Photoplethysmography-based In-Ear Sensor System for Identification of Increased Stress Arousal in Everyday Life

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Abstract— **In this work, we present an in-ear system for physiological and psychological stress detection based on photoplethysmography, acceleration, and temperature measurements. The complete system is used to extract vital signs from healthy subjects, who are exposed to psychologically demanding tasks. The newly developed sensor system is integrated into our IPANEMA body sensor network and, thus, can be used in combination with several sensor modalities. The capability of the stress level estimation is validated in an human stress experiment. To obtain information on the current stress level, several well-known indicators are utilized like the heart rate variability, surgical stress index or the Oliva and Roztocil index.**

I. INTRODUCTION

Photoplethysmography (PPG) is an optical method for measuring blood volume. It is a non-invasive method commonly employed by modern personal health-care professionals. Nowadays, photoplethysmograms are often obtained from a pulse oximeter. Pulse oximetry is an extension of PPG's application. Vital signals, including heart rate (HR), hemoglobin oxygen saturation and the estimation of trends of blood pressure can be obtained continuously and in real-time by using this method, providing *in-vivo* critical information for the diagnosis [1]. A pulse oximeter comprises generally LEDs, a photo diode and the signal acquisition system. Also, in-ear solutions for photoplethysmographic measurement application for vital parameter extraction had been proposed before [2].

Mental stress is a common burden in the modern society. It is of great interest, how people react being exposed to mental stress. Negative stress arousal is even suggested to be linked both with psychological and physiological diseases [3]. Recently, researchers have made efforts in in-time assessment of current stress level utilizing various sensing modalities [4]. Major challenges in stress assessment are 1) an effective way of producing a reliable measurement and 2) the significant difference in physiological response among individuals.

In this work, the developed in-ear PPG sensor system is employed in an experiment. It provides information not only on biosignals like HR and S_pO_2, but also head motion during given tasks. A more detailed analysis is then performed to investigate their possible correlation with stress. Parameters that may indicate an increased exposition to physical or mental stress are known as heart rate variability (HRV), the surgical stress index (SSI), and the Oliva and Roztocil index (ORI). HRV is one of the most reliable bio-marker on the autonomous nervous system and has been used, for example, in driver state assessment to quantify the current stress level [5]. The HRV can be obtained using different techniques; within this contribution, continuous wavelet transformation (CWT) is performed for spectral analysis. Besides the HRV, we apply the SSI, that originally was designed for recognizing the stress level during surgery, which is an unconscious response related to ANS system [6]. The SSI utilizes both normalized heart beat interval and the plethysmographic pulse wave amplitude. In contrast, the ORI is based on the pulse wave geometry [7].

This contribution is organized as follows. In section II, the developed hardware setup and the already existing IPANEMA body sensor network are introduced. Also, we describe the applied algorithms for the signal processing and derived vital parameters for stress detection. Section III shows an overview on the obtained results with respect to the points addressed in section II. Finally, section IV gives a conclusion of the presented system and proposed algorithms for stress detection.

II. METHODS AND MATERIAL

A. IPANEMA Body Sensor Network

The *Integrated Posture and Activity Network by MedIT Aachen* (IPANEMA) is a multimodal body sensor network (BSN) that has been developed at MedIT [8]. It consists of several different sensor nodes and one master node that synchronously collects all the data from each of the sensor nodes and forwards it via bluetooth to a further processing PC system or alternatively stores it on SD card. Within the star-shaped network, each of the single nodes is modular structured with a main board and a case-specific extension board, such that sensor designs can be easily adapted. The IPANEMA main board includes a 16 bit MSP430F1611 microcontroller by Texas Instruments (TI), a charging controller LTC3558 by Linear Technology for the 330 mAh lithium polymer battery, and a wireless transciever chip CC1101 by TI for the network-internal 433 MHz ISM band communication. Also, the main board is equipped with digital IOs, including I^2C and SPI, and input ports for the integrated ADC.

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B. Sensor Setup

The sensor setup for the newly developed in-ear sensor system for the IPANEMA BSN contains several modalities, such as PPG, acceleration, and temperature measurements. The obtained biophysiological information should be used to get a reliable estimation of the patient's current stress status. The sensor design is shown in fig. 1. In the following the different parts of the hardware implementations of the sensor systems are explained in detail.

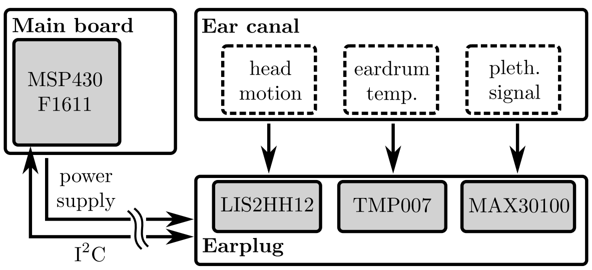
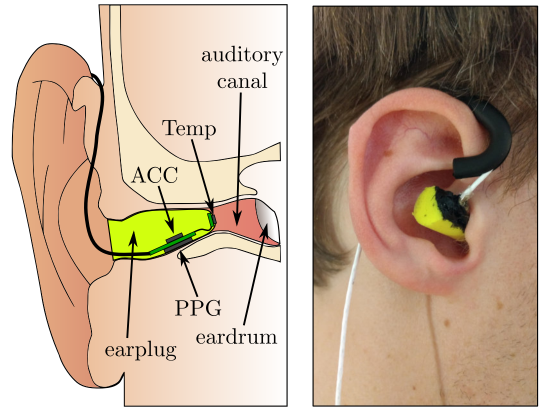


Fig. 1. Hardware setup within the IPANEMA BSN.

1) Pulse Oximetry: The photoplethysmographic measurement is performed to obtain information on the heart rate (HR), respiration rate (RR), and the saturation of peripheral oxygen (S_pO_2), respectively. For this purpose, we established the integrated analog front end (AFE) MAX30100 by Maxim which already has internally combined signal preprocessing and optical components. Also, it has ambient light cancellation (ALC) and analog-to-digital converters (ADC) on-board. The MAX30100 has integrated a red LED with a wavelength of approximately $\lambda_R = 660\,\mathrm{nm}$ and an infra-red (IR) LED with a wavelength of $\lambda_{IR} = 875\,\mathrm{nm}$ on a space of $5.6\,\mathrm{mm} \times 2.8\,\mathrm{mm} \times 1.2\,\mathrm{mm}$. Each channel is sampled with a 16 bit resolution at a sampling frequency of 100 Hz.

2) Accelerometer: To identify head motion that may cause signal artifacts during PPG measurements we use an accelerometer (ACC) directly placed on the opposite side of the PPG sensor (cf. fig. 2). Due to its small size of $2.0\,\mathrm{mm} \times 2.0\,\mathrm{mm}$ we decided for the LIS2HH12. It has a $\pm 8\,\mathrm{g}$ full scale range with a resolution of 16 bit. The ACC data is internally downsampled to a sampling rate of 100 Hz.

3) Temperature: There are two different measurement techniques to acquire the human body temperature. The first one is a contact-based thermal resistor that changes resistance according to variation of the human skin temperature. Since the skin temperature differs from the human core temperature and depends on many environmental factors, measurements close to the body center in general are more reliable. Thermopile IR measurements on the eardrum surface are a common procedure as the eardrum is highly perfused by warm arterial blood. In the proposed measurement system, we integrated the TMP007 by TI to get information on variation of the human core temperature. Temperature has been sampled with a rate of 33 Hz. For individual calibration purposes, we need to transfer voltage difference of the thermopile element and the die temperature next to the captured object temperature which results in a total of $3 \cdot 16$ bit.



(a) (b)

Fig. 2. (a) Schematic in-ear sensor setup. (b) Subject with applied in-ear sensor.

C. Signal Processing

Before more sophisticated algorithms are applied, the waveforms are preprocessed to increase signal-to-noise ratio (SNR) and separate the AC and DC information of the PPG signals. An appropriate preprocessing is an essential foundation that affects the overall performance. Spectral filters separate DC and AC information in frequency domain and is capable of reducing noise. However, it can cause distortion to certain extent on the raw waveforms, which results in errors in the following processing, for instance the normal-to-normal intervals (NN intervals). In this contribution, a preprocessing stage combining spectral band-pass filter and a simple Kalman filter (**K**) approach with a one-dimensional state space for reducing the white noise in the ACC and PPG measurement data is designed in order to extract DC and AC information separately and preserve the original PPG waveforms.

D. SSF Transformation

For the determination of the current stress level, a reliable heart rate evaluation is needed. Also, the S_pO_2 calculation is based on the peak detection in the PPG signal. Besides assuming white measurement noise, photoplethysmographic signals always have distortion to certain extent. In-band noise, motion artifacts, electrical noise, and the dicrotic pulse, disturb the recognition of the correct peaks. Solely applying a local maximum detection in most cases is insufficient. Therefore, in this contribution an adaptive algorithm is applied that is based on the slope sum function (SSF) transformation [9], where not only max-peaks but also min-peaks will be detected on both infra-red and red channel PPG. The complete algorithm can be divided into the following steps:

1) The SSF transformation of the band-pass filtered IR signal is calculated using

$$\chi_i = \sum_{k=i-w}^{i} \Delta x_k, \tag{1}$$

and

$$\Delta x_k = \begin{cases} \Delta s_k & \text{if } \Delta s_k > 0 \\ 0 & \text{if } \Delta s_k \leqslant 0 \end{cases}, \tag{2}$$

where χ_i is the SSF transformation, s_k is the current sample point, w is the window length, and Δs_k is difference between two neighboring sampling points s_k and s_{k-1}.

2) The local maxima of the SSF function are determined by a peak finding algorithm. Incorrect peaks will be eliminated by two criteria: At first, two peaks need to be separated by a zero area according to the SSF algorithm. Secondly, the amplitude of the current peak should exceed a certain adaptive threshold of 30% of the previous confirmed peak. Thus, the signal time line is divided in so-called *quasi-pulse-intervals*.

3) Within these quasi-pulse-intervals we now search for the local maximum in the IR and red PPG signal which indicates the real heart beat or the arrival of the pulse wave, respectively. In addition, the position of the local minimum is evaluated within each *maximum-pulse-interval*.

E. Motion Artifact Compensation

The quality of the PPG signal and, thus, the derived information on HR and S_pO_2 is influenced by many different environmental factors, like measurement noise, ambient light changes or motion artifacts. Especially in the case of motion artifacts, filter processing needs additional information, whereas measurement noise has been addressed before by applying digital filtering and ambient light cancellation is already integrated in the utilized hardware. Similar to solutions proposed in [10], we utilized the acceleration information that is obtained from the back of the MAX30100 (cf. fig. 2(a)) in combination with an adaptive filter approach. The acceleration data in all three channels is preprocessed using a Kalman filter for eliminating the white noise. Then, we calculate the norm of the 3-dimensional acceleration vector, which results in constant gravity value while staying in resting position. After filtering the acceleration norm by applying a low cut-off frequency high-pass filter, we can easily identify episodes of high movement by thresholding the resulting signal. Those areas of specific minimal length above a certain threshold are labeled as *contaminated* which means that the corresponding PPG episode is possibly corrupted and further filtering steps need to be performed. Threshold values were determined experimentally. As shown before, the PPG waveform is filtered by a spectral band-pass filter. In uncorrupted signal episodes, the passband band width is given with $0.5\,\text{Hz} - 31\,\text{Hz}$. In contrast, if a motion artifact is detected the spectral window for the band pass filter is adapted to a narrow band filter with center frequency according to the previously estimated heart rate f_{est}. For a short period of time, the heart rate is assumed to stay largely constant. Thus, the passband parameters are changed to cut-off frequencies at $f_{est} + 0.33\,\text{Hz}$ and $f_{est} - 0.167\,\text{Hz}$ which allows for a HR detection between $f_{est} - 10\,\text{bpm}$ and $f_{est} + 20\,\text{bpm}$. That means during motion the heart rate is more likely to be increased than decreased. The whole signal processing chain for motion artifact compensation is shown in fig. 3.

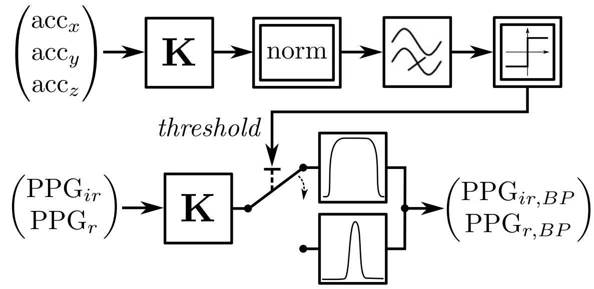


Fig. 3. Schematic signal processing chain for motion artifact compensation in the PPG waveforms using ACC data.

III. Results

A. Vital Parameter Extraction

The extracted vital parameters are validated against the clinically approved reference system SOMNOlab 2 by Weinmann Medical Technology. Therefore, we take PPG from three healthy test subjects in resting position recording both IPANEMA in-ear sensor data and reference system finger-clip waveforms. The recording time for each subject was at least 60 s after the subject has arrived in static resting period. Afterwards, raw PPG waveforms of both IPANEMA BSN and reference system were processed by the same peak detector with identical parameters. The statistic evaluation is listed in tab. I. Clearly, it can be observed from the results that the IPANEMA PPG offers good heart rate measurement. The mean value of IPANEMA PPG sensor system has a deviation of about 1.675 beats per minute compared to the reference. Moreover, the reference data has a smoother waveform, which is reflected in its less SD value. Both differences on mean value and SD seem to result from the low SNR of the PPG waveform from the Max30100, which disturbs a precise detection of peaks, or from the imperfection of the peak detector itself with respect to noise reduction. In addition, the position of measurement has to be taken into account since measurements in the inner ear may be more imprecise compared to finger-clip fixation due to disadvantageous contact pressure.

TABLE I
Statistic evaluation of heart rate measurement.

Participant	**IPANEMA PPG** [bpm]		**Reference PPG** [bpm]	
	Mean	STD	Mean	SD
P1	69.5876	24.0704	71.3857	12.1751
P2	60.5288	17.0863	62.1714	5.385
P3	74.769	14.8684	76.3525	8.8801

Also in fig. 4, a comparison between the calculated heart rate of both IPANEMA PPG and reference PPG waveform is given. It can clearly be observed that the reference heart rate is followed with promising accuracy during rate variability. Nevertheless, algorithm results obtained from reference PPG data obviously gives a smooth, less volatile heart rate estimation. In contrast to both of the two other sensor modalities the temperature evaluation is not part of this contribution since the individual calibration routine is not sufficiently processed yet. Thus, this topic will be part of future investigation.

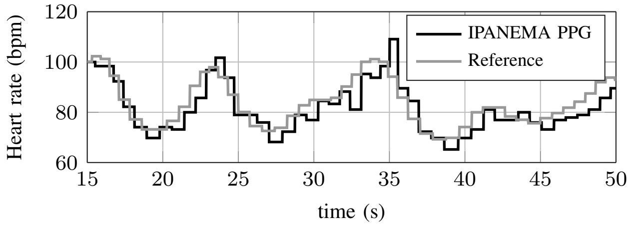


Fig. 4. Comparison of calculated heart rate between developed sensor setup and reference system.

B. Experimental Setup

To achieve a sufficient database of stress impacted vital parameter measurements we performed a physiological stress experiment with five healthy subjects with an average age of 27.4 and standard deviation of 1.67 years (3 male, 2 female). None of them suffered from heart disease, took drugs or were severe smoker which possibly leads to abnormalities in heart rate and oxygen saturation in blood. Within this experiment, each subject had to calculate an amount of 40 additions by mental arithmetic within a time of 5 s. Data was recorded both by IPANEMA BSN and the SOMNOlab 2 reference system. The experiment was segmented in mainly three parts: After the principal investigator had explained the basic task and experimental setup, the subject was asked to relax for approximately 120 s to get a normal heart activity reference basis (phase I). The subsequently following mental arithmetic phase (phase II) had a maximum time of $40 \cdot 5\,\mathrm{s} = 200\,\mathrm{s}$. After being exposed to this individual psychological stress, the subject had another 60 s to return to a static resting state again (phase III).

C. Higher Order Analysis

After the experiment was performed the data was investigated on diagnostic significance in each of the parameters HR, S_pO_2, HRV, SSI, and ORI. A brief overview on the results is given in tab. II. Two vital parameters, HR and S_pO_2, changed significantly in all subjects during the experiments. On one hand, HR was increased only at the beginning of the experimental period and returned to a normal level within the stress exposition. On the other hand, the S_pO_2 maintained a high level during the whole period. It is plausible considering a higher oxygen saturation is needed in a high-stress episode.

The three remaining higher order parameters show less significant behavior and, thus, will also be part of further investigation. In this experiment, HRV showed decreased value in the stress exposed episode as expected, but returned to a much higher value in the second resting phase. Since the HRV was calculated on a longer time period, there is no standard deviation given in tab. II for this parameter. In contrast, SSI shows stress level proportional characteristics and therefore gives a reliable information on the current mental stress exposition within this experiment. The ORI however, just responded to the amount of stress arousal as expected in two participant data sets. Therefore, this index is not considered for further application in that specific scenario.

TABLE II

STATISTIC EVALUATION OF THE MENTAL STRESS EXPERIMENT.

Index	Phase I		Phase II		Phase III	
	Mean	STD	Mean	SD	Mean	SD
HR [bpm]	80.07	6.07	86.52	6.78	72.43	4.73
S_pO_2 [%]	97.70	0.58	98.34	0.45	97.95	0.33
HRV [L/F]	2.58	–	2.37	–	5.09	–
SSI [points]	46.67	13.30	54.47	5.88	48.40	6.15
ORI [points]	0.331	0.06	0.337	0.04	0.350	0.05

IV. CONCLUSIONS

Within this contribution, a PPG sensor system is presented, which allows not only for PPG measurement but also motion and body temperature recording. It is successfully combined with the IPANEMA BSN for on-body sensing. It can be used for e.g. clinic purpose, scientific research and personal health-care. It features a minimized size so that the in-ear measurement is realized. The signal processing of the data is described and the outcomes are evaluated and validated against a clinically approved reference system. The results show that the main subject are capable of offering reliable measurements under low motion artifact. However, in order to reach a sufficiently measuring quality, calibration is necessary for the pulse oximetry and eardrum temperature monitoring. A medical experiment related with psycological stress arousal was performed on five participants. From the data obtained during the experiment, vital parameters like HR and S_pO_2 are extracted and the photoplethysmography is analyzed using various methods like HRV, ORI and SSI. Among them the HR, S_pO_2, HRV, and SSI have shown significant changes during the experiment, which is considered to be related with stress level. In contrast, ORI has less capability of indicating high stress arousal.

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