Potential and Challenges of Body Area Networks for Affective Human Computer Interaction

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Abstract. The Human++ program aims at achieving highly miniaturized, wireless, intelligent and autonomous body sensor nodes to assist our health, comfort and lifestyle. In this paper the concept of body area network is applied to wireless monitoring of emotions, thus opening a new, affective, dimension in human computer interaction. A prototype body area network targeting the monitoring of physiological responses from the autonomous system is introduced, and tested for the classification of discrete emotions. Using data fusion and regression analysis, we show that the wireless physiological data can be mapped in real-time to an estimation of an individual's arousal level. Results in a controlled environment are presented, and specific challenges that need to be overcome for a widespread use of the technology are discussed. Finally, we show how advances in micro-power generation devices may lead to fully autonomous systems in the future.

Keywords: Ambulatory, Body area networks, Emotion monitoring, Ultra-low-power, Wireless.

1 Introduction

It is anticipated that micro and nano-system technology will increase the functionality of lifestyle and healthcare devices to gradually match the needs of society. It is expected that, in the next decade, technology will enable people to carry their personal body area network (BAN) that provides medical, lifestyle, assisted living, sports, entertainment and computer interface functions for the user. This network comprises a series of miniature sensor/actuator nodes, implanted or located at the body surface. Each node has its own energy supply, consisting of storage and energy scavenging devices. Each node has enough intelligence to carry out its task. Furthermore, each node is able to communicate with other sensor nodes or with a gateway node worn on the body. The gateway node communicates with the outside world using a standard telecommunication infrastructure such as a wireless local area or cellular phone network. On the other extremity of the network, experts then provide services to the individual wearing the BAN. Intelligent or expert systems further include data fusion algorithms for the aggregation of body sensor data into metrics quantifying an individual's health status, his physical, cognitive and emotional state. Next generation of

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BAN will include feedback loops for health, performance or stress management, and may enable a new, affective, dimension in human computer interface.

Early deployment of technology in different application cases are translated into critical technology obstacles that will need to be solved. The Human++ research program tackles key technology challenges associated to micro-power generation and storage, ultra-low-power radios, ultra-low-power DSPs, sensors and actuators [1]. The ultimate target is the development of miniaturized body sensor nodes, truly non-invasive, capable of data analysis and wireless communication and powered by body-energy.

In this paper the use of body area network technologies to enable affective human computer interface is discussed. In the following sections we will present a body area network for ambulatory monitoring of physiological responses from the autonomous nervous system, and show how this platform can be used to monitor an individual's arousal level in real-time. Furthermore, we will highlight key challenges that need to be addressed in the coming future. Finally, we will show how recent advances in micro-power harvesters enable autonomous wireless physiological monitors. A world which adapts to one's emotions and feelings may not be that far out anymore…

2 Enabling Ambulatory Wireless Emotion Monitoring

Monitoring of emotions or mental health has received a special interest in the last few years. In this context, emotion is usually defined as a mental and physiological state associated with a wide variety of feelings, thoughts, and behaviors. Following this definition, monitoring physiological and cognitive signals should enable to understand and "read" the emotional state of an individual in a particular situation. When based on non-intrusive measurements, this will enable new ways of human-machine interaction, and therewith a new range of applications in the domains of (mental) health management, safety, entertainment and ambient intelligence.

Emotion can be defined in terms of discrete emotional states [2] or as a position on the 2-dimensional arousal-valence space [3], or as a combination of both [4]. A number of groups have reported a wide range of studies to the objective evaluation of emotions, investigating varying modalities such as facial expressions [5], vocal patterns [6, 7], physiological responses [8, 9] or combinations of the above [10]. As a starting point to better capture technology opportunities and challenges for body area networks when applied to mental health monitoring and affective HCI, we have chosen to focus on monitoring physiological responses from the Autonomic Nervous System.

2.1 Body Area Network for Monitoring Autonomic Nervous System Responses

We recently reported the realization of a low-power body area network for monitoring ECG, respiration, skin conductance and skin temperature [13]. Each of these modalities is known to be regulated by the Autonomic Nervous System, and thus represent interesting candidates to capture ANS responses to external stimuli. The system, illustrated on Fig. 1, consists of two low-power miniaturized body sensor nodes which communicate with a receiver connected to a pc or to a data logger. The first node is integrated in a wireless chest belt and monitors ECG (lead-I) and respiration. The second node is integrated in a wireless wrist sensor and monitors skin conductance and skin temperature. The total size of each individual node is approximately 40 x 25 x 8 mm^3, including battery, sensors and read-outs. Power consumption of the ECG/respiration node is 2.5mA, whereas the wrist-based sensor consumes 4mA, mainly due to an infra-red temperature sensor. Low-power and high performance ECG monitoring is achieved through the use of a proprietary single channel ASIC for biopotential read-out [11]. The ASIC consists of AC coupled chopped instrumentation amplifier, a spike filter, and amplification stage with constant gain, and a variable gain amplifier stage. The variable gain amplifier can be used to electronically adjust the gain of the readout for varying needs of EEG, ECG and EMG applications. Power consumption of the ASIC is 60uW, leading to an average consumption of 75 uW for the ECG read-out.

Fig. 1. Integrated body area network for ambulatory monitoring of physiological responses from the Autonomic Nervous System

This body area network for ANS responses monitoring has been tested in controlled environment to evaluate its potential usage for monitoring emotional states [13]. 10 subjects (mean age 29.3, 3 females, 7 males) are involved in the study. They are asked to watch 5 emotionally arousing film clips to elicit sadness, happiness, fear, disgust and neutrality [12], while wearing the wireless monitoring equipment. At the end of each clip, the subjects fill a self-report questionnaire. The 5 film clips are grouped into 3 categories in function of their expected arousal level: fear and disgust, happiness and neutral, and sadness. The four physiological signals are analyzed offline, and a set of 13 features are extracted based on general physiology considerations and previous studies on emotion recognition [16]. The 13 features are then mapped to 2 axes using Fisher Mapping. Linear Discriminant Classification is finally used to classify the data. This process eventually leads to error rates of 0.36 computed using leave-one-out cross-validation on the data-set, which is similar to previous studies on emotion classification [9, 13, 15].

2.2 Real-Time Arousal Monitoring

In a second study, we have investigated the possibility to use the proposed BAN system as an enabling technology platform for performing real-time measurement of an individual's arousal level [17]. 20 healthy volunteers are involved in the experiment. A movie extract is chosen as the arousal stimulus, characterized by a calm beginning followed by a building-up phase culminating to a frightening event. A reference or target arousal function is defined as being zero during most of the movie, except in a region surrounding the frightening event (see [17] for all details on the choice of the target function). Volunteers are asked to watch the movie while their physiological signals are monitored using the wireless system. All tests have been performed in a controlled laboratory environment, in order to minimize the sources of distraction that may eventually lead to unexpected and uncontrolled increases in arousal. A set of features is extracted from the ECG and skin conductance signals, found to be the most responsive parameters to the tests. In a second step, these features are combined in an optimal arousal estimator using linear regression against the target arousal level. The outcome of the regression analysis is a set of coefficients, characterizing the importance of each individual feature in the final estimation of arousal. All algorithms are implemented in the Matlab computing environment. All algorithms are real-time, such that the process of feature extraction and arousal estimation can be applied in real-time on incoming signals measured using the BAN system.

The resulting estimator has then been used to monitor the arousal level of individuals wearing the system. Several tests have been performed in various environments, varying from laboratory to public places. As much as possible, the test subject was isolated from the outside world, for instance by using headphones. The test protocol used for these tests consists of four parts: a short movie to get acclimatized, a modified Stroop test [], an audio extract and a movie fragment. The Stroop test is modified to induce confusion (and hence mental stress) in the second part of the test. The audio extract is a 3-minute very relaxing piece of classical music abruptly disturbed by noises of several kinds after 120 and 150 seconds, expected to trigger startling responses. The movie clip is identical to the one used to develop the arousal monitor. An example of the estimated arousal level over the test sequence is given in Fig. 2 or one of the test subjects. In this figure, the solid line gives the estimated arousal over time. The dashed, vertical lines represent the events, as specified by the name shown directly to the right of these lines. It can be seen from this picture that the subject did not show a significant increase in estimated arousal during the modified Stroop test. There was, however, a sharp and large increase in estimated arousal level just after the audio events and the movie event. Apart from the expected responses, there are also some responses that clearly do not origin in any of the events. These false positives can be due to anything that triggers the subject's mind, such as an arousal triggering thought, or something surprising in the surrounding environment.

Overall, the arousal monitor has proven to work quite reliability in controlled environment—that is, in a lab setting where distraction opportunities are minimized. It has also been shown that the conclusions can be generalized from movie to other arousing stimuli, as suggested in Fig. 2. However, further experiments are needed before conclusions can be drawn about the extension of the results to non-controlled

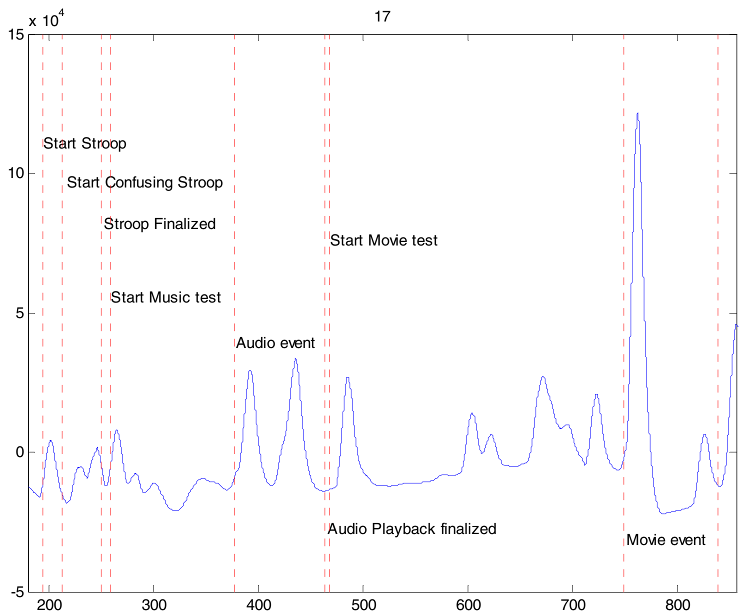

Fig. 2. Estimated arousal level over the part of the test protocol: modified Stroop test, audio extract and movie clip. Dashed vertical lines give the timing of the events.

environments. The low-power monitoring platform presented here certainly will facilitate the transition from lab to real-life environments.

2.3 Technology Challenges

The evaluation of the low-power body sensor network for ANS responses monitoring in different application cases offers new perspectives towards an objective, wireless and ambulatory monitoring of an individual's emotions. This technology evaluation exercise also leads to a better understanding of application requirements, and to the identification of important technology challenges that shall be addressed to eventually enable widespread deployment of body area networks for human computer interaction.

- **Ultra-low-power electronics:** current prototypes still mostly rely on low-power COTS components, from which the best lead to typical current consumption ranging from 1 to 10 mA, depending on the application. We previously showed that most of the power is consumed in the wireless transmission of the data, or in local processing of the data [1]. In some cases, sensors are also found to consume a significant part of the power. Further research is needed on ultra-low-power analog interfaces, sensors, DSP and radios. The ultimate target is to reach a total power consumption of 100 µW per body sensor node.
- **Autonomous systems:** the prototypes presented in this paper can run for a few days at full functionality. Breakthroughs in ultra-low-power technologies will

eventually enable months or years of autonomy. To come to a truly autonomous system however, it should be able to operate over its full lifetime without maintenance. Harvesting energy from the environment during the operation of the system will allow the system to run eternally with a battery or a super-capacitor acting only as a temporary energy buffer.

- **Multi-parameter sensors:** emotion monitoring is a complex problem, which is further reinforced by the fact that the underlying psycho-physiological aspects are not yet fully understood. Extending the range of functionality to include new sensing modalities will be crucial in fostering research in this area, leading to new discoveries. On the short term, multiple available sensors can be combined in the same system to enrich the information available, such as muscle tension, brain activity, voice, etc. On the longer term, novel sensing technologies are needed to reliably measure more complex parameters such as chemical compounds, hormones and proteins in body fluids, whilst pursuing ultra-low-power consumption. Continuous measurement of cortisol in saliva would for instance open new perspectives in stress monitoring.
- **Dry electrodes:** widespread acceptance of body area networks for human computer interface is expected to be intimately related to the comfort and easy of use of the system. Most of current systems for ECG, EMG and EEG monitoring require wet, gel electrodes to be attached to the skin or the scalp. Although they have the major advantage of providing good quality signals, gel electrodes exhibit significant drawbacks with regards to long-term use and ease of set-up. Dry electrode technology is required to enable simple setup of the system by the user itself. Several research groups have explored the area of dry electrode for EEG monitoring applications, for instance [19]. Further research is required to systemically tackle the issues of signal quality, robustness to motion artifact and bio-compatibility.ï
- **Increasing functionality:** most of today's body-worn sensors act as simple gateways, passing on the information to a central hub where the data is converted into actionable information. Emotion monitoring requires simultaneous monitoring of multiple sensors on the body, and the local extraction of relevant information out of the sensor data. Low-complexity and real-time algorithms are required to enable intelligent autonomous systems. Furthermore, compromises between local processing of the data versus data streaming or data storage exist and need to be investigated. A rational approach to distributed processing will allow achieving optimal performances for minimized power consumption.
- **Integration technology**: as body sensor nodes shrink in size and power consumption, end-user acceptance and compliance will eventually be bound to comfortable of use. Pioneering research in electronic integration technology has led to first functional prototypes of ultra thin chip packages [20] and stretchable interconnects [21]. Electronic integration in bi-dimensional flexible and stretchable foils will enable disappearing body sensor nodes, integrated in patches, clothes or even fashion accessories.

Addressing these technology challenges will lead to increased functionality, higher performance, better integration and decreased power consumption, thus bringing technology for ambulatory emotion monitoring closer to the end-user. In the next section we show how advances in micro-power generation systems already pave the way towards autonomous wireless sensor systems, enabling new perspectives for affective human computer interaction.

3 Towards Autonomous Wireless Health Monitors

The body is an under-estimated source of energy. It has been shown that the heat flow generated by the human body generates a power density of about 20 mW/cm^2 in average. This makes body thermal energy an interesting candidate for harvesting. Thermal-energy harvesters are thermoelectric generators which exploit the Seebeck effect to transform the heat flow from the human body to the environment into electrical energy, typically showing efficiencies of 0.1 to 3 %. Besides the energy dissipated by the body, much energy is also available from the surrounding environment, mainly from electromagnetic radiation (natural and artificial light). A recent survey of commercially available photovoltaic solar-cells has shown that indoor photovoltaic cells are capable of generating a maximum of 8 to 14 μW/cm^2 (depending on the type of cell) at perpendicular incidence and under 400 Lux. The type of light source was found to have only a minor effect on the generated power density.

In 2007, we reported the first autonomous health monitoring systems powered by thermal-energy harvesters: a wireless autonomous pulse-oximeter powered by a wrist-watch type TEG, and a wireless autonomous EEG monitoring system powered by a head-band type TEG [22, 23]. An important issue with these prototypes was the dependence of the generated power on the ambient temperature. To cope with this issue, we realized an improved prototype of autonomous wireless EEG monitor, featuring a hybrid power supply [24], as illustrated in Fig. 3. This power supply combines a TEG, which uses the heat dissipated from a person's temples, and Si photovoltaic cells. The TEG is composed of six thermoelectric units made up from miniature commercial BiTe thermopiles. Two high-efficiency Si photovoltaic cells are integrated on the left and right sides of the head, each of them having an area of 4x8 cm^2. These cells play the double function of converting ambient light into electricity, and serving as a part of the radiator to ensure effective heat transfer from the head into the environment. Exploiting the advantages of dual energy sources, the dimensions (size and weight) of the TEG have been reduced in comparison to previous prototypes, the power/volume ratio increased, and the range of ambient temperature at which the system works reliability widened.

To enable their use in electronic device, the TEG requires advanced power management circuitry to optimize harvested power efficiency. Typically, the TEG continuously charges a battery or a super-capacitor, which then provides power to electronic modules. Voltage up-converters are usually added to match the need for higher voltage power-supply of different electronic components. In parallel to the TEG power conversion circuit, a secondary power management circuit allows charging the battery directly from photovoltaic (PV) cells.

Fig. 3. Autonomous wireless EEG system powered by body heat and ambient light

The EEG system integrates a proprietary ultra-low-power biopotential readout ASIC [11], and the whole system consumes only 0.8 mW. The entire battery-free 2-channel EEG system is wearable and integrated into a device resembling headphones, as illustrated in Fig. 3.

This example shows that prototypes of autonomous health monitoring systems can be achieved today. Nevertheless, it also suggests that research in miniaturization of energy harvesters system using micro-machining techniques is necessary to further miniaturize the devices, and make them available at a reasonable cost. Furthermore, miniaturization is intrinsically related to power consumption, as the micro-power module, harvester and/or battery, is making up for most of the size of wireless sensor systems. Energy harvesting techniques for body sensor network can achieve a power density of 10 to 100 $\mu W/cm^2$, with today's TEG achieving 25 $\mu W/cm^2$ in average. The technology challenge will thus be to make the step from low-power electronics (10-100 mW) to ultra-low-power technologies (0.1-1 mW).

4 Conclusion

In this paper, the concept of body area network has been applied to wireless monitoring of physiological responses from the autonomic nervous system, paving the way towards wireless ambulatory monitoring of emotions. The proposed prototype integrates early technology achievements from the Human++ research program on wireless autonomous sensors. Using data fusion and regression analysis the wireless physiological data can be automatically analyzed in real time, allowing the determination of an estimated arousal level. The future will see the integration of additional sensor modalities, to enable real time monitoring of a person's emotional state as a combination of arousal and valence. Furthermore, widespread acceptance of body area networks for human computer interface will require overcoming key technology challenges in terms of ultra-low-power radios, DSPs and analog interfaces, dry electrode research and 2D flex/stretch electronic integration. In particular, this paper suggests how advances in micro-power generation devices may lead to fully autonomous systems in the future.

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