Designing a Biocontrol Interface for Commercial and Consumer Mobile Applications: Effective Control within Ergonomic and Usability Constraints


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Designing a Biocontrol Interface for Commercial and Consumer Mobile Applications: Effective Control within Ergonomic and Usability Constraints

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Abstract

The design of devices that use bioelectric signals as a human-computer interface (biocontrollers) is discussed with an emphasis on the developments necessary to create user friendly consumer products. The use of dry rather than hydrogel electrodes that are placed on easily accessible and socially acceptable skin locations is a constraint on this design that has only recently been achievable. To be acceptable for most applications, it is shown how the electrodes and associated electronics must be imbedded in existing interface designs such as steering wheels and game controllers or must be part of wireless, technology-based clothing such as watches, arm bands, and glasses. The optimization of these constraints based on the desired interaction is demonstrated using specific application examples.

1 Introduction

Over the past decade, the increasing and successful research and development of the “biocontroller” has enabled individuals to interact directly with computing devices using physical motion and emotion as measured by bioelectric signals (Lusted and Knapp, 1996, Picard and Healey, 1997, Hudlicka, 2003, Nasoz et.al., 2004). The focus of the work on biocontrollers has primarily been on investigating many different usage scenarios and creating the necessary signal processing algorithms to map the complex patterns in the physiological signal to usable interactions within the scenario. (See Table 1 for summary of physiological signals and associated interactions.) The testing of these algorithms usually involves interfaces that are not ergonomically designed. Many biocontrollers are composed of wet (hydrogel) electrodes held by devices such as baseball caps (for EEG or EOG) or tape or large elastic bands (for EMG or EKG) which are then wired to data acquisition devices. If biocontrollers are to be used in the consumer and/or commercial world, certain ergonomic and usability constraints on the interface design will be necessary. The goal of our work has been to create a real-time biocontroller interface that is aware of the user’s emotional, cognitive, and physical state and that can be worn comfortably, socially acceptably, and without interfering in any way with the interaction. In this paper we will discuss the constraints placed on the biocontroller in mobile consumer and commercial applications and highlight the innovations that have enabled biocontrollers in certain application domains to emerge from the lab environment and cross the threshold toward productization.

2 Biocontrol Interface Design within Constraints

The constraints on the design of the biocontroller interface are largely dictated by the interaction scenario and can be broadly categorized into two areas:

1. Electrode placement and wearability
2. Signal processing and mobility

2.1 Electrode placement and wearability

2.1.1 Placement

The sensors (electrodes) used to acquire the bioelectric signal need to be placed in locations on the body that are optimal for acquiring the particular signal of interest. For most EMG applications, some form of armband or legband
<table>
<thead>
<tr>
<th>Table 1: Summary of Physiological Signals Used for HCI</th>
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<tbody>
<tr>
<td><strong>Broad Definition</strong></td>
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<tr>
<td><strong>Galvanic Skin Response (GSR)</strong></td>
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<tr>
<td><strong>Electrocardiogram (EKG)</strong></td>
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<tr>
<td><strong>Electrooculogram (EOG)</strong></td>
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<tr>
<td><strong>Electromyogram (EMG)</strong></td>
</tr>
<tr>
<td><strong>Electroencephalogram (EEG)</strong></td>
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</table>

is used to position the electrodes over the muscle group targeted as the EMG signal source. For instance, a band worn on the forearm monitors the EMG activity of the muscles that control finger and hand position. Thus, these EMG signals can be used to interpret gestures of the hands and mapped accordingly to directional game controls. In addition to simple placement issues, the electrodes must be stabilized relative to the skin or else motion artifact will contaminate the EMG data as the user moves. So the sensor bands must be carefully designed both for comfort and functionality. Figure 1 shows armband and headband designs that satisfy the above requirements.
For EEG signal acquisition, the electrodes need to make positive contact with the skin or scalp without interference from the hair. For convenience, the forehead is often used as the point of contact for the EEG electrodes. Also, the mastoid area (behind the ears) can be used since this is a convenient area on the head that is generally not covered with hair growth. In traditional EEG science, the electrodes are made to electrically connect with the scalp either by shaving the hair or wetting the hair with gel or cream electrolyte. These scalp contact methods are unacceptable for a consumer product. Accordingly, the best hardware systems for electrode placement are a headband or glasses (as shown in Figure 2) that touch the forehead and mastoid. A well designed headband is comfortable and holds the electrodes securely against the skin to prevent movement artifact caused by the slippage of the electrode on the skin.

The EOG can be measured by combining forehead electrodes with two electrodes placed below the left and right eyes which can be seen in the left hand picture in Figure 2. This same array configuration can be used to pick up facial gestures.

The most optimal locations for measurement of GSR are on the palm of the hand, finger tip, or sole of the foot. For consumer applications this means placing electrodes in objects that would be normally gripped as part of the interaction such as a steering wheel or game controller or possibly inside gloves.

In summary, the biocontroller must be able to be worn as part of normal technology-based clothing (watch or other armband, headphones, glasses, or other headband, or in the grip of a steering wheel or game controller). Therefore, the only acceptable locations for sensors are on the arms, hands, forehead, and mastoid.
2.1.2 Wearability

One of the keys to achieving the wearability goal is the development of a dry electrode sensor system for measuring the desired physiological signals. While disposable hydrogel or other electrolyte-based electrodes are appropriate for clinical physiological recordings or bioelectric signal research, they are entirely inappropriate for most commercial and consumer applications. Possible exceptions to this might be mobile physiological monitoring, home sleep monitoring, or interfaces for people with disabilities. Even in these applications, dry electrodes are highly desirable if they can achieve the necessary impedance and motion artifact immunity necessary.

If properly designed, the dry electrode should be easy to use and yield high quality signals. This technology also creates the possibility for the development of biosignal consumer products that contain no vestige of medical technology in the form of wet electrodes. Indeed, a dry sensor can be placed in a wrist watch, for instance, and the user would be unaware that biosignals were being acquired from the surface of the skin.

There are three challenges encountered with transdermal biosignal recording that need to be addressed in designing dry electrodes:

- Consistent signal quality across users
- Motion artifact
- User comfort

To address these challenges several research groups have been experimenting with different dry electrode structures (Griss et. al., 2000, DeLuca, 2002, Harland et. al., 2002). We have currently designed and built a low-cost dry electrode array with a special micro-geometry at the electrode surface in order to stabilize current fluctuations between the electrode and the skin. These sensors are composed of an array of 90um “bumps” on a 65um pitch. As shown in Figure 3, the electrodes are placed on a small band which enables the electrode elements to float in relation to each other. This design allows the electrode contacts to conform to individual contours on the body and provides equal pressure against the skin – important for obtaining the best signal to noise ratio from the sensor. The surface micro-structure produces sufficient friction at the electrode-skin interface to prevent the relative motion that is the source of most motion artifact. Figure 4 and Figure 5 show EKG and EMG recorded using this electrode array.

![Figure 3: Array of three micro-machined dry electrodes](image)

![Figure 4: EKG recorded from electrode array shown in Figure 3](image)
2.2 Signal Processing and Mobility

2.2.1 Signal Processing

The electronics of a biosignal interface are responsible for amplifying, filtering (analog), digitizing, and analyzing the bioelectric signal. Trade-offs in the design of the electronics include:

- Needed bit resolution vs. cost and power consumption
- S/N ratio vs. cost
- Latency vs. signal recognition accuracy
- Processor performance vs. signal recognition accuracy
- Latency vs. frequency resolution

To explore these trade-offs further, the design of a specific biosignal interface will be discussed. Figure 6 shows a block diagram of a mobile wireless physiological monitoring unit (WPM) used for EMG, EOG, EKG, and GSR control of computers, musical instruments, and embedded systems. The WPM is designed to be a consumer/commercial controller that does not require the user to have any experience in using biological controller devices and that requires no skin preparation. The “pod” portion of the WPM has three sensor inputs: built-in dry electrodes (see Figure 7), an external input for a dry or hydrogel electrode array, and accelerometers for motion sensing. The motion sensing expands the capability of the WPM to measure both isotonic and isometric gestures. The data from the three signal sources are then multiplexed, digitised at 500Hz sampling rate per channel, processed, and wirelessly transmitted to a receiver pod. Since the WPM was not designed to measure the very small signals of the EEG (10µV and smaller), a 10bit A/D converter was used to keep cost and power consumption low. Using a built-in low-noise differential amplifier circuit with active (“driven”) feedback, the WPM can accurately measure signals down to 10µV. At these low voltages, the S/N ratio was kept above the inherent 60dB SQNR of the ADC by extensive shielding and linear regulation of the battery supply.

Only simple low-latency, digital filtering tasks such as 50/60Hz notch filtering, signal averaging (comb filtering), and RMS calculations are performed on the processor. This enables the 8051 processor core of the RF microcontroller to process the data in real-time. With the exception of comb filtering, all group delays are kept below 10mS to achieve little noticeable latency. More complex processing tasks such as feature recognition for gesture control or emotional state recognition are “off-loaded” to the PDA or PC.
2.2.2 Mobility
Many HCI environments such as desktop computing do not require mobility and therefore wired interfaces are satisfactory. Indeed in video gaming, for liability reasons, mobility is often discouraged. However, in situations where wireless transmission of the biosignal data is desirable, the system needs to be designed with range, signal quality, and bandwidth requirements in mind. These factors, coupled with the signal processing requirements discussed previously such as latency, S/N ratio, and processor performance create a complicated set of design criteria. Again, the design of the WPM will be used as a case study.

The WPM was designed with two separate RF wireless systems. Both support the necessary 56 kbaud bandwidth to support 3 channels of data at the 500Hz sampling rate of 2 byte data. The first RF circuit uses a 868 (Europe) / 915MHz (US) frequency hopping digital transceiver based on a single chip RF processor. The communication protocol was designed for zero packet loss (no introduced noise). This was accomplished by buffering/resending of lost packets. When packet loss has caused the buffering to increase the latency beyond a prescribed threshold, a
warning LED flashes to tell the user to move closer to the receiver. To keep power consumption low, this first RF method has a range of only 3 meters. Unfortunately, this RF technique demands approximately 50% of the 8051 processing time leaving less time for signal pre-processing. As shown in Figure 6, it also requires a custom receiver system which increases overall system cost.

The second communication method is a standard Bluetooth serial interface. This enables the WPM to communicate with all off-the-shelf Bluetooth enabled devices, such as cell phones and PDA’s, eliminating the need for a custom receiver. The Bluetooth interface requires the use of a separate RF processor, however, thus increasing cost and power consumption. Large amounts of packet loss, especially in the presence of other 2.4 GHz devices such as 802.11, microwave ovens, and other Bluetooth devices is also a severe drawback of this approach.

3 Applications

Table 1 outlines how specific HCI scenarios dictate many of the constraints in the design of a biocontroller. We have recently designed solutions for three of these scenarios: operator monitoring, video game control, and music performance.

<table>
<thead>
<tr>
<th>Signals / Application</th>
<th>Sensor Placement</th>
<th>Wearability</th>
<th>Processor Requirements</th>
<th>Communications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operator Monitoring</td>
<td>GSR, EKG, EOG</td>
<td>Steering wheel, gloves, watch</td>
<td>Only dry electrodes</td>
<td>Wired into the vehicle or wireless communication to vehicle</td>
</tr>
<tr>
<td></td>
<td>Emotion (Stress), Fatigue, Eye movement</td>
<td>Game controller handset, glasses, watch</td>
<td>Only dry electrodes</td>
<td>For safety, direct connection usually desired</td>
</tr>
<tr>
<td>Video Game Control</td>
<td>GSR, EKG, EMG, EOG, EEG</td>
<td>Arm and facial gesture (continuous control and state recognition)</td>
<td>Only dry electrodes</td>
<td>Wireless system required – noisy 2.4 GHz environment might require custom RF approach</td>
</tr>
<tr>
<td>Artistic Performance</td>
<td>GSR, EKG, EMG, EOG, EEG</td>
<td>Arm bands, headbands, watch, gloves</td>
<td>Only dry electrodes</td>
<td>For computer use; wireless for mobile control of devices such as wheel chairs</td>
</tr>
<tr>
<td>Interfaces for Disabilities</td>
<td>GSR, EKG, EMG, EOG, EEG</td>
<td>Arm bands, headbands, glasses, watch</td>
<td>Possible use of hydrogel electrodes for EEG and EOG</td>
<td>Wired for computer use; wireless for mobile control of devices such as wheel chairs</td>
</tr>
</tbody>
</table>

3.1 Operator monitoring – automotive and industrial

Several research centers have been investigating the use of mobile physiological monitoring for automobile drivers (Healey and Picard, 2000). The aim for this application is to enhance safety by monitoring the driver’s state of
awareness. If specific physiological symptoms of sleep or fatigue appear, the driver can be alerted. One of the primary design considerations for the operator interface is to make a monitor system that is basically invisible so the driver does not have to wear sensor hardware or deal with monitoring equipment. We have designed a monitoring system that uses dry electrodes placed in the steering wheel to measure EKG, GSR, and skin temperature. From this data, aspects of the driver’s emotional state can be estimated. The cognitive state recognition introduces latency low to react to the onset of fatigue. This system is directly wired into the electronics of the vehicle.

We have also created a self contained physiological monitor for motocross riders. Here, dry electrodes are placed in the gloves of the rider. As in the automobile system, the electrodes record ECG and GSR. The data is then used to assess the rider’s emotional state during the course of a race. As a promotion for RedBull beverages we gathered physiological data remotely from a professional motorcycle rider and processed the data to derive the rider’s emotional responses as he careened around the race track. The data was time locked with video cameras so that the rider’s emotional responses could be correlated with events on the track. The animated graphics on the RedBull site (www.redbullcopilot.com) show the rider’s heart rate along with his emotion intensity synchronized to various camera shots around the race course. Generally, the rider’s stress level was relatively constant with indications of elevated heart rate and emotional response just preceding some of the hair-pin turns on the track.

3.2 Interfaces for game control

Bioelectric signals have been used to control various aspects of video game play. To investigate how to use these signals with different game interaction scenarios with ergonomically viable hardware, we developed a biocontroller research platform (BRP). The system, which can capture up to 8 independent bioelectric signals, is connected to the USB input of a Sony PS2. All of the signal processing is performed by the PS2 processor. Studies of latency, S/N ratio, and bandwidth can all be performed on the device. Determining how to dynamically calibrate for individual users is one of the critical uses of the BRP. For example, alpha activity (the 8-12Hz component) of the EEG can be used as one feature of an assessment of a user’s relaxation state. High alpha activity correlates with a relaxed or “defocused” state. Figure 8 shows this alpha activity for one individual. Figure 9 shows the resulting RMS assessment of the alpha level. The threshold level of alpha activity that corresponds to relaxation is unique to an individual and must be calibrated. More importantly, the dynamic properties of the alpha activity are unique to an individual and therefore the dynamic properties of the RMS assessment must also be customized to the individual. These properties can vary over time, so continuous, adaptive re-calibration techniques are necessary. This type of calibration and re-calibration is necessary for all the bioelectric signals used in game control and must be relatively fast and transparent to the game play for bioelectric controllers to a viable game interface.

![Figure 8: 8-12Hz (Alpha) Activity Measured on the Forehead By the BRP System](image-url)
From the results of user testing of interaction design, electrode design and placement, processor latency, and calibration using the BRP, a PS2 emotion interface was created (see Figure 10). The interface augments the standard game controller using a dry electrode array similar to that shown in. This design enables measurement of EKG, GSR, and temperature to estimate emotional state. The ergonomics of the game controller are unaffected by the bioelectric measurement. Latency under 30mS was achieved by the PS2 for recognition of simple stress levels.

3.3 Performance control
We have been working since 1989 on various techniques for mapping biosignals to music synthesizer controls (Knapp and Lusted, 1990). The first such system, the Biomuse, used an embedded signal processor to achieve low enough latency for real-time control. However, the system did not meet any of the other design criteria outlined in Table 2. The Biomuse was wired (not mobile) and used hydrogel electrodes making it unacceptable for a consumer product. Since then various mobile biocontroller devices such as the “Conductors Jacket” (Nakra, 2000) have been used for dynamic music interaction. Atau Tanaka of Sony, CSL has recently been using the WPM as shown in Figure 7 worn on the forearms to detect EMG (Tanaka and Knapp, 2002). The EMG RMS calculation is optimised for relatively low latency while preserving steady output at constant tension levels. The dry electrode interface means that no preparation is necessary and the wireless design enables complete freedom of motion.
4 Conclusion
The technology now exists to enable biocontrollers to move from the research laboratory into commercial and consumer applications. Companies such as BioControl Systems and Bodymedia are creating products that use bioelectric signals as an integral part of a human computer interface. The success of these and other ventures will depend on how well the interface is designed within the ergonomic and usability constraints of the targeted application.

References


