Wireless Physiological Monitoring and Ocular Tracking: 3D Calibration in a Fully-Immersive Virtual Health Care Environment

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Abstract— **Wireless physiological/neurological monitoring in virtual reality (VR) offers a unique opportunity for unobtrusively quantifying human responses to precisely controlled and readily modulated VR representations of health care environments. Here we present such a wireless, light-weight head-mounted system for measuring electrooculogram (EOG) and electroencephalogram (EEG) activity in human subjects interacting with and navigating in the Calit2 StarCAVE, a five-sided immersive 3-D visualization VR environment. The system can be easily expanded to include other measurements, such as cardiac activity and galvanic skin responses. We demonstrate the capacity of the system to track focus of gaze in 3-D and report a novel calibration procedure for estimating eye movements from responses to the presentation of a set of dynamic visual cues in the StarCAVE. We discuss cyber and clinical applications that include a 3-D cursor for visual navigation in VR interactive environments, and the monitoring of neurological and ocular dysfunction in vision/attention disorders.**

I. Introduction

The complexity of modern health care introduces many confounding elements that may be associated with medical error and health care acquired harm [1], [2]. Although today's clinicians have a multitude of electronic devices designed to promote safe medication practices, little has been done to determine which visual stimuli distract clinicians during performance, or to design effective visual cues to reduce error. Indeed, it is the multiplicity of equipment itself that can lead to delay or distraction when attempting to provide care [3], [4]. A key obstacle to determining the object of attention, or inattention, is the lack of tracking devices able to compute focus of gaze in space and time.

Here we report on the development of a unique human-machine interface that both records and responds to physiological and behavioral measures of subjects or patients immersed in virtual reality simulations of health care scenarios. The system is embedded in the StarCAVE, a fully immersive 3-D visualization virtual reality (VR) environment in the California Institute of Telecommunications and Information Technology (CalIT^2) [5]. CAVE-CAD, computer aided design software developed by our interdisciplinary team for use within the StarCAVE, maps user responses in 3-D space plus time. A real-time 'bio-cursor' uses electrooculography (EOG) synchronized with VR head tracking to reveal attention to specific elements in the virtual environment. The bio-cursor is programmed to detect focus of gaze, and is further capable of detecting muscle and neural responses from electromyogenic (EMG) and electroenphalographic (EEG) biopotentials. The system provides real-time feedback of each eye's location, providing a means to indicate the object of focus within models projected in the StarCAVE. The bio-cursor's ocular coordinate signals can be harnessed to enable hands-free control of the VR display, react to simulations, and to drive the interactive CAVE-CAD modeling software that allows clinicians and architects to assay the function of health care environments during the design process. Ultimately, we envision that the wireless bio-tracker will be used to assay visual attention during real clinical procedures, in real health care environments.

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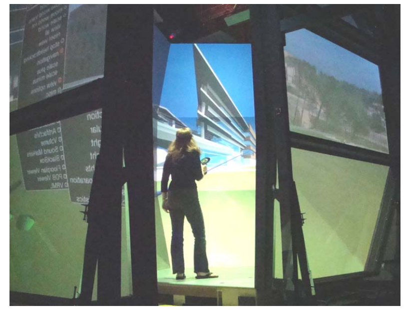

Fig. 1. CalIT2 StarCAVE immersive visualization virtual reality environment [6] for controlled human experiments in interactive health care and architecture [5].

II. Immersive 3-D Visualization and Virtual Health Care

A. StarCAVE

The StarCAVE at CalIT^2, a five-sided virtual reality room with stereo projections on 360-degree screens surrounding the viewer [6], provides a central resource to this project and serves as an immersive visualization virtual environment for controlled experiments in interactive health care [5]. The StarCAVE offers 3-D stereo, 20/40 vision in a fully horizontally enclosed space with a diameter of 3 m and height of 3.5 m. A combined resolution of over 68 million pixels–34 million per eye, distributed over 15 rear-projected walls and two floor screens. Each of the five sides of the room has three stacked screen tiles, with the bottom and top screens titled inward by 15 degrees to increase the immersive experience, while reducing stereo ghosting. Each screen tile is served by a polarized pair of projectors, powered by a high-end, quad-core PC running on Linux, with dual nVIDIA graphics processing units (GPUs) to generate highly complex stereo images, and with dual network cards to achieve gigabit Ethernet/10GigE networking.

The StarCAVE environment is fully immersive, and interacts with the subject through a 3-D joystick as well as a head tracking sensor system. The head tracking system installed on a hat worn by the subject registers the subject's location and orientation in space and projects 3-D visual fields accordingly. Both the joystick and the head tracking system use four infra-red cameras that detect infra-red reflective balls to map position and orientation. The actual 3-D position for the viewer's head as well as the joystick are calculated and logged over time so that the viewer position and interactions are dynamically tracked in the virtual setting.

B. CAVE-CAD

A major advantage of the StarCAVE VR environment for fully immersive virtual health care is the capability to dynamically alter the environment while logging subject responses in the design of controlled experiments. Our team has developed novel interactive computer-aided design software (CAVE-CAD) that enables experimenters to change the visual configuration of scenarios while they are immersed in the StarCAVE. This approach eliminates the traditional step of creating a 3-D model at a desktop computer, before bringing it into a virtual environment, thus allowing for much shorter turnaround times when changes to the model are to be made and immediately visualized in VR. The user is immersed in the CAD "drawing" in full-scale, and has the ability to directly interact in 3D with the geometry and immediately respond to changing geometries, materials and lighting. An example of a user navigating in virtual space in the StarCAVE emulating an architectural environment is depicted in Fig. 1.

The immersive and interactive capabilities of the StarCAVE VR environment are further augmented with simultaneous physiological and neurological monitoring of the subject responses to enable a new class of controlled experiments in virtual health care.

III. Physiological and Neurological Monitoring

We have developed and tested a customized non-contact biopotential sensing and logging device that can detect and collect EEG, EMG, EOG, and ECG (electrocardiogram) signals from the body and transmit the digitized waveforms over a Bluetooth wireless link [9]. The unobtrusive sensor operates without conductive contact to the skin, and can be mounted over hair or over clothing without conductive gel or other skin preparation. Other versions of the sensor make use of dry-contact sensors [7] as well as conductive fabric to integrate sensing into apparel worn by the user. These advances contribute to the mobility and simplicity of the subject experience during continuous brain and ocular activity monitoring in the StarCAVE VR environment. The EEG/EOG system directly interfaces with the StarCAVE computing platform through a Bluetooth communication link.

A. Wireless Integrated Biopotential Sensors

The recording system consists of a chain of active electrodes connected along a single common wire. While the system is designed to operate with non-contact electrodes for EEG and ECG use [8], [9] as shown in Fig. 2, it also operates with dry-contact [7] or standard gel-based wet-contact electrodes, and for other signal modalities such as EOG and EMG. The sensors can be either in direct contact with the skin or embedded within fabric and clothing. A small base unit powers the entire system and contains a wireless transmitter to send data to a computer or other external device. Near the base unit, a single adhesive or dry contact sensor placed anywhere convenient is used to establish the ground reference for the system.

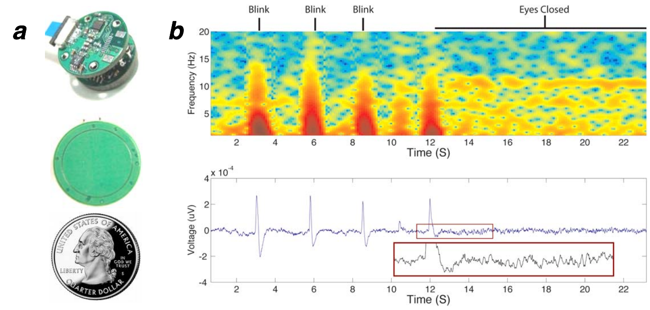

Fig. 2. Non-contact EEG/ECG biopotential recording [9]. (a) Integrated biopotential acquisition, filtering and decimation unit operating at 600μW power. (b) EEG alpha wave and eye blink activity, recorded from the occipital lobe over haired skull.

Fig. 3. Bio-cursor head-mask with six EOG electrodes.

B. Wireless EOG 3-D Eye Tracking Bio-Cursor

Although EOG signals have found widespread use in biomedicine for monitoring of ocular and vestibular eye movement disorders as well as identifying of REM activity during sleep staging, only recently EOG has revealed a consistent measure of eye gaze direction for tracking direction of gaze in human-computer interfaces [10]. Here we report the first use of EOG for tracking focus of gaze in 3-D, as a 'bio-cursor' user interface embedded in the StarCAVE VR environment.

We have adapted the wireless integrated biopotential array for EOG use in the prototype 3-D eye tracking bio-cursor. The system uses DC-coupled gel-based wet-contact active electrodes rather than intrinsically AC-coupled capacitive non-contact sensors [8], [9] to capture low-frequency components in the EOG signal that are required for continuous eye tracking.

The EOG head-mask is depicted in Figure 3. Six electrodes are positioned on the facial skin symmetrically around both eyes, to record both horizontal and vertical differential components in the EOG signal. These EOG signals relay the dipole moments of both eyeballs and are sufficient to register azimuth, elevation, and vergence of gaze through calibration as outlined in Section IV.

Software embedded in the CAVE-CAD environment simultaneously logs stimulus, head position and EOG/EEG analog data converted at a rate of 400 samples/s to 2 byte-digits, sent via Bluetooth to a Linux system. The system is designed to record and log the EOG/EEG signals synchronously with the user's position and interactions in the virtual world, cueing analysis based on physiological/neurological events of interest and virtual stimuli of interest.

A calibration procedure to quantify and optimize the capacity of the EOG system to identify focus of gaze in the 3-D VR field of view is presented next.

IV. Calibration of 3-D Ocular Movements

The EOG bio-cursor serves to dynamically track in 3-D the visual focus of the subject interacting with the VR health care environment. It is therefore critical to the performance of the system to calibrate the mapping from EOG signals to a reliable and reproducible estimate of 3-D ocular focus in the VR field of view. Since currently existing eye tracking systems are limited to 2-D for use with standard flat displays, we developed a novel calibration method to perform the mapping.

The calibration procedure correlates eye position with EOG within the 3-D field of view, linked to the viewer's head location, in the StarCAVE. A dynamic calibration stimulus is presented in the form of a yellow ball moving through virtual 3-D space. The position of the ball is modulated by three independent periodic wave functions, which each independently scan the space uniformly in the azimuth, elevation, and vergence dimensions. This modulation of the ball position in 3-D virtual space relative to the head coordinates of the subject guarantees a uniform spread in coverage of the angular deflections of the eye ball tracking stimulus across the field of view.

A. EOG Model of Ocular Angular Deflection

Differentials between horizontally positioned EOG electrodes measure horizontal ocular deflection (azimuth), and differentials between vertically positioned EOG electrodes measure vertical ocular deflection (elevation) [10]. Furthermore, a simple geometric model accounting for the EOG signals in response to 3-D focus of gaze in stereo vision shows that vergence in stereo vision can be obtained by differencing the azimuth estimates of both eyes. The geometry of the model is illustrated in Figure 4 (a), and yields approximate expressions for the spherical coordinates (r, θ, ϕ) of the visual target (focus of gaze) in terms of the azimuthal and elevation angular deflections (θ_l, ϕ_l) and (θ_r, ϕ_r) of the left and right eyeballs, in the limit where the distance r (or 'vergence' between the target and the center of the eyes is significantly larger than the distance d between the eyes:

$$\begin{aligned} \theta &\approx \frac{\theta_l + \theta_r}{2} \\ \phi &\approx \frac{\phi_l + \phi_r}{2} \\ r &\approx \frac{d\,\cos\theta}{\cos\phi\,(\theta_l - \theta_r)} \end{aligned} \tag{1}$$

These expressions show that while the azimuth θ and elevation ϕ of the focus of gaze directly correspond to the average azimuth and elevation of the ocular angular deflections, the vergence is inversely proportional to the difference between the two ocular azimuth angles $\theta_l - \theta_r$. The challenge in accurately estimating vergence is to resolve small azimuth differences in already small differential EOG signals.

For small angular deflections θ and ϕ, the EOG electrode voltages V_i $(i = 1, \ldots 6)$ are approximately linear in θ and ϕ, and furthermore $\cos(\theta) \approx 1$ and $\cos(\phi) \approx 1$ in (1) so that an approximate linear relationship can be assumed between the vergence coordinates and EOG electrode voltages:

$$\begin{pmatrix} \theta \\ \phi \\ \frac{d}{r} \end{pmatrix} = W \begin{pmatrix} V_1 \\ \vdots \\ V_6 \end{pmatrix} \tag{2}$$

where W is a matrix of parameters that depend on the geometry of EOG sensor placements relative to the ocular frame of reference, and where constant DC offsets have been subtracted out. Note the inverse dependence on vergence r in the variable d/r for linearity and the scaling by the inter-ocular spacing d for a dimensionless representation. The linear relationship (2) is the basis of the calibration procedure.

B. Calibration Stimulus

Rather than computing W from the geometry, we calibrate the parameters in W from measurements by regressing the model (2) under a known calibration visual stimulus. For effective calibration under noisy EOG measurement conditions, it is important to choose a calibration visual stimulus that most uniformly excites the dynamic range of the variables under regression. We chose a triple-harmonic stimulus

$$\begin{aligned} \theta &= A_1\,\cos(\omega_1 t) \\ \phi &= A_2\,\cos(\omega_2 t) \\ \frac{d}{r} &= A_3\,\cos(\omega_3 t) \end{aligned} \tag{3}$$

with angular frequencies ω_1, ω_2 and ω_3 randomly in the [0.8 Hz, 1.2 Hz] interval, and suitably small amplitudes A_1, A_2 and A_3. The length of the calibration interval is chosen much larger than $1/\min_{i \neq j} |\omega_i - \omega_j|$, and is 200 seconds in this pilot study.

V. Results

The above calibration procedure was performed off-line on time-stamped EOG data recorded simultaneously with the sequence of the dynamic calibration stimulus presented to the subject in StarCAVE. A screenshot of the graphical user interface for EOG data collection, integrated in the CAVE-CAD software environment, is shown in 4 (b). The grid (green dots) super-imposed on the calibration stimulus (yellow ball) serves as a reference for head fixation throughout the data collection. Multiple sessions, each with 200 seconds of continuous 6-channel EOG data, and with various tri-harmonic calibration stimuli (3), were collected on a male subject.

Results of the calibration on a 100 second fragment of the measured EOG data are given in Figure 4 (c), showing the calibrated azimuth θ_y and elevation ϕ_y reconstructed from the EOG data, relative to the ground truth azimuth θ_s and elevation ϕ_s estimated from the calibration visual stimulus. No effort was made to eliminate signal artifacts in the data, which are clearly visible, such as eye blinks and involuntary saccades during the recording, as well as sources of impulse noise in the EOG measurement. Evaluation of the standard

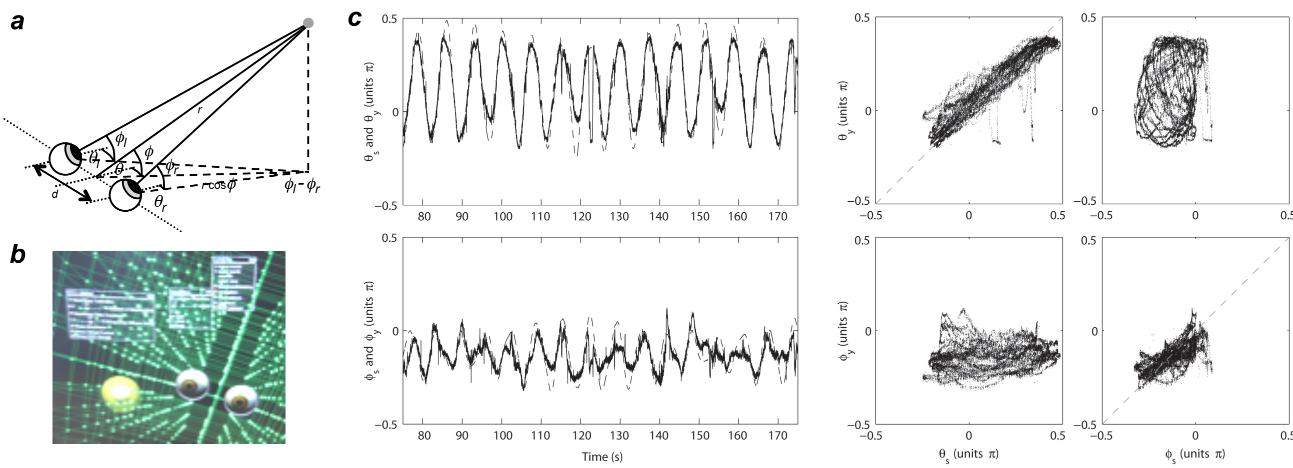

Fig. 4. 3-D Eye tracking 'bio-cursor'. (a) Ocular angular deflection geometry. (b) Graphical user interface for calibration visual stimulus. The virtual eyes are aligned with the subject's eyes during the calibration procedure. (c) Calibrated azimuth θ_y and elevation ϕ_y ocular angular deflections reconstructed from measured 6-channel EOG, versus ground truth azimuth θ_s and elevation ϕ_s estimated from the tri-harmonic calibration visual stimulus.

error in reconstructed and ground truth angles with this data yields an estimate of absolute, integral integral resolution of 13.9° rms over 132.4° range in azimuth, and 12.6° rms over 75.1° range in elevation.

This integral estimate assumes ocular tracking over 100 seconds of smooth visual pursuit. Future extensions of the EOG bio-cursor technology may perform calibration continuously in the background to dynamically correct for drift and low-frequency noise in the EOG signal. Such dynamic corrections are possible since the subject is capable of providing feedback on cursor drift through directed saccades. An estimate of error in ocular tracking during such saccades can be obtained from the above continuous data by evaluating relative standard error over much shorter time intervals. For blocks of EOG data spanning 0.2 seconds, evaluation of differential standard error yields an estimate of differential resolution of 3.2° rms over 21.1° average excursion in azimuth, and 2.3° rms over 12.3° average excursion in elevation. According to the model (1) with $d = 8$ cm and $\cos(\theta) = \cos(\phi) = 1$, this azimuth resolution supports a worst-case frontal vergence resolution of 0.3 m at 0.5 m distance.

VI. Conclusion

We presented and reported first results on a system for physiological/neurological monitoring and ocular tracking of a subject freely interacting in a 3-D virtual health care environment. The unique feature of the technology is that it enables tracking of 3-D focus of gaze in a fully immersive VR environment, using wirelessly recorded EOG signals.

We envision multiple applications and opportunities in e-Health and remote care. The wireless monitoring systems deployed in the controlled laboratory of the StarCAVE may be applied to test healthcare outcomes in emulated medical environments, to yield answers to clinical questions such as where a surgeon looks for information in the midst of an operation, what attracts the attention of care-givers attending in urgent situations, or which conditions are correlated with a healing environment.

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