On the Design of HI-based Biofeedback Interfaces

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Abstract— **Humanistic Intelligence (HI) is defined as having two embodying elements. (1) It is a signal processing framework in which the human and the computer use each other as peripherals in a feedback loop. (2) The HI processing apparatus is inextricably intertwined with the natural capabilities of the human mind and body. Biofeedback (or biocybernetic) interfaces made possible through analysis of physiological signals, such as electroencephalograms (EEG), electrocardiograms (ECG), skin conductance (SC), blood pressure (BP) and respiration can provide a means to realize HI. The HI-Comp project builds upon previous work (e.g. the WearComp project) to develop a wearable computer that is physiologically responsive . HI-Comp requires signal analysis research in both offline and online situations to develop appropriate pattern detection algorithms. EEG signal analysis can be performed using Fast Fourier Transform (FFT) for power analysis, and the Hilbert Transform for phase analysis. The first HI-Comp, the HI-Cam, is a wearable personal imaging application of HI that uses FFT power analysis on the EEG signal to control various features of an EyeTap system. The HI-Cam system, therefore, provides biological interfaces that will lead to true extensions of the mind and body.**

I. Introduction

In recent years, there has been a growing interest in the field of wearable computers. Government and business have taken notice with various groups investing heavily into wearable computing research. A number of books and scientific papers have been written on the subject. Because this work has been of great interest in the scientific community there has been an increasing desire to understand the basic directions and design requirements in developing a wearable computer system. To faciliate progress in wearable computer development, a theoretical framework is needed to understand the signal processing challenges faced in this domain.

Humanistic Intelligence (HI) proposes a signal processing framework in which the processing apparatus (such as a wearable computer) is inextricably intertwined with the natural capabilities of our human body and mind, working in synergy with the human user rather than as a separate entity. The goal of this work is to directly assist, rather than replace or emulate human intelligence.

Humanistic Intelligent devices are continuously active devices that work in parallel with the user to integrate the user within a feedback loop of an intelligent control system as seen in Fig 1. In order to integrate the human and computer into the HI framework, a number of requirements must first be satisfied.

The system must be:

- **Unrestrictive** to the user, in the sense that it does not prevent the user from interacting with the real world;
- **Unmonopolizing** of the user's attention;
- **Observable** by the user;
- **Controllable** by the user;
- **Attentive** to the environment (environmentally aware);
- **Communicative** to other systems or people;
- **Personal** in the sense that the human and computer are inextricably intertwined;
- **Constant** (both operationally and interactionally).

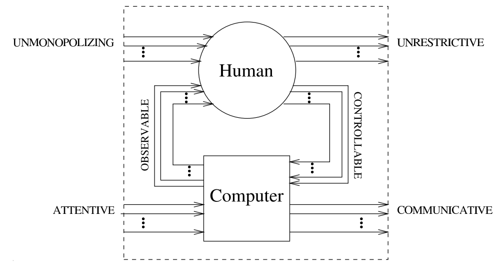

Fig. 1. The six signal flow paths for the new mode of human–computer interaction provided by HI-Cam. These six signal flow paths each define one of the six attributes of the HI-Cam. The observable signal flow path is provided by a head mounted display(HMD), the controllable signal flow path is made possible by a biofeedback measuring device.

The WearComp [1], a prime example of wearable computing, embodies HI's philosophy. It makes use of an EyeTap viewfinder to control the user's mediated reality. The HI model established the inextricable interaction between human and machine in wearable computing. In particular, the "Personal" aspect is the most important of the aforementioned qualities of HI. The synergy that develops between human and computer is completely central to wearable computing. The term "context awareness" is a term that alludes to this idea. Context awareness being the dependence of the machine's operation and performance based upon the user's context. However, in the HI definition of context awareness, it is not limited to the awareness gained by the machine. Instead, context awareness has both a computer and a human perspective and illustrates the symbiotic nature of the system. The efficiency of this dynamic human-machine system depends not only on the machine's awareness of the human's context, but also vice versa. The human is aware of the machine's context, for example during design process or during its operation. Thus, to facilitate and optimize the emerging synergies, both bodies must establish continuous awareness and adapt to one another when necessary.

This integration is illustrated in Fig 1. However, the highest level of integration between human and machine can be acheived through the communication of physiological or bioelectric signals. This accomplishment, however, is no easy task.

The human body consists of a vast complexity of physiological signals operating in parallel, and synchronously to various biological clocks. ECG signals, responsible for regulation of the heart, for example run on regular clocks that can be measured and quantified. Our brain exhibits various EEG signals that run at measurable intervals, chaotic interactions that are difficult but possible to discern. Even our digestive system is controlled by regular electrical signals given off by the brain. Every organ in the body, is regulated in one form or another by bioelectrical signals. Bioelectricity is the primary means of communication in the human body, that control every possible aspect of our lives, from sleeping to eating to moving to breathing. Thus, in many ways, the human body is analogous to the operation and performance of a computer. Whereas a computer uses an electrical clock based on the vibration of a quartz crystal, the body relies on various biochemical or bioelectrical processes as clocks to maintain its operation. This huge analogy between the two systems is what enables us to intertwine them together in a feedback loop, and thus make Humanistic Intelligence a reality.

The HI-Comp project builds upon the wearcomp towards the ultimate realization of HI, whereby the user and computer are interacting on an electrical level. The human's bioelectrical signals are fed to the computer to interpret the state of the user. The computer's electrical signals are sent to the user and outputted in the form of a visual display. This signal processing framework facilitates the basis of new forms of interaction between the two entities.

The goal of the HI-Comp is to use various forms of biofeedback to realize HI. These physiological indicators include electroencephalograms (EEG), electrocardiogram (ECG), respiration, skin conductance (SC), temperature, and blood pressure (BP). Such biological signals processed by the HI-Comp can then be cross-referenced and conveniently displayed on the EyeTap viewfinder. This framework enables the user to achieve effortless control and interaction with the physical or virtual world through their own physiological will.

The first embodiment of a HI-Comp, known as the HI-Cam [2], is a computer that is fully humanistically intelligent and aware of the user's state. This project focused on enabling the apparatus to "learn" what is visually important to the wearer and thereafter function as a fully automatic camera [3], taking pictures without the need for conscious thought or effort from the wearer. With applications such as the HI-Cam, we are moving away from the 'point and click' metaphor, toward the 'look and think' metaphor – toward making this intelligent camera system a true visual memory prosthetic which operates without conscious thought or effort, while at the same time aiding the user's daily function and thus improving the quality of life. One of the most significant challenges of creating a HI-Comp device such as the HI-Cam is the ability of the apparattus to properly interact with the brain. This presents the need to create various analysis techniques for recognizing the signals generated by the neurons in the brain and optimizing the performance of the machine to respond to these signals.

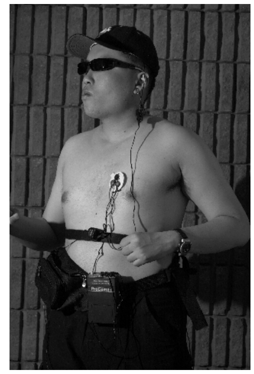

Fig. 2. The wearable HI-Cam as worn by one of the participants jogging outdoors. Sensors are distributed throughout the body to make measurements such as ECG with the patch, and respiration with the belt. The ThinkingCap, contains the EEG sensor that is shielded internally with a copper mesh. Biofeedback is provided through the EyeTap viewfinder(the sunglasses). The ProComp A-D converter on the waist collects all the necessary physiological data for processing by the wearable computer.

In the design of the HI-Cam, the EEG signal showed changes in the brain's electrical fields, and a simple classifier enabled the device to increase and decrease the brightness of the video that was captured by the camera. The classifier was based on the motor related Mu desynchronization [4] of the signal obtained from one electrode that acquired the EEG signal. The fact that we were able to achieve a reliable control level with the use of only one electrode reduced the complexity of the analysis and made the HI-Cam a more practical device that can be comfortably worn.

Research into the HI-Cam, and development of HI-Comp, requires an interdisciplinary approach towards development of devices that are wearable, reliable, and usable. A combination of knowledge from signal processing, physiology (especially neurophysiology) and user interface design become necessary.

A practical application of HI-Cam is seen in Fig 2.

II. The HI-Comp/HI-Cam Apparattus

A. Hardware Description

HI-Comp devices require both the ability to collect and process various forms of physiological data. Usually this data collection is done through some kind of analog-to-digital (A-D) converter, the digitized data is then processed by the wearable computer to make sense of the chaotic information.

For example, the HI-Cam apparatus consisted of the ProComp+ biofeedback device that was connected to the serial port connection of a wearable computer. The ProComp+ performed the acquisition of biological data from the participants, which was then fed into the wearable computer for signal processing and analysis.

The ProComp+ biofeedback device, is essentially an A-D converter that provides a digitized representation from the various physiological signals from the participants' body. There are eight channels on the ProComp+ device two for EEG(accuracy: +5% and +0.3uV, range: 0 - 200 uV, bandwidth: 2-40Hz), two for ECG(accuracy: +5% and +0.3uV, range: 0-1600uV)one for SC(accuracy: +5% and 0.2uS range: 0-30uS), one for BP, and one for respiration. Non-invasive cutaneous Ag/Ag-Cl electrodes provided connection between the channels of the A-D converter and the participants, while a fiber optic cable provided transmission data to the wearable computer.

The processing capability of the HI-Cam is provided by a wearable computer that is capable of wireless Internet connectivity, and can record video or audio. Parallel and serial ports readily provide access to external input and output devices. In the HI-Cam set up, the wearable computer must perform both the signal processing and run the application. These tasks however could be processed separately by two independent processors in the future. The internet capability also enable transmission of vital signs data across a network.

B. Sensor Description

HI-Comps are worn throughout the user's daily life and as such, must be unobtrusive yet able to gather necessary data from the user's body. There are many components that are distributed throughout the user's body to operate a HI-Comp. The HI-Cam, for instance, consisted of many different sensors integrated with the user's clothing, the ThinkingCap is one example.

The ThinkingCap is one component of a typical HI-Comp, a copper mesh shielded hat, provided the protection necessary for the measurement of EEG signals. A network of Ag/Ag-Cl electrodes sewn into the inside of a copper-mesh hat provided a tight-custom fit that allowed sufficient conductivity to obtain reasonable EEG measurements from the surface of the user's scalp.

Various other electrodes and sensors are distributed throughout the body to collect other physiological data. An example, is the SweatShirt, a shirt that integrates various sensors to measure such parameters as sweatiness, respiration, and ECG. Our group currently researches the creation of materials that act as everyday clothing but also sense. These kinds of sensors will not only be conspicuous to others but also will not interfere with the user's daily function.

C. HI Philosophy in Software Design

The philosophy behind Humanistic Intelligence was important to any HI-Comps system's software design. There was a clear need from the very beginning for parallelization since all of the body's biological signals work together as a parallel and synchronized system, the interfacing computerized system must also act in parallel. The advantage of a parallel system is clear, since various threads of execution could perform analysis [5] on specific physiological signals. This means that parallel analysis, and display of physiological signals could be performed in real-time. Parallelism also allowed additional flexibility to the software, since specific modules and functionality could be easily adjusted for the particular brain-computer interfacing task at hand. This approach was important in the software architechture of the HI-Cam program Fig 3 shows a screen shot of the software running on an EyeTap viewfinder that provides visual feedback to the user. The various threads of physiological information are displayed to the user, and can be forwarded to a medical professional for further assessment.

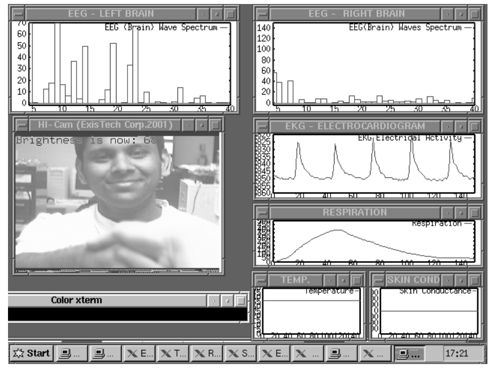

Fig. 3. The HI-Cam software runs in parallel with the body's physiology and provides visual feedback to the user through the EyeTap viewfinder as displayed

III. EEG Signal Analysis

Collaborative research into signal analysis was performed with the Department of Physiology at the University of Toronto. Research performed here, along with results from previous studies, would be used to help an active HI-Comp recognize various neurological states and respond accordingly.

Thus, developing an EEG signal analysis algorithm to recognize changes or patterns in particular parameters, requires three stages: 1. Preliminary Offline Research - to develop an algorithm and identify parameters that correlate well with specific tasks, 2. Preliminary Online verification with a non-wearable computer - to verify and refine the developed algorithm, 3. A Proposed Wearable Design - to ensure the algorithm and apparattus works in situ and would therefore allow for the creation of an intelligent biofeedback system based upon EEG recognition.

A. Preliminary Offline Research

The construction of a pattern detection design relies upon correlating specific EEG patterns with particular motor related tasks. EEG and EMG were read using standard lab equipment, rather than the ProComp+ used in the HI-Cam apparatus. EMG sensors placed on various muscles recorded tasks such as tapping the right index finger. This allowed demarcation of the motor event in correspondence to the changing EEG pattern. Various attributes of the EEG pattern occuring close to the event could then be analyzed, and changes in these signal parameters can then be correlated with a particular physical event. In addition, patterns can be extracted from information obtained over many electrodes or recording sessions.

Advantageously, this method makes no a prioi assumptions as to which region of the brain might be responsible for a particular task. Much of the underlying mechanisms of these activities remain uknown, and we make no attempt to propose a plausible candidate for the detected patterns. Instead, the algorithm's generality allows for application to a wide range users, independent of their dynamic behavior. Furthermore it has been shown [6] that the coordination of brain or motor activity does not depend on a particular region in the brain, but rather large scale integration of several regions.

A.1 Power Analysis

In the HI-Cam, a simple analysis algorithm was employed with the means of detecting for the motor related Mu desyncronization in the brain. Further evidence for this pattern of activity in the brain across subjects comes from event-related desyncronization (ERD) studies where Mu power has been found to decrease before and during movement [2].

Frequency Selection:

The 8-30 Hz bandwidth is to be chosen since these bands are known to be important for movement related classification.

Classification:

The FFT power spectrum is obtained according to the formula:

$G(f) = FFT(g(t))$

Power is given by $P = \frac{G(f)G^*(f)}{n^2}$

where $g(t)$ is the data, and n is the number of data points in the signal.

A discrete sum of the power of the all the frequencies between 8 and 30 Hz can then be obtained. This data would be also be passed through a 3 tap rectangular filter.

A.2 Phase Analysis

The offline program is designed to operate on stored EEG data with the intent of detecting for phase synchrony between any pair of electrodes obtained from arbitrary cranial regions. In this design, the stored data from the EEG cap is passed through a Laplacian operator, whereby the average of the surrounding electrodes is subtracted from the signal obtained from a particular electrode. This increases spatial resolution of the acquired signal. The data from all channels is then passed through a bandpass filter. Our analysis focuses on three ranges of frequency, namely 8-12Hz, 18-22Hz and 38-42Hz, which are of known interest.

The intent of this approach is to detect phase synchronization of the recorded waveforms both on a local and large scale basis. To characterize this phenomenon an analytic signal approach based on the Hilbert transform was used:

$$\psi(t) = s(t) + j\bar{s}(t) = A(t)e^{j\phi(t)}$$

where $\bar{s}(t)$ is the Hilbert Transform of $s(t)$, $A(t)$ is the instantaneous amplitude and $\phi(t)$ is the instantaneous phase.

$$\bar{s}(t) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{s(\tau)}{t-\tau}d\tau$$

where the integral is taken in the sense of the Cauchy Principle Value

Other means of finding the signal's instantaneous phase in relation to EEG are also discussed and examined in literature [7]. An advantage of using phase with regards to brain signals is that we can separate phase from magnitude as an isolated measurement which contains particularly temporal information of the brain. Furthermore, recently it has been shown that the phase synchronization of gamma-band EEG oscillation (occuring around 40Hz) is a general mechanism of transiently connecting neural assemblies [9]. Since distinct processes within the hippocampus and rhinal cortex in humans, support declarative memory formation, an approach which incorporates phase analysis also presents potential use in the HI-Cam system to create memory driven features.

Where synchronization describes the exhibition of functional relationships between two processes or signals due to interaction [8], an example is phase locking. The condition for phase locking is defined by:

$$|n\phi_1(t) - m\phi_2(t)| < constant$$

where n, m and ϕ are based on the analytic signal formula. Usually, in the offline analysis, 34 electrode channels spaced across the scalp obtain data that are compared using the aforementioned phase analysis method. The offline pattern detector program looks for the phase locking condition between each electrode channel combination lasting for at least 200 ms. The program then inspects the phase locking condition and records its onset. The onset of the phase locking is compared to the event occurence as detected by the EMG. If the detected onset falls to within a particular window of time before and after the event a correct detection is marked otherwise a false is marked. The correct and false detection percentages are saved. These files are ranked according to the degree of phase locking. Once saved, they can be kept for later online detection of EEG patterns.

B. Preliminary Online Research

The online program design directly utilizes the results from the offline program on a non-wearable computer system. Here phase analysis is performed in a similar manner to that of the offline program. The top five channel combinations are to be chosen in the online program, and they are to be continuously scanned for the expected phase locking. If a phase locking condition is detected, the program indicates to the subject that an event, such as tapping the finger, was detected. This serves as a feedback loop which over time can improve the control of the user and simulates conditions in the HI-Cam system.

C. Proposed Wearable Design

After a viable algorithm has been found through preliminary online and offline research a proposed wearable design is created. This proposed design begins with Human-Machine integration followed by a controlled simulation.

C.1 Human-Machine Integration Method

Integration of the human-machine system required adapting the machine and human to one another. In the successful HI-Cam design an EEG electrode was sewn comfortably into the copper mesh isolated "ThinkingCap". The use of conductive paste, ensured a reasonable signal from the electrode which was applied to the vertex of the scalp. This location was chosen since the largest amplitude EEG activity can be picked up at the vertex due to the sinus of cerebral spinal fluid (CSF) lying between the two hemispheres. ECG electrodes were connected to the mid-clavicular line in the 5th intercostal space of the participants, in close proximity to the heart. Meanwhile, the EEG signal, ECG signal, respiration and temperature is plotted in real-time to create a profile of the human user. This design integrates human user and machine by providing a display feedback to the user, and physiological biofeedback to the computer.

C.2 Controlled Simulation

A controlled simulation is necessary to verify HI-Comp functionality system in situ, after the wearable design is finished. User control could be realized, as in the HI-Cam, by altering the average FFT coefficient power for the 8 - 30 Hz bandwidth making use of motor related Mu desynchronization. This method allows for 3 degrees of freedom in controlling the brightness of the screen. To increase brightness, a user could close the eyes and relax. This would raise the displayed average power value above a threshold, at which time the brightness would increase. To decrease the brightness, the displayed average value would go below a threshold, by focusing on 3 dimensional random hand movements. To maintain the brightness the user's eyes would stay open and through observation of the displayed biofeedback signals, the average FFT coefficient power was sustained between the lower and upper thresholds. Similarly, a controlled simulation taking advantage of phase analysis could be performed to verify the success of the system's pattern detection algorithm. In any case, this controlled simulation lays the groundwork for user studies.

IV. Future HI-Comp Directions and Applications

Brainwaves are perhaps the next most natural step for input in a wearable computer system. Present day input devices on wearable computer systems are often cumbersome and difficult to use. EEG however is an adjustable input signal to a wearable computer that requires little training, and is simple to use.

So far, our group's research was focused mainly on the EEG signal and some work on ECG. HI-Comp's next step however will be to incorporate a higher level of intelligent processing by integrating even more information into the HI-Comp framework. The many channels of physiological information available to the wearable computer enables detailed user profiles to be constructed. Various strategies of analysis can correlate the several physiological signals in parallel, and consequently provide user state information that is richer and more accurate.

Analysis performed on the signal can be used to diagnose situations where the user's health is at risk. As a medical device, the HI-Comp offers immediate preliminary diagonosis capability. This valuable information could be analyzed by the on board wearable system for diagonosis or analysis, but could also sent to experts. In medical emergencies, valuable time can be saved because experts (such as medical specialists) can receive diagonostic information as soon as possible and react accordingly, saving precious time. Consequently, the HI-Comp does not only faciliate integration into a human-computer framework, but also weaves the human into the tapestry of a larger network.

A system oriented design approach involving cross-disciplinary knowledge is necessary. Humanistic Intelligence requires understanding many issues relating to human-machine interfaces, physiology, and signal processing to achieve results. The HI-Cam project is a first endeavour into developing a system that truly integrates the computer with the human, so that the computer acts as an organ. The non-invasive, wearable, and convenient characteristics of such a HI-Comp makes it practical for it to act as a natural extension of the human body and mind.

V. Acknowledgements

The authors would like thank Thought Technologies support. We would also like to thank Dr. Mackay for his indispensable neurophysiology expertise, also James Fung and Corey Manders for their assistance.

References

[1] S. Mann *Humanistic Intelligence: WearComp as a New Framework and Application For Intelligent Signal Processing* Proceed. of IEEE Vol. 86, No.1.11, Nov. 1998, pp. 2123-2151

[2] S. Mann, D. Chen, and S. Sadeghi *HI-Cam: Intelligent Biofeedback Processing* 5th International Symposium on Wearable Computing, October 2001.

[3] Steve Mann, "Wearable computing: A first step toward personal imaging," *IEEE Computer*, vol. 30, no. 2, Feb 1997, http://hi.eecg.toronto.edu/ieeecomputer/index.html.

[4] H. Ramoser, J. Muller-Gerking and G.Pfurtscheller, *Optimal Spatial Filtering of Single Trial EEG During Imagined Hand Movement* IEEE Trans. Rehab. Eng., vol. 8, pp. 441-446, Dec, 2000. newblock 1999.

[5] D. E. Rumelhart and Eds. J. L. McMlelland, *Parallel distributed processing*, MIT Press, Cambridge, MA, 1986.

[6] F. Varela, J.P. Lachaux, E. Rodriguez and J. Martinerie *The Brainweb: Phase Synchronization and Large-Scale Integration* Nature Reviews: Neuroscience, vol.2, pp. 229-239 April 2001.

[7] J.P. Lachaux, E. Rodriguez, J. Martinerie and F.J. Varela *Measuring Phase Synchrony in Brain Signals* Human Brain Mapping, vol.8, pp. 194-208 1999.

[8] M.G. Rosenblum, A.S. Pikovsky and J. Kurths *Phase Synchronization of Chaotic Oscillators* The American Physical Society, vol.76, pp. 1804 March 11, 1996.

[9] J. Fell, P. Klaver, K. Lehnertz, T. Grunwald, C. Schaller, C.E. Elger, and G. Fernandez *Human memory formation is accompanied by rhinal-hippocampal coupling and decoupling* Nature Neuroscience, vol. 4, no. 12, pp. 1259 - 1264 December 2001