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A Novel Non-contact Radar Sensor for Affective and Interactive Analysis

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Abstract—**Currently, many physiological signal sensing techniques have been applied for affective analysis in Human-Computer Interaction applications. Most known maturely developed sensing methods (EEG/ECG/EMG/Temperature/BP etc. al.) replied on contact way to obtain desired physiological information for further data analysis. However, those methods might cause some inconvenient and uncomfortable problems, and not easy to be used for affective analysis in interactive performing. To improve this issue, a novel technology based on low power radar technology (Nanosecond Pulse Near-field Sensing, NPNS) with 300MHz radio-frequency was proposed to detect humans' pulse signal by the non-contact way for heartbeat signal extraction. In this paper, a modified nonlinear HRV calculated algorithm was also developed and applied on analyzing affective status using extracted Peak-to-Peak Interval (PPI) information from detected pulse signal. The proposed new affective analysis method is designed to continuously collect the humans' physiological signal, and validated in a preliminary experiment with sound, light and motion interactive performance. As a result, the mean bias between PPI (from NPNS) and RRI (from ECG) shows less than 1ms, and the correlation is over than 0.88, respectively**.

I. INTRODUCTION

NUMBER of new devices for Human-Computer Interaction (HCI) have been developed recently in either commercial market or academic field to drive more human imagination of further applications. Regarding to the HCI model, there are several different methods, including physical action of body, oral language expression and personal physiological signal, used for affective status evaluation. For objective evaluation, many methods based on physiological signal analysis are broadly used to transfer physiological parameter to psychological condition index. In terms of bio-signal sensing techniques, there are various possibilities to obtain one's biological information. Currently, many advanced bio-signal sensing technology are developed to directly measure electrocardiogram (ECG/EKG), photoplethysmograph (PPG), electroencephalogram (EEG), electromyogram (EMG) and body temperature signal for further data analysis. Most of those technologies need to use additional electrodes and probes to obtain desired information in a contact way. The common used technology based on heart signal is to calculate trend of heart rate (HR) and heart rate variability (HRV), which is a measure of the naturally occurring beat-to-beat changes in heart rate, for evaluate emotion condition. The sympathetic (SNS) and parasympathetic (PNS) branches of the autonomic nervous system (ANS) antagonistically influence the lengths of time between consecutive heart beats. The heart rate variability analysis is a powerful tool in assessment of the autonomic function. The source information for HRV is a continuous beat-by-beat measurement of inter beat intervals. In some clinical reports, HRV is validated it is related to emotional arousal. The heart rate parameters (HR and HRV) have been investigated widely and derived affective index are validated which is relative to one's emotional status [1-3]. The most widely used methods include time-domain and frequency-domain for short-term and long-term data analysis. Based on the frequency analysis, the power spectral density (PSD) is used to provide basic information on the power distribution across frequencies by the discrete Fourier transform. The power information in different frequency range for affective analysis is commonly separated into High Frequency (HF) 0.15-0.4Hz, Low Frequency (LF) 0.05-0.15Hz and Very Low Frequency (VLF) under 0.05 Hz. For example, the High-frequency (HF) activity has been shown decreasing under conditions of acute time pressure and emotional strain [4] and elevated state anxiety, presumably related to focused attention and motor inhibition [5]. The HRV has been shown to be reduced in individuals reporting a higher frequency and duration of daily stress. For commercial applications, the methods used heartbeat signal include: ECG, blood pressure, and the pulse wave signal derived from a PPG, and ECG measurement is considered with high priority because of its clear waveform. ECG is an electrical signal measured with special conductive electrodes placed on chest around heart area or limbs. The other approach to measure cardiac intervals is a measurement of pulse wave. PPG is less invasive and simple method of measurement based on photoplethysmograph, which is a signal reflecting changes in a blood flow detected when infrared light is emitted towards microcirculatory blood vessels. Depending on blood flow volume certain portion of that light is absorbed letting other part to pass or be reflected. An optical sensor detects a quantity of light passed (or reflected from) the blood flow producing a waveform identifying pulse wave. Such waveform can also be processed to derive beat-by-beat interbeat intervals. Although PPG gives the summary information reflecting both cardiac and blood vessel components of HRV, some research studies showed a significantly high correlation between inter beat interval data

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measured by both ECG and PPG in short-term steady-state recordings. However, the measurement methods might be inconvenient to emerge consciousness or mental state to HCL applications.

In this paper, a new integration system combined a non-contact sensing technology based on low-power radar and a re-modified nonlinear HRV calculated algorithm, was proposed to perform in a designed interactive system. The proposed novel non-contact method using Nanosecond Pulse Near-field Sensing (NPNS) technology is applied on detecting pulse from brachial artery at the site of the wrist, and extract the Pulse-to-Pulse Interval (PPI) to obtain desired heartbeat information. In this study, an interactive performing experiment which combined sound, light stimulation was designed to collect volunteers' physiological information from ECG and proposed method for system evaluation. The proposed sensor performs wearable, and the information system is designed to continuously collect the audience's bio-signal and interaction details that could feedback immediately.

II. Method and System

For the purpose of non-contact artery pulses detection, a signal processing with correlation processing system is utilized. The proposed technology is based on multiplication of the reference radio-frequency (RF) pulse and the echo RF pulse delayed by the time interval during which the signal is spread to the investigated subject and back to the receiver through antenna. The probing signal is presented in the form of short RF pulses having comparable with a period of oscillations filling the probing pulse. After the de-modulation process of emitted and received signal, the output signal of a correlation system is proportional to the phase difference between the probing RF pulse and the echo RF pulse. The essential architecture of proposed radar sensing method was present in Figure 1. The system includes transmitter, antenna and receiver; the signal processing and displaying part. The transmitter emits RF signal, and the receiver collects echo RF via designed antenna. The obtained signal is processed by a microcontroller and displayed on a computer terminal.

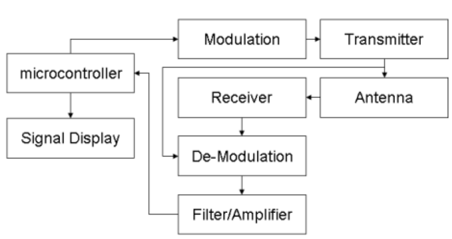

Fig. 1 Architecture of proposed NPNS based radar system for artery pulse signal detection

For measurement setup, the proposed NPNS based pulse sensing technique includes a NPNS transmitter and receiver connected to a dedicated flat dual-antenna. The function block of dual-antenna NPNS sensor is for pulse signal detection from the artery at the site of wrist simultaneously, as shown in Figure 2. The NPNS transceiver is operated by a microcontroller based board with digital signal processing software. The microcontroller based board provides the wireless communication function (Bluetooth 2.1) to transfer data from NPNS transceiver to a computer terminal in real-time for data analysis.

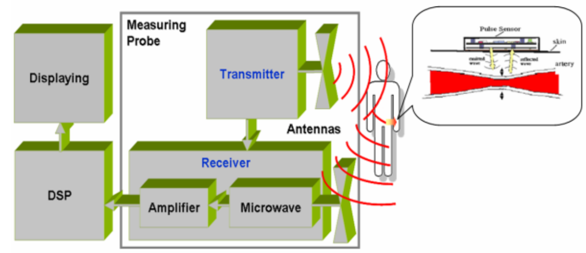

Fig. 2 Illustration of nanosecond pulse near-field sensing radar

A. Nanosecond Pulse Near-field Sensing Method

The NPNS radar technology, which comprises low power miniature radar with 300MHz electromagnetic (EM) wave of the transmitted by the antenna RF pulse, is proposed in this study. The de-modulated signal carrying useful information performs through analyzing the phase difference between the reflected and the reference RF pulse signals. The radar uses correlation system; it is based on multiplication of reflected and reference RF pulse signals. The output signal of the correlation system is proportional to amplitude and phase difference between those signals. The emitted RF signal and the signals reflected from moving and motionless objects are shown in Figure 3.

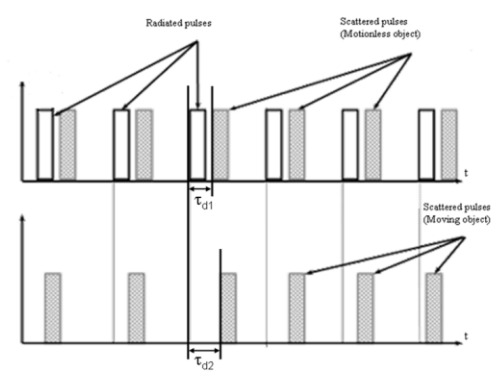

Fig. 3 Illustration comparison of the signals with/without motion in proposed NPNS

For the radar design, the EM signal works in interference and reflections conditions of signals reflected from stationary and moving objects around the artery. Time slots, opening the receiver at the moment of the input of the signal reflected from the artery through skin, muscle and bone at distance defined, are formed in the receiving path to eliminate signal distortion due to interfering pulses. The reference RF pulse signal is conducted to input of the mixer. During reference RF pulse time interval radar detects received signal, all rest time the receiver is shut. This defines time slots of the received RF pulse detection and distance range which has high sensitivity. Reflected pulses which arrive after the end of the reference RF pulse will not be detected. The oscillator generates two RF pulses, one pulse is transmitted, and another one is used as reference RF pulse. Oscillator could be switched on and off during 1–2 ns, this allows to have pulse length as low as 5 ns. Switches are changing their state when oscillator is off, and the transition time does not affect pulse length value. The Mixer has one channel signal output connected to the low-frequency signal processing sub-circuit. In the output channel, a signal is formed which is in-phase with respect to a reference signal. This eliminates the probability that phase of reflected RF pulse will fall at low sensitivity area of the Mixer. The band pass filter process signal which correspond to the heartbeat from the body movement. The investigated subject is in a fixed position; the amplitude of the output signal after processing is characterized by the following ratio:

$$A = \frac{E_0 E_1}{2} n T_0 \cos(\varphi) \tag{1}$$

where E_0 is a maximum amplitude of the probing RF pulse; E_1 is a maximum amplitude of the received echo RF pulse; T_0 is a period of oscillations of the probing RF pulse; n is a whole number of periods of oscillations filling the probing RF pulse. The phase difference value φ in the expression (1) is defined by the time of spreading the electromagnetic waves to the investigated subject and back:

$$\varphi = 4\pi \frac{R_1}{\lambda}, \tag{2}$$

where λ is a wavelength of oscillations filling the probing RF pulse; R_1 is a distance between the investigated subject and the sensor. The function diagram of NPNS radar is shown in Figure 4.

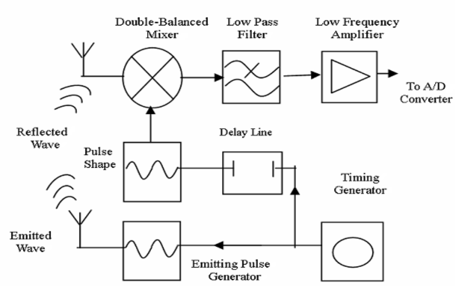

Fig. 4 The function diagram of NPNS sensing circuit

B. Signal Processing

As continuous arterial pulse signal was detected by NPNS radar, peak-to-peak intervals (PPI) of pulse signal is extracted by moving windows peak detection method shown in Figure 5. At the same time, time tick of PPI is generated circularly to locate the time of each PPI for HRV calculation. In this study, the HRV analysis was based on both time and frequency domain. For time domain analysis, the PPI value was collected within 64 seconds and update HRV by each PPI input. The mean (Mean) and the standard deviation (STD) of PPI data are applied on variation calculation of

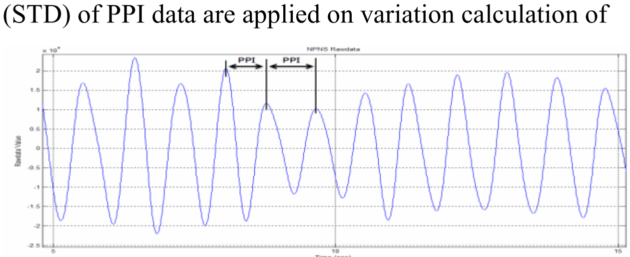

Fig. 5 Example of PPI estimation of pulse signal

heartbeat in real-time. Furthermore, in frequency domain, the PPI data with 64 seconds according to time tick information are re-sampled by nonlinear cubic-spline interpolation method. The numbers of reconstructive points of PPI are 256 points and these points are transformed into frequency domain by 256 points Fast Fourier Transform (FFT). The original and re-sampling data was shown in Figure 6.

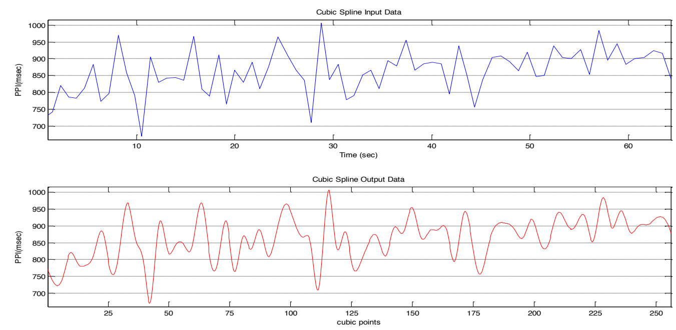

Fig. 6 Original and re-sampling result of PPI data by cubic-spline method

For frequency analysis, the sample rate of HRV calculation is defined as 4 Hz (256 points / 64 seconds), and the resolution of FFT per index is 0.015625 Hz (4 Hz/256 points) in this paper. The frequency power are divided into three segments: very low frequency (VLF: <0.04Hz), low frequency (LF: 0.04–0.15Hz) and high frequency (HF: 0.15–0.4Hz). The total power (TP: < 0.4Hz) is also calculate. Moreover, the obtained parameters, including Mean, STD, the ratio of VLF/TP, LF/TP, HF/TP and TP, are used as affective index for human emotion status evaluation. The flowchart of data analysis was shown as Figure 7.

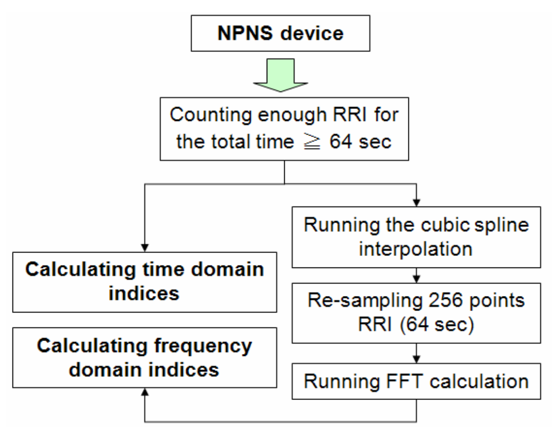

Fig. 7 Signal processing flowchart of proposed method for emotion status evaluation

In this study, an interactive performing system with various interactive stimulation (sound/light/image) designs was also proposed to provide volunteers' implicit feedback to evaluate sensing and data analysis method was shown in Fig. 8. Here, innovative information architecture was applied to build a pilot system to verify the system concept. The proposed sensing technology is used to monitoring artery pulse signal continuously, and the heartbeat parameters (HR/HRV) are calculated in real-time in the performing experiment.

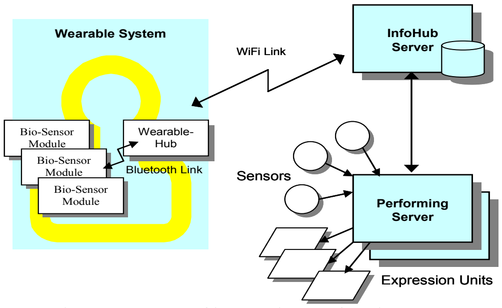

Fig. 8 Structure of interactive performing system

III. Results

With respective to the preliminary test, six postures, including standing, lying, sitting, hand up, touch head and walking, were applied on examination. In the experiment, volunteer wear proposed NPNS sensor and ECG detector for heartbeat signal collection at same time. The proposed NPNS sensor with flexible antenna design and integrated wireless communication module (Bluetooth 2.1) was shown in Figure 9. The wearable bracelet design was also proposed for performing experiment.


Fig. 9 Illustration of NPNS module and built prototype

The volunteer sequentially behaving the motions described above and the comparison result of PPI and RRI was shown in Figure 9. As a result, the correlation during stable status with standing, lying and sitting was 0.96, 0.92, 0.99. The correlation during active statuses with hand up, touch head and walking was 0.79 in average. The total mean correlation for all motion status is about 0.88.

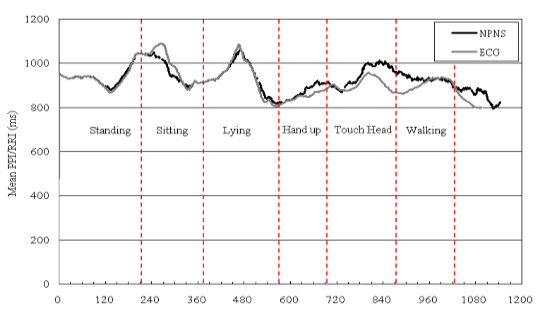

Fig. 9 Result of PPI and RRI obtained from NPNS and ECG sensor

With respect to the preliminary test with interactive performing, the platform system was set-up with a wooden frame bound with sound and image was designed to build up as soft atmosphere. The scenario of experiment was show in Figure 10. The volunteer wore the bracelet of NPNS sensor to experience the interactive performing, and the PPI information was transferred to server for further affective index calculation. Simultaneously, the affective information was feedback to modulate performing content as an interactive experiment.

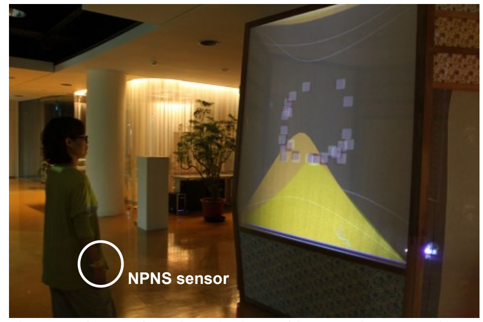

Fig. 10 The performing design of interactive experience

In this study, the affective information was translated as image, which combines three symbol elements including bird, wave and spot. The graphic parameters of shown image according to HR or HRV, such as bird-like symbol in the centre of picture drifts by the trend of HR, the wave-like shapes vary in larger amplitude when LF/HF ratio becomes higher and the colour and intensity of square-spot also by HR. The symbolized affective status was shown as Figure 11.

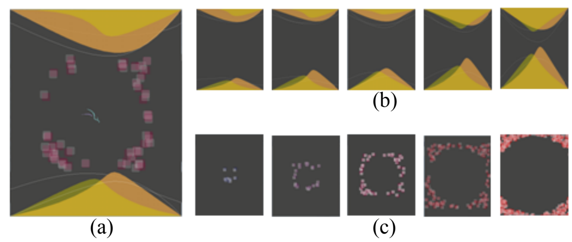

Fig. 11 The image of symbolized affective status. (a) the entire image projected on the screen where there is one small bird-like symbol with drift-speed of Heart-Rate, (b) the wave-like shape varied in different LF/HF ratio conditions and (c) the colour and density of square-spot of different Heart-Rate values.

IV. Conclusions

In this paper, the low power NPNS sensor and affective index calculation algorithm were constructed for measuring pulse signal in a non-contact way. The heartbeat and relative HRV information can be easily detected and estimated in real-time. For the prospective development, integration of all functions, including sensing, signal processing and wireless data transmission, into a dedicated system can be helpful to provide long-term and continuous emotion status analysis for personal healthcare and consuming product.

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