The G-sensor is used to detect the head status. Furthermore, the data transmission interface between the sensor module and the smartphone is using Bluetooth.

The PPG data are transmitted to the smartphone in real-time and the smartphone is used to perform digital signal processing include FIR digital filter and compute the physiological parameters such as HR. The PPG waveform and HR information are shown on the display of smartphone. If the abnormal physiological signal is detected, the smartphone will use the sound alarm and vibration alert to warn the driver. At the same time, physiological data and GPS location are also be transmitted to the remote server (remote health care center) via the 3G mobile network, so that the staff on the center can monitor the newest information and understand driver's driving status. Therefore, the driver can find the best solution at the first time.

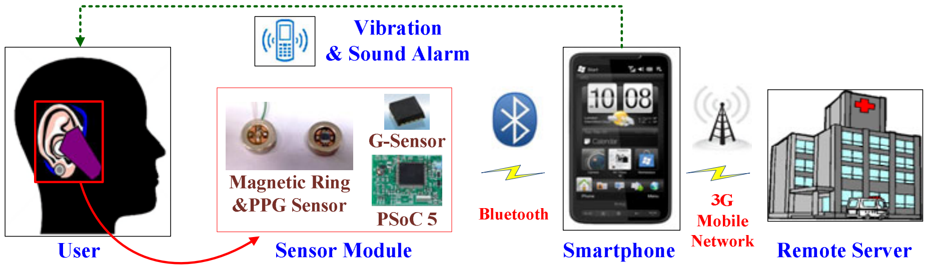

Fig. 1. System block diagram

2.1 Sensor Module

The sensor module can be divided into PPG sensor and microprocessor module.

PPG Sensor. The PPG sensor is composed of an IR LED (infrared light emitting diode), a silicon photodiode, and a 3-axis G-Sensor (ADXL335). All devices are using SMD components to implement in order to reduce hardware size, so that it is comfortable to wear on the earlobe. In order to reduce motion artifact, we use the transmission method to measure PPG signal on earlobe. Besides, LED and silicon photodiode are put into the separate magnetic ring. Fig. 2 shows the optical sensors and magnetic rings. The two magnetic rings can attract together to clamp the earlobe. This structure not only makes LED light directed beam to the receiver, but also makes the sensor contact with the earlobe become more stable and can reduce motion artifact.

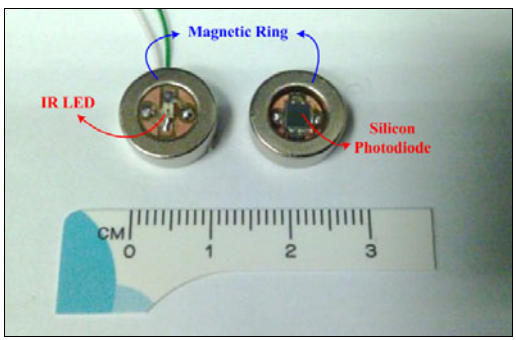

Fig. 2. PPG sensor and magnetic rings

Microprocessor Module. PSoC 5 is a main chip for our microprocessor module. It includes a Cortex M3 processor, OPAs, multiplexers, ADCs, DACs, GPIOs and UARTs. The PPG signal is processed by a high-pass filter (cut-off frequency is 0.48Hz), a low-pass filter (cut-off frequency is 4.82Hz), and an amplifier (gain is 120) through internal OPAs. Then, the processed PPG signal and G-Sensor signals (Ax, Ay, Az) are fed into internal 4-to-1 multiplexer. The output signal of the multiplexer is connected to the internal 8-bit ADC and convert to digital signals. The sample rate is 100Hz for each channel. Finally, the processed signals are sent to UART, which is connected to a Bluetooth module for data transmission. The Baud rate is 9600. Fig. 3 shows the detail hardware block diagram. Orange blocks are internal blocks of PSoC.

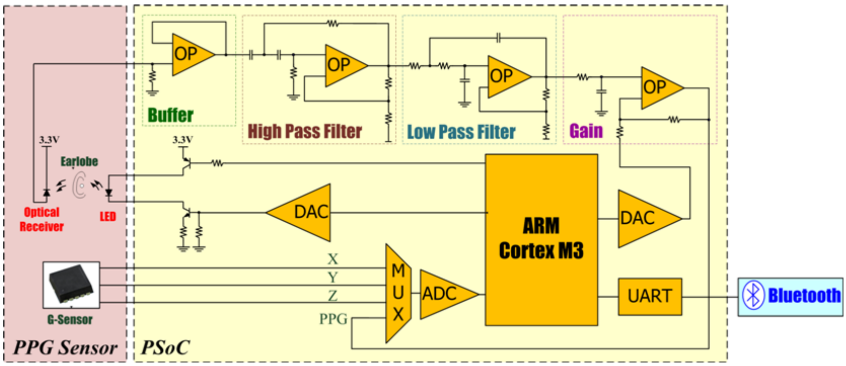

Fig. 3. Hardware block diagram

2.2 Smartphone Platform

On the choice of mobile phones, we choose HTC HD2. It uses windows mobile 6.5 operating system and contains a 1GHz processor and 448MB RAM. We use Microsoft Visual Studio 2008 C# .Net for smartphone application program development. Fig.4 shows the software flow chart on the smartphone platform.

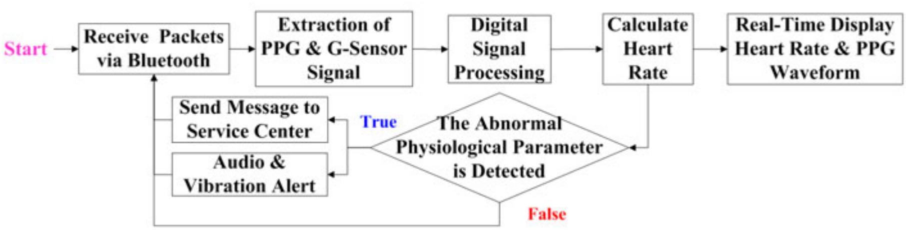

Fig. 4. Software flow chart on the smartphone platform

First, it receives and unpacks the data packets via Bluetooth module. Second, through signal processing to calculate the HR, and then shows the PPG signal waveform and HR on the LCD display of smartphone for users to observe. After the signal analysis, the system will use vibration or audio to alert drivers to take a rest or to find out medical service immediately when the abnormal physiological parameter is detected. Fig. 5(A) is the physiological monitoring interface. It can show the PPG waveform and HR information on smartphone. Fig. 5(B) shows the setting interface, it can set alert conditions and feedback methods for alert. Fig. 5(C) is the alert interface when the abnormal physiological signal is detected.

(A) (B) (C)

Fig. 5. (A) Physiological monitoring interface. (B) Physiological setting interface. (C) Alert interface when abnormal physiological signal is detected.

2.3 Heart Rate Detection Methods

The heart rate is determined by the Peak-Peak Interval (PPI) of PPG waveform. PPI calculation is shown in Equation 1. The n_{th} PPI (PPI_n) is determined by the n_{th} peak index (P_n) and the $n\text{-}1_{th}$ peak index (P_{n-1}) and sampling frequency. 'S' means the sample rate of PPG signal and heart rate is calculated by Equation 2.

$$PPI_n = \frac{P_n - P_{n-1}}{S}. \tag{1}$$

$$HR_n = \frac{60}{PPI_n} = \frac{60 \times S}{(P_n - P_{n-1})}. \tag{2}$$

Signal Process. In order to calculate HR, we must get the exact peak location of PPG waveform. Fig. 6 shows signal processing steps for PPG peak detection.

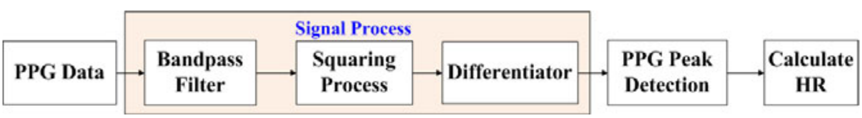

Fig. 6. Signal processing steps for PPG peak detection

Fig. 7 shows PPG signal processing steps. Signal processing steps include bandpass filter, squaring process and differentiator. Fig. 7(A) is an ECG signal as a reference. Fig. 7(B) is the original PPG signal. First, in order to attenuate noise, the signal passes through a digital bandpass filter that cutoff frequency is 0.8Hz and 4Hz. Fig. 7(C) shows the output of this filter. The next process after bandpass filtering is squaring. We use the squaring to enlarge the signal characteristic. Fig. 7(D) shows the output of the squaring. After the squaring is differentiation. Information about the slope of the PPG signal is obtained in this derivative stage. We use this slope to detect the position of the PPG's peak. Fig. 7(E) shows the output of the differentiation.

Peak Detection. We utilize the slope feature and set a dynamic threshold to detect the PPG's peak. When the PPG slope value is larger than this threshold, then PPG peak position can be detected on the first slope value which is less than or equal to 0. Fig. 8(A) shows the slope feature of PPG signal after the differential process. The beginning of detection, *Flag* is set to false. When the slope value is larger than the threshold, the *Flag* is set to true and this slope value is recorded to the buffer. When the *Flag* is true and slope value is smaller than or equal to 0, then we can get the PPG's peak index (position) in this moment. Afterwards we take out the maximum slope value from the buffer and use it to update the new threshold. We can calculate the peak to peak interval after the peak index is obtained. Finally, we clean the buffer and restart to detect next peak. Fig. 8(B) shows the flow chart of the peak detection.

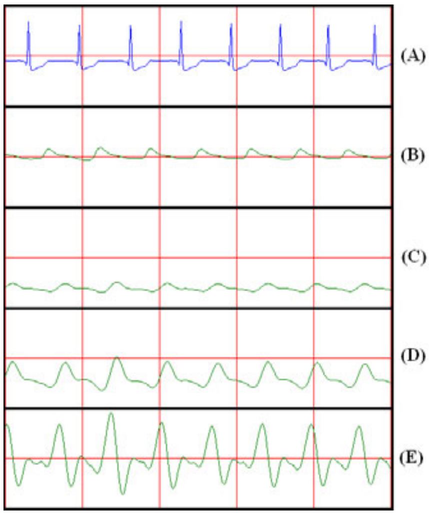

Fig. 7. PPG signal processing steps. (A) ECG signal as a reference. (B) Original PPG signal. (C) Output of bandpass filter. (D) Output of squaring process. (E) Results of differentiator.

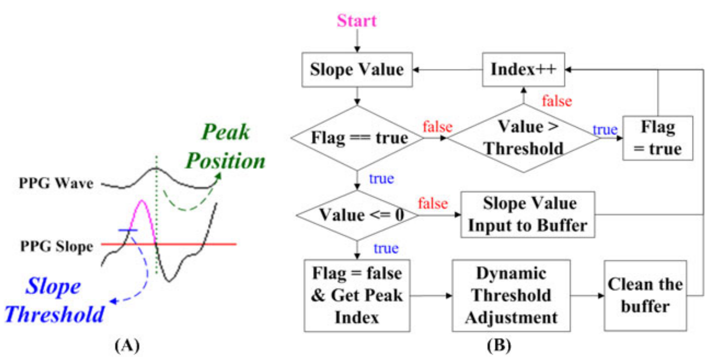

Fig. 8. (A) The slope feature of PPG signal. (B) The flow chart of the peak detection.

Dynamic Slope. Threshold Adjustment and Peak-to-Peak Period Estimation. The dynamic slope threshold is updated with the previous maximum slope value of PPG waveforms. The initial threshold value, we can select a small threshold to ensure that the first peaks can be detected. Each period we can get a maximum slope value, so that we can use this maximum slope value to multiply a coefficient to generate a new threshold for detecting the next PPG peak. According to the Equation 3, the n_{th} threshold (T_n) is determined by the previous maximum slope value (S_{n-1}) and coefficient value (T_C). In this study, this coefficient value is 0.35.

$$T_n = S_{n-1} \times T_c . \tag{3}$$

In addition to dynamic threshold adjustment, we also set a time window to reduce the occurrence of error peak detection. The time window is also dynamic adjusted by previous PPI. PPI_L is the minimum time window, and PPI_H is maximum time window. PPI_L and PPI_H are calculated by Equation 4 and Equation 5. If we detected a peak point and the new PPI is smaller than PPI_L, then this point will be considered that is an error and ignore it. If we can't detect any peak in this maximum time window, then the threshold should be initialized to initial threshold. Fig. 9 shows the dynamic slope threshold adjustment and the time window.

$$PPI_L = PPI_{n-1} \times 70\% \tag{4}$$

$$PPI_H = PPI_{n-1} \times 130\% \tag{5}$$

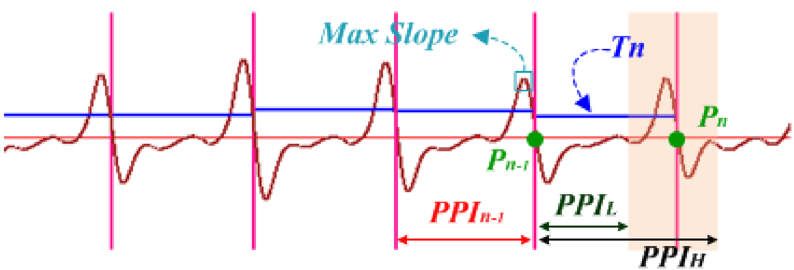

Fig. 9. Dynamic slope threshold adjustment and the time window

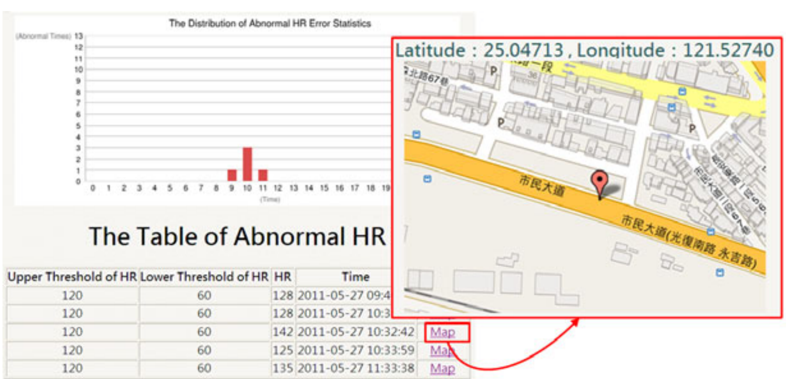

Fig. 10. The database management web page and the GPS coordinates show on Google Map

2.4 Remote Server

The smartphone can real-time transmit the abnormal HR value and GPS coordinates to the remote server by 3G mobile network. On the server, we use MySQL database and PHP web page to read the information. It can also use the Google API chart to show the abnormal state, and use Google Map to show the driver's position. Therefore, the staff in service center can monitor driving conditions quickly and clearly via the web page. The database management web page for the abnormal HR statistics is shown in Fig. 10. When click the "Map" of the database, the GPS coordinates can be shown on Google map.

3 Results

The accuracy of HR detection will describe in following. In the past, motion artifact is the most common problem on wearable PPG system. Therefore, our verification methods focus on the behaviors that may cause motion artifact when the driver wears this device. The common behaviors for the driver such as talking, watching left and right side mirrors, and head shaking. Therefore, we design a five-minutes testing procedure (Table 1). Test procedure has 10 stages, each stage has 30 seconds, includes rest (stage 1, 3, 6, 8, 10), reading the article and read out the sound (stage 2). In the stage 4 and stage 5, system will sound at the second and fourth second of every five seconds, it repeats six times in both stage 4 and stage 5. The tester who heard the first sound need immediately to turn his head to see right/left side (mirror direction), and immediately return back to front when the second sound. In stage 7 and stage 9, the tester need to continuous shake head for 30 seconds.

Table 1. The test procedure of five minutes

Stage	Time(mm:ss)	Behavoir
1	00:00 ~ 00:30	Rest.
2	00:30 ~ 01:00	Reading the article and read out the sound.
3	01:00 ~ 01:30	Rest.
4	01:30 ~ 02:00	See the mirror on right side
5	02:00 ~ 02:30	See the mirror on left side
6	02:30 ~ 03:00	Rest.
7	03:00 ~ 03:30	Continuous head shaking (left and right).
8	03:30 ~ 04:00	Rest.
9	04:00 ~ 04:30	Continuous head shaking (up and down).
10	04:30 ~ 05:00	Rest.

In this test, we measure PPG signal by our self-made sensor module. At the same time, we use ECG signal to verify the heart beats. There are 5 people were tested, each person records 4 times and each time records 5 minutes. Tester is requested to sit on the chair in all test stages. The range of all testers' HR is from 62 to 100 bpm. The results show the difference in heart beats between the ECG method and our method there is 0 in all driving behaviors test. Table 2 shows the heart beats of both methods.

Table 2. Heart beats of both ECG and PPG methods

Tester	n	Method	Stage 1	Stage 2	Stage 3	Stage 4	Stage 5	Stage 6	Stage 7	Stage 8	Stage 9	Stage 10	Total
A		PPG	50	49	49	48	50	51	50	50	50	50	497
	1	ECG	50	49	49	48	50	51	50	50	50	50	497
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	48	47	48	47	47	47	48	47	46	48	473
	2	ECG	48	47	48	47	47	47	48	47	46	48	473
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	47	45	46	47	45	46	45	48	45	45	459
	3	ECG	47	45	46	47	45	46	45	48	45	45	459
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	49	48	49	49	48	48	48	48	48	48	483
	4	ECG	49	48	49	49	48	48	48	48	48	48	483
		Diff.	0	0	0	0	0	0	0	0	0	0	0
B		PPG	31	36	32	32	31	31	33	33	33	32	324
	1	ECG	31	36	32	32	31	31	33	33	33	32	324
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	33	34	33	33	31	32	34	35	34	33	332
	2	ECG	33	34	33	33	31	32	34	35	34	33	332
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	34	35	33	31	31	32	31	32	34	33	326
	3	ECG	34	35	33	31	31	32	31	32	34	33	326
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	33	35	33	33	32	33	33	33	35	32	332
	4	ECG	33	35	33	33	32	33	33	33	35	32	332
		Diff.	0	0	0	0	0	0	0	0	0	0	0
C		PPG	38	40	38	35	36	36	37	38	39	38	375
	1	ECG	38	40	38	35	36	36	37	38	39	38	375
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	38	39	39	36	35	39	37	38	38	39	378
	2	ECG	38	39	39	36	35	39	37	38	38	39	378
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	39	39	41	39	39	41	39	41	40	41	399
	3	ECG	39	39	41	39	39	41	39	41	40	41	399
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	38	42	39	37	38	39	38	39	41	40	391
	4	ECG	38	42	39	37	38	39	38	39	41	40	391
		Diff.	0	0	0	0	0	0	0	0	0	0	0
D		PPG	36	39	38	37	37	38	40	37	41	38	381
	1	ECG	36	39	38	37	37	38	40	37	41	38	381
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	38	41	36	41	40	40	43	42	42	39	405
	2	ECG	38	41	36	41	40	40	43	42	42	39	405
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	34	35	36	34	36	34	38	34	38	33	352
	3	ECG	34	35	36	34	36	34	38	34	38	33	352
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	36	38	35	34	34	32	36	34	36	34	349
	4	ECG	36	38	35	34	34	32	36	34	36	34	349
		Diff.	0	0	0	0	0	0	0	0	0	0	0
E		PPG	42	44	43	40	40	41	41	42	42	42	417
	1	ECG	42	44	43	40	40	41	41	42	42	42	417
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	41	43	40	41	40	41	41	40	42	42	411
	2	ECG	41	43	40	41	40	41	41	40	42	42	411
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	42	42	41	39	40	42	39	40	42	40	407
	3	ECG	42	42	41	39	40	42	39	40	42	40	407
		Diff.	0	0	0	0	0	0	0	0	0	0	0
		PPG	41	41	39	38	40	40	39	40	40	39	397
	4	ECG	41	41	39	38	40	40	39	40	40	39	397
		Diff.	0	0	0	0	0	0	0	0	0	0	0
Total		PPG	788	812	791	771	770	783	790	791	806	786	7888
		ECG	788	812	791	771	770	783	790	791	806	786	7888
		Diff.	0	0	0	0	0	0	0	0	0	0	0

4 Discussion and Conclusion

We test the sensor module's current consumption in two conditions. One is for data transmission rate of 100 byte/sec that is only transmitting PPG data. The total current consumption of our sensor module is 77.357 mA, includes the 23.629 mA current consumption of Bluetooth module. Another is for data transmission rate of 600 byte/sec that is including 3-axies data of G-Sensor, PPG data, one start and one stop characters. Total current consumption of this sensor module is 88.714 mA, includes the 34.129 mA current consumption of Bluetooth module. It still has space to reduce current consumption by changing LED control method and perform data compression.

In the Bluetooth transmission test, the transmission error rate is 0 in the open space within 10 meters, so it's no problem to transmit physiological signal in the car. In the 3G mobile network transmission tests, we use smartphone to transmit the packets to the remote server per second for 1000 times continuously. The average packets transmission time of 1000 times is less than 350ms, so that it can achieve the purpose of real-time transmission.

In this paper, we present a smartphone based physiological monitoring and alert system for driver to monitor their HR in real time. When the abnormal HR is detected, smartphone will automatically warn driver to achieve the real-time alert function. Besides, remote health care center can also monitor the newest driver's status and location via the 3G mobile networks. Therefore, the driver can find the best solution at the first time. It is expected the traffic accidents caused by the abnormal physiological signals can be reduced via the real-time alert function. We also proposed a new PPG sensor structure that is combining the sensors with magnetic rings to reduce motion artifact. Experiments have shown that this system can monitor driver's HR and has not been affected by the motions caused by general driving behaviors.

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