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Wearable Two-Channel PPG Optical Sensor with Integrated Thermometers for Contact Measurement of Skin Temperature †

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Abstract: Many factors affect the photoplethysmography (PPG) signal quality, one of them being the actual temperature of the skin surface. This paper describes the process of design, realization, and testing of a special wearable PPG sensor prototype with the contact thermometer measuring in detail the skin temperature in the place where the optical part of the PPG sensor touches a finger/wrist. Performed experiments confirm continual increase of temperature at the place of worn PPG sensors during the whole measurement influencing mainly the PPG signal range. Other parameters seem to be temperature independent or influenced by other factors – blood pressure, heart rate, etc.

Keywords: photoplethysmography optical sensor; wearable sensor; PPG wave features; contact skin temperature measurement

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1. Introduction

At present, the cardiovascular magnetic resonance imaging (MRI) is an important imaging technique used for investigation of the heart structure and its function. However, in this type of a non-invasive examining device, the pulsating current in the gradient coil system generates mechanical vibration and acoustic noise [1]. Such a vibration is often accompanied by a local heating effect which can be measured by a contactless method using a thermal imaging camera [2]. The shape of the peripheral pulse wave of the photoplethysmography (PPG) signal reflects the current state of a human cardiovascular system including changes in the arterial stiffness, the blood pressure (BP), and the heart rate (HR) [3]. These parameters can be used for detection of the stress effect [4], [5] also during examination in the MRI device working with the low magnetic field [6] which is our final long term research aim.

The quality of the sensed PPG signals and the determined PPG wave features depend also on the actual state of the skin at the position of the optical sensor. The age and gender as well as the skin color and the temperature of the skin surface can have influence on the PPG signal, too. Our previous solution of wearable PPG sensors [7] does not allow direct temperature measurement by any contact thermo-element during the PPG signal sensing. For precise determination of PPG wave parameters, the current temperature should be measured at the same time as the PPG signal is sensed. As follows from the reactions of the tested persons we know that majority of them gradually felt pressing and thermal effect on a finger (wrist) at the contact of the sensor with the skin. While the time duration of the PPG signal sensing was about 1 minute, the total time of wearing the optical sensor was about 15 minutes (including the initial time for basic manipulation during sensor mounting, creation of BT connection with a control laptop, calibration, and testing of the obtained PPG signals in the real-time monitoring mode).

Motivation of the current work was to confirm or reject this subjective feeling of local warming by practical measuring experiments using a special prototype of the multi-channel wearable PPG sensor with integrated thermometers. In addition, we try to formulate a recommendation about a proper arrangement and timing of PPG signal sensing to obtain the desired PPG parameters with a sufficient accuracy. Described first-step experiments were realized in the normal laboratory conditions with planned further application for measurements inside the running low-field MRI device [7], [8].

This paper describes the process of design, realization, and testing of a special prototype of a two-channel wearable PPG sensor with the contact thermometers to carry out a detailed measurement of the skin temperature at the point where the optical part of the PPG sensor touches a finger/wrist. Received data (PPG signal/temperature values) are next processed and analyzed statistically. Obtained partial and summary results for all tested persons are presented separately depending on the type of the processed data using graphical as well as numerical forms. Performed measurements confirm continual increase of temperature at the place of worn PPG sensors during the whole measurement experiment with the main influence on the PPG signal range. Other parameters seem to be temperature independent or affected by other factors – BP, HR etc.

2. Methods

2.1. Determination of PPG wave Properties and Analysis of Temperature Value Sequences

For description of signal properties of the sensed PPG waves the energetic, temporal, and statistical parameters can be determined. Currently used methodology of the PPG wave properties including the heart rate determination from the PPG wave was described in more detail in [8]. The smoothing and de-trending operations must be applied on the sensed raw PPG signal in the frame of pre-processing. All systolic peaks P_{SYS} are located, their min/max levels (Lp_{MIN}/Lp_{MAX}) and the PPG signal offset level (L_{OFS}) are determined as shown in Figure 1a. The mean signal offset value $\mu\, L_{OFS}$ is then used to calculate the relative percentage PPG signal range S_{RANGE} as

$$S_{RANGE} = ((Lp_{MAX} + Lp_{MIN})/2 - \mu\, L_{OFS})/AD_{RES} \times 100\ [\%], \quad (1)$$

where AD_{RES} is the resolution of the analog-to-digital converter used to digitize the analog signal output of the PPG optical sensor. Next, the modulation (ripple) of heart pulses in percentage is calculated as

$$HP_{RIPP} = (Lp_{MAX} - Lp_{MIN})/Lp_{MAX} \times 100\ [\%]. \quad (2)$$

The peak positions P_{SYS} are next applied to determine the heart cycle periods T_{CP} and using the sampling frequency f_S [Hz] the heart rate is evaluated as $HR = 60 / (T_{CP} \times f_S)$ [min^{-1}] – see Figure 1b. The two-channel PPG parallel signal (PPG_A, PPG_B waves) can be used to determine distances between P_{SYS} positions in samples ($\Delta\, P_{SYS}$). These values are applicable for calculation of relative percentage parameter *rPTT*, invariant on the current *HR* value

$$rPTT = (PTT / T_{CP}) \times 100\ [\%]. \quad (3)$$

where *PTT* represents the pulse transmission time defined as a time difference between two systolic peaks measured in parallel by sensors located at a known distance [9] calculated as $PTT = \Delta\, P_{SYS} / f_S$ – see Figure 1c,d.

To describe temperature changes during the measurement with the time duration t_{DUR}, the linear trend is calculated by least squares fitting technique of linear regression. For practical use the difference $\Delta\, T$ between temperature value estimated at the start and the end of measurement ($\Delta T = T_{END} - T_{START}$) is determined. Next, the gradient parameter T_{GRAD} is calculated as the ratio

$$T_{GRAD} = (\Delta T / t_{DUR}) \ [°C / s], \quad (4)$$

The positive ΔT and T_{GRAD} values show the raising temperature trend, the negative ones represent the falling trend. During the current experiments we have obtained sequences of T1, T2 temperature values measured in parallel by two thermometers. From these sequences the differential parameter $T12_{DIFF}$ was determined from the values at T_{END} positions. For summary comparison, the relative variability (HR_{VAR}, T_{VAR}) was next calculated as a ratio between the mean μ and the standard deviation σ of an input sequence X (HR or T) as $X_{VAR} = (\sigma X / \mu X) \times 100$ [%]. Thus, in the final numerical comparison, the temperature parameters of T_{VAR}, ΔT, T_{GRAD}, and $T12_{DIFF}$ were used. In the case of PPG signal properties, the differential values (ΔHR_{VAR}, ΔS_{RANGE}, ΔHP_{RIPP}, and $\Delta rPTT$) separately for each PPG wave ($PPG_{A,B}$) were calculated.

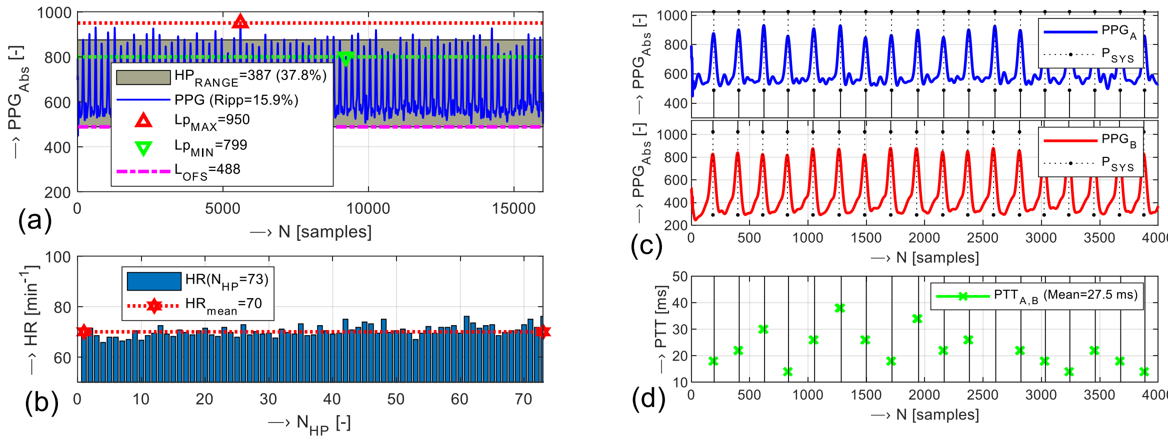


Figure 1. Example of determination of temporal and pulse transmission time parameters: (**a**) 15-k sample two-channel PPG signal (PPG_A wave) with determined Lp_{MAX}, Lp_{MIN}, and L_{OFS} values together with HP_{RANGE} and heart ripple parameters, (**b**) HR values corresponding to pulse periods T_{HP} (N_{HP} = 70) and a mean HR, (**c**) visualization of P_{SYS} positions of 4092 sample parts of PPG_A and PPG_B waves, (**d**) determined PTT values with their mean value; f_s=250 Hz.

3. Objects, Experiments and Results

The developed wearable two-channel PPG sensor with two integrated thermometers (further called "PPG-4TP") consists of:

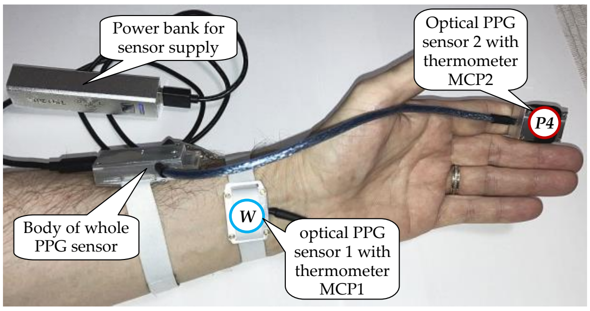
- the micro-controller board Adafruit Metro Mini 328 (Adafruit 2590) by Adafruit Industries, NY, USA, based on the processor ATmega328 by Atmel Company, working at f_{CLK} = 16 MHz with eight 10-bit A/D converters, including also the hardware SPI port, the hardware I2C port and the hardware UART to USB [10];
- the bi-directional communication BT module MLT-BT05 by Techonics Ltd, Shenzhen, China, working in the BT4.0 BLE standard at 2.4 GHz;
- two optical PPG sensors working in a reflectance mode with fully integrated analogue interfaces – the Crowtail-Pulse Sensor (ER-CT010712P) by Elecrow Company, Shenzhen, China (further called "OS1") and Gravity Heart Rate Sensor (SEN0203) by Zhiwei Robotics Corp., Shanghai, China (next called "OS2");
- two integrated precision I2C thermometers ("MCP1", "MCP2") based on Adafruit MCP9808 temperature sensors [11] by Adafruit Industries, NY, USA.

All sensor components are powered via the USB port by the 5V power bank THAZER (with 2200 mAh capacity). Used MCP9808 sensors enable temperature measuring in the range of -40°C to +125°C range with a typical accuracy of ±0.125°C [11]. Each sensor includes three address pins so up to eight sensors can be connected in parallel to a single I2C bus. To enable further measurements in a weak magnetic field environment of the MRI device, the whole PPG sensor consists of non-ferromagnetic components and all parts are fully shielded by aluminum boxes against the radiofrequency disturbance. The currently realized *PPG-4TP* sensor prototype enables: (1) real-time monitoring and displaying of PPG signals picked up currently from optical PPG sensors and thermometers, (2) continuous real-time two-channel PPG signal measurement with selected sampling frequency f_S = {125, 250, 500, and 1000 Hz} in data blocks of N_{MEAS}= {1k, 4k, 16k, 32k and 64k} samples. In parallel, the temperature values from two MPC9808 sensors can be taken in time intervals T_{INT} = {0.2, 1, 2, 4, and 10 s}.

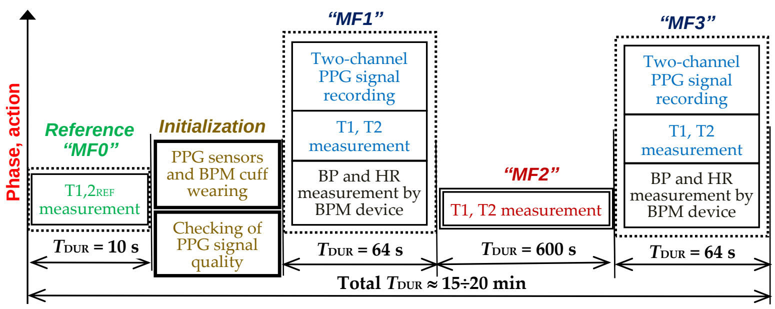
Developed PPG sensor was tested in two steps: after checking of functionality including the BT data transmission to the control device and verification of quality of real-time two-channel PPG signals and temperature T1, T2 values from thermo-sensors MCP1, MCP2, practical measuring experiments in the normal laboratory conditions were realized. They consist of real-time sensing of two PPG waves and temperature values from two thermometers simultaneously with parallel control measurement of BP and heart rate values (HR_{BPM}) by a BPM device. In this case, the tested person was sitting with both hands laid on a table located in a quiet office room; no visual or acoustic stimuli were present during the measurement (no conversation, no drinking, etc.).

Measuring experiments started with the reference phase (MF0) during which a 10-s record of temperature $T1,2_{REF}$ values were measured with both MCP sensors freely laid on the desk. Within the initialization phase, optical PPG sensors OS1 and OS2 were mounted on the person's left/right hand and the pressure cuff of a portable BPM device was worn on the other arm of the tested person. Then in the monitoring mode, was verified the quality of sensed PPG signals before start of the practical measurements in three main phases (MF1-3). In the frame of MF1, MF3 phases, two-channel PPG signals were recorded together with measured temperatures T1, T2.

The first optical PPG sensor OS1 with the thermo-sensor MCP1 was placed on the wrist artery (*W*), the OS2 sensor with MCP2 thermo-sensor was worn successively on the index finger (F4) as demonstrated by an arrangement photo in Figure 2a. In parallel, the BP and HR_{BPM} values were measured manually on the opposite hand using the portable BPM device Microlife BP A150-30 AFIB by Microlife AG, Widnau, Switzerland. In the phase MF2 with the time duration of 10 minutes (600 sec), the values from thermo-sensors MPC1, MPC2 were received and stored to an output file without PPG signal sensing. The total time duration of whole experiments is approx. 15÷20 minutes (depending on the length of the initialization part – see the time schedule in Figure 2b). In the MF0 phase the temperature values were taken in the intervals of T_{INT} = 1 s, during the MF1 an MF3 phases T_{INT} = 0.2 s was applied, and for measurement in the MF2 phase T_{INT} = 4 s was used.



(a)



(b)

Figure 2. Arrangement of PPG and temperature measurement experiments: (**a**) principal photo, (**b**) used experimental and time schedule.

The currently collected corpus of two-channel PPG signals and temperature sequences consists of records taken from eight non-smoker volunteers — six males (P1-6M) and two females (P1-2F) — with a mean age of 50 years. Each database record includes: (1) two PPG wave files (containing PPG signals and T1, T2 sequences sensed in parallel during the MF1 and MF3 phases) accompanied by two files with BP and HR values measured manually by the external BPM device; (2) two separate files with temperature and time values recorded during the MF0 and MF2 phases.

Partial and summary results obtained for all tested persons are evaluated separately in dependence on the processed signal type. Partial results of signal parameters determined from PPG waves taken within the MF1 and MF3 measurement phases for one person are shown in Figure 3; summary numerical values of investigated differential parameters for all tested subjects are enumerated in Table 1. The demonstration example of concatenated temperature sequences from the MF0-3 phases for the MCP1, MCP2 thermo-sensors can be seen in Figure 4; visualization of corresponding statistical parameters is shown in graphs in Figure 5. Summary temperature differential and statistical parameters separately for the MCP1, MCP2 thermo-sensors for all tested persons are presented in Table 2.

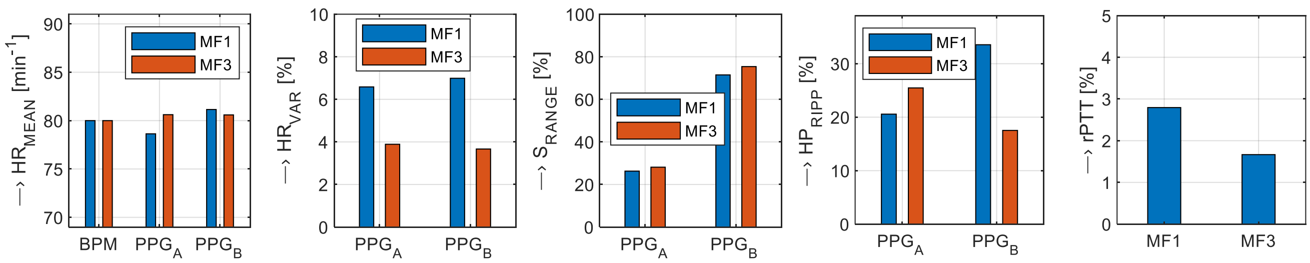


Figure 3. Partial results of PPG signal properties taken in the MF1 and MF3 phases for person P1M (from left to right): mean HR values, HR variations, PPG signal range and HP ripple, and relative PTT values.

Table 1. Summary mean differential parameters together with their std (in parentheses) determined separately for PPGA and PPGB waves within MF1, MF3 phases; for all tested persons.

PPG Signal	Δ *HR*VAR [%]	Δ *S*RANGE [%]	Δ *HP*RIPPLE [%]	Δ r*PTT* [%]
PPGA	-2.70 (1.51)	7.10 (3.35)	1.33 (1.35)	-0.496 (0.86)
PPGB	-3.32 (1.59)	3.19 (2.35)	-6.15 (1.46)	

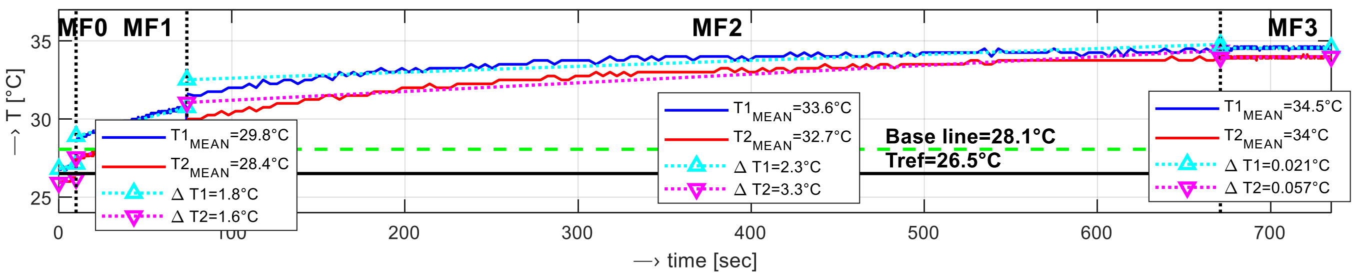


Figure 4. Concatenated sequences from thermo-sensors MCP1, MCP2 together with fitted linear regressions, calculated mean and Δ *T* values; concatenate for measuring phases MF0-3, *T*REF = 26.5°C, baseline for MF1-3 measurements is 28.1°C, tDUR=738 s, person P1M.

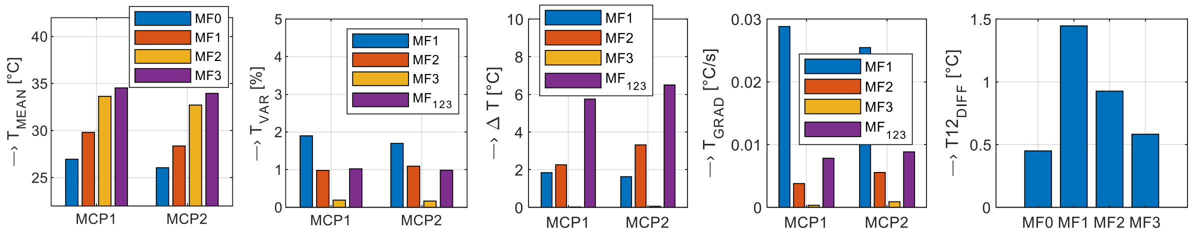


Figure 5. Statistical parameters determined from temperature sequences T1, T2 from thermo-sensors MCP1, MCP2 introduced in Figure 4 (from left to right): mean values, relative variations, Δ T values, gradients, and differential T12 values between MCP1's and MCP2's for each of three measurement phases (MF1-3); final values MF_{123} determined for whole measurement.

Table 2. Summary temperature mean parameters together with their std (in parentheses) determined inMF0-3 phases separately for MCP1, MCP2 thermo-sensors, for all tested persons.

Phase	T_{VAR} [%]		Δ *T* [°C]		T_{GRAD} [°C/s]		$T12_{DIFF}$ [°C]
	MCP1	*MCP2*	*MCP1*	*MCP2*	*MCP1*	*MCP2*	
MF0	—	—	—	—	—	—	0.11 (0.2)
MF1	0.47 (0.63)	0.49 (0.54)	1.3 (0.72)	1.1 (0.66)	0.0208 (0.0113)	0.0175 (0.0103)	1.37 (0.8)
MF2	0.67 (0.2)	0.68 (0.23)	1.9 (1.50)	2.4 (1.51)	0.0031 (0.0024)	0.0041 (0.0025)	1.08 (0.9)
MF3	0.19 (0.02)	0.24 (0.08)	0.04(0.04)	0.04 (0.03)	0.0006 (0.0007)	0.0006 (0.0005)	0.93 (0.8)
MF0-3	0.45 (0.3)	0.47 (0.2)	4.3 (2.1)	4.1 (2.1)	0.0058 (0.0021)	0.0056 (0.0030)	0.87 (0.5)
Summary	0.46 (0.019)		4.20 (0.087)		0.0057 (0.0002)		—

4. Discussion and Conclusions

The performed experiments have demonstrated the continually raised temperature during all 12-minute measurements consisting of MF1-3 phases. It was caused partially by internal heating from powered analogue parts of optical sensors but mainly by contact warming from the skin of the hand (wrist and finger) of the tested person. Next, it was found that the temperature increase depends heavily on the placement of the PPG sensors: higher Δ *T* were obtained from the thermo-sensor MCP1 located on the wrist but the final increase of T2 values taken from the index finger by the MCP2 thermo-sensor was always lower. While the difference between T1 and T2 values obtained in the reference phase MF0 was minimal (typically given by a chosen precision of the used thermo-sensors), the maximum $T12_{DIFF}$ was detected usually at the end of the MF1 phase and it was practically constant until the end of the whole experiment. The same trend was observed for T_{GRAD} parameter but the variability of T1, T2 values was slightly higher in frame of the MF2 phase as documented the summary values in Table 2.

Temperature changes have also influence on the parameters of PPG signals sensed in the M1 and MF3 phases – compare summary values in Table 1. Two-channel PPG signals (PPG_A and PPG_B waves) taken in the MF3 phases have always higher S_{RANGE} in comparison with the one sensed in the MF1 phase during which the temperatures T1 and T2 are lower. In the case of the HP ripple, this trend was not finally confirmed – so these values are practically temperature independent. Higher relative variation of HR values determined from PPG waves in the MF1 phase have direct relation with lower PPG signal range (generally similar to the signal-to noise ratio in the signal processing area). Finally, detected slight (although not important) changes in the *rPTT* parameter can be affected by other factors – mainly by the blood pressure.

The final recommendation following from the experiments performed currently is to keep worn the optical PPG sensors on the tested fingers (wrist) cca 5÷10 minutes before the start of the PPG signal sensing to obtain proper PPG waves with sufficient signal range and pronounced systolic peaks. It is important to obtain subsequently determined parameters with the proper accuracy.

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