The Future of Human-in-the-Loop Cyber-Physical Systems

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A prototyping platform and a design framework for rapid exploration of a novel human-in-the-loop application serves as an accelerator for new research into a broad class of systems that augment human interaction with the physical world.

Human-in-the-loop cyber-physical systems (HiLCPSs) comprise a challenging and promising class of applications with immense potential for impacting the daily lives of many people. As Figure 1 shows, a typical HiLCPS consists of a loop involving a human, an embedded system (the cyber component), and the physical environment. Basically, the embedded system augments a human's interaction with the physical world.

A HiLCPS infers the user's intent by measuring human cognitive activity through body and brain sensors. The embedded system in turn translates the intent into robot control signals to interact with the physical environment on the human's behalf via robotic actuators. Finally, the human closes the loop by observing the physical world interactions as input for making new decisions.

Examples of HiLCPSs include brain-computer interface (BCIs), controlled assistive robots,[1] and intelligent prostheses.

HiLCPS applications offer benefits in many realms—for example, the population of functionally locked-in individuals would benefit tremendously from such systems. Because these individuals cannot interact with the physical world through their own movement and speech, they often must rely heavily on support from caregivers to perform fundamental everyday tasks, such as eating and communicating. As the "Fundamental Autonomy for Functionally Locked-In Individuals" sidebar describes, a HiLCPS could aid in restoring some autonomy by offering alternative interfaces to the cyber-physical environment for interaction, communication, and control.

MULTIDISCIPLINARY CHALLENGES

Designing and implementing a HiLCPS poses tremendous challenges and is extremely time-consuming. Experts from many disciplines need to join forces to successfully solve these challenges.

Transparent interfaces

Traditional dedicated interfaces to the virtual world, such as the keyboard, mouse, and joystick, are less suitable for augmenting human interaction in the physical world. This environment requires transparent interfaces that use existing electrophysiological signals such as electroencephalography (EEG), electrocardiography (ECG), and electromyography (EMG), which measure electrical signals emitted by the brain, heart, and skeletal muscles, respectively. Additional auxiliary sensors
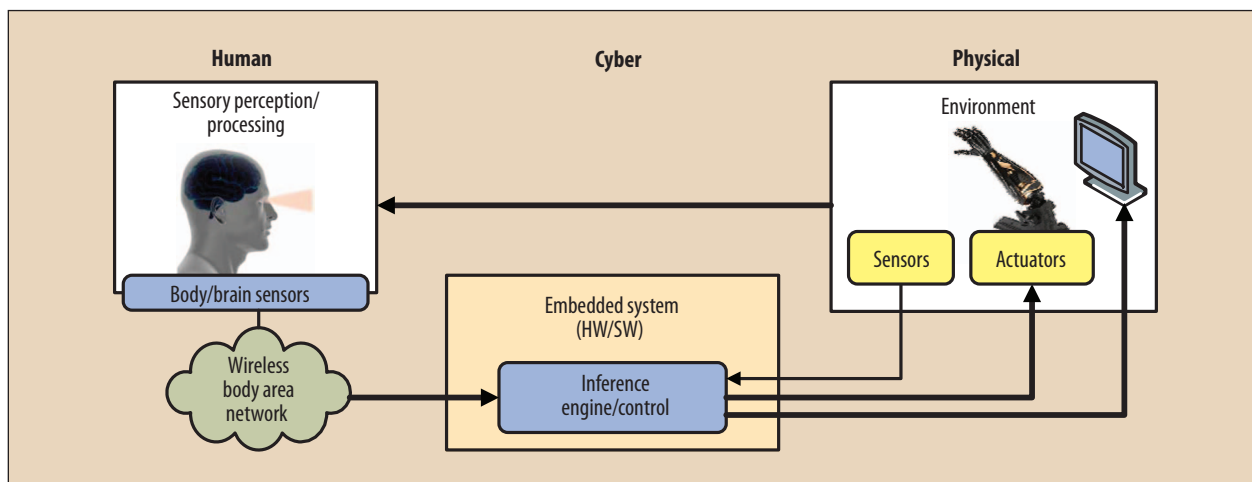
Figure 1. Human-in-the-loop cyber-physical system (HiLCPS). The loop consists of a human, an embedded system, and the physical environment.

to monitor the respiratory rate, pulse oximetry, and skin resistance can help provide a more comprehensive view of the whole body.

The challenge with analog interfaces is in accurately detecting electrophysiological signals: electric potentials can be as low as in the mV range. Moreover, connecting a human to a host of wires to centrally gather these signals is not only impractical but also too restrictive. The optimum solution is to have a distributed sensor network with power-efficient and reliable communication, for example, through wireless body area networks (WBANs).

Human intent inference

HiLCPSs put high demands on intent inference algorithm design because input signals are inherently noisy. Intelligent sensor fusion can help compensate for inconsistent measurements of individual sensors and form a complete, coherent picture from the multimodal sensor input. One approach to deal with the interpretation of noisy signals is to take the physical world context into account, eliminating contextually impossible decisions such as actions that are not physically possible given the current state of robot control, or letters that do not make sense given the language used for typing interfaces. Because a HiLCPS continuously interacts with the physical environment, real-time intent inference is crucial for keeping up with the constantly changing environment.

Fundamental Autonomy for Functionally Locked-In Individuals

A human-in-the-loop cyber-physical system (HiLSPS) can offer assistive technology that helps to restore fundamental autonomy—self-feeding and communication—for people who are functionally locked-in due to various neurological or physical conditions. Depending on their clinical diagnosis and condition, these individuals might have full cognitive capabilities yet lack the ability to execute any motor actions that can generate movement or speech. Consequently, they rely heavily on caregivers to accomplish everyday tasks.

We are developing a HiLCPS that augments the neurophysiological capabilities of a functionally locked-in individual to facilitate self-feeding, communication, mobility, and digital access. As depicted in Figure A, we intend to build a brain-computer interface (BCI)-controlled wheelchair as a mobility platform, construct a robotic arm for self-feeding, and establish a communication interface. In addition to restoring the ability to meet basic needs, a HiLCPS can help to close the digital divide, making it possible for users to access the informational and social resources that computers offer and contributing to a sense of self-fulfillment that is essential for a productive life.
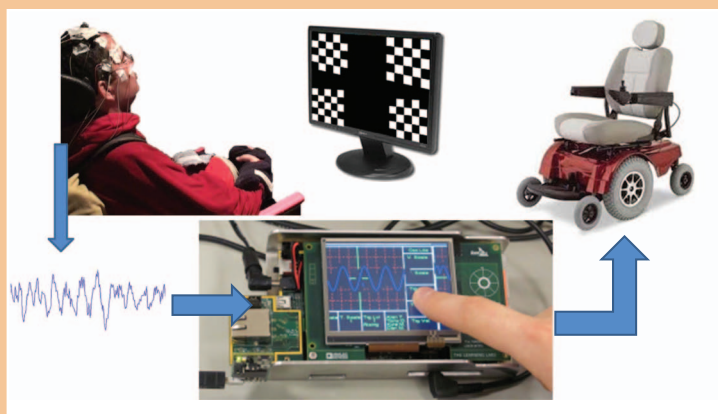
Figure A. Restoring fundamental autonomy for functionally locked-in individuals through a HiLCPS.
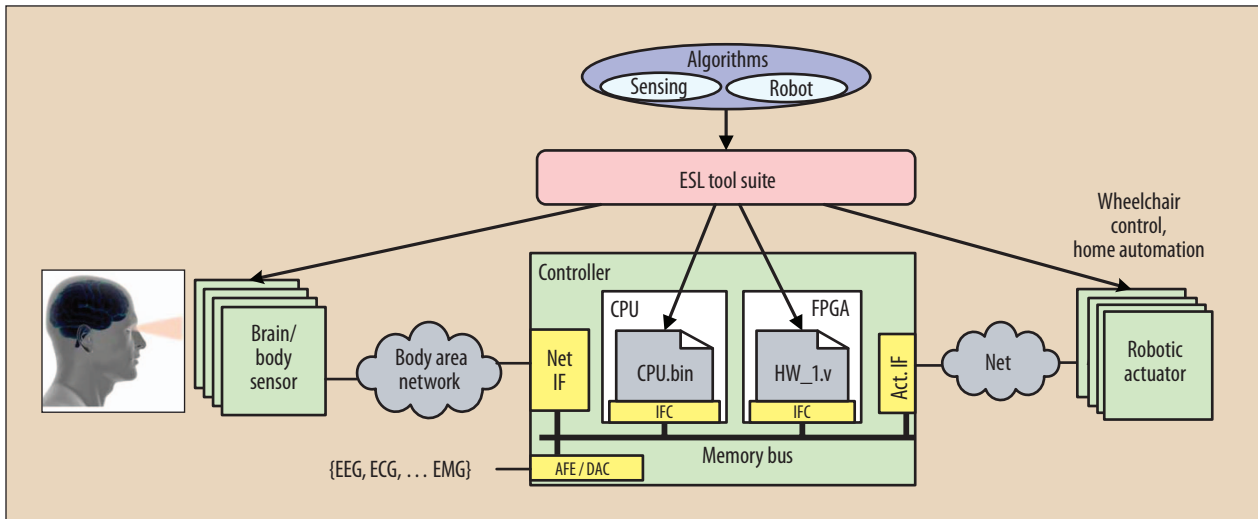
Figure 2. Framework for automatically generating embedded code (HW/SW) from abstract brain-computer interface algorithms. An electronic system-level (ESL) tool suite analyzes the algorithm at its input for computation complexity. It then generates a distributed implementation across hardware and software.

Robotics with shared governance

In spite of recent advances in robotics research, the design and control of robotic systems capable of autonomous operation remains a challenge. In the HiLCPS context, additional issues arise—for example, robots operate in close proximity with the human, which poses strict safety requirements.

Decision algorithms also must divide governance between human and machine. While the human can make top-level decisions, their local realization is better done autonomously. The overall aim is to require only conceptual decision making from the human. However, safety overrides might be required to avoid implausible actions, depending on the overall physical state.

Building a HiLCPS requires tackling various multidisciplinary design challenges, including

- efficient embedded system design;
- cognitive intent detection algorithms using brain or other neurophysiological signals;
- actuator and robotics to realize an intended outcome or effect in the physical world; and
- distributed sensor architectures with suitable, power-efficient communication mechanisms.

We use a holistic design process to approach these multidisciplinary challenges. Our envisioned methodology and unifying framework for HiLCPS design offers an automated path for implementing body/brain computer interface (BBCI) algorithms for intent inference as well as for robot control on an embedded real-time platform. Automating the path to implementation lets algorithm developers explore real-time integration and simplifies exploring the shared human/machine governance.

A HOLISTIC DESIGN FRAMEWORK

A HiLCPS must be realized in an efficient embedded implementation that fulfills both functional and nonfunctional requirements. Unfortunately, algorithm designers typically are not embedded systems experts, so they need an integrative framework that bridges disciplines. Ideally, such a framework allows algorithm designers to achieve embedded implementations at the push of a button.

The key to HiLCPS adoption and integration is an efficient, robust, and reliable embedded implementation. As Figure 2 shows, an embedded control platform is at the heart of the HiLCPS that we are building. The sensing inputs (primarily EEGs) are directly connected through a specialized analog front end (AFE) and digital-to-analog converter (DAC). Auxiliary sensors interface with the embedded control platform through a body area network. Sensor fusion and intent inference algorithms execute mainly on an embedded processor assisted by a custom hardware component implemented in a field-programmable gate array. The FPGA is essentially dedicated to signal preprocessing to clean up the noisy input signal. A network interface transmits top-level decisions to the robotic actuators, which in turn interact with the environment.

In addition to being reliable and efficient, the algorithms developed for intent inference and robotics navigation/control also must be robust from a nonfunctional perspective. Of particular concern are maintaining power efficiency—to allow battery-powered operation—and meeting real-time performance constraints as mandated by interaction with the physical world. In addition, fusing sensor data from multimodal distributed sensors and shared human/robot governance demands distributed operations.

Traditionally, algorithm design and its embedded implementation were approached sequentially, first by al-

gorithm and then embedded system experts, respectively. But this sequential process creates a long delay between algorithm conception and its embedded realization. In addition to prolonging the time to market, this delay forces algorithm designers to make simplifying assumptions about the physical environment until the algorithms finally are translated to a real platform. Consequently, much of the cross-discipline optimization potential is lost.

Using a holistic methodology for developing design automation concepts can overcome most problems and consequences associated with sequential design.[2] In our methodology, designers develop algorithms in the high-level languages with which they are familiar. They then enter the input algorithm together with a description of the underlying platform—constant, in our case—into the electronic system level (ESL) tool suite, which analyzes computation demands on the granularity of function blocks. The ESL tool suite generates code for both the CPU and the FPGA. As part of its overall synthesis process, the tool inserts interface code for hardware/software communication automatically.[3] In effect, the ESL tool suite operates as a system compiler, as it compiles a high-level application to run atop an embedded platform across hardware/software boundaries.

The ESL flow paves the path for cross-discipline optimizations. For example, it allows exploring different distributions of sensor fusion and intent inference. An event classification algorithm could directly execute on an intelligent sensor, which would increase the processing demand on the sensor but dramatically reduce communication—transmitting just the events of interest instead of a constant stream of data samples. This design freedom helps embedded architects devise low-power, high-performance systems.

BBCI researchers can use the automation framework to develop embedded algorithms without requiring specialized embedded knowledge. The ESL flow hides implementation-level details, enabling designers to focus on the important issue of algorithm and model development. Through automation, BBCI researchers will be able to directly test their algorithms in an embedded setting, enabling the development of a new class of real-time algorithms that can exploit the combination of sensing, analysis, and decision making.

CONTEXT-AWARE SENSING OF HUMAN INTENT

The use of multimodal physiological signals from the operator's body and brain is an established idea in human-computer interaction and more broadly in human interface design for control systems. With the advent of portable and affordable systems and increased computing power in recent decades, growing interest has focused on the use of physiological signals easily measurable from the skin on the arms or legs and also from the scalp. EEG, which measures electric potential on the scalp, has become the mainstay of noninvasive BCI design.[4] There is considerable interest in developing not only BCI-controlled systems but also systems that combine EEG and other physiological signals such as EMG and gaze position.

The convergence of improved and less costly technologies now makes it possible to develop prototypes using these multimodal input mechanisms for HiLCPS applications. We foresee that, in the next decade, commercial applications using such interfaces will emerge. Some start-up companies in the gaming and entertainment markets are already experimenting with these ideas and are offering reasonably successful products. Of course, the real challenge is to design commercial systems with a higher threshold for success in terms of accuracy, robustness, response time, and reliability.

> The ESL flow hides implementation-level details, enabling designers to focus on the important issue of algorithm and model development.

That said, it is much harder to reliably infer a user's intent with physiological signal-based interface designs than with a classical joystick or keyboard. Electrophysiological signals are inherently orders of magnitude noisier than their engineered electromechanical interface counterparts. Consider, for example, recently popularized speech- and gesture-based interfaces, which are struggling with many real-world issues such as relevant source separation in ambient noise or relevant object segmentation with moving background clutter as they find their role in the marketplace.

BBCI designs that rely on signals like EEG and EMG are prone to similar problems in terms of signal-to-noise and interference ratios. Clearly, the operator's brain and body are being used for other internal physiological functions that have nothing to do with the intent that needs to be conveyed to the BBCI system. Therefore, although careful signal processing design and feature engineering are crucial, they might not be sufficient in some cases. The low signal-to-noise and interference ratios simply make incorporating context a requirement in intent inference.

To improve the intent inference accuracy, BBCI designers must develop algorithms that adaptively take into account the current application as well as the operator's preferences and historical behavior. For example, a BCI-based keyboard interface uses EEG traces to select letters, but there is room for improvement in the prediction success rate. Incorporating language models, which capture
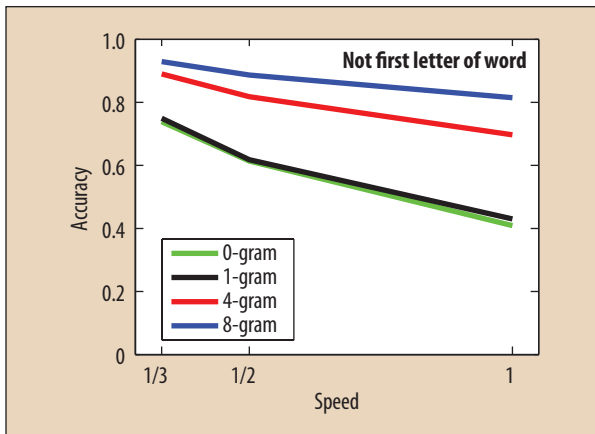
Figure 3. Letter selection among 28 possible symbols demonstrating accuracy versus speed for the preliminary RSVP Keyboard design when fusing EEG evidence from multiple trials for each symbol. Speed is inversely proportional to the number of trials.

the likelihood of character sequences, in the inference logic with proper Bayesian fusion helps to achieve improved results in terms of both accuracy and speed. Figure 3 shows the speed/accuracy tradeoff for different n-gram model orders on the RSVP Keyboard, a recently developed BCI-based keyboard interface.[5]

Generalizing from this example, the principle of utilizing contextual information and application-specific priors as routinely prescribed in machine learning theory becomes essential and could make the difference between success and failure—that is, the human's acceptance or rejection of the system/interface.

In our robotics applications, we are building and modifying contextual information and probabilistic models of desired behavior and outcome sequences, with the intent of creating HiLCPS designs that will eventually operate successfully in the real world. For this, we use tools from adaptive signal processing, machine learning, and robotics when they are available, and we develop new tools and methods when necessary. Although generic recursive Bayesian modeling and inference procedures have been well established, existing parametric and nonparametric models that can be used within these frameworks might be insufficient. We anticipate that most of the effort in incorporating contextual information and application-specific priors in inference and intent detection will be spent on modeling.

So far, we have developed a preliminary brain-controlled robot prototype, shown in Figure 4, that allows an operator to remotely navigate a robotic platform, such as a wheelchair, using steady-state visual evoked potentials (SSVEPs) induced by flickering light patterns in the operator's visual field. A monitor shows four flickering checkerboards that emit periodic square waves with different frequencies. Each checkerboard and frequency corresponds to one command to control the robot.

In our prototype, the four commands represent the desired target locations D1, D2, and D3 as well as the stop command. To select a command, the operator focuses his or her attention on the desired checkerboard on the monitor. After the operator focuses on one checkerboard, the visual cortex predominantly synchronizes with the checkerboard's flickering patterns—fundamental and harmonic frequencies. Like any brain activity, the visual cortex's activity will result in voltage fluctuations that can be measured on the scalp. Accordingly, we place an elec-
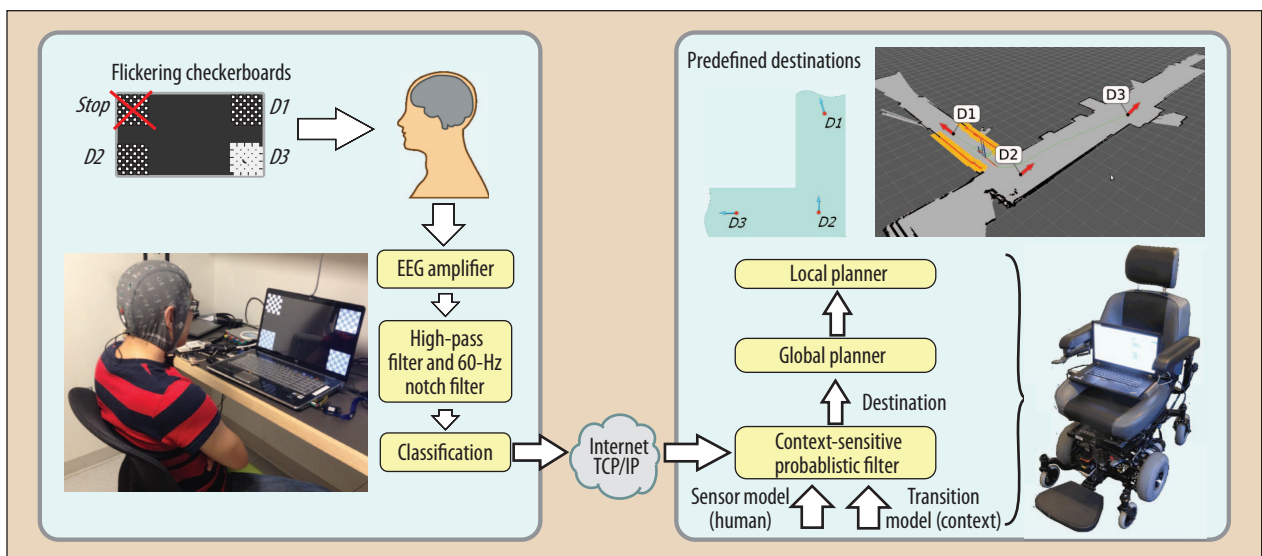
Figure 4. System architecture for the BCI-based control of an intelligent wheelchair as an example of a HiLCPS. (left) The semi-autonomous wheelchair receives brain signals from the user for a high-level activity; (right) it then executes the tasks of path planning, obstacle avoidance, and simultaneous localization and mapping.

trode on the scalp near the occipital lobe where the visual cortex is located to pick up these EEG signals.

Distinguishing which checkerboard the operator has focused on requires analyzing the power spectrum of signals gathered close to the visual cortex. The power spectrum shows the power contribution over different frequencies; Figure 5 shows a typical power spectrum for a flickering frequency of 15 Hz. Clearly visible is the peak at 15 Hz, which is the fundamental frequency, as well as at 30 Hz and 45 Hz, which are the second harmonic and third harmonic, respectively. By recognizing the peaks in the power distribution, the system can infer the checkerboard the operator is focusing on, and thus identify which command the operator would like to select. The inference system then sends the detected command via TCP/IP to the robot for execution.

In a more advanced approach, this frequency encoding can be replaced by showing different pseudorandom sequences, for example, m- or Gold-sequences. Then, the system can use template matching or other temporal-modeling-based decision-making mechanisms.

Figure 6 shows the average responses of the visual cortex for four separate 31-bit m-sequences flickering the visual stimuli at 30 bits per second.[6] Notice that the visual cortex response clearly varies for different m-sequence visual inputs. Thus, this approach might make it possible to utilize ideas from digital communication theory, where commands can be encoded with unique signature sequences and inference methods, robust to interference from neighboring flickering objects, and more reliably distinguished (as in CDMA communications) using code-based filtering. This latter approach might further have the benefit that natural brain activity can strongly influence the power spectrum, so pseudorandom-code-based stimuli can be potentially detected and classified more reliably than frequency-based visual stimuli.

In our first prototype design, we found that an operator could achieve greater than 99 percent accuracy in selecting between four commands for the robot using one-second EEG signals per decision along with the m-sequence coded
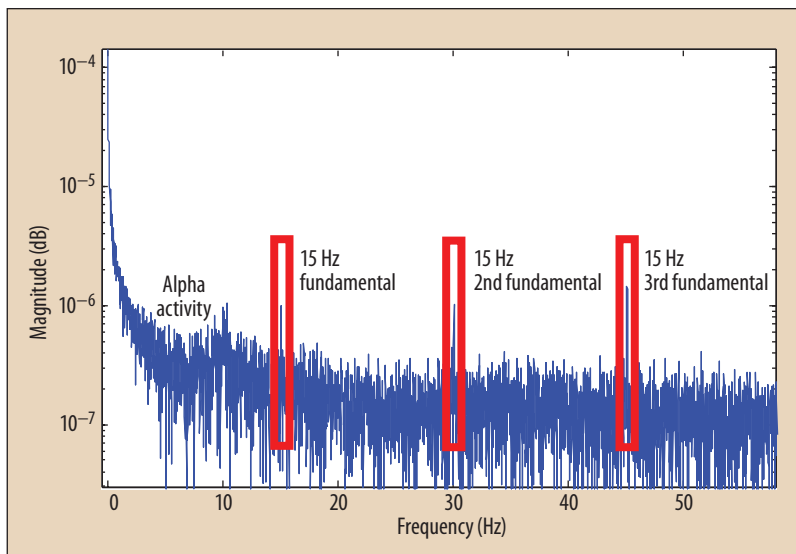
Figure 5. SSVEP power spectrum for a flickering LED visual stimulus blinking on/off following a 15-Hz square wave with 50 percent duty cycle.
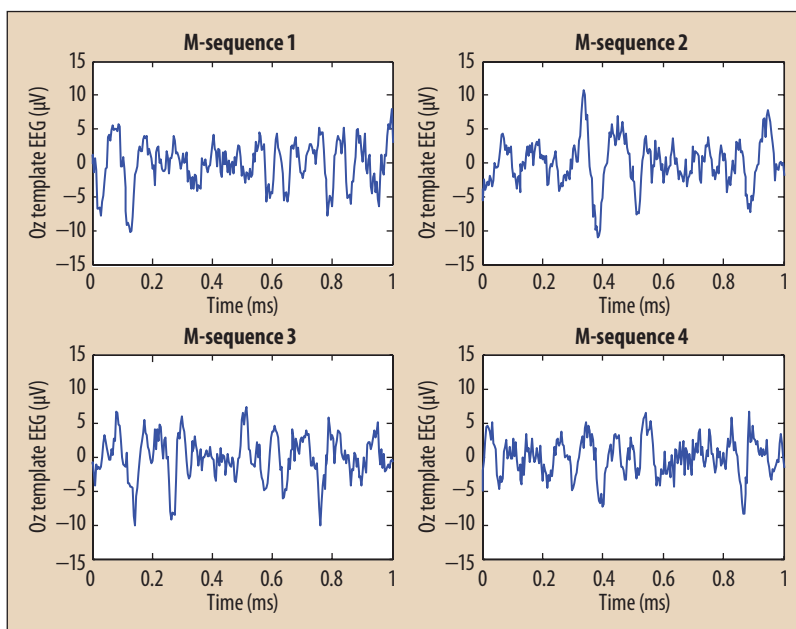
Figure 6. SSVEP average waveforms in response to four separate m-sequences controlling the flickering patterns of checkerboard patterns displayed on an LCD monitor. All signals are measured at Oz in the international 10-20 configuration, with the stimulus located central to the visual field at a distance of approximately 60 cm.

flickering paradigm to induce SSVEPs in the brain with simple nearest-template classification. Further research is needed to make more commands available in the limited visual field, which requires better signal processing because interference from nearby flickering patterns causes a reduction in accuracy.

Our future research will focus on improving signal processing and statistical inference with the help of better physiological signal modeling and improved contextual

modeling. We still need to include other physiological signals and signal processing on the embedded platform for optimal real-time performance and integration.

ROBOT ASSISTIVE TECHNOLOGY

Robotics, the integration of sensing, computation, and actuation, is integral to a HiLCPS as robots provide the interaction with the physical world.[7] Even though robotics research and enabling technologies for practical applications are making significant progress, it is essential to develop novel methodologies for the design, modeling, and control of robotic systems that can work safely with people in shared spaces. Modular and reconfigurable designs, plug-and-play integration of cyber and physical components, composability, and optimizing the role of the human comprise a short-list of current HiLCPS research challenges.[7]

> **Robots can and probably should perform tasks such as precise low-level motion planning, solving an optimization problem, and operating in dirty, dull, and dangerous situations.**

New applications

While robot assistive technologies cover a range of applications from helping persons with autism to eldercare to stroke rehabilitation, an essential area of research is the development of intelligent wheelchairs and safe robotic arms to assist physically locked-in individuals.[1] State-of-the-art wheelchair-arm systems can perform obstacle avoidance, simultaneous localization and mapping (SLAM), path planning, and motion control with a shared autonomy framework.

However, important research questions for implementing shared control of an intelligent system still remain: Who controls the system—human or machine—and when? Under what circumstances does the human or the machine override a decision? How can HiLCPSs decide adaptively on the level of autonomy? Early efforts in the development of smart wheelchairs tackled these issues by providing the user with an external switch or button to trigger a change in operation mode. Another approach is to implement the mode change automatically, where the shared control switches from human control to machine control and vice versa.[8]

Within the experimental setup and control architecture for a HiLCPS testbed developed by our research teams at Northeastern University and Worcester Polytechnic Institute, the semiautonomous wheelchair receives brain signals from the user for a high-level task such as Navigate-to-Kitchen, and then executes the tasks of path planning, obstacle avoidance, and SLAM. Using the robot operating system for wheelchair navigation results in a modular communications and software design.

Shared control

In the HiLCPS context, there are certain tasks in which humans are and probably always will be superior to robots, such as perception, intuitive control, and high-level decision making. On the other hand, robots can and probably should perform tasks such as precise low-level motion planning, solving an optimization problem, and operating in dirty, dull, and dangerous situations. Therefore, the investigation of new control interfaces and shared control methods that can effectively delegate tasks and blend the control between robots and human operators will make it possible to field robot systems that act in direct support of humans.

We can classify most currently deployed robots in two categories: fully autonomous, performing specific tasks; and teleoperated, with little to no intelligence. Although not all human-robot interactions fall into these two categories, they represent most currently available systems. The development of control techniques that will dynamically shift the level of control between the human operator and the intelligent robot will be the key to increased deployment of HiLCPSs.

Within this shared control framework, addressing the tight physical interaction between the robot and human remains a key research problem.[9] To operate robots in close vicinity of humans, global safety protocols should be developed, and fail-safe modes should be implemented to realize a practical system. In addition, force and tactile sensing interfaces can be used for physical human-robot interaction to enable safer operation of a robot near a human operator.

Modularity and reconfigurability

Modular and reconfigurable robot design is another important aspect of engineering the future HiLCPS. Modularity requires reusable building blocks with well-defined mechanical, communication, and power interfaces. It allows low-cost development, reusable hardware and software components, and ease of maintenance as well as improvements in design time and effort.

Reconfigurability brings together modules such as sensors, actuators, and linkage in various configurations to compose robotic systems for environment interaction. Modular and reconfigurable cyber and physical components will enable the accelerated and cost-effective composition of HiLCPSs.

WIRELESS BODY AREA NETWORKS AND PHYSIOLOGICAL SIGNALS

In addition to EEGs, auxiliary sensors that measure physiological changes in blood pressure, muscle activity,
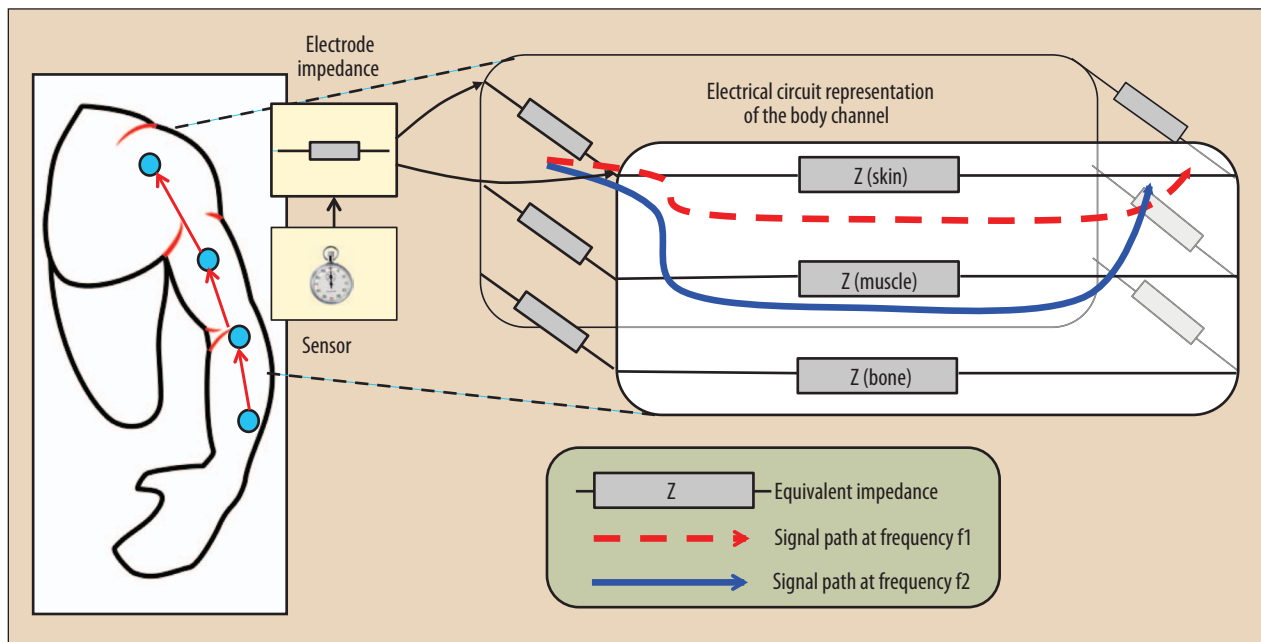
Figure 7. Overview of the WBAN through body-coupled communication. Different types of body tissue—skin, fat, muscles, and bone—each offer varying but measurable levels of signal impedance.

and skin conductivity, among others, can significantly enhance a HiLCPS's capabilities. In addition to intent inference, these sensors can detect any sudden abnormal changes or stress that the human cannot otherwise communicate. In addition to alerting caregivers to medical emergencies, such a sensor network also provides a context for the inference engine/control module. Thus, an assistive WBAN makes it possible to understand both the intent and the condition of the human signaling that intent.

A WBAN comprises small interconnected sensors that can either be placed noninvasively on the subject's body or surgically implanted within it. These sensors can monitor a wide range of physiological and emotional states and communicate this sampled data to a centralized monitoring entity.[10] Because our goal is to develop an open platform for the holistic and automatic design of embedded HiLCPSs, our work will address several unique architectural and functional characteristics of WBANs related to the limitations of energy (especially for implanted sensors), heterogeneity, and interference.

Our general approach leverages the human body as the communication channel, resulting in significant reduction in the energy used compared to RF transmission using electromagnetic waves. In this new body-coupled communication (BCC) paradigm, the signals are placed through electrical impulses directly in or on the surface of human tissue, at the point of data collection by the sensors. As a key motivation, the energy consumed in BCC is shown to be approximately 0.37 nJ/bit—three orders of magnitude less than the low-power classic RF-based network created through IEEE 802.15.4-based nodes.

The wide variety of available monitoring applications requires transmitting periodic scalar data or continuous pulses, ranging from cardiovascular state monitoring to one-shot emergency notifications, such as indicating the onset of an epileptic seizure, that must take precedence over all other forms of periodic monitoring. The high bandwidth availability of BCC, approximately 10 Mbps, sufficiently accommodates the needs of such varied sensor measurements. Moreover, this form of communication offers considerable mitigation of fading as it is not impaired by continuous body motion and disruption to a clear line of sight, as is common in the RF environment. This allows for simpler modulation and signal generation/reception schemes that the sensor's limited onboard capability can accommodate.

Finally, BCC can overcome the typical problems of external interference in the ISM band's various channels, which typically carry transmissions from wireless local area networks, including Bluetooth and radiation from microwave ovens. However, this injected signal should remain in the 100-KHz to 60-MHz range: at the lower end of the frequency scale, there is a risk of interfering with the internal and implanted electrical signals from devices within the human body, such as a cardiac pacemaker. At the higher end, above 100 MHz, the average height of a human body approaches the same length as the signal's wavelength, making it function as a lossy antenna and causing it to radiate the energy externally.

Our work mitigates this potential problem by using the electrical circuit-equivalent representation of the body channel,[11] in which different types of body tissue—skin,

fat, muscles, and bone—each offer varying but measurable levels of signal impedance, as Figure 7 shows. As an example, the fat layer's relative permittivity varies from $1.0 E + 2$ at 100 KHz to $2.0 E + 1$ at 5 MHz. This frequency-specific change in signal conduction levels must be considered in link-layer design. Moreover, the electrodes' contact impedance means that the signal is differentially applied to the input point.

Our link-layer design uses this channel model to identify the loss of signal strength and construct simple error correction schemes that ensure reliable packet delivery. If multiple sensors report a signal being forwarded to a distant pickup point on the body, the total charge density must be less than 350 μC/cm², which will determine which sensors can concurrently access the body channel to send their measurements.[12]

Depending on node placement, the transmitting sensor will also need to optimize both the injected signal power and the frequency, as these signals propagate to a different extent within the human tissue and along the surface distance from the generation point. This will lead to power/frequency tuples uniquely assigned to each neighbor node, such that only a single node is addressed with that combination, further reducing the packet header lengths and interference possibility.

As an initial demonstration, we will use skin conductivity and muscle activity monitoring sensors placed at five locations—both palms, both arms, and the torso. These sensors will send inputs periodically via BCC to a predetermined collection point on the body, from which the physiological data will be transferred to the embedded control system. The channel characteristics will define the required complexity of signal modulation and error correction capability, which both the signal-generating sensor and the embedded controller must support. These inputs will provide clues to the system when the human operator registers his or her intent. For example, heightened stress levels alter skin conductivity and cause involuntary muscle action, a factor that influences the subsequent robotic actuation.

The BCC paradigm will usher in a new communication method for the BCI system to gather enhanced knowledge of the human condition, which will empower it to make better situational decisions on the needs of the integrated intent-decision closed-loop system.

HiLCPSs offer an exciting class of applications both for restoring or augmenting human interaction with the physical world and for researchers faced with the interdisciplinary challenge of combining semiautonomous robotics, WBANs, embedded system design, and intent inference algorithm development.

Our holistic design methodology enables cross-disciplinary optimizations and facilitates the cross-pollination of ideas across four previously disjoint disciplines, thus leading to otherwise unachievable advances. In addition, our outlined project establishes an open prototyping platform and a design framework for rapid exploration of a novel human-in-the-loop application, serving as an accelerator for new research into a broad class of cyberphysical systems. **C**

Acknowledgments

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