Biosensor Technologies for Augmented Brain–Computer Interfaces in the Next Decades

This paper focuses on recent and projected advances of a wide range of sensor and acquisition neurotechnologies enabling online brain–signal processing in everyday, real-life environments, and highlights current and future approaches to address the challenges in this field.

By Lun-De Liao, *Member IEEE*, Chin-Teng Lin, *Fellow IEEE*,
Kaleb McDowell, *Senior Member IEEE*, Alma E. Wickenden, *Member IEEE*,
Klaus Gramann, Tzyy-Ping Jung, *Senior Member IEEE*, Li-Wei Ko, *Member IEEE*, and
Jyh-Yeong Chang, *Member IEEE*

ABSTRACT | The study of brain–computer interfaces (BCIs) has undergone 30 years of intense development and has grown into a rich and diverse field. BCIs are technologies that enable direct communication between the human brain and external devices. Conventionally, wet electrodes have been employed to obtain unprecedented sensitivity to high-temporal-resolution brain activity; recently, the growing availability of various sensors that can be used to detect high-quality brain signals in a wide range of clinical and everyday environments is being exploited. This development of biosensing neurotechnologies and the desire to implement them in real-world applications have led to the opportunity to develop augmented BCIs (ABCIs) in the upcoming decades. An ABCI is similar to a BCI in that it relies on biosensors that record signals from the brain in everyday environments; the signals are then processed in real time to monitor the behavior of the human. To use an ABCI as a mobile brain imaging technique for everyday, real-life applications, the sensors and the corresponding device must be lightweight and the equipment response time must be short. This study presents an overview of the wide range of biosensor approaches currently being applied to ABCIs, from their use in the laboratory to their application in clinical and everyday use. The basic principles of each technique are described along with examples of current applications of cutting-edge neuroscience research. In summary, we show that ABCI techniques continue to grow and evolve, incorporating new technologies and advances to address ever more complex and important neuroscience issues, with advancements that are envisioned to lead to a wide range of real-life applications.

KEYWORDS | Augmented brain–computer interface (ABCI); biosensor; cognitive-state monitoring; electroencephalogram (EEG); human brain imaging

L.-D. Liao is with the Department of Electrical Engineering, National Chiao Tung University, Hsinchu, Taiwan and also with the Brain Research Center, National Chiao Tung University, Hsinchu 300, Taiwan.
C.-T. Lin is with the Department of Electrical Engineering, National Chiao Tung University, Hsinchu, Taiwan, the Brain Research Center, National Chiao Tung University, Hsinchu, Taiwan, and the CS/EE Departments, National Chiao Tung University, Hsinchu 300, Taiwan (e-mail: ctlin@mail.nctu.edu.tw).
K. McDowell is with the Translational Neuroscience Branch, Army Research Laboratory, Aberdeen Proving Ground, MD 21005 USA.
A. E. Wickenden is with the Sensors & Electron Devices Directorate, Army Research Laboratory, Adelphi, MD 20783 USA.
K. Gramann and **T.-P. Jung** are with the Swartz Center for Computational Neuroscience, Institute for Neural Computation, University of California at San Diego, La Jolla, CA 92093 USA.
L.-W. Ko is with the Brain Research Center, National Chiao Tung University, Hsinchu, Taiwan and also with Department of Biological Science and Technology, National Chiao Tung University, Hsinchu 300, Taiwan.
J.-Y. Chang is with the Department of Electrical Engineering, National Chiao Tung University, Hsinchu 300, Taiwan.

I. INTRODUCTION

As the proliferation of technology dramatically infiltrates all aspects of social life, the development of strategies and techniques to enhance human–computer interfaces is becoming increasingly important. Recent developments in neurotechnologies are addressing these issues through novel concepts that directly link brain activity to computers. Major forerunners in this area are brain–computer interfaces (BCIs), which are based on a direct communication pathway between the human brain and an external device and have been primarily applied in laboratory and clinical settings. As biosensing technologies continue to progress in the upcoming decades, the ability to image brain activity will move away from traditional BCI settings and into everyday environments. Such capabilities will enable the development of potentially revolutionary approaches that will alter the nature of how people interact with technology in their everyday environments through novel augmented BCIs (ABCIs), which are BCIs that can be used by individuals for everyday use.

Several existing imaging technologies are currently used to sense brain activity for both basic research and clinical applications, including functional magnetic resonance imaging (fMRI) [1], positron emission tomography (PET) [2], electroencephalograms (EEGs) and optical brain imaging techniques (i.e., near-infrared spectroscopy (NIRS) [3], laser speckle imaging [4], and functional photo-acoustic imaging (fPAM) [5], [6]). fMRI offers multiparametric and noninvasive measurements of blood oxygenation [7], blood flow [8], and oxygen metabolism, making this approach especially useful in imaging the brain, muscles, the heart, and cancers as compared with other medical imaging techniques, such as computed tomography (CT) or X-rays [1], [9]. The PET imaging technique is most useful in combination with anatomical imaging methods, such as CT. Modern PET scanners are now available with integrated high-end multidetector-row CT scanners, which can perform sequential scans during the same session [2]. These imaging techniques are powerful tools for human brain imaging; however, the machines used for these techniques are bulky and thus difficult to use for measuring human brain activity in real-life applications [3]. In contrast, the machines used for optical brain-imaging techniques are relatively smaller and are capable of assessing hemodynamic changes associated with brain activity [5], [6]; however, the reconstructed images from NIR suffer from poor spatial resolution due to the diffusive nature of light in biological tissue [10]–[12]. A magnetic or optically based system for measuring brain activity in everyday applications remains to be discovered.

Of all the current imaging modalities, EEG offers the most near-term potential for applications in everyday environments. EEG is a powerful technique that can provide high temporal resolution to directly reflect the dynamics of brain activity [13], [14] and has been widely used for both medical diagnoses and neurobiological research [15]–[19]. EEG-based BCI techniques acquire, process, and then translate signals from brain activity into machine codes or commands to provide a direct communication pathway between the brain and the external world [18], [20], [21]. The acquisition of brain activity by EEG-based BCIs can be divided into two categories [21]: invasive [22], [23] and noninvasive [24], [25]. Invasive BCIs use sensors inside the human/animal brain to obtain high-quality brain-activity signals or to send external signals into the brain [22]. Invasive systems provide a reliable manner for connecting neurons and devices based on appropriate surgical techniques; however, the relative increase in signal quality as compared with scalp-based sensors has been disputed [26]. Furthermore, for everyday applications in healthy populations, any potential benefit based on increased signal quality must be balanced against the potential risks associated with both the surgery and the long-term implantation of these devices.

Noninvasive EEG-based BCIs, which measure the electrical activity of the brain using electrodes placed along the scalp skin, have been shown to provide a feasible method for communication of the human brain with external devices [27]–[29]. As compared with other mobile imaging approaches, the usability and strong reliability of these noninvasive devices, which are worn on the outside of the head and are removable, have made the use of EEG signals the most common approach for BCIs [30]. In recent years, EEG sensors and sensing circuit designs have enabled the integration of sensors into portable multimodal acquisition devices to measure a wide variety of physiological signals. Conventional wet Ag/AgCl electrodes are most frequently used to measure EEG signals [19]. The characteristics of conventional wet electrodes, including their applications [31], have been widely studied and discussed in detail. With proper skin preparation and the use of conductive gels, the quality of the EEG signal measured by wet electrodes is excellent. However, the use of wet electrodes, which require an extended setup and preparation time and are based on an electrolyte being applied to the user's hair, greatly limit the applicability of BCIs for everyday use. Recent efforts in sensing technologies have shown progress in the development of dry sensors that have the potential to dramatically improve system usability [32]–[34]. This progress coupled with advancements in signal processing techniques is enabling mobile brain imaging and novel BCI concepts that will influence many aspects of everyday life and a broad population of users. At the current pace of research, the development of new EEG-based ABCI devices with novel, highly usable, comfortable, robust and noninvasive sensors for everyday applications is expected in the upcoming decades.

In this paper, we review a variety of biosensing techniques and ABCI approaches that are based on the associated devices. The basic principles of each technique are summarized, and examples of their use in cognitive

applications are also provided. Makeig *et al.* [35] and Lance *et al.* [36] have conducted a thorough review of the advances in signal processing and ABCI applications. Developments in biosensors for ABCI applications are described in Section II. Section III discusses the recent development of a noninvasive biosensing device for human brain imaging and an advanced device for mobile brain imaging in everyday applications. Finally, in Section IV, we briefly discuss the expected trends for ABCI applications in the upcoming decades.

II. THE DEVELOPMENT OF BIOSENSING TECHNIQUES FOR ABCI APPLICATIONS

A. Wet Sensors

Conventional wet electrodes are the most frequently used sensors for measuring EEG signals. Many types of wet electrodes are available, and their individual characteristics and clinical applications have been widely studied and discussed in detail [31], [37], [38]. The various types include the following: 1) disposable electrodes (pre-gelled types); 2) reusable disc electrodes (gold, silver, stainless steel or tin); 3) saline-based electrodes; and 4) needle electrodes. For noninvasive multichannel measurements, electrode caps are preferred, which are placed on the surface of the user's scalp. The most common wet electrodes are coated with Ag–AgCl and have a diameter of 1 to 3 mm with long, flexible leads that can be easily plugged into the readout circuit device. Ag–AgCl electrodes can accurately record small potential changes over relatively short durations [39]. In contrast, needle electrodes are preferred for long recordings and are invasively inserted under the scalp.

The development of effective and comfortable EEG sensors for everyday use requires the consideration of several factors, including 1) the ability to acquire high-quality signals from a wide range of individuals with different head shapes and sizes, hair types and lengths, and scalp properties (e.g., scalp toughening due to ultraviolet light exposure of balding areas or different chemical or soap residues associated with hygiene practices); 2) long-duration inter-application sensor stability, sensor attachment, and user comfort issues; 3) the effects of long-term use (multiple acquisitions) on sensor stability/durability and the head/scalp; and 4) other practical considerations such as simplicity of application and cost. Additionally, the type and design of the electrode can have a significant impact on artifact signals (see [37] for a discussion on the developments in signal processing and machine-learning algorithms).

Novel Wet Approaches: Recently, Alba *et al.* explored the benefits of a cross-linked polyacrylate gel at the electrode/skin interface. As a superabsorbent hydrogel, polyacrylate can absorb an electrolyte solution and swell to a degree far beyond typical contemporary electrode materials, provid-
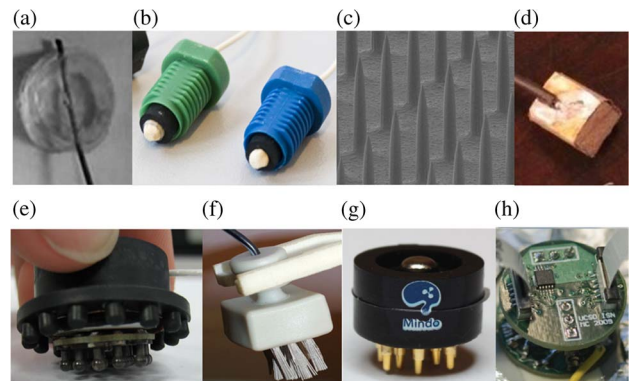
Fig. 1. *Several types of EEG sensors: (a) wet sensors; (b) water-based EEG sensors proposed by Volosyak et al. [42]; (c)–(g) dry EEG sensors developed by Yu et al. [46], Liao et al. [34], Matthews et al. [54], Grozea et al. [56], and Liao et al. [33]; and (h) noncontact EEG sensors.*

ing a strong hydrating effect to the skin surface [40]. This hydrating power allows the material to increase the effective skin contact surface area through wetting and noninvasively decreasing or bypassing the highly resistive barrier of the stratum corneum. Cross-linked sodium polyacrylate gel was synthesized using a method proposed by Sohn *et al.* [41]. The dimension of the polyacrylate gel electrode is illustrated in Fig. 1(a). The development of water-based sensors for EEG-based BCI applications was studied by Volosyak *et al.* [42] [see Fig. 1(b)]. This group has shown that water-based sensors can measure EEG activity using tap water as the interface to the scalp. However, movement artifacts, primarily influenced by the shape of the electrode, remain one of the major problems with such electrodes. This group has also concluded that optimal designs of the electrode and the electrode materials for maintaining low impedance still require future improvement.

B. Dry Biosensors

With proper skin preparation and the use of conductive gels, the EEG signal quality from wet sensors is excellent [19]. However, the skin preparation processes used to reduce the skin-electrode contact interface impedance can be time-consuming and uncomfortable for the user [43], making them impractical for everyday use. Furthermore, as the EEG signal quality may degrade over time as the skin regenerates and/or the conductive gel dries [43], these electrodes require repeated skin preparations and gel applications, which may also cause allergic reactions or infections. Issues also arise when measuring a location of interest that is covered with hair, which can lead to insufficient skin-electrode contact area, especially for long-term applications.

To overcome these problems, dry-contact- and noncontact-type EEG sensors have been developed to improve EEG measurements [31], [44]–[46]. Dry contact sensors

can be separated into the following types: 1) dry micro-electromechanical system (MEMS) sensors [see Fig. 1(c)]; 2) dry fabric-based sensors [see Fig. 1(d)]; 3) hybrid dry sensors [see Fig. 1(e)–(g)]. Dry MEMS EEG sensors use "microneedles" to reach the skin to acquire the EEG signals without the use of conductive gels on the forehead or at other hairless sites [45]. The characteristics of dry MEMS EEG sensors have been discussed in detail [47], including the dependency of the electrode-skin-electrode impedance (ESEI) on electrode size [47]. However, depending on their design, these sensors can be slightly invasive as the electrodes (microneedles) penetrate the stratum

corneum and sometimes live skin layers, possibly resulting in pain or infection. These dry MEMS sensors can perform well in measuring EEG signals when applied to the forehead or other hairless sites; however, evidence regarding the quality of the EEG signals at sites covered with hair using dry MEMS-based EEG sensors is less convincing.

Recently, fabric-based sensors were proposed for measuring biopotential signals [48]–[52]. Beckmann *et al.* have conducted detailed investigations of the characterization of fabric materials with different fabric specifications for electrocardiography (ECG) measurements [51]. Baek *et al.*
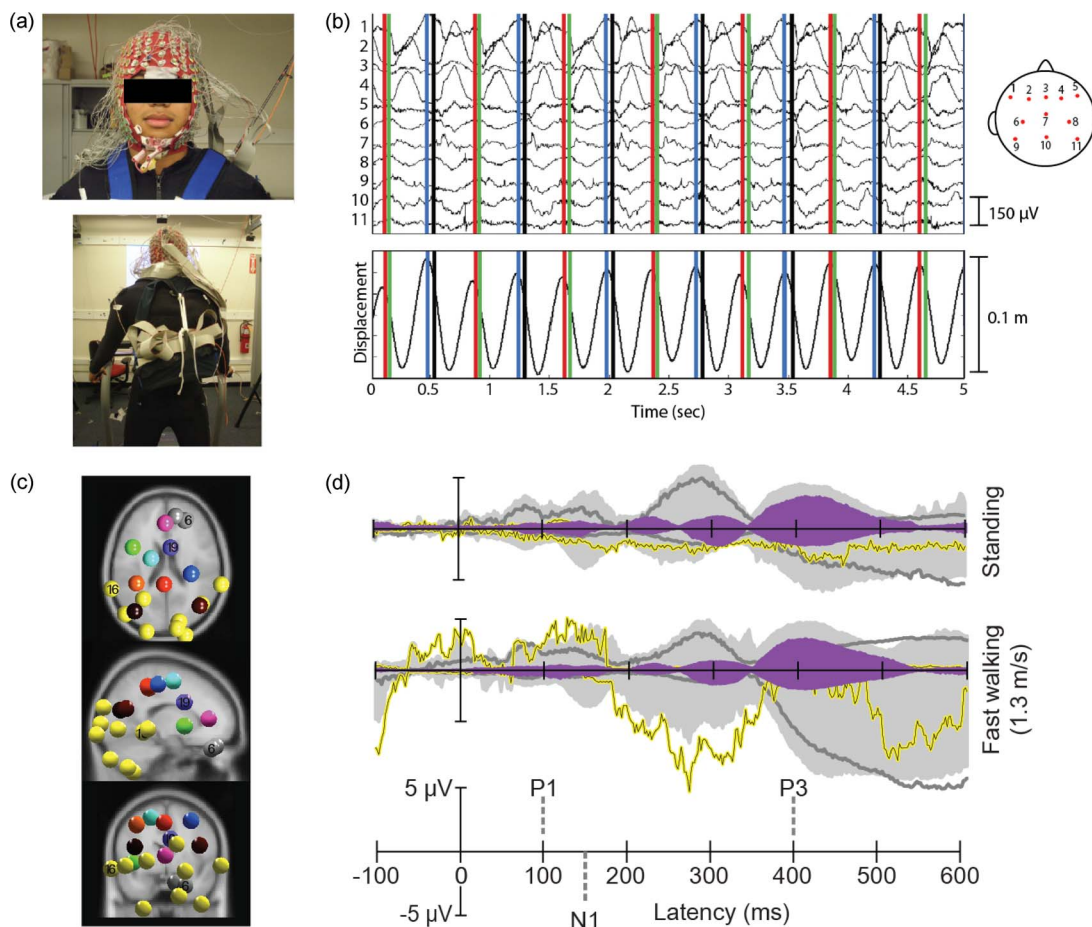
Fig. 2. *(a) Photograph of a participant wearing a 256-channel EEG cap with motion capture emitters placed on the cap and along standard positions in a full-body motion capture suit; the same participant seen from behind wearing a backpack containing the EEG amplifier system. (b) Spontaneous EEG activity recorded for selected channels (as indicated on the figure's head to the right), showing single-channel activity during several stride cycles and (below) vertical center-of-mass displacement during the gait cycle. The gait cycle begins and ends with the left toe raised (red vertical lines). The other vertical lines indicate the timing of the left heel strike (black vertical lines), the right toe lift (blue vertical lines), and the right heel strike (green vertical lines). (c) Centroids of independent component (IC) clusters (colored spheres) visualized in the Montreal Neurological Institute brain volume in horizontal, sagittal, and coronal views. The gray and yellow spheres represent eye and neck muscle activity clusters, respectively. The spheres of other colors mark the centroids of brain IC clusters. (d) Grand-mean event-related potential (ERP) envelopes (maximum and minimum channel ERP values for each latency) time-locked to target stimulus onset for two different movement conditions. The light gray shaded area shows the summed back-projection of all IC clusters. The purple shaded area shows the back-projected contribution of the IC cluster with equivalent dipoles in or near the anterior cingulate cortex [19 in (d)]. The yellow and dark gray traces show the back-projected contribution of a representative neck muscle cluster [16 in (d)] and a representative eye movement cluster [6 in (d)], respectively.*

Fig. 3. *Wearable EEG devices: (a) Emotiv, (b) NeuroSky, (c) Zeo, (d) StarLab, (e) EmSense, (f) nia Game Controller, (g) Mindo 4 with dry foam electrodes, and (h) Mindo 16 with dry spring-loaded probe sensors.*

fabricated a polydimethylsiloxane (PDMS)-based dry electrode for long-term ECG measurements [50]. Both studies indicate that long-term biopotential signal monitoring is possible using fabric-based electrodes [48]. The test results also indicate that the performance of fabric-based electrodes is comparable to that of commercial Ag/AgCl electrodes for ECG applications. More recently, Lin *et al.* developed foam-based sensors wrapped in conductive fabric materials to acquire forehead EEG signals [34] [see Fig. 1(d)]. They also showed that the foam-based sensors have the potential to reduce motion artifacts when obtaining measurements from a freely moving user using conventional wet electrodes. Compared with dry MEMS-based EEG sensors, fabric-based sensors are relatively comfortable and noninvasive. However, fabric-based sensors for acquiring EEG signals at sites covered with hair require further improvement because the contact area of the skin-electrode interface is significantly reduced by the presence of hair.

In addition to the previously described types of dry sensors, Matthews *et al.* proposed a hybrid dry sensor for EEG measurements [53]–[55] [see Fig. 1(e)]. This sensor, which combines high-impedance resistive and capacitive characteristics, contacts the scalp surface without any skin preparation and is dependent on the high contact impedance between the scalp and the electrode. However, these sensors possess hard substrates, which led to discomfort or even pain on the scalp surface when force was applied for attachment. The hard substrate also led to EEG signal distortions caused by motion effects [31]. Moreover, the fabrication cost for a high contact impedance electrode may be higher than for other types of dry EEG electrodes, such as fabric-based electrodes. In response to this concern, Cristian *et al.* presented a new, low-cost dry EEG sensor made of flexible metal-coated polymer bristles [56] [see Fig. 1(f)]. They suggested that the dry bristle sensors produce high-quality EEG recordings and are thus suitable for a wide range of EEG studies and BCI applications. Moreover, Liao *et al.* proposed a novel dry spring-loaded

contact probe EEG sensor for measuring EEG signals, especially at sites covered with hair [33] [see Fig. 1(g)]. Each of the spring-loaded probes is used to attach the sensors tightly to the scalp surface. These probes were designed to be inserted into a thin plate for additional conductivity. Most importantly, this thin plate is flexible so that it will fit the scalp surface well when applying force to the sensor. The spring-loaded probes and thin plate serve as a buffer to avoid causing pain when force is applied to the sensor and to improve the skin-electrode contact impedance. An injection molding process is used to package the sensors, which can decrease the fabrication cost of the entire acquisition system, depending on the cost of the electrodes. Test results have demonstrated the feasibility of using dry spring-loaded probe electrodes for measuring EEG signals at sites covered with hair.

Noncontact (capacitive) sensors with spaces between the electrode and the body and without skin preparation also have the potential to acquire EEG signals [57] [see Fig. 1(h)]. However, dry capacitive sensors are sensitive to motion artifacts [31], and Gert *et al.* indicated that designing an amplifier to acquire signals with such high source impedance remains a challenging issue [31]. Because of these issues, dry capacitive sensors require further improvement.

C. Nano- and Microtechnology Sensors

Nanoelectronic device technology holds promise for the next generation of electronics, leading to advancement through the development of novel sensors, flexible, transparent, and wearable high-performance electronics, smart bandages, optoelectronics, on-chip electronic-optical coupling, radiation hard electronics, and communications and processing electronics for deployable sensor platforms. For example, researchers in Spain and the United Kingdom have developed a new method for measuring electrical activity in the brain that uses sensors constructed from carbon nanotubes (CNTs) [58]. Ruffini *et al.* also demonstrated the use of carbon-nanotube-based dry sensors in biopotential signal studies [44], [58]. In the future, active, short-range communication of information between body-worn sensors may be enabled by spin-torque nano-oscillators (STNOs). These devices are being actively studied as a technology for magnetic memory applications, and may also be used as miniature frequency-agile radio frequency (RF) sources and sensitive magnetic field detectors [59]. For example, the extremely low-power (250 pW) transmission of microwave radiation through air has been demonstrated from a discrete 50-nm device, with broadband frequency agility over at least four octaves of frequency without conjugate matching [60], enabling a new class of low-power wireless communications for wearable sensor technologies. Bio-inspired nanotechnologies mimicking gecko foot structures are being developed as engineered reversible adhesive devices to enable mm- to cm-scale robotic platforms to crawl on surfaces [61] and

may be applicable to future biocompatible dry electrode adhesives for EEG sensors. Maturing micro- and nano-electromechanical system (MEMS/NEMS) technologies also hold promise for novel actuation devices, tactors and state-measurement devices. In the future, carbon-based or other biocompatible nanoscale sensing technologies may be envisioned that could be injected into blood vessels, cross the blood-brain barrier, attach to specific neurons or cells, sense the desired signals and transmit to an external receiver though the intact skull. While a very high spatial-temporal resolution of the EEG signals could potentially be provided in this manner, the resolution of many significant technical and ethical considerations will be required to facilitate the use of such technologies, similar to the existing drug-development protocols.

D. Multimodality Sensors

In addition to those sensors that are only used to measure EEG signals, the simultaneous recording of hemo-dynamic responses using NIRS and neural activity using EEG through multimodality sensors while users receive stimulation is also a critical issue in the neuroscience domain. NIRS and EEG techniques are based upon different imaging principles, and therefore, cross-validation can improve our understanding of both the relationship between hemodynamic responses and neural activity underlying cortical activation and the biophysics behind the measurement techniques themselves. Furthermore and critical to ABCIs, simultaneous NIRS and EEG imaging can provide novel insight into the phenomenon of neurovascular coupling changes for studying human brain mapping in everyday environments. Takeuchi *et al.* developed a head cap for both NIRS and EEG whole-brain imaging [62], and neurohemodynamic changes have been addressed in detail. Cooper *et al.* also proposed a novel probe design for simultaneous EEG and NIRS imaging of cortical activation in the human brain [63]. To accomplish this imaging, an "opto-electrode probe" was designed to house both an EEG electrode and an optical fiber bundle. This probe illustrates the potential applications of simultaneous NIR and EEG imaging. Although such novel ABCIs could provide simultaneous EEG and NIRS imaging, conductive gels and proper skin preparation are still required on the scalp skin surface at the electrode sites. In the future, we envision that dry EEG sensors will be integrated into simultaneous EEG and NIRS imaging.

III. INTEGRATION OF BIOSENSORS AND SENSING DEVICES INTO ABCI SYSTEMS

A. Current Developments in Biosensing Device Technology

Basic System Design: Traditionally, EEG systems have used relatively bulky, wired laboratory or clinically oriented equipment to measure EEG signals. Analog EEG signals are directly transmitted to a sensing device through wires that limit the routine activity of users. Recently, small wearable EEG acquisition devices have become available that are capable of recording EEG signals without hindering the user in the performance of routine tasks in everyday operational environments (for a detailed overview of wearable EEG-based BCI technology, refer to [64], [65]). Wearable EEG systems have been developed using headbands [66]–[68], headphones [69], caps [70], helmets [55], headsets [71], [72] and even cat ears [73]. Their shape determines the potential positions of the electrodes, which limits their functionality; however, the design of wearable EEG devices must consider both functionality and appearance. For example, a forehead-based system would not effectively utilize evoked potentials from the visual cortex, which are typically measured from electrodes located on the posterior portion of the head.

Analog Front-End: An instrumentation amplifier is used to augment the small signals received from electrodes and requires careful design to achieve a high signal-to-noise ratio (SNR). The common-mode rejection ratio (CMRR) is usually used to evaluate amplifier instruments, i.e., an amplifier with a higher CMRR reduces the common-mode noise in measurements. The traditional implementation of amplifiers uses a three op-amp configuration, which requires precise matching of the resistors used in the feedback network to achieve a high CMRR. Such matching usually requires expensive laser-trimmed resistors that consume a significant amount of chip area. One technique for overcoming this problem is to use current feedback instrumentation amplifiers [74]–[76], which requires two resistors to adjust the gain, but the resistors are not required to be matched. The advantage of a current feedback instrumentation amplifier is that it could be implemented using CMOS techniques and could reduce the chip area due to a lower resistor count, which is critical for amplifier miniaturization.

During the acquisition of EEG signals, which contain low frequencies, flicker noise (1/f noise) and input-referred dc offsets are undesirable signals that must be suppressed to achieve a high SNR. Flicker noises are signals in which the spectrum is inversely proportional to the noise. Input-referred dc offsets are caused by electrode polarization. Depending on the electrode placement, these dc offsets can be large and can easily saturate high-gain instrumentation amplifiers. Chopper amplifiers are commonly used for reducing the noise associated with op-amp imperfections and input-referred dc offset voltage. This modulation transposes the signal to the odd harmonic frequencies of the chopper frequency. After modulation, the signals are amplified and demodulated back to the original frequency band. The input offset voltage and noise are demodulated to the higher harmonics of the chopper frequency in the second multiplier. Another technique for

Table 1 Comparison of Wireless BCI Systems

	Reference						
	Chi et al. [67]	Lin et al. [66]	Wang et al. [68]	Torfs et al. [69]	Riera et al. [70]	Matthews et al. [55]	Brown et al. [71]
Appearance	Headband	Headband	Headband	Headphone	Cap	Hamlet	Headset
Signal	EEG/ECG	EEG	SSVEP	EEG	EEG/ECG	EEG	EEG
Number of Channels	4	8	4	2	4	12	8
Gain	10000	6000	8000	-	-	-	4000
Sampling Rate	343	512	128	256	256	4000	500/1000
Filter	0.7-159	1-50	0.01-50	-	0.1-100	1-50	-
Resolution of A/D	16	12	12	12	16	16	11
Transmission	Bluetooth	Bluetooth	Bluetooth	RF transmitter	Zigbee	RF transmitter	RF transmitter
Controller	PIC24	Micro-controller	MSP430	MSP430	-	-	MSP430

reducing input-referred dc offsets is autozeroing. Autozeroing amplifiers typically operate in one of two phases: the sampling phase or the output phase. Autozeroing can meet low-offset requirements but may not be suitable for low-power applications [77] because it requires the offset to be stored on a capacitor that may be relatively large and may thus increase power consumption. This issue should be resolved before it is used in EEG-monitoring applications. In [78], the authors apply autozeroing to an instrument amplifier and use a low-pass filter for noise-cancelling feedback.

Transmission Medium: EEG acquisition devices are usually designed for low-power consumption and low cost. The acquired signals are transmitted to another device with a high-end processor through a transmission medium. Currently, most projects use conventional wireless technology such as Bluetooth [66]–[68], 802.15.4/Zigbees [70], or RF transmitters [55], [69], [71], [72]. Bluetooth was developed as a replacement for cables and is a common feature in laptops and cellular phones. However, it also has a heavy protocol stack and high power consumption. In contrast, the protocol stacks of RF transmitters and 820.15.4/Zigbees are light and more efficient in terms of their power use, but they are less common in laptops.

Multichannel EEG transmission should have a high data rate and high power consumption. Compression technology can be used to reduce the data rate. Lossless compression schemes are reliable but have lower compression ratios [79], [80]. Lossy compression schemes [81], [82] have high compression ratios but introduce artifact issues.

Table 1 summarizes the EEG acquisition devices mentioned above [55], [66]–[71], which are responsible for wirelessly acquiring EEG signals and transmission data. Signal processing requires high computation power and is handled by hosts such as computers and cellular phones. Therefore, acquisition devices could be implemented with low-cost microcontrollers. Microcontrollers acquire digitized EEG signals from an ADC through a serial interface. According to the Nyquist-Shannon sampling theorem, the sampling rate should be greater than twice the maximum frequency of the acquired EEG signals. For example, SSVEP signals with a maximum frequency of 50 Hz are acquired, using a sampling rate of 128 Hz. A higher sampling rate and a higher resolution provide better accuracy for EEG signals but also increase the data rate and power consumption.

B. Technologies That Will Change Future Biosensing Techniques for ABCIs

Miniaturization of Power Sources: The miniaturization of power sources will enable the development of lightweight, portable sensor technologies. Li-ion battery technology, in which the energy density is proportional to the voltage of the cell, is being advanced through the development of high-voltage cathodes and electrolytes capable of operating at those higher voltages. Researchers at the U.S. Army Research Laboratory (ARL) have developed breakthrough electrolytes that allow for the operation of high-voltage lithium-nickel-manganese spinel oxides at 4.7 V against Li with 99% Coulombic efficiency and 85% capacity

retention after 200 cycles [83]. ARL researchers have also developed a stabilized 4.8-V lithium-cobalt-phosphate high-voltage cathode. Such a stabilized cathode can be cycled against Li with only 12% capacity loss compared with 33% capacity loss for the same cathode without stabilization after 10 cycles. This increased capacity retention has not been previously achieved [84]. Power sources using energetic materials based on nuclear isomers are being investigated for future power generation. Radioisotopes possess intrinsic energy storage that is more than 100 times greater than that of fuel cells and batteries, and they have the potential ability to release that energy upon demand. Recent results have demonstrated an induced energy release from isomers using neutrons [85], and alpha-based isotope batteries are being studied as a long-lived power source with an anticipated 50-year lifetime [86], which exceeds current battery lifetimes. Power conversion systems are being investigated at the cubic-millimeter, milligram scale to create high-efficiency, high-power-density actuation systems. CMOS design techniques, such as specific guard-rings and floating wells, that enable on-chip handling of more than 20 V in a 130-nm 1.2-V CMOS process have been demonstrated [85] and represent a significant step towards the high voltages required for novel actuators. MEMS-based ultraminiature air-core inductors with high-quality (Q) factors ($Q > 20$) and inductance densities (> 100 nanohenries/mm^2) have been shown to outperform most inductors fabricated with thin magnetic films, forming the basis for high-efficiency, high-frequency (> 20 MHz) boost converters [88]. Novel techniques using capillary wicking are being used to shape magnetic or high-k dielectric nanoparticles into complex 3-D microstructures [89], resulting in power conversion device components that show significant improvements in capacitance or inductance with no parasitic effect on the quality factor (i.e., efficiency) up to 200 MHz. Nano-electronic devices are also being explored, including super-capacitors for energy storage [90] and graphene-based metal-insulator-metal (MIM) diode structures for harvesting energy and rectifying antenna structures.

The design of power-efficient control theory is another approach to achieving reduced power requirements for sensor array information processing. Bio-inspired and bioplausible control theory, in which the control laws could, in principle, be implemented on the neural substrate of simple insects, is being investigated for applications in which computational power is extremely limited. Research groups, such as Richard Murray's group at Caltech, are developing control theories that focus on tight coupling between the temporal dynamics of the system and the temporal properties of the control algorithm [91]. These bioplausible algorithms use approaches that involve parallel, asynchronous information processing and emerging circuit technologies, such as those being developed in the DARPA-sponsored SyNAPSE (Systems of Neuromorphic Adaptive Plastic Scalable Electronics) project. These

technologies could, for example, facilitate the fusion of inputs from different sensor modes that have distinctly different time constants, such as EEG and fMRI, enhancing localization of the brain response for improved BCI interactions.

Mobile Human Brain Imaging for Real-Life Applications: Traditional neuroscientific approaches to measuring and imaging the hemodynamics coupled to neural activity that accompany cognitive processing (e.g., fMRI, PET) permit only minimal movement of the participants' hands or feet. This restriction of the participants' movement range is necessary to avoid movement of the signal-generating volume, i.e., the participants' brain, which cannot be followed by the heavy sensor arrays [92]. In addition, brain imaging techniques that directly measure electrical activity originating from the neural populations underlying cognitive processing further restrict the movement of the participants' head and eyes to avoid contamination of the signal of interest with current source activity originating from the neck, supracranial, and facial muscles as well as strong current source activity stemming from horizontal and vertical eye movement. From the standpoint of embodied cognition, however, cognitive processes are tightly coupled to physical activity and make use of our physical structure to reach behavioral goals [92], [93].

Consequently, results from traditional imaging approaches can only explain the neural basis of cognitive processes that are restricted to specific recording environments and do not necessarily reflect natural cognitive processing. Thus far, no investigation has compared human brain dynamics during free movement in the world with the brain dynamics of restricted behavior during traditional laboratory experiments. New results from animals in motion, however, demonstrate a direct coupling of behavioral states with brain states [94], [95]. These studies support the assumption that changes in behavioral states are accompanied by changes in brain dynamic states to adapt to differences in incoming sensory information. While the restrictions of traditional brain imaging approaches do not invalidate theoretical views formed on the basis of such experiments, several recent investigations in human participants point to a tight coupling of motor behavior and, for example, attention and spatial cognition. An example of such coupling was described by Wykotska and colleagues [96], demonstrating a direct influence of (planned) movement on target detection when targets were defined by features relevant to the movement. The authors showed that shape-defined targets were detected faster when participants planned to grasp a target object while luminance-defined targets were detected faster when participants planned on pointing towards the target object. An even more pronounced coupling of active behavior with human brain dynamics could be expected for spatial cognitive processes that are tightly coupled to and make efficient use of idiothetic information derived from

the vestibular and proprioceptive system [97]. Spatial updating of one's own position and orientation is a prerequisite of successful spatial orientation but relies heavily on idiothetic information that is absent in traditional brain imaging approaches. As a consequence, the brain dynamics accompanying active spatial orientation including physical rotation will provide novel insights into the brain dynamics associated with idiothetic information processing and will thus help us better understand the brain dynamics associated with spatial orientation. To overcome the restrictions of traditional imaging approaches and to investigate the brain dynamics accompanying active behavior in humans, our group, recently developed and demonstrated a mobile brain/body imaging (MoBI) approach [91], [98]–[100]. Through various experiments, we demonstrated the feasibility of this concept and revealed interesting insights into the cognitive dynamics of attention during treadmill walking [98] and into the coupling of cortical activity with gait-cycle phases [100]. However, these experiments were clearly restricted because of the hardwiring of the EEG system. In [99], the analysis of human brain dynamics for subjects who were standing and walking at different speeds was demonstrated. However, the cable sway associated with the displacement of the participants' heads while running required extensive template-based artifact rejection (see Fig. 2). In another experiment [Gramann *et al.*, unpublished manuscript], the use of traditional hard-wired EEG sensors restricted the movement range of the participants' heads when they attempted to actively orient towards laterally placed objects in their environment. In general, in the field of motor control and physical behavior, numerous attempts to study active cognitive processing have been hampered due to these types of issues associated with the tethered nature of standard EEG equipment. Classic examples include EEG studies of shooting that have been largely limited to static targets as opposed to reactive, dynamic targets; studies of golf that have been largely limited to putting as opposed to driving and studies of basketball that have been limited to free-throw shooting as opposed to any other aspect of game-play. These examples demonstrate the need for wireless sensor systems to allow for future investigation and deeper insights into the architecture of active and mobile cognition.

Advanced Flexible Electronics and Display Technologies: Future ABCIs are envisioned to be moving towards seamless integration with users' clothing and the environment; advancements in technologies such as flexible electronics and displays, which are maturing to provide lightweight, rugged, and ultralow-power flexible imaging systems for high-yield manufacturing processes, will enable such improvements [see, for example, http://flexdisplay.asu.edu/]. Full-color organic light-emitting-diode (OLED) displays have been demonstrated on plastic substrates, and charge-transfer complex molecular OLED systems have been integrated into emissive flexible displays to dramatically

enhance the charge injection and transport properties of organic devices [100]. Flexible reflective displays for system-level integration have transitioned in industry to meet emerging information technology needs for the mobile soldier. Large-area distributions of flexible electronic circuits, discrete elements, and sensors are being integrated with flexible solar cells, antennas, and solid-state lighting to enhance next-generation displays. Enhancements in carrier transport, brightness, and speed are being investigated with the use of flexible and stretchable silicon or metal technologies [102]. These technologies will enable the creation of high-performance conformable circuits that are needed for more seamless integration of ABCIs into clothing as well as advanced concepts for smart clothes and body armor. Stretchable silicon-integrated circuits that can be applied directly to the skin have recently been demonstrated [103]. These tattoo-like structures are an example of the new epidermal electronics technology that can be used to directly measure vital signs. Such advancements will permit a range of advancements from novel approaches to sensor design to the collection and integration of high-density signals across numerous behavioral and physiological sources for enhanced ABCI performance.

IV. TRENDS IN ABCIs

A. Current Applications of ABCIs

Wet electrodes have their own readout circuit systems and are reliable for clinical applications. For dry/noncontact electrodes, developing the proper readout device for everyday use is important. Devices with dry electrodes are more convenient and comfortable than traditional EEG systems with wet electrodes [31] and are, thus, more practical for use in everyday applications. Although dry/noncontact EEG devices have not been proposed or used for clinical applications, many commercial devices use EEG measurements for entertainment (Neurosky, Emotiv, StarLab, EmSense, and nia Game Controller) [104], [105] and for monitoring personal sleeping status (MyZeo) [106], as shown in Fig. 3(a)–(f). These figures demonstrate that the development of portable EEG devices with dry electrodes has become an important goal for mobile human brain imaging.

Recently, Lin *et al.* proposed a wearable, wireless EEG device (Mindo) for everyday use [32]. The Mindo 4 EEG device with 4-channel foam electrodes has proven to be reliable for controlling games according to the user's mental focusing state based on signals from forehead sensor sites [34], as shown in Fig. 3(g). It also has the potential to acquire the EEG status during sleep. Another multichannel EEG device, Mindo 16, which has spring-loaded probe electrodes, was designed by Lin *et al.* for wirelessly measuring EEG signals, especially at sites with hair, as the corresponding dry sensors have the potential to properly reach the scalp skin through the hair [see Fig. 3(h)]. In addition to wireless EEG

devices with dry contact electrodes, Gert *et al.* designed a wireless device with non-contact electrodes for measuring both EEG and ECG [107]. There is no doubt that developing a truly wearable, wireless EEG device using dry/noncontact electrodes and extending the limitations of this technique from basic research to clinical applications are important goals. Highly desirable characteristics of future devices include a minimized readout circuit size and easy preparation when using dry electrodes.

B. Future ABCI Applications Based on Advanced Biosensing Technology

Gaming control, homecare, and rehabilitation engineering applications are potential future applications of ABCIs in the coming decades. ABCI applications for gaming are one of the major focuses of this technology, and existing prototypes demonstrate the feasibility of games controlled by an ABCI [40]–[42]. It is possible that an EEG-based BCI device with novel EEG sensors that is capable of interpreting the cognitive relevance of neuron interactions in the brain will become available and reliable in the near future [108]. Another feasible future trend for ABCIs is remote monitoring, which can be used in homecare and rehabilitation engineering applications [109]. The elderly and ill often prefer living in their own houses to being in a hospital, but living alone can be dangerous because of unpredictable accidents such as falling and epileptic seizures [110]. Remote-sensing and monitoring would enable the remote monitoring of a user's EEG signals. EEG-based ABCIs may be able to assist with depression and many other psychological and cranial nerve diseases, such as schizophrenia, Parkinson's disease and seizures, in the

near future. We refer the reader to another paper written by Lance *et al.* [36] for details of future ABCI applications.

V. SUMMARY

We have studied a wide range of approaches to ABCIs and explored their applications to neuroscientific questions and cognitive engineering. We have provided insights into the fundamental basis of many ABCI techniques and highlighted important considerations for their practical implementation. The miniaturization of sensors, electronics, and power sources; the design of power-efficient information processing; and the emergence of flexible electronics and display technologies have the potential to radically enhance future ABCI capabilities. We hope that these details will help those who are interested in using or developing biosensing techniques for ABCIs to understand the key aspects that should be considered when acquiring measurements or analyzing data.

We have surveyed the large body of literature that discusses studies in which biosensing technologies and devices have been successfully used for ground-breaking and important research on ABCIs and their applications. The development of ABCIs is a rapidly expanding field that is continually evolving to embrace new technologies and real-life applications. ∎

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ABOUT THE AUTHORS

Lun-De Liao (Member, IEEE) received the B.S. degree in mechanical engineering from Chung Yuan Christian University, Taiwan, in 2006, the M.S. degree in engineering science from National Cheng-Kung University, Taiwan, in 2008, and the Ph.D. degree in electrical engineering from National Chiao Tung University (NCTU), Taiwan, in February 2012. He is currently a Postdoctoral Fellow at the Brain Research Center, NCTU.

In recent years, his research interests have included biomedical optics imaging, advanced sensing techniques, cognitive neuroscience, and neuroimaging.

Mr. Liao was the recipient of the 2005 Best Paper Award from National Society of Engineers, Taiwan; 2006 the AUO Award; 2006 the Acer Long-Term 3nd-prize Award; 2007 Top Research Paper Award of Year by SPIE Journal paper is selected; 2007 the MekTec 3nd-prize Award; 2007 the Acer Long-Term 2nd-prize Award; 2009 SID Travel Fellowship; 2009 IEEE Intermag Travel Fellowship; 2009 the Best Paper Award from the Symposium on Nano Device Technology; 2010 Best Paper Award from International Symposium on Biomedical Engineering. He also won the 2011 Young Investigator's Award from the world association for Chinese biomedical engineers for his contributions on medical imaging & bioelectronics domain.

Chin-Teng (CT) Lin (Fellow, IEEE) received the B.S. degree in control engineering from National Chiao-Tung University (NCTU), Hsinchu, Taiwan, in 1986 and the M.S.E.E. and Ph.D. degrees in electrical engineering from Purdue University, West Lafayette, IN, in 1989 and 1992, respectively.
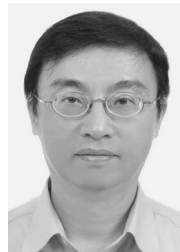
Since August 1992, he has been with the College of Electrical Engineering and the College of Computer Science, NCTU, where he is the Provost and the Lifelong Chair Professor of the Department of Electrical Engineering. He served as the Founding Dean of Computer Science College of NCTU from 2005 to 2007. He is the author of the textbook author of *Neural Fuzzy Systems* (Prentice Hall) and *Neural Fuzzy Control Systems with Structure and Parameter Learning* (World Scientific). He has published over 165 journal papers, including about 77 IEEE transactions papers. His research interests are in translational neuroscience, computational intelligent technologies, soft computing, brain-computer interface, smart living technology, intelligent transportation systems, robotics and intelligent sensing, and nano-bio-information technologies and cognitive science (NBIC).

Dr. Lin was elevated to IEEE Fellow in 2005 for contributions to biologically inspired information systems. He was honored with Outstanding Electrical and Computer Engineer (OECE), Purdue University in 2011. He was a member of the Board of Governors (BoG) of the IEEE Systems, Man, Cybernetics Society (SMCS) from 2003 to 2005 and IEEE Circuit and Systems Society (CASS) (2005–2008), and the current AdCom member of IEEE Computational Intelligence Society (CIS) (2008–2010). Dr. Lin is the IEEE Distinguished Lecturer from 2003 to 2005. He currently serves as an Editor-in-Chief (EIC) of IEEE TRANSACTIONS ON FUZZY SYSTEMS. He was an associate editor (AE) of IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS, PART II. He also served as the Deputy EIC of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS, PART II from 2006 to 2007. Dr. Lin is the General Chair of FUZZ-IEEE 2011 held in Taipei, and was the Program Chair of the 2006 IEEE International Conference on Systems, Man, and Cybernetics held in Taipei. He was the president of Board of Government (BoG) of Asia Pacific Neural Networks Assembly (APNNA) from 2004 to 2005. Dr. Lin has own the Outstanding Research Award granted by National Science Council (NSC), Taiwan, since 1997 to present, the Outstanding Professor Award granted by the Chinese Institute of Engineering (CIE) in 2000, and the 2002 Taiwan Outstanding Information-Technology Expert Award. He was also elected to be one of 38th Ten Outstanding Rising Stars in Taiwan (2000). Dr. Lin is a member of Tau Beta Pi, Eta Kappa Nu, and Phi Kappa Phi honorary societies.

Kaleb McDowell (Senior Member, IEEE) was born in Frederick, MD, on July 10, 1970. He received the B.S. degree in operations research and industrial engineering from Cornell University, Ithaca, NY, in 1992, the M.S. degree in kinesiology from the University of Maryland, College Park, in 2000, and the Ph.D. degree in neuroscience and cognitive science from the University of Maryland, College Park, in 2003.

He is currently the Chief of the Translational Neuroscience Branch and Chair of the Neuroscience Strategic Research Area at the U.S. Army Research Laboratory (ARL) in Aberdeen Proving Grounds, MD. Since joining ARL as a Research Psychologist in 2003, he has contributed to over 30 reviewed publications, and has led several major research and development programs focused on neuroscience, indirect vision systems and vehicle mobility. His current research interest focuses on translating basic neuroscience into applications for use by healthy populations in everyday, real-world environments.

Dr. McDowell received Department of Army Research and Development Achievement awards for technical excellence in 2007 and 2009 and the ARL Award for Leadership in 2011.

Alma E. Wickenden (Member, IEEE) received the B.S. degree in physical science in 1985, and the M.S. and Ph.D. degrees in materials science and engineering from Johns Hopkins University, Baltimore, MD, in 1989 and 1993, respectively.

She is a Senior Researcher with the Army Research Laboratory's Sensors and Electron Devices Directorate in Adelphi, MD. Her research interests include electronic materials, nano-/microelectronic sensor devices, and bio/neuro-inspired control theory for power-constrained sensor arrays. She established ARL's Nanoelectronics Team and the ARL Science Outreach for Army Research (SOAR) multidisciplinary internship program. She currently serves as the Technical Assistant to ARL's Associate Director of Science & Technology, with responsibilities for the technical oversight of the quality and direction of ARL's Science and Technology programs. She has published over 80 publications in the field of wide bandgap III-nitride semiconductor materials and nanoelectronics.

Dr. Wickenden is a member of the IEEE and the American Vacuum Society, where she is a member of the Electronic Materials & Processing Division Executive Committee.

Klaus Gramann received the Pre-Diploma in psychology from Justus-Liebig-University Giessen, and the Diploma and Ph.D. degree in psychology from Rheinisch-Westfaelisch-Technical University Aachen in 1998 and 2002, respectively.

He worked as a Postdoctoral Researcher in the Ludwig-Maximilians-University Munich, Department of Psychology from 2002 to 2007, and the Swartz Center for Computational Neuroscience, University of California at San Diego, La Jolla, from 2007 to 2011. After spending half a year as a Visiting Professor at the Brain Research Center of National Chiao Tung University, Hsinchu, Taiwan, he is now Professor for Cognitive Psychology at University Osnabruck, Germany. His research focuses on neural dynamics of spatial orientation and visual attention and the development of a mobile brain imaging method.

Tzyy-Ping Jung (Senior Member, IEEE) received the B.S. degree in electronics engineering from National Chiao-Tung University, Taiwan, in 1984, and the M.S. and Ph.D. degrees in electrical engineering from The Ohio State University, Columbus, in 1989 and 1993, respectively.

He was a Research Associate with the Computational Neurobiology Laboratory, The Salk Institute, La Jolla, CA. He is currently a Research Scientist and the Co-Director of the Center for Advanced Neurological Engineering, Institute of Engineering in Medicine, University of California at San Diego (UCSD). He is also an Associate Director of the Swartz Center for Computational Neuroscience, Institute for Neural Computation, and an Adjunct Professor of Bioengineering at the UCSD. In addition, he is a Professor of Department of Computer Science, National Chiao Tung University, Hsinchu, Taiwan. His research interests are in the areas of biomedical signal processing, cognitive neuroscience, machine learning, time-frequency analysis of human EEG, functional neuroimaging, and brain computer interfaces and interactions.

Li-Wei (Leo) Ko (Member, IEEE) received the B.S. degree in mathematics from National Chung Cheng University in 2001, the M.S. degree in educational measurement and statistics from National Taichung University in 2004, and the Ph.D. degrees in electrical engineering from National Chiao Tung University (NCTU), Taiwan, in 2007.

He is currently an Executive Officer of the Brain Research Center (BRC) in NCTU, and the Assistant Professor in Department of Biological Science and Technology in NCTU. He is also the Visiting Scholar at Institute for Neural Computation in University of California at San Diego. His primary research interests are to apply computational intelligence technologies such as time-frequency analysis and neural networks to analyze neural activities associated with human cognitive functions and develop the mobile and wireless brain machine interface in unconstrained, actively engaged human subjects in daily life applications. Relevant research fields cover neural networks, neural fuzzy systems, machine learning, brain computer interface, and computational neuroscience.

Dr. Ko is an Associate Editor of the IEEE Transactions on Neural Networks in the IEEE Computational Intelligence Society.

Jyh-Yeong Chang (Member, IEEE) received the B.S. degree in control engineering in 1976 and the M.S. degree in electronic engineering in 1980, both from the National Chiao-Tung University, Hsinchu, Taiwan, and the Ph.D. degree in electrical engineering from the North Carolina State University, Raleigh, in 1987.

During 1976–1978 and 1980–1982, he was a Research Fellow at Chung Shan Institute of Science and Technology, Lung-Tan, Taiwan. Since 1987, he has been an Associate Professor in the Department of Electrical Engineering, National Chiao-Tung University, where he is currently a Professor. His current research interests include neural fuzzy systems, video processing and surveillance, and e-health systems.