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Physiological Sensor Suite Using Zero Preparation Hybrid Electrodes for Real Time Workload Classification

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Quantum Applied Science and Research is working closely with the Aberdeen Test Center to develop an integrated system to monitor warfighter physiology. This need has been recognized by two recent major programs: the Defense Advanced Research Projects Agency's Augmented Cognition program and the U.S. Army's Warfighter Physiological Status Monitor program. However, these programs were limited by inadequate development of fully deployable noninvasive sensors and in the number of physiological variables they could simultaneously measure.

Warfighters need to rapidly perceive, comprehend, and translate combat information into action. To aid them, robust gauges have been developed for classification of cognitive workload, engagement, and fatigue, which simplify complex physiological data into one-dimensional parameters that can be used to identify a subject's cognitive state during the varied tasks carried out in a training environment.

This article describes the two main hardware modules that form part of an integrated Physiological Sensor Suite (PSS): a Physiological Status Monitor (PSM) and a module for the measurement of electroencephalograms (EEGs). The PSS is based on revolutionary noninvasive bioelectric sensor technologies. No modification of the skin's outer layer is required for the operation of this sensor technology, unlike conventional electrode technology that requires the use of conductive pastes or gels, often with abrasive skin preparation of the electrode site.

The PSS was designed to be wearable and unobtrusive, with an emphasis on the capability of long-term monitoring of physiological signals. These factors are of considerable importance in operational settings where high end-user compliance is required. The PSM is a simple belt that is worn around the chest. The EEG system has already been incorporated into a soldier's Kevlar helmet and tested successfully during combat training.

Data are acquired using a miniature, ultralow-power, microprocessor-controlled multichannel data acquisition (DAQ) unit that transmits data wirelessly to a base station/data logger worn by the subject. The DAQ unit is worn on the body close to the measurement point, reducing the amount of cable clutter and minimizing the impact on subject mobility without introducing motion artifacts.

Hardware

Hybrid biosensors

Electrophysiological measurements in the PSS are performed using hybrid (capacitive/resistive) bioelectrode technology. An electrocardiogram (ECG) sensor of the type used in the PSM is shown in *Figure 1*.

The EEG module uses hybrid sensors that are capable of measurements of through-hair EEG *(Figure 2)*. Electrical contact is made via a set of "fingers," each of which is small enough to reach through hair and make electrical contact to the scalp between hair follicles. The inner circular section is sprung to follow the head contour.

Electrophysiological measurements using hybrid bioelectrodes are enabled by a proprietary common mode follower technology. The common mode follower is used as a reference for the biosensors so that the common mode signals appearing on the body are dynamically removed from the measurement, typically achieving a common mode rejection ratio of 50 to 80 dB.

Physiological status monitor

The PSM *(Figure 3)* measures ECG signals, body temperature, respiration data, body position, and actigraphy. Proprietary ECG and acceleration/respiration/temperature sensors are incorporated into a belt worn around the chest. The outputs of the ECG and acceleration/respiration/temperature sensors are combined to determine the health status of the subject.

The Gain/Filter module acquires the ECG and acceleration/respiration/temperature data, stores it on a FLASH card, and wirelessly transmits the data via an

Figure 1. Hybrid electrocardiogram biosensor (with a U.S. 25 cent coin for scale).

ultralow-power wireless link to a local base station. The system is easy to install and use and operates for several days from a single AAA lithium ion battery.

EEG sensor harness

The EEG harness shown in *Figure 4* fits under the Kevlar helmet of a soldier. Sensors are positioned at the nominal CZ, C3, C4, FZ, F3, F4, PZ, and P4 10–20 array positions. The array is anchored to a standard helmet harness, and a mechanical isolation system isolates the array from the helmet motion during strenuous activity. The harness and Kevlar helmet have been worn without discomfort for periods of up to 3 hours by solders performing combat tasks.

Miniature low-power data acquisition unit and base station

The DAQ unit was designed to address the general requirements for multichannel EEG, ECG, electro-oculorgram, and electromyography data acquisition. Sixteen-bit sigma-delta analog-to-digital converters simultaneously acquire up to 12 channels of near medical quality data, even in environments with high levels of electromagnetic interference.

The EEG module acquires data at a rate of 240 sps, but data rates of up to 1,000 sps are possible. Aliasing of out-of-bandwidth signals is less than −80 dB between 1 Hz and 50 Hz. To conserve power the microprocessor operates in a low-power "sleep" mode when not acquiring data, and the run time when acquiring eight channels of EEG data is in excess of 80 hours from two AAA batteries.

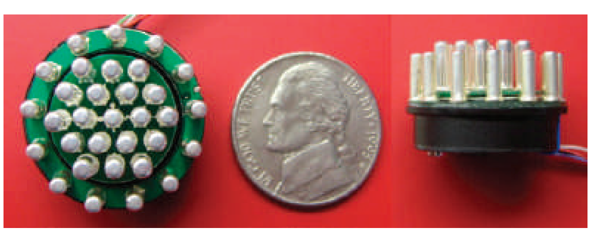

Figure 2. Hybrid electroencephalogram biosensor (with a U.S. 5 cent coin for scale).

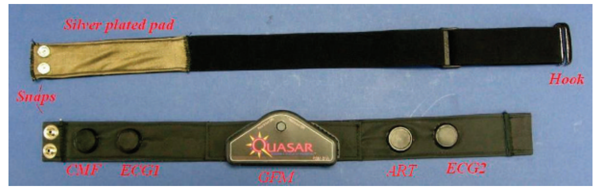

Figure 3. Physiological status monitor belt.

The short range wireless transceiver in the DAQ forms a Personal Area Network with a custom Base Station that is worn on the subject's hip or carried in a backpack, logs data to a FLASH card for storage, and communicates with external systems via proprietary, 802.11 or Bluetooth wireless protocols, Ethernet, USB 1.1 or 2.0, or RS-232.

To conserve power, the wireless transceiver transmits information in a data "burst" mode, and data rates up to 2.5 ksps have been achieved.

Measurements

Validation testing has been performed on two subjects at a Future Combat Systems technology demonstration (at the Boeing facility in Huntington Beach, California); on four subjects at a Honeywell facility in Minneapolis, during a NATICK data gathering exercise; and on two solders performing combat tasks in a realistic training environment at the Aberdeen Test Center in Maryland. Classification accuracy of cognitive workload from subjects at Aberdeen reached 90 percent or higher for both participants. The data presented in this article were obtained during extensive testing under simulated operational conditions at Quantum Applied Science and Research. In all of the measurements no preparation of the scalp was performed at the hybrid electrode sites. Preparation of the scalp for the wet electrodes included abrasion with Nu-Prep, followed by cleaning with alcohol and then application of Grass EC2 electrode paste.

Figure 4. Hybrid sensor array incorporated into a soldier's Kevlar helmet. Left: The outer aluminum ring and weights load the harness correctly when the helmet is not present. Right: Electroencephalogram system with helmet attached and ready for use, including wireless module.

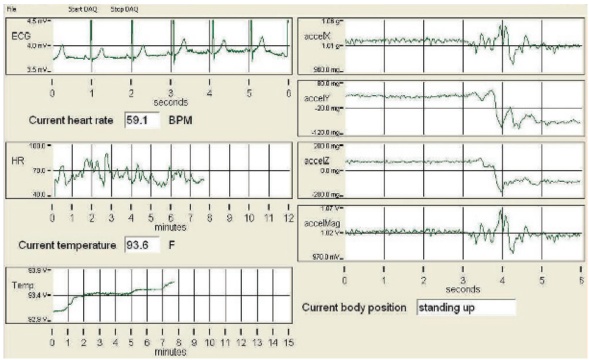

Figure 5. Screenshot showing electrocardiogram and accelerometer data collection using the physiological status monitor.

Physiological data recorded by PSM

A screen capture of physiological data (ECG, temperature, and acceleration) from a subject wearing the PSM is shown in *Figure 5*. ECG data acquired in real time is converted to heart rate, where the accelerometer data are used to correct for motion artifacts.

Equivalence of EEG signals detected by hybrid electrodes and conventional wet electrodes

Simultaneous measurements were made using hybrid/wet electrode pairs positioned at the nominal CZ and FZ positions. Less than 5 mm separated the hybrid and wet electrodes placed at each position.

In *Figure 6* hybrid and wet electrode data are overlaid to illustrate the similarity in the signals measured. Alpha activity is observed in all electrodes, and the correlation between hybrid and wet electrodes is in excess of 90 percent at both electrode sites.

EEG measurement during subject motion

Figure 7 compares EEG data recorded with a subject sitting (upper trace) and with a subject walking on a treadmill at 2 mph (lower trace), measured with the wireless EEG system. The signal level in both traces indicates no significant increase in artifact during subject motion.

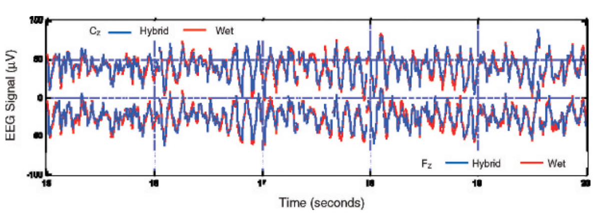

Figure 6. Comparison of electroencephalogram data (eyes closed) recorded using hybrid and wet electrodes. The data are high pass filtered at 1 Hz and low pass filtered at 30 Hz with 8th-order Bessel filters.

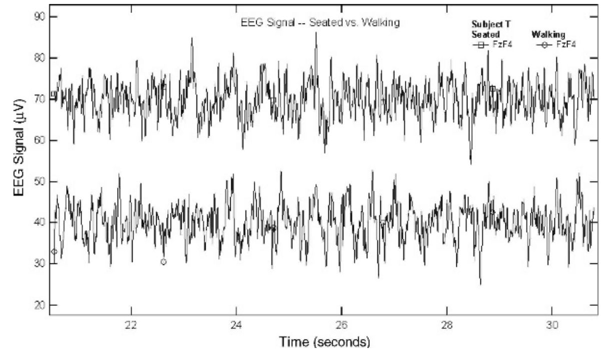

Figure 7. Representative difference data for the FZF4 electrode sites when the subject is sitting (upper trace) or walking on a treadmill at 2 mph (lower trace). The data are high pass filtered at 1 Hz and low pass filtered at 30 Hz with 7th-order Bessel filters.

Real time classification of workload

Figure 8 shows the result for real time classification for a subject walking at 2 mph on a treadmill and performing N0 (low) and N3 (high) workload tasks. Two trial data sets were first collected to train a workload classifier: a passive trial, during which the subject listened to music, and a trial in which the subject performed a divide-by-seven task. The classification results in *Figure 8* were derived using classifiers constructed from training data sets collected 19 days earlier. The vertical axis is the probability that the subject is undergoing a high workload task. The N0 task shows a low probability (always less than 30 percent); the N3 task shows a significantly higher probability, reaching 100 percent on numerous occasions.

Figure 9 shows the EEG system being used for real time classification of cognitive workload and engagement while subjects play a first-person shooter video game. Classifiers were constructed for each subject using three training data sets: data collected during passive viewing of the game, while fighting two

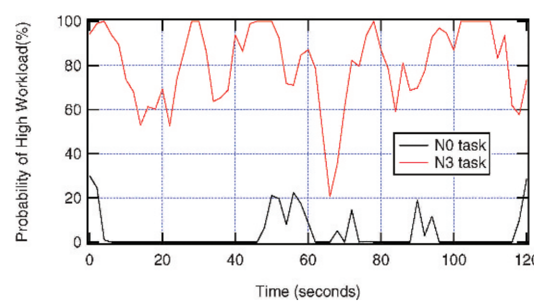

Figure 8. Real time classification while subject was walking at 2 mph on a treadmill and performing an N0 task and an N3 task. Two trial data sets were collected to train the classifier at different workload levels: a passive trial, during which the subject listened to music, and a trial in which the subject performed a divide-by-seven task.

Figure 9. A test system for assessing workload and engagement of computer gamers.

enemies in the game, and while fighting 25 enemies in the game. The classifiers for a given subject were then used to perform real time classification of workload while the subject was playing the game.

A screen capture for the subject engaging 25 enemies is shown in *Figure 10*. The workload indicator on the right of the screen is a real time estimation of the cognitive state of the subject and is a combination of two separate classifiers: a Workload classifier (High/Low) and an Engagement classifier (Engaged/Disengaged). The subject's workload level in *Figure 10* (High) is an accurate reflection of the workload at this level of difficulty in the video game.

Table 1 presents the classification accuracies for each classifier for a series of tests conducted on 4 separate days (over a period of 10 days). Intrasession cross validation for each day was performed using 60 percent of the data for training and 40 percent for classification and repeating this process eight times. Real time classification accuracies are also presented for data in which the training data sets are from one day and classification was performed during testing on a subsequent day. The 4 days of testing have been paired as shown in *Table 1* because the protocol was altered to

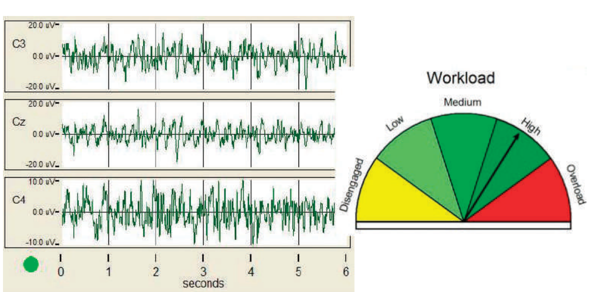

Figure 10. Laptop screenshot showing data collection and engagement classifier running on the gaming subject of Figure 5. The traces on the left are electroencephalogram signals at C3, CZ, and C4 respectively. The Workload indicator shows the real time output of the classifier.

Table 1. Classification accuracy

Training data set/ classification data set	Workload classifier (%)	Engagement classifier (%)
Cross validation, March 28	83.6	89.1
Cross validation, April 1	86.1	88.2
Cross validation, April 5	83.4	84.9
Cross validation, April 6	73.8	84.3
March 28/April 1	81.4	81.1
April 5/April 6	74.8	78.8

32 enemies for April 5 and April 6 because of an increased proficiency of the subject at playing the video game.

The results in *Table 1* demonstrate that the Workload and Engagement classifiers routinely achieve greater than 80 percent classification with 8 seconds of temporal smoothing. Similar classification accuracies are also found when the training data sets are taken from a different day, demonstrating the classifiers' robustness to daily variations in physiological state.

Final remarks

Quantum Applied Science and Research has developed an integrated system for measuring warfighter physiology. The wireless EEG system is compact, lightweight, and ultralow powered. Using innovative noninvasive bioelectric sensors that operate through hair without skin preparation or conductive gels, EEG data of quality similar to that of conventional wet electrodes can be obtained. The noninvasive nature of the EEG system (i.e., zero skin preparation, minimal wiring) permits greater subject freedom of motion and considerably improves user compliance for such systems. Hardware has been integrated with robust proprietary classifiers that enable real time determination of cognitive workload, engagement, and fatigue. Mechanical isolation built into the harness permits the recording of high quality EEG data even during subject motion.

Military applications of the PSS include monitoring of physiological states for Dismounted Infantrymen, or cognitive state monitoring for Command & Control personnel. Applications of the EEG system extend beyond cognitive state determination to medical applications, such as the monitoring of patients with epilepsy or other neurological conditions, and to computer interfaces for the disabled. ❑

Dr. R. Matthews is the leader of QUASAR's Biosensor Development Program. He leads the development of bio and medical applications and has been responsible for all

clinical trials and technology demonstrations of biosensing devices. Dr. Matthews has extensive, in-depth experience in developing a broad range of practical EM sensing systems for airborne, land, underwater, and man-carried operations. These projects include being the lead designer and engineer on a series of research programs culminating in a total of more than $30 million in R&D funds to build a land mine detection system. While working for Quantum Magnetics (QM), Dr. Matthews was stationed at the IBM Thomas J. Watson Research Center, where he worked closely with IBM on the development and commercialization of advanced magnetic technologies. This work formed a key part of the superconducting technology development agreement between IBM and QM. Dr. Matthews led the development of instrumentation using high-temperature superconducting magnetic sensors for biomagnetic measurements. He also played a key role in the development of a multisensor magnetic gradiometer and contributed to work using magnetoresistive sensors for buried explosive detection. Before coming to the United States, Dr. Matthews worked on the development of a superconducting gravity gradiometer, a geophysical exploration device to be flown in light aircraft to survey for massive ore bodies. This work was aimed at commercializing the sensor for the geophysical exploration market. Dr. Matthews is author or coauthor on many scientific publications and is the inventor or co-inventor on numerous patents. Dr. Matthews earned his Ph.D. in Physics from The University of Western Australia. E-mail: Inquiries@quasarusa.com