Galvanic Intrabody Communication for Affective Acquiring and Computing

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Abstract—The human machine interface (HMI) is a main communication method between human and computer. Through current HMI, a machine receives and accurately responds to the commands instructed by the users. In the next generation of HMI, machines will be required to deal with more challenging problems/decisions (such as affective evaluations, ethical quandaries, and other innovations) in a self-governing manner. Thus, future HMI should be able to provide information about users' emotion to the machine for affective evaluation. In this paper, we focus on the natural connection method that can improve machines in making the acquaintance of the users. However, connecting sensors scattered on the human body poses serious problems concerning comfort and convenience. Therefore, the authors introduce the Intra Body Communication (IBC) for connecting various physiological sensors on the human body such that the physiological information can enrich the capability of the computer in cognition of the user's emotion. In addition, the authors also reported two pilot studies: using the IBC for connecting the physiological sensor on the human body and using the physiological parameters to estimate the degree of fatigue of the user.

Index Terms—Human machine interface, intrabody communication, emotion evaluation, fatigue degree.

1 Introduction

Traditional human machine interface (HMI) is an important topic in the area of computer science. Evolving from mechanical switches and text-based interplay to graphical interface, HMI has been growing from the industry era to the information epoch. Nowadays, HMI has made life a lot easier and lets the general public enjoy a more relaxed and autonomous life. However, the general feeling on computer/machine is regarded as precise but indifferent because they follow only preset rules of logic without alternate leniency. We consider that the machine is apathetic partly because the current input device for the machine is mostly keyboard and pointing devices. On top of this, there is no room for the machine to fetch the affective information of the user besides achieving the targeting objective. The device merely delivers the commands to the machine regardless of the emotional status of users. We certainly believe that HMI would definitely exceed its current self in the future: from purely apathetic reasoning to rule-based decisions with considerations of a user's emotion, and even to dealing with ethical problems [1]. One of the potential ad hoc topics is to embed HMI with affective interaction. As a matter of fact, affective detection is not new. A polygraph is the famous classical example for detecting the emotion of the users. A polygraph uses physiological parameters such as blood pressure, heart rate, etc., for assessing the emotion information of the users. For instance, imagine that a massage chair/machine can appropriately stimulate the corresponding vital reflex points according to different muscles' tiredness, offering a truly affective therapeutic massage. Recent research in HMI with affective enhancement has also brought out a lot of interesting consumer electronics applications, such as driver alert system [2], Emotion RECognition System-II (EREC-II) [3], Intelligent Tutoring Systems [4], [5], [6], [7], etc.

Among many different possible affective parameters [8], the physiological parameters would provide a significant basis [9] for emotion detection and evaluation. This is particularly true for the handicapped community to attract more pampering attention as they generally have encountered difficulties in expressing explicit feedback to the machines. It would be helpful if the physiological parameter would provide assistance in implicit communication with the machine. However, retrieving the physiological parameters from the body of the user is complicated and cumbersome; this is due to the fact that abundant wires result from the diverse measurement sites of physiological parameter measurement. According to Peter et al. [10], several key limitations of current HMI/HCI systems include:

- unwieldy wires between sensors and a processing unit,
- lack of system integration of individual sensors effectively, and

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- interference on the wireless communication channel shared by multiple devices.

Therefore, we intend to introduce a relatively new communication technique, called Intra Body Communication (IBC), for transmitting the physiological parameters via the human body such that the interconnected wires between sensors can be reduced to minimum. In this paper, we are going to describe two feasibility studies. The first one is to demonstrate physiological signals (such as electrocardiography (ECG)) that can be faithfully transmitted across the human body via IBC, while the second one can send the muscle EMG to the tiny central hub at the convenient portable site (such as location at the wrist) of the user by using the IBC and then evaluate the relative fatigue of the users. The pilot studies show the feasibility of using IBC for wearable sensors data exchange to evaluate the emotion status of the user. These pilot studies explore the feasibility of developing a tiredness alert system for long-term computer users. The extension of the methodology can be extended to other consumer electronic products such as driver status detection and an effective indictor for better massage machine. Moreover, we also hope that this preliminary study can help to introduce the less mentioned topic—IBC in the area of affective computing.

2 Intrabody Communication

IBC is a technique designed for sending data via the human body. Although the constituents and the electrical properties of the human body are complex, the human body is regarded as a conducting medium in the macroscopic sense. Rigorously, the electrical properties of human tissues can be modeled by suspension cells in saline according to Roth [11]. Tissues are conductive in general, but experiments manifest that the electrical properties of the tissues are frequency dependent [12]. The overall impedance of a tissue can be represented by a parametric equation consisting of four Cole-cole dispersions [13]. IBC is different when compared with classical techniques such as radio wave radiation, optical communication, etc. It explores an alternative for the sensors/devices that adhere to the human body. In the aspects of engineering, this alternative has several advantages. First, the power consumption of the IBC is tiny; in the experiment of Handa et al., the power for transmission of ECG signal is only 8 μW [14]. This implies longer battery life and smaller dimension. In addition, the electric field of IBC belongs to near electromagnetic field and the strength of the IBC decreases as the cube of distance [15]. Therefore, IBC does not occupy precious RF spectrum and does not generate electromagnetic noise to neighboring devices. In other words, IBC is less susceptible to eavesdropping and provides higher security to implanted devices. Last but not least, as the demand of interconnecting devices on the body increases, IBC can provide unmatched advantages unsusceptible to motions of any kind and without hindering the user's movements.

The first IBC application prototype was developed by Zimmerman and colleagues in 1995, who derived the concept from a project by using electric field to position measurement [15], [16], [17]. The current research on IBC has become diverse and more research groups have become interested in this topic since then. Application prototypes such as electrocardiography monitoring [14], virtual typing

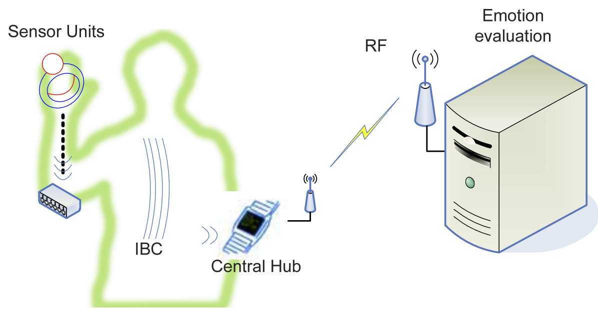

Fig. 1. The block diagram of the system for emotion evaluation.

system [18], system on chip [19], and so on, have been developed. In addition, fundamental investigations such as channel measurements [20], [21], numerical simulations [22], [23], model developments [24], etc., are carried out.

Two general variants of IBC have been developed [20]. The Capacitive coupling technique is a two-electrode approach, with a capacitive coupling to the external environment as reference. The Capacitive coupling type IBC can achieve lesser channel attenuation and data rate, but environmental interference could be serious. Another implementation of the IBC is the Galvanic coupling technique. The Galvanic coupling type is a four-electrode approach, two for the transmitter side and two for the receiver. In terms of the channel attenuation and the data rate, the Galvanic Coupling type seems to be modest. However, the Galvanic Coupling type IBC is less prone to environmental interference and is able to communicate with the devices implanted in the human body.

Fig. 1 illustrates the diagram for using the IBC for connecting various physiological sensors, wearable sensors, etc., on the human body. Body-centric transducers gather the user's bioinformation (ECG, EMG, EOG, movements, etc.) and forward it to the central hub located on the wrist of the user. Considering the power efficient attribute of IBC, the devices can be miniaturized and fabricated as SOC in fashion accessories. Then, the center hub adapts the physiological information and sends it to the external machines for emotion evaluation through a radio frequency transmitter.

3 Electrocardiography Signal Transmission

In our first study, the electrocardiogram of the user was recorded and transmitted. Selecting the ECG for sending over the human body for affective computing has several distinct reasons. First, the ECG is suitable for evaluating the emotion of the user among the physiological parameters. In pioneering research, the feasibility of using the ECG for emotion recognition was demonstrated [25], [26]. Regarding the technological aspects, the ECG is considered a strong biosignal that can be measured on the surface of the human body by using noninvasive measurement technology [27]. This advantage is obvious for HMI, where convenience and reliable operation are emphasized. Additionally, selecting ECG can reflect rich emotion information such as joy, excitement, sadness, fear, etc. This information can enhance the interaction between computer and user.

The system block diagram is shown in Fig. 2. In the diagram, a sophisticated biosignal amplifier was built to

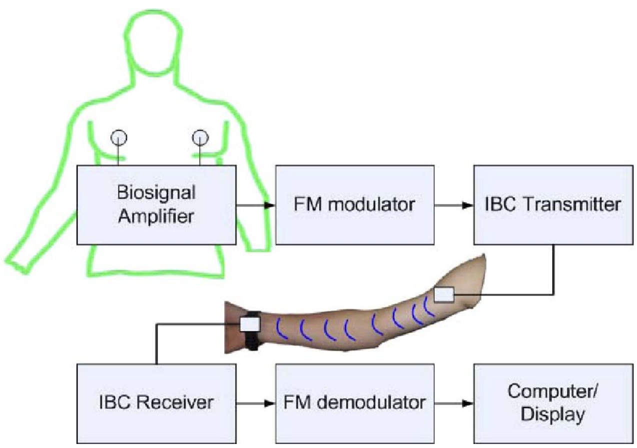

Fig. 2. The block diagram of the system for Electrocardiography signal transmission.

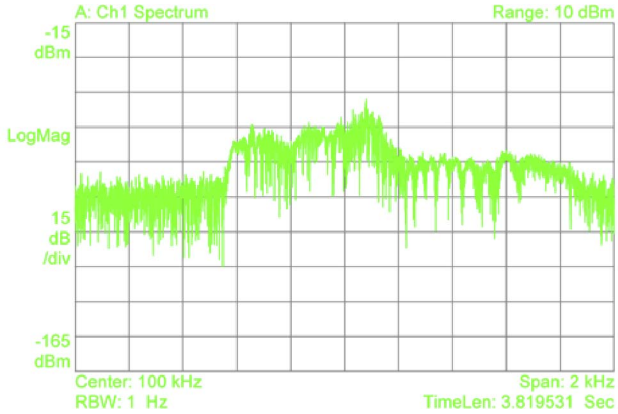

Fig. 3. The spectrum of the IBC signal received.

pick up the ECG signal from the user. During the experiment, disposable Ag/AgCl surface electrodes were used to pick up the biosignal. These electrodes are adhesive and coated with a thin layer of conducting gel such that secure and reliable recording can be achieved. For the biosignal amplifier that retrieved the ECG signal from the user, the gain of the amplifier was set to 100 dB with at least 80 dB common mode rejection ratio (CMRR) over the bandwidth of the ECG signal. The input impedance of the amplifier was very high (over 1 Mohm) and a set of filters was embedded so that power line interference, motion artifacts, and external interference noises were removed.

The processed signal was then fed into an FM modulator with carrier frequency at 100 kHz. The maximum frequency deviation was set to 4 kHz. In the current study, analog modulation was chosen in order to show the feasibility; nonetheless, more advanced modulation and digital modulation can replace it for different purposes.

The IBC transmitter block was one of the core modules in our experiment setup. The modulated signal was conditioned so that it was suitable to apply to the user's upper arm. The IBC transmitter mainly realized two important functions: single-ended-to-differential-mode conversion and voltage-to-current conversion.

The single-ended-to-differential-mode converter transformed the modulated ECG signal to differential signal in order to maintain symmetrical signal applied to the human body. This prevented the possible alteration of the pH of the tissue and the generation of toxic substances by the electrodes applied to the human body [28].

The voltage-to-current converter was used to control the amount of current passed through the human body. This converter overcame the impedance variations of the human tissues and limited the maximum current applied to the user. Currently, the maximum current is set to 1 mA. This value is below the perception threshold of the human body, in according with the guidelines of ICNIRP [29].

The IBC signal was then applied to the upper arm of the user by using a pair of stimulating electrodes which have better biocompatibility [30] and resistance to corrosion. The IBC signal propagated along the arm of the user and the receiver module picked up the IBC signal from the human body of another pair of stimulating electrodes. In our preliminary experiment, the separation between the transmitter electrodes and receiver electrodes was 80 mm. According to the mathematical model developed as (1) [31], [32], the attenuation of the IBC signal over the human limb is around 40 dB.

$$\begin{aligned} V_s(r,\phi,z) = &\sum_{m=1}^{\infty}\sum_{n=0}^{\infty}\Big[E_{smn}I_n\Big(\frac{m\pi r}{h}\Big)\cos(n\varphi) \\ &+ F_{smn}I_n\Big(\frac{m\pi r}{h}\Big)\sin(n\phi) + G_{smn}K_n\Big(\frac{m\pi r}{h}\Big)\cos(n\varphi) \\ &+ H_{smn}K_n\Big(\frac{m\pi r}{h}\Big)\sin(n\phi)\Big], \end{aligned} \tag{1}$$

where I_n is the modified Bessel function of the first kind of order n and K_n is the modified Bessel function of the second kind of order n. s represents the sth layer of the model. The constants E_{smn}, F_{smn}, G_{smn}, and H_{smn} were derived with the impedance of the skin, fat, muscle, and bone given by the parametric models of Gabriel et al. [13] with the dimensions of the human limb and IBC electrodes.

The design of the IBC receiver was mainly based on the characteristics of the channel and the general requirements of devices connected to the human body [33]. The detection of the IBC signals was analogous to the biopotential acquisition to some extent, except the center frequency of the signal was 100 kHz. Therefore, we employed an instrumentation amplifier with 6 dB gain. The instrumentation amplifier also has high input impedance (1 Mohm) and CMRR (at least 80 dB) so that the receiver has the capability of detecting the IBC signal without much interference from the biological activities of the user.

The signal received was then converted by using the FM demodulation module. Eventually, the recovery signal was sent to the computer for further emotion evaluation.

3.1 Results

In our study, we recruited a healthy male without any chronic or cardiovascular disease, according to his testimony and our observations. Additionally, after attending our experiment, no obvious adverse effect was observed and reported by the subject.

The results of the experiment can be found in Figs. 3 and 4. The first figure shows the spectrum of the output of the instrumentation amplifier representing the IBC signal received from the limb of the testing subject. The center

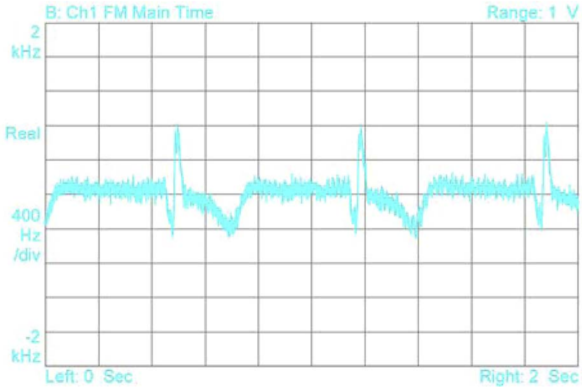

Fig. 4. The ECG signal recovered from the IBC signal received.

frequency of the received signal was 100 kHz spanned around 2 kHz. The signal-to-noise ratio was alright for detection and the peak energy of the signal was around -45 dBm due to relatively high attenuation of the communication channel, i.e., the human body and the low transmitter power for the protection of the experimental volunteer.

Fig. 4 shows the biosignal reconstructed from the IBC signal received. Followed by the FM demodulator, the ECG signal was recovered. From the received ECG, we found that the signal was basically suitable for emotion evaluation. However, the ECG signal was slightly distorted and contaminated by the noise.

4 Muscle Fatigue Evaluation

In the second study, we intended to use EMG to evaluate the fatigue of users. In the common human computer interface, the major interaction method relies on mouse and keyboard to deliver the commands to the computer, as illustrated in Fig. 5. Generally, people are skillful at delivering instructions with these traditional interfaces. However, it is obvious that these input methods lack information for evaluation of the user's emotions. As a result, the computer gives response with little cognition of the emotions of the user. No affective-related interaction can be performed according to the user's emotion/tiredness. One of the feasible ways to enhance the traditional HMI is incorporating the physiological information of the user [8], [34].

In this study, we would like to collect the surface electromyography (sEMG) of muscles on the shoulder in order to facilitate the computer's analysis of the degree of fatigue of the long-time computer user. In the meanwhile, the sensors were connected by using the IBC so that the interconnected cables could be reduced. For the sake of convenience, the receiving end of the IBC was located on the mouse so that the user can perform routine computer work at the same time. When the user worked with the mouse of the computer, the sEMG could deliver to the computer by touching the electrodes on the surface of the mouse. Hence, the relative fatigue information for long-time computer users could be detected and can probably give advice (such as take a break).

sEMG is the endogenous bioelectricity generated by the muscle and is detected on the surface of the human body [35]. Each muscle fiber generates an action potential event

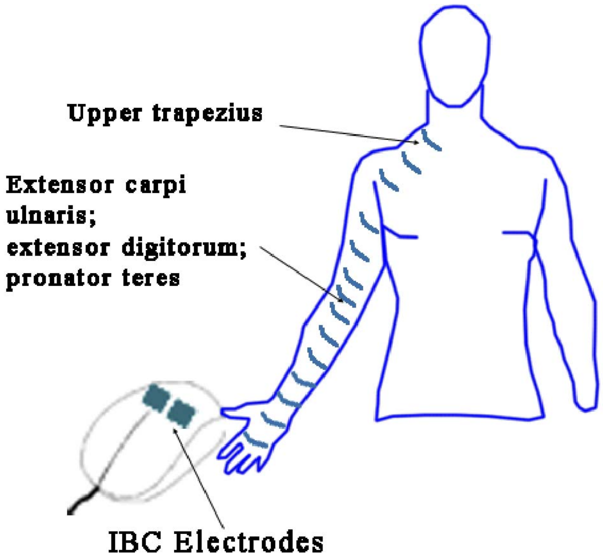

Fig. 5. Illustration of the degree of fatigue evaluation system.

whenever activated. The detected sEMG is a spatial and temporal superposition of numerous muscle fibers within a muscle. Therefore, the sEMG signal contains the action potential events of the fast and slow twitch muscle fibers. The analysis of the signal generated by the fast and slow twitch muscle fibers facilitates the evaluation of the fatigue degree of the particular muscle [30]. In the daily manipulation of the computer mouse, many muscles are involved, namely, the extensor carpi ulnaris extensor digitorum, pronator teres, and upper trapezius muscles, etc. [36], [37].

To demonstrate the feasibility of evaluating the fatigue degree by using the sEMG, we measured the fatigue degree of the bicep muscle. In order to shorten the duration of the experiment, we requested the users to elevate a 9.5 kg dumbbell to accelerate the fatigue degree process. The sEMG of the bicep muscle of the user was measured simultaneously. In order to evaluate the fatigue degree of the muscle, we made use of the properties of the fast and slow twitch fibers. Generally, the fast twitch fiber produces a signal with higher frequencies. Whenever the muscle generates force, both slow and fast twitch fibers contribute. However, the fast twitch fiber switches off when fatigue develops in the muscle. We used this property to identify the fatigue degree of a specific muscle by analyzing the mean/median frequencies of the sEMG as the phenomenon associated with the fast twitch fibers is higher than the slow twitch fibers in general.

4.1 Result

Four healthy male subjects were recruited for this study. According to our observations and the testimonies of the subjects, they had no previous records of chronic diseases or neuromuscular problems. After the experiment, the subjects reported that they felt tired and had short-term aching pain. The symptoms disappeared in a few days and no long-term problem correlated with the experiment.

The sEMG recorded during the experiment can be found in Fig. 6. Since the dumbbell used in the experiment was heavy, all subjects could not maintain the position for over 60 seconds. From the recorded sEMG, the amplitude of the

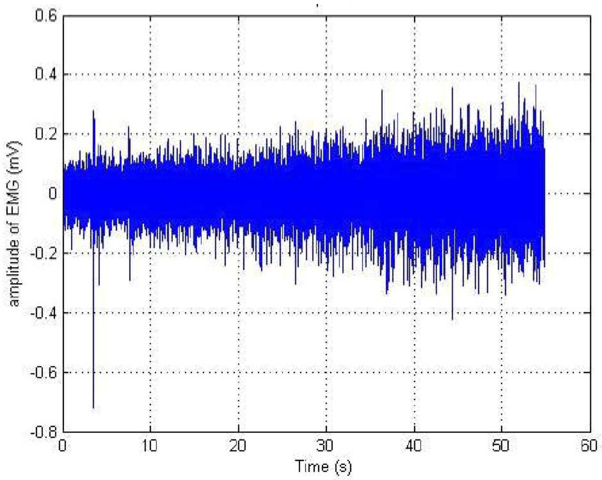

Fig. 6. The sEMG record of a typical subject.

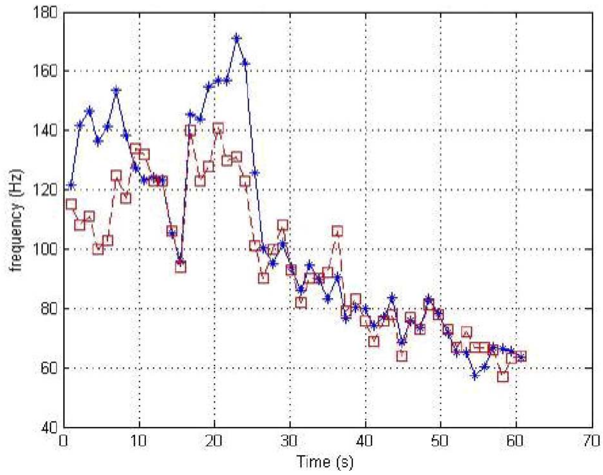

Fig. 7. The mean and median frequency of the sEMG of a subject.

sEMG was increasing. This was probably because the subject was trying to maintain the position even if he felt very tired. From the time domain plot of the sEMG, no evidence related to the fatigue of the subjects.

Therefore, we processed the sEMG signal and used windowed Fast Fourier Transform (FFT) to decompose the frequency components of each window of the sEMG signal. Then, the mean and median frequencies of each window were calculated. The typical calculation results of one of the subjects in the experiment are shown in Fig. 7. In the figure, the blue line with star symbols is the median frequency calculated from the windows FFT of the sEMG, while the red line with square symbols is the mean frequency. Both median and mean frequencies of the sEMG were decreasing with time, indicating that the muscle of the subject was getting tired. Some of them started shivering at 50 seconds, implying that the experiment had pushed their muscles close to the limit. The results are consistent with all the subjects in the experiment.

Additionally, from the study we also found that the mean frequency is of less variation than the median frequency. This suggests that using mean frequency for fatigue degree evaluation will be better [38], [39], [40].

5 Discussion and Conclusion

To facilitate autonomous machines for making affective decisions in the next generation of HMI, affective parameters of the user can complement the knowledge basis during machines' reasoning processes. This advancement requires an enhanced HMI to deliver the affective information to machines. Among a variety of affective information types, physiological parameters would provide a significant basis for emotion evaluation. Therefore, by incorporating this information into machines, affectively behaved machines can be developed in response to the emotion of the user.

In this paper, the authors introduced the IBC to provide a relatively natural connection to diverse physiological sensors on the human body. By using the Galvanic IBC, the abundant cables and surplus electromagnetic radiation/interference can be reduced. As a result, convenient and multivariate emotion parameters can be used to enrich the emotion cognition capability of the machine.

However, in order to fully accomplish affective acquiring and computing, several technological synergy effects should be achieved. First, with the continuation of shrinking miniature wearable biological sensors using SOC techniques, users will really feel free of lingering inconveniences with IBC. Second, with the advances of biosignal analyses and effective computing algorithms, more and speedier emotion evaluations can be obtained.

In the future, the authors would like to explore IBC for affective computing into the implanted devices. Initial analyses expect improvement over traditional methods in terms of convenience and gain. In the near future, a more gentle and considerate machine can be developed.

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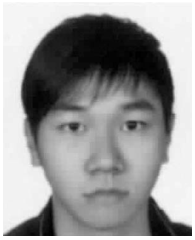

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