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14. ABSTRACT
Warfighters who suffer combat, training or accidental injuries that damage their sensory capabilities or mobility have great difficulty returning to productive lifestyles once healed from the initial trauma. This project advanced technologies for non-invasive sensory and mobility augmentation in order to allow these individuals to regain hope and social, productive lifestyles. We addressed the needs of these wounded warriors through evaluation of current sensory substitution technology, identification of specific injured servicemember requirements for sensory augmentation, development and demonstration of new sensory substitution techniques and application of these techniques to mobility enhancing devices to improve teir usability.

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Final Report for

Sensory Substitution for Wounded Servicemembers

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a. Scientific and Technical Objectives

Warfighters who suffer combat, training or accidental injuries that damage their sensory capabilities or mobility have great difficulty returning to productive lifestyles once healed from the initial trauma. This project advanced technologies for non-invasive sensory and mobility augmentation in order to allow these individuals to regain hope and social, productive lifestyles. We addressed the needs of these wounded warriors through evaluation of current sensory substitution technology, identification of specific injured servicemember requirements for sensory augmentation, development and demonstration of new sensory substitution techniques and application of these techniques to mobility enhancing devices to improve their usability. Specifically we accomplished the following objectives:

1) Identified sensory substitution requirements specific to wounded servicemembers for partial mitigation of vision sensory and mobility losses.
2) Improved the usefulness of available sensory substitution technologies for injured military servicemembers through software, hardware and data fusion.
3) Developed sensory substitution systems for warfighters suffering from loss of vision, balance and hearing.
4) Developed sensory substitution enabled assistive mobility devices to provide functional restoration for servicemembers with mobility loss.
5) Investigated novel sensory substitution interface technologies.

b. Approach

Advances in warfighter personal protection and combat casualty care have markedly improved battlefield survivability rates for those wounded in action. The traumatic brain injury and somatic polytrauma suffered by this growing population may evolve over many months post trauma and manifest significant loss of one or more sensory channel. Specific areas of the brain (e.g., the visual cortex) receive information from specific sensory organs (e.g., the eyes) in the form of pulses carried by afferent nerves. Sensory feedback from these organs, associated with interaction with the environment, guides and reinforces sensory perception. Because perception takes place in the brain, not at the end organ (Bach-y-Rita, 1972), the brain can reinterpret signals from specific nerves with appropriate sensory feedback. While non-invasive sensory substitution technologies do not provide *replacement* for lost sensory capabilities, they can *augment* residual sensation. This iterative, interdisciplinary research and development project dramatically improved sensory substitution interface and mobility assist exoskeleton technologies. Through sensory substitution device demonstrations, we solicited subjective situation awareness feedback from injured servicemembers and identified technology requirements specific to the needs of this population.

c. Concise Accomplishments

During this project (16 April 2007 - 31 December 2008), we conducted organizational meetings that included a site visit by the ONR program manager. We executed subcontracts to Wicab, Inc., (Middleton, WI) and ForeThought Development, LLC, (Blue Mounds, WI) to initiate development of modernized electrotactile interfaces. We presented project overview, goals and technology demonstrations to the Commander U.S. Army Medical Command/Acting The Surgeon General, MG Gale Pollock. We demonstrated the BrainPort® (Wicab, Inc., Middleton, WI) vision system that interfaces to the tongue, as well as IHMC's prototype peripheral vision tactile torso interface to three blind veterans and one active duty blind servicemember. An additional veteran with traumatic brain injury (TBI) and two civilians, all with partial visual impairment, evaluated the vision sensory substitution systems. The servicemember with TBI also evaluated the passive mobility assist exoskeleton, which enabled him to walk at a normal gait, unassisted, for the first time since emerging from his coma. We prototyped an electrotactile hearing aid and an integrated multisensory balance augmentation system. We provided the Naval Medical Center-San Diego and the Atlanta Veterans Affairs Hospital with Wicab, Inc., balance prosthetic/ therapy devices for use in their protocols with veteran/active duty servicemembers with balance disorders (including TBI).

d. Expanded Accomplishments

Sensory substitution refers to the remapping of sensory data from one sensory capability to other channels of information perception. Sensory loss resulting from congenital defect, environmental exposure or trauma can be mitigated by appropriate use of sensory substitution interfaces that present data using intact sensory pathways. The plasticity of the brain allows a user to learn to perceive the substituted data with little cognitive effort. For maximal benefit, the interface must intelligently pre-process the incoming data to account for differences in capability between the alternative channels and the ones normally used to perceive given sensory data. Many devices and approaches for sensory substitution have been developed, and the concept itself is a century or more old (Machts, 1920). Modern computer and electronic design, however, has now enabled the development of intelligent, non-invasive, human-centered interfaces unobtrusive enough to be used in everyday activities. During this project, we advanced these existing technologies, creating sensory substitution interfaces that could mitigate sensory and mobility loss. All components of this project related to technology development and application. The four areas of effort included: sensory substitution interfaces (SSI), mobility assist exoskeletons (MAE), process integrated mechanisms (PIM) and electrochemical sensory displays. Sensory substitution prototypes were developed for components of vision, balance and audition. Wearable exoskeleton devices, including powered exoskeletons with custom designed compliant rotary joint actuators and passive exoskeletons that mimic natural, energy efficient human gait and weight bearing were developed for mobility assistance. Preliminary investigations were performed to evaluate possible candidate chemicals for electrochemical transmission of signals and to determine issues associated with network bandwidth usage by the multiple sensory and display software components in the sensory substitution and exoskeleton systems.

Development

Sensory Substitution Interface (SSI)

IHMC completed two major tasks in SSI technology development: device development and interface integration. For device development we contracted two companies with prior expertise in development of electrotactile interfaces, Wicab, Inc. (Middleton, WI) and ForeThought Development, LLC (Blue Mounds, WI). Each of these companies had previously developed prototype and research devices based on technologies originally invented by the late Paul Bach-y-Rita and his team at the University of Wisconsin. These products were advanced as part of this project. In addition, IHMC advanced an in-house designed vibrotactile interface. These three devices comprised the tactile display technologies developed for use as SSIs. Additionally, IHMC implemented a twelve channel surround sound processor system that provides directional (spatial) audio.

The SSIs were used to develop systems that could provide sensory substitution to wounded servicemembers with vision, hearing or balance loss or various combinations thereof.

Tactile Interfaces

Wicab, Inc., BrainPort® device: The BrainPort® devices available at the start of the project consisted of a 10x10 tongue array. An earlier prototype employed a 12x12 array that was deemed too large for some users. While the 100 tactile transducer (tactor) array suffices for balance sensory substitution, the low spatial resolution does not support vision or hearing substitution well. As part of this project, Wicab, Inc., increased the resolution of the arrays to 18x18 and finally to 25x25 electrodes while maintaining the same array size (Figure 1).

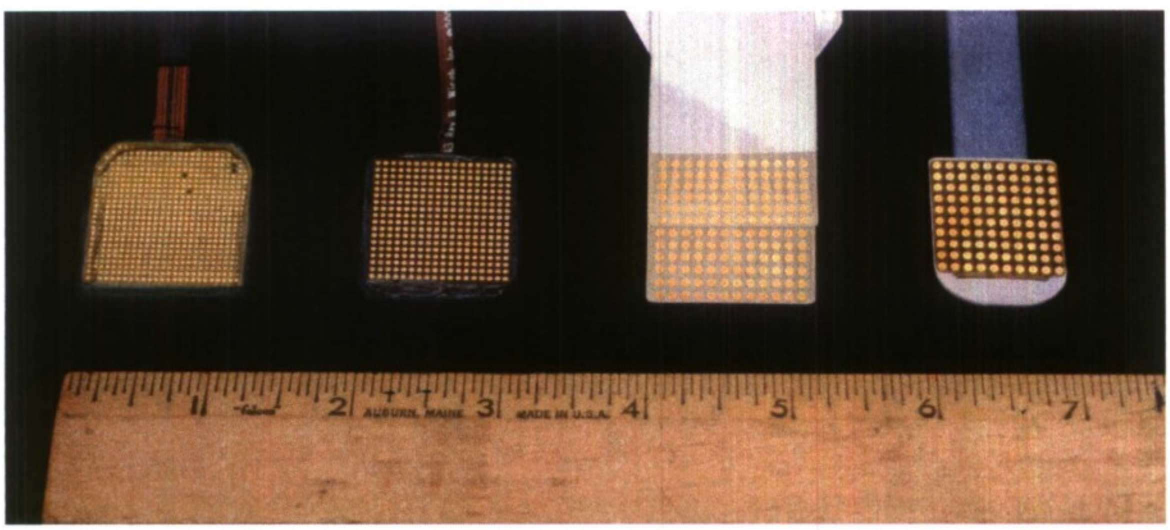

Figure 1: Wicab, Inc., BrainPort® Intra-Oral Device (IOD) progression, *right to left*, 10x10 and 12x12 low density IODs available at the beginning of this project, 18x18 medium density IOD used for demonstrations in this project and 25x25 high resolution IOD delivered at the end of the project.

The smaller, more densely packed arrays in these prototypes increased performance of the BrainPort® concept sufficiently to prove its usefulness for vision and hearing applications. Improvements included: moving more circuitry into the Intra-Oral Device (IOD) to minimize cable size, revising the

IOD assembly process to reduce electrode erosion by capping the gold electrodes with 316LVM stainless steel, encapsulating the IOD in epoxy resin to reduce moisture intrusion into the circuitry and reducing the system power consumption to lower system weight. These project developments have been incorporated into the newest version of the BrainPort® vision device now available for clinical research investigations.

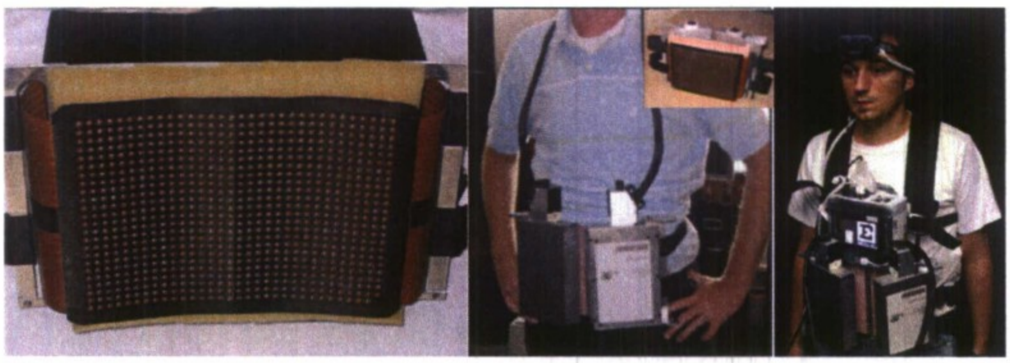

Figure 2: From *left to right*, ForeThought Development, LLC, VideoTact™ array, worn by itself on the abdomen and worn in conjunction with the BrainPort® vision system.

ForeThought Development, LLC, had developed their original VideoTact™ abdominal array in the 1990s to provide a bridge for the blind as personal computer user interfaces moved from textual to graphical paradigms. While a number of their arrays were produced, the decade old technology relied on computer interfaces and integrated circuits which are no longer available or in common use. For this project, ForeThought Development created a modified version of their original VideoTact that employs a modern Ethernet (TCP/IP) control interface as well as packaging changes to make the system more compatible with IHMC's tactile torso interface (TTI) and the BrainPort® systems (Figure 2). Moving from a dedicated 16 bit PCI card interface to an Ethernet interface minimizes the weight of the cable that tethers the unit (and the user) to the computer and allows any PC to control the interface (e.g., laptops, tablets, ultra mobile PCs, etc.). These smaller PCs can be worn on the body, making the system fully wearable for navigation in free space. The techniques developed in this project were used to set the requirements for the next generation system that will be miniaturized, untethered and wearable under the user's clothes.

The IHMC TTI system (Figure 3) is an in-house developed implementation of the U.S. Navy/NASA/IHMC Tactile Situation Awareness System (TSAS), a novel tactile situation awareness (SA) display designed for aviation (Raj, Kass & Perry, 2000). For this project, it was updated with new printed circuit boards to allow remote digital enable/disable control of individual tactors (a function that was previously controlled only by physical switches). This allows for selective disabling of tactors by the control software. This also ensures perception, even in a location with a broken tactor, through the spatial summation provided by activating neighboring tactors at appropriate intensities. The mechanism of donning and doffing the TTI garment was simplified and a second garment was assembled to enable two individuals to use the system simultaneously.

Figure 3: From *left to right*, IHMC's TTI control hardware and the TTI garments. Front panel lights indicate left TTI channels 1-4 manually disabled (no illumination) and right TTI channels 1-4 disabled remotely via software (blue). Enabled tactors (green) turn red during thermal shutdown and yellow when driving a bipolar waveform.

Comments made by blind demonstration participants indicated some limitations to video camera based sensory substitution. For instance, the blind do not always turn on room lights and, while they can easily learn to control the camera field of view, the requirement to actively adjust zoom prevents the natural simultaneous perception of foveal and peripheral vision used by sighted individuals. In particular, touching a recently blinded individual without verbal notification (e.g., to tap his or her shoulder) can lead to a startle response as he or she can not perceive anyone approaching. To provide simultaneous peripheral and foveal vision substitution, IHMC designed and breadboarded a sensor that could provide 360 degree peripheral vision via the TTI. It uses conventional infrared (IR) light emitting diode (LED) transmitters and television remote detector parts spread over twenty four emitter/receiver pairs evenly distributed and mounted to a cap worn by the user (Figure 4).

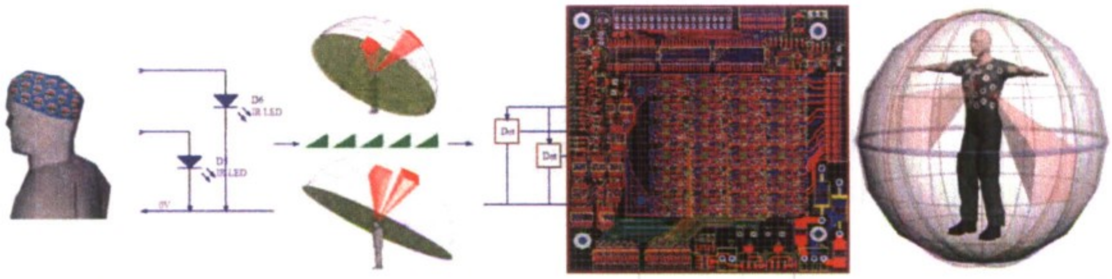

Figure 4: left to right, cap bearing IR emitter/receiver modules; LEDs illuminate sequentially; LEDs driven by a 38KHz pulsed variable chirp signal; IR detectors receive reflected 38KHz IR signals; Printed circuit board to implement 24 channel detector; TTI representation of detected signals.

Initial tests indicate that the circuit provides accurate detection of IR reflective objects in a range from 2 inches to 15 feet. Distance is correlated with time by capturing returns from a 'chirp' illumination signal using 64 time-sequential 24-bit frames. Linear and inverse square-law power output can be alternated for near and far field detection, respectively. A PC-104 form-factor multilayer circuit board was designed to provide this functionality in a modular, small package suitable for testing as a body worn device (Figure 4). Software determines which LED caused the reflection as well as its intensity at the time of detection to estimate range. This provides azimuth, elevation and range to physical objects in the environment. Future development will include moving the software-based algorithm into a Field Programmable Gate Array (FPGA) chip. This implementation should improve performance by allowing a rapid segregation of detected movements that result from self-motion from those due to objects moving in the environment. This will pre-filter the data so that minor head movements do not cause excessive TTI activity and to increase the saliency of objects moving in the environment.

Dynamic Posture and Balance System

The current BrainPort® Balance Device prosthetic (Figure 5) can effectively substitute for lost vestibular (i.e., otolith) organ function by providing missing balance organ cues. Using a triaxial accelerometer embedded in the intra-oral device, this system displays head tilt as a tactile stimulus that deviates from the center toward the edge of the array in two degree increments up to ten degrees (heathy individuals with a normal upright posture will fall if their tilt angle exceeds approximately 12.5 degrees). As patients progress through a three month rehabilitation program, however, they rapidly learn to utilize other balance system cues. After completing the training protocol, users with vestibular deficits no longer need the BrainPort® Balance Device and can return to many of their previous activities of daily living (ADLs). Users may gain this lasting effect by incorporating data from the remaining portions of the balance system, namely the somatosensory sense (touch, muscle stretch receptors, joint position, etc.) and vision, as well as any residual vestibular function.

Loss of the vestibular organ often occurs rapidly following trauma, surgery or exposure to ototoxic substances (e.g., antibiotics) and the confusing sensations may overwhelm the individual and instill a fear of activity due to falls and paroxysmal nausea. Standard vestibular rehabilitation physical therapy consists of progressively more provocative perturbing maneuvers to stress the patient's balance and desensitize them from nausea. The BrainPort® Balance Device may mitigate the fear of falling during rehabilitation, allowing more rapid sensorimotor reorganization for integration of the alternate sensory cues.

Unfortunately, not all balance disorders arise solely from vestibular deficit. Traumatic brain injury, peripheral neuropathy, spinal injury and amputation(s) may also dramatically affect balance. In addition, the BrainPort® device provides veridical balance information only when the user stands upright, with his or her feet inline with and below the shoulders. For example, an individual leaning over to pick up a dropped item may change stance and remain completely stable, but the BrainPort® would only indicate (on the tongue array) that the individual's head has tilted beyond degrees.

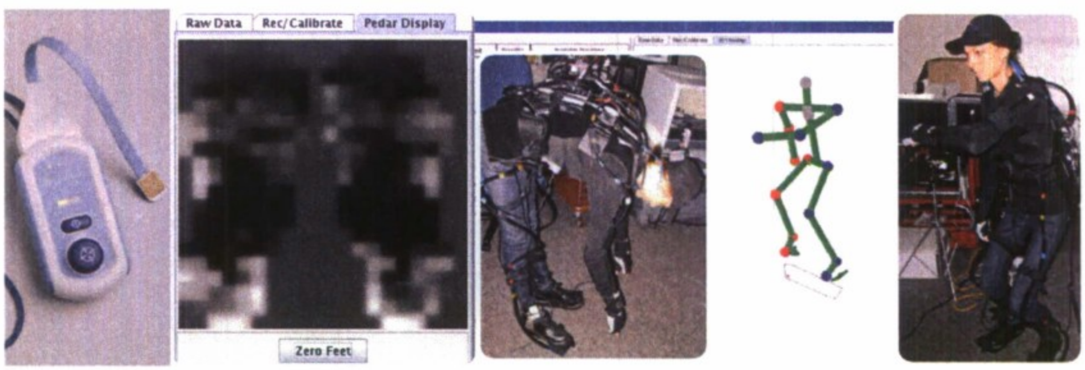

Figure 5: *left to right*, BrainPort® Balance Device; Visual display of insole load cell activity; and Dynamic balance assistance prototype. Graphic (green avatar) indicates that user (right most inset) has a stable stance as the CG (small magenta dot) remains within her center of pressure stability polygon (projected below the avatar's feet). CG deviations outside the box are presented to the user tactually.

In order to provide a more fully functional and dynamic balance sensory substitution system, IHMC created a system (Figure 5) that accurately determines both the center of pressure between the user's feet and his or her center of gravity (CG). As long as the center of gravity remains over the center (within 12.5 degrees of the edges of the user's contact patch with the ground), he or she should be able to balance without changing stance. This system employs custom designed insole pressure transducer arrays with 132 load cells in each insole (Pressure Profile Systems, Inc., San Diego, CA) and a full body, wearable motion capture system (ShapeWrapII, Measurand, Inc., Fredericton, NB). The insoles determine center of pressure under each foot while the motion capture system determines the position of each foot relative to the torso to determine the convex polygon in which the CG must remain for stability. Using a look-up table of average mass for hands, forearms, head, torso, legs and feet, the system calculates the moment of each appendage to estimate the three dimensional location of the CG (Figure 5). The angle relative to the contact patch polygon can represent deviations from stable stances tactually on the BrainPort®, VideoTact or TTI. The ShapeWrapII system and the Pressure Profile system both use wireless radio frequency communications (802.11b and Bluetooth, respectively) to transmit data to the control computer running IHMCs AMI balance agent software, allowing the user to move freely indoors or outside during ADLs.

Hearing Substitution

IHMC developed a prototype, wearable stereo hearing substitution system that presents a stereo tactile audio spectrograph on the tongue. This can enhance the saliency of human speech in the ambient acoustical environment and can be implemented using either the VideoTact® or the BrainPort® (Figure 6). The system decomposes audio from two microphones, computer generated audio and pre-recorded audio files into frequency spectrograms that are presented visually and tactually. By implementing software voice recognition techniques, the system identifies components of the audio stream that contain human speech phonemes and selectively increases the amplitude of those sounds. This increases the power of the phoneme frequency in the spectrogram, enhancing the salience of human speech in the ambient auditory environment.

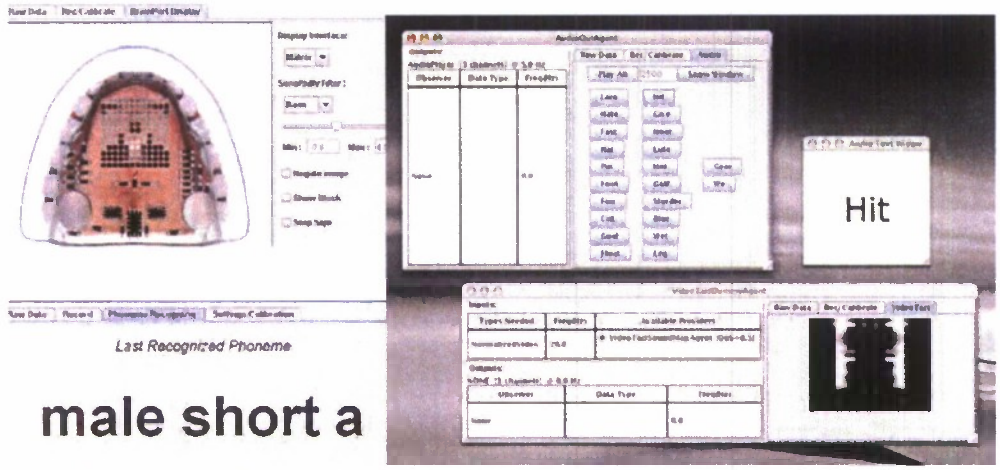

Figure 6: *left*, BrainPort® display showing stereo presentation of a sound containing a short "a" with augmentation of the "a" frequencies' power; *right*, Auditory sensory substitution training system for VideoTact showing pre-recorded words used for training and recognition.

During training, the system displays a word as text and as both visual and tactile spectrograms. After training, the computer monitor is blanked, and the system displays only the tactile spectrogram of each word to the participant. Initial evaluations with a limited vocabulary (22 words representing different phonemes) indicate that users can reach 70% correct recognition with 20 minutes of training. Future development will focus on improving stereo perception for locating sound sources and improving speech perception. A tactile hearing aid could eventually assist servicemembers who cannot benefit from a cochlear implant. Signal processing software could also be developed to enhance localization and identification of particular sounds (e.g., phones, car horns, fire alarms, etc.).

Software Integration

The above systems utilized IHMC's Adaptive Multiagent Integration (AMI) architecture to integrate previously existing software agents rapidly with new equipment. AMI uses standardized Java (Sun Microsystems, Inc, Santa Clara, CA) programming techniques. Explicit ontological definitions associated with each agent allow rapid integration of new agents into the architecture. This is possible because the system makes data connections between agents automatically based on data types and relative quality of similar data streams. A large complement of devices, including video, audio, pressure, orientation and psychophysiologic sensors, have already been integrated as software agents into this Adaptive Multi-agent Integration (AMI) architecture (Johnson, Kulkarni, Carff, Raj & Bradshaw, 2005), as have the original BrainPort® and TSAS interfaces. The architecture is inherently scalable, using available processing power on wired or wireless networks. AMI allowed us to send sensor signals to multiple displays across different modalities (e.g., video, audio, vibrotactile, electrotactile, etc.) simultaneously or separately to evaluate various sensory substitution implementations.

The AMI architecture supports hierarchical data reduction, conditioning and polishing such that at each level of reduction, suites of sensor data can be estimated. This significantly improves usability by providing feedback without overwhelming the user with data (Drakunov & Meystel, 1998). For example, at the sensor input level, readings are inherently noisy but exhibit a systematic pattern of distortion that can be used to "polish" out the errors (Teng 1999; 2004). Observer agents in AMI (with both linear and non-linear explicitly defined system and subsystem models) provide continuous data estimates to replace intermittent sensor data loss or corruption (DeCarlo, Zak & Drakunov, 1996; Drakunov, 1992). Observers operate as computational "mental models" to provide estimates of missing or erroneous data based on available data. An example of how AMI works follows.

Using the AMI architecture, we implemented a system that enabled blind users the ability to interact with a graphical user interface (GUI) while controlling sensory substitution tactile displays with their intact extraocular muscles (even with prosthetic eyes). Correctly estimating the user's visual point of regard requires knowledge of eye position relative to the head, the user's head position in space and calibration with respect to the environment or area of interest (e.g., the GUI). The mathematical and geometrical foundation of gaze tracking uses Euler angles and quaternions. The Euler angle terms correspond to rotations (Euclidean frame of reference) relative to the local base of a plane. The quaternion equations extend the concept of rotation from 3 dimensions to 4 dimensions, allowing determination of more precise angular position by avoiding singularities inherent to Euler angle calculations that cause "gimbal lock" in aircraft.

Our gaze estimation (Figure 7) implementation uses successive frame transforms based on quaternions and is calculated using Java3D libraries. For this project, we wrote low level code using Java Native Interface (JNI) methods to access data from manufacturer supplied device drivers. Java AMI software agents were then created to call the JNI code for the head tracker and eye tracker systems. Simple data polishing performed in these algorithms reduce jitter and filtered out eye blinks. A third agent combines the input from these agents to estimate gaze (eye point of visual regard) which provides an additional level of smoothing.

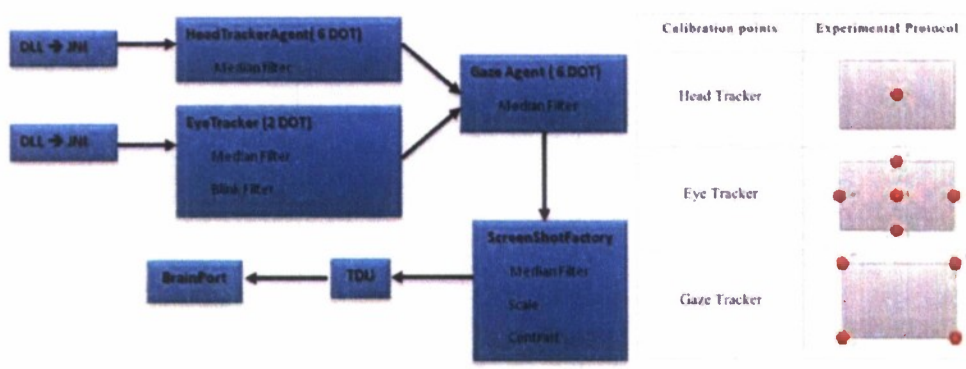

Figure 7: *left*, Schematic of visual substitution of gaze via the BrainPort®; *right*, Calibration procedure to register gaze to screen coordinates.

A nine point procedure calibrated the agents relative to a computer monitor (detents were created along the bezel of the monitor and blind users were instructed to imagine looking at their finger tip when they touched each detent). This gaze position estimate provides the x, y and z coordinates of the point of regard relative to the screen. This then allows another agent to take a screen shot (100-200 pixels) at the gaze point and send it to the Tongue Display Unit (TDU) Agent, which grayscales and normalizes the image before transmitting it to the BrainPort® (Figure 8).

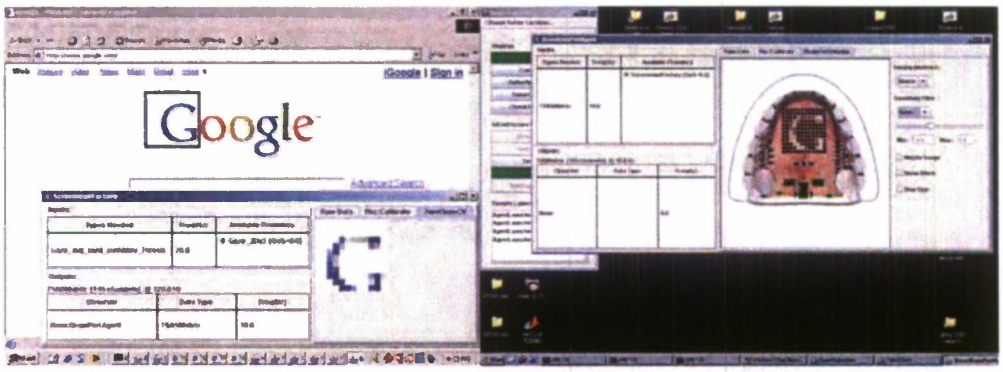

Figure 8: *left,* Gaze position marked by black reticle and sampled (inset); *right,* Visual representation of tactile image sent to BrainPort® based on gaze position.

One drawback to multi-agent systems relates to their network bandwidth usage. This increases with the number of agents and the rate of data signals (e.g., when using video and audio streams). The process integrated mechanism (PIM) concept was evaluated as a method of managing network usage to ensure timely delivery of data to all displays. PIMs operate as a single collaborating system by virtue of a single program that moves rapidly between all the available processors in the system (wired and wirelessly networked). Using a single program greatly simplifies the complexity of developing a solution for coordination and collaboration while at the same time improving the ability to debug, verify, and validate the solution and ensuring predictable network traffic. Only the program's state variables pass over the network from node to node as each processor performs its operations in turn. This makes the network traffic consistent and manageable, even with high data rates and multiple agents. Our approach encapsulates related agents as single PIM nodes, such that agents related to a given function operate normally in AMI, but the top level (the

Gaze Agent, in this example) would connect to other agents (e.g., the Screen Shot Agent, the BrainPort® Agent, etc.) through a PIM architecture. This allows access to each high level function in the overall architecture without flooding the network with only locally relevant traffic. The observer and PIM approaches can improve robustness, resiliency, predictability and efficiency in complex sensory substitution systems.

Electrochemical interfaces

The current BrainPort® electrotactile array electrode size and placement density has reached the limit of industrial flexible circuit manufacturability. We reviewed a number of alternative concepts for creating smaller, more densely packed electrodes to provide higher resolution displays. These included magnetic patches coated with an enzyme that diffuses into the tissue to stimulate the nerves, electrically actuated microfluidic arrays that release neurotransmitters (Glutamate, Kainate, Quisqualate, Alpha-amino-3–hydroxy-5-methyl-4 isoazolepropionic acid, N methyl D aspartate, etc.) to stimulate synapses directly and nanowire arrays for nanoscale electrochemical stimuli. Individually addressable nanowires would provide the high spatial resolution and high sensitivity needed to maximize resolution and could result in more effective chronic neural interfaces. Exploiting these technologies was outside this projects scope.

Mobility Assist Exoskeletons (MAE)

Commonly, there are two approaches to exoskeleton design: the first is pseudo anthropomorphic; the second is anthropomorphic, where the joints are co-located as close as possible and where there are connection points at the thigh and shank as well as the foot. Although many exoskeletons have been developed, most are designed for performance (strength and endurance) augmentation and have been pseudo-anthropomorphic; the exoskeleton and the user's joints do not coincide exactly and the only connection point is at the end of the limb, making them unsuitable for applications where the exoskeleton must move the user's limbs to ensure normal gait. IHMC designed and prototyped two anthropomorphic Mobility Assist Exoskeleton concepts designed for those with weakness, loss of sensation or paralysis of one or both lower extremities. One prototype passively enforces normal gait trajectories using compound joints with multiple degrees of freedom that mimic knee and ankle motion. This device also passively locks the knee and ankle joints when weight is applied by the user. IHMC also developed powered exoskeletons that can track user initiated movements and augment strength (for those with lower extremity weakness) or move the user's legs in a normal gait pattern (for those with paralysis). Walking in these exoskeletons loads the user's legs with his/her body weight which should reduce the rate of muscle and bone degradation associated with loss of ambulation. A return to an upright posture also enhances cardiovascular fitness and helps with ADLs and social interactions which evolved around bipedal ambulation.

Passive Dynamic MAE

The Passive Dynamic MAE seeks to meet the immediate functional and ongoing therapeutic need of persons with difficulty walking due to paresis, weakness or atrophy of the leg muscles, or due to partial or total paralysis from the waist down. The passive dynamic mobility exoskeleton developed by IHMC (Figure 9) provides support for normal gait and posture by mimicking the highly efficient natural motion of the legs. The MAE mechanical joints follow all movements of the legs with minimal interference and dynamically adjust to the user's posture and gait. The joints lock automatically with body weight shifts using artificial "tendons" to support the user. The MAE supports walking without undue exertion or discomfort to prevent musculoskeletal deterioration and other complications associated with inactivity and lack of lower extremity cyclic weight bearing.

Figure 9: Initial passive dynamic MAE (left & center); revised passive dynamic MAE (right).

Using a passive dynamic MAE could increase ambulatory activity to support sensorimotor reorganization and cardiovascular fitness during rehabilitation. The MAE itself does not support full body weight; rather, the bones of the user actually carry the load. The exoskeleton merely holds the knee so it does not collapse, provides support at the thigh, and stabilizes the foot. A mechanical linkage controls the angle of the foot according to the position of the knee, so that the foot forms a stable base of support. The same linkage, together with a toe-lift spring, causes the correct foot trajectory for ground clearance (dorsiflexion) during the swing phase. For protection, the exoskeleton mechanically prevents any motion outside the natural range, while an allowance in the linkage allows the foot to extend beyond the ordinary linkage-determined walking values. When seated, the patient's feet, for example, rest comfortably and naturally flat on the floor.

Two passive prototypes were developed during this project and the second version significantly reduced the weight and bulk of the MAE to allow use when worn under loose clothing. Passive dynamic MAEs do not require batteries or other power sources, however, they cannot directly augment strength to allow stair climbing or rising from a seated position without additional injection of power. These activities would require a more complex energy storage capability or powered actuators.

Future improvements to the passive dynamic MAE systems would include linkages to generate proper pelvic motion and support and a stable, yet compliant knee and foot suspension for more dynamic activity power such as raising or lowering the knee while bearing load and standing from a sitting position or stair climbing.

Powered Dynamic MAE

To ensure comfort and to align the actuator joints to those of the user, the initial *powered* dynamic MAE prototype provides numerous position adjustments for the exoskeleton joints and the body connector braces. The ranges of adjustments were chosen to fit the 10^{th} to 90^{th} percentile of users (Tilley, 2002; NASA, 2006). The exoskeleton includes a 3-degree of freedom (DOF) hip joint that adjusts to a wide range of different sized individuals using a curved roller bearing, which locates the center of rotation approximately at the user's hip joint. Spring mechanisms allow moderate misalignment in a small range of rotation (±10 deg) at the hip joint and provide unidirectional dorsiflexion of the foot at the ankle to lift the toe during walking. The dynamic lower extremity joints were modeled as fixed, single axis joints such that each actuator axes passes through the approximate center of the user's corresponding joint. As with the passive MAE, the powered dynamic MAE does not support the weight of the user; the user's weight is transmitted through his/her bone structure to the ground. This ensures that a user's bone structure experiences normal gravitational induced loads during walking to reduce bone loss caused by disuse. The exoskeleton does support its own weight by providing a load path through the leg and feet structures to the ground and the user provides balance control using torso movements and a pair of arm crutches.

Rotary Series Elastic Actuator (RSEA)

IHMC chose series elastic actuators for mobility assistance because of their force control capabilities and their compliant behavior in the operational environment (Sensinger & Weir, 2005). The key element of a series elastic actuator is the stiff spring placed in series with the actuator. The actuator control system determines the actuator output force from the spring constant and the amount of compression of the spring (detected by a high resolution position encoder). Unlike the position control methods used with industrial robots, force control allows the system to react quickly to perturbations or obstacles that might be experienced in the real world. Rotary Series Elastic Actuators (RSEAs) developed specifically for this project were used to power the exoskeleton's joints as compact, efficient, compliant joint actuators (Figure 10).

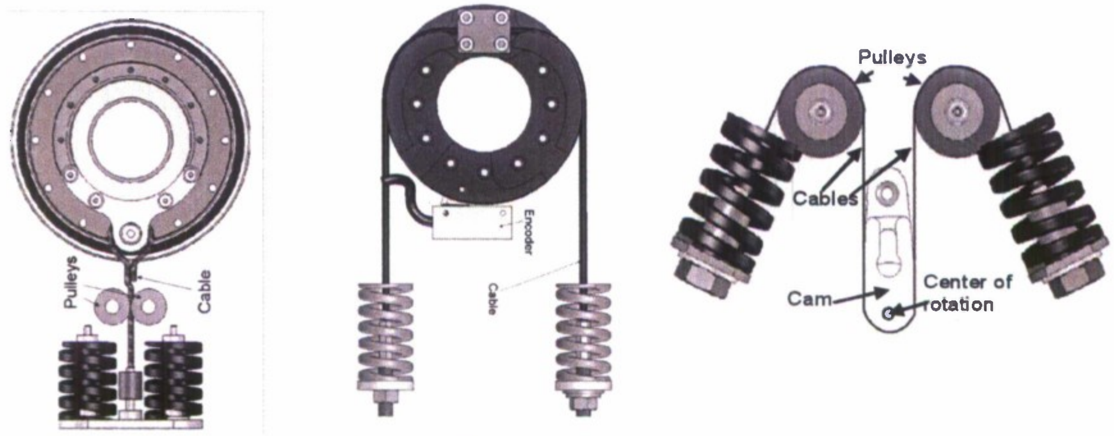

Figure 10: CAD drawings of three different Rotary Series Elastic Actuator designs tested in this project. The design on the left uses a single cable and has a non-linear torque versus angular deflection profile. The design in the middle uses two cables and springs and has a linear torque versus angular deflection profile. The design on the right uses cam shaped surface and pair springs to produce a non-linear torque versus angular deflection profile.

In contrast to their linear counterparts, rotary actuators do not require hard anchor points against which to exert force across a joint. This allows the use of soft, compliant interfaces to the lower extremities and torso and tolerance to misalignments. To prevent overextending the user's joints, the exoskeleton's joints have been fitted with mechanical limit stops tested to withstand the full power torque capabilities of the motors and amplifier setup. In addition to position and force sensors on each RSEA actuator, the MAE has foot switches at the heel and the toes to detect if the foot is on the ground and enable the control system to determine whether the exoskeleton is in the single support (only one foot is loaded), double support (both feet loaded) or toe off stage of the gait cycle.

We designed three different Rotary Series Elastic Actuators and compared their performance. The design that exhibited the most linear torque versus deflection profile also demonstrated the best torque and position closed-loop bandwidth performance, and following mechanical design optimization, was used for all six actuated DOF (see Table 1).

TABLE I

LIST OF THE EXOSKELETON DEGREES OF FREEDOM AND THEIR CONTROL METHOD.

Joint	Control Method	Range of Motion
Hip Pitch (extension)	Actuated	+42° (fwd), -30°(back)
Hip Roll (adduction)	Actuated	+25° (out), -30° (in)
Hip Yaw (rotation)	Passive	± 10°
Knee Pitch (extension)	Actuated	+0 °, -90 °
Ankle Pitch (dorsiflexion / plantar flexion)	Passive	+20° (up), -35° (down)
Ankle Roll (inversion / eversion)	Constrained	N/A
Ankle Yaw (rotation)	Constrained	N/A

The RSEA control system can use both low and high impedance within the rated bandwidth and torque output of the actuator, enabling strategies of torque, position, or impedance control or combinations thereof. As a performance enhancement device, the MAE operates in torque control mode; for disable assist applications, the MAE uses position control mode. The exoskeleton is controlled by an off-board microprocessor control system, and connects via a multiwire tether for power, control and data transfer.

Zero Assistance Control

A successful MAE device should assist the user when needed, but not obstruct the user otherwise. In zero assistance control mode, the IHMC MAE performs gravity compensation to relieve the user of the weight of the hardware, but not to provide any strength augmentation. While walking with a regular gait, a user's joint angles were recorded using a ShapeWrapII (Measurand, Inc., Fredericton, NB, Canada) wireless, wearable motion tracking system. With the IHMC MAE in this mode the user can ambulate normally while feeling little or no resistance. Figure 11 shows a comparison of the user's hip and knee flexion joint angles while walking with and without the IHMC Mobility Assist Exoskeleton in zero assistance control mode.

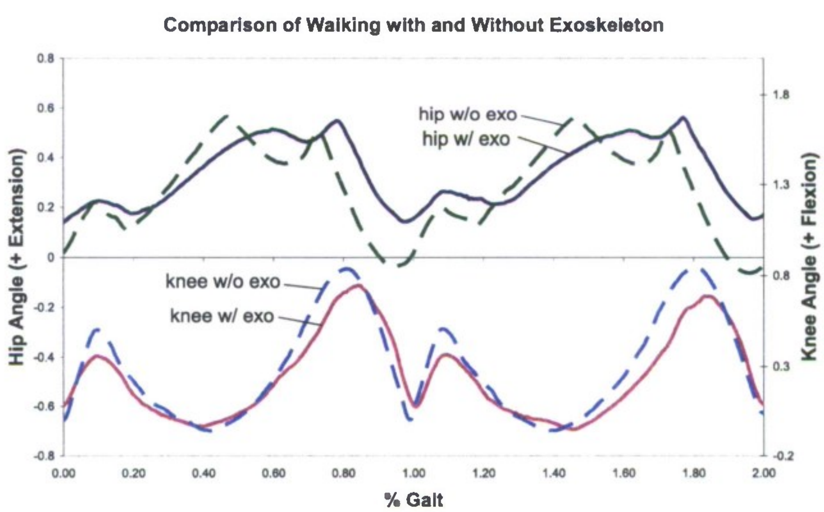

Figure 11: Comparison of hip and knee joint data without exoskeleton and with exoskeleton in zero assistance mode for regular walking. Scale and offset of joint angles show minimal changes with MAE during ambulation.

Performance Enhancement

In performance enhancement mode, the MAE counters the gravitational forces on the user, as well as any loads on the user, including the MAE system itself, using a torque control mode based on a function of the gait phase of the leg (swing or stance), the configuration of the joints, and the desired amount of assistance.

Gait Rehabilitation

The IHMC Mobility Assist Exoskeleton (Figure 12) has great potential for gait rehabilitation because of its high fidelity impedance control that can be incorporated into a mobile system. This allows for over ground gait training during, for example, rehabilitation for hemiparetic stroke survivors. The MAE control software can define the behavior of each joint separately to utilize different combinations of position and force control.

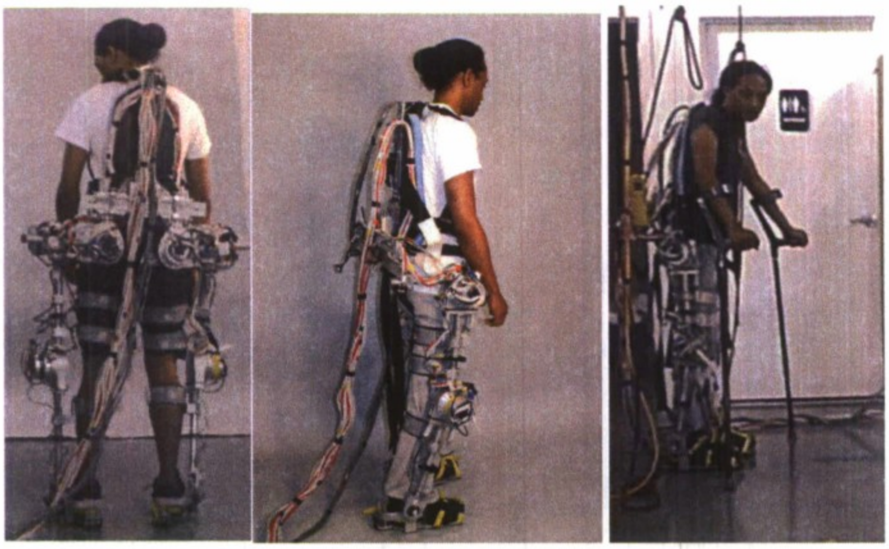

Figure 12: IHMC Mobility Assist Exoskeleton modified for straight line walking. The hip ab/ adduction actuators and the hip internal/external passive rotation degrees of freedom have been replaced with a rigid link.

In this example, the MAE assists the weak leg with force control and provides zero assistance to the strong leg. Dynamically adjusting the amount of assistance provides varying levels of augmentation (or resistance) during strength rehabilitation and can even allow a user with lower extremity paralysis to ambulate. For patients with no motor control in the lower extremities, the exoskeleton operates in disable assist mode, generating position trajectories for the joints while the user provides balance through motions of the torso and by the use of crutches.

During initial testing for disable assist mode, it was determined that the user's center of mass was shifted too far back. In order move the center of mass toward the users center of gravity, the hip ab/adduction actuators and the passive hip internal/external rotation mechanism were replaced with a rigid link. Straight line walking does not require these degrees of freedom so this change does not affect system performance. While an able-bodied user ambulated wearing the MAE in zero assistance control mode, joint positions and loads on the feet were recorded to disk. Various types of gaits were recorded, including static and dynamic walks, with a range of swing leg ground clearance gaits. For evaluation (with able-bodied users), the actuators function under position control and move the joints to generate locomotion according to trajectories generated from the recorded data. Because the IHMC Mobility Assist Exoskeleton has a passive ankle, toe off force was intentionally limited in the gait recordings.

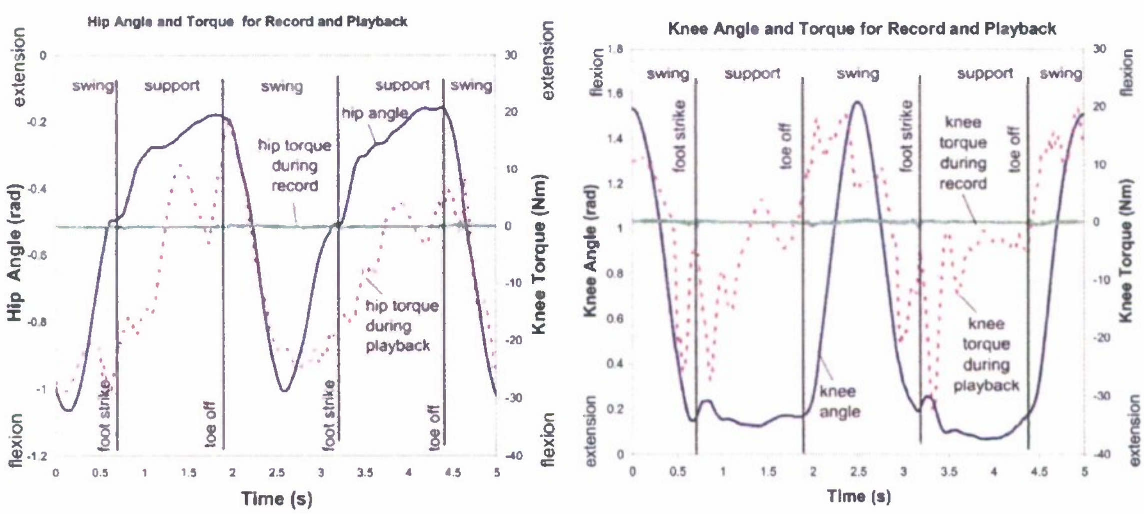

Figure 13: Graph of hip flexion (left graph) and knee flexion (right graph) angle and torque data for recording and playback of able-bodied user wearing the IHMC Mobility Assist Exoskeleton. The user was intentionally walking with a hyper extended support knee and exaggerated knee flexion during swing for large ground clearance. During recording, both hip and knee joint torques are approximately zero because the actuators were in zero assistance mode. During playback, the user tried not to use his leg muscles, which is shown by the required joint torque being non-zero.

Figure 13 shows the results from the recording and playback trials for one of the researchers using the MAE in disable assist. During playback, negligible error manifested between the actual and desired joint angles.

Disable assist mode provides dynamic collaboration between the user and the exoskeleton through adjustable playback speed and playback pause at any point during the walking gait. The user must anticipate the next move of the exoskeleton's lower extremities and adjust his/her torso position to unload the upcoming swing leg during double support phase. Four IHMC researchers tested the disable assist mode using the same recorded disable assist appropriate gait data file that featured small steps, very little knee flexion during support, and large knee flexion during swing. Within thirty minutes of practice, all of the users could walk a short distance at full playback speed and provide balance support with forearm crutches.

Demonstrations

All demonstrations were conducted primarily for the edification of the users to give them a "sneak peak" at future technologies that may soon be available to them. Their subjective, critical comments helped guide later development. Each servicemember was fully informed about the technologies and risks involved in the demonstrations. Care was taken during briefings to ensure that their expectations of the technologies matched current device capabilities. All provided permission to use their likenesses in reports and presentations and no data was collected or recorded during the demonstrations. Early brain plasticity, previous sensory capabilities, technical savviness and eagerness to regain social interactions likely contributed to rapid assimilation and mastery of the sensory technologies shown by these participants. Prior research indicates that congenitally blind civilians or those for whom decades have past since injury require much more time and cognitive effort to reach similar outcomes.

Sensory Substitution Technologies

Four profoundly blind servicemember or veteran (3 Army, 1 Marine) participants evaluated the sensory substitution systems. Each progressed rapidly through the training and demonstrations for vision sensory substitution, exhibiting their high level of motivation and the intuitiveness of the research technologies. For the BrainPort® vision device, we based our initial training protocol on one which is currently being employed at Wicab. In our test room, a high contrast environment was created using black backgrounds overlaid by white objects or vice versa (Figure 14).

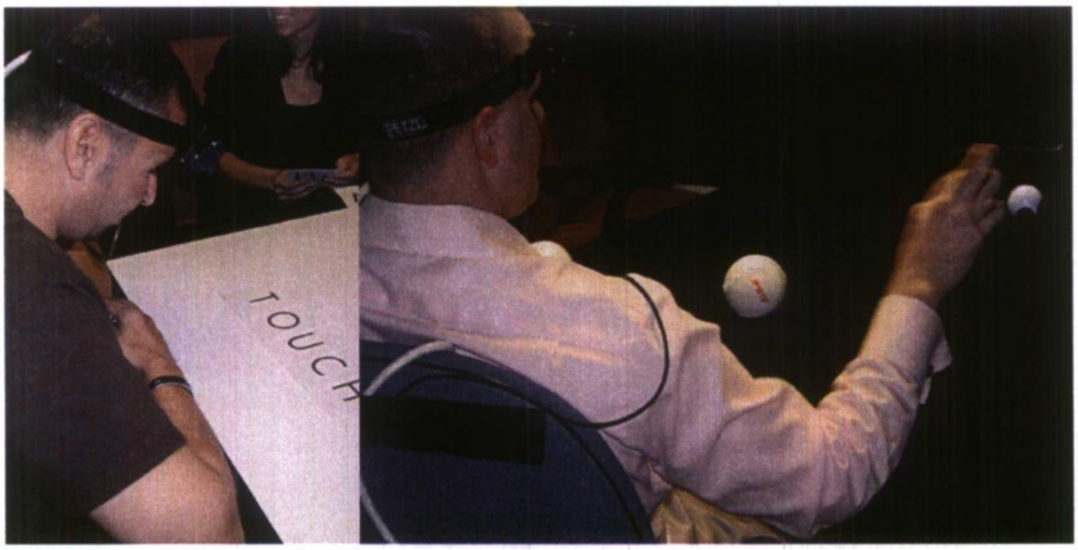

Figure 14: Blind servicemembers training on BrainPort® Vision system. *left*, Reading a word, and, *right*, Identifying and picking up a ball.

To orient subjects with the device, we first introduced a white pipe (approximately 1 meter) in static vertical, horizontal and diagonal positions. User's were asked to identify the positions and use the BrainPort® zoom function to perceive depth. This was followed by the presentation of the letter C, then shapes such as circles, squares, triangles and diamonds. For these first tasks, the participants were encouraged to touch and explore the pipe, shapes and letters to help them correlate the novel tongue sensations with more familiar stereognosis. Reading proficiency was then tasked, as subjects were asked to learn the distinguishing characteristics of each letter and then read words printed on a sheet; most were able to read 3-5 word sentences at a reasonable rate (Figure 14). To test more advanced depth perception, three balls of varying sizes were placed in front of the subject in staggered position, and they were asked to identify and pick up the largest (or smallest) of the group. The static orientation training concluded when each servicemember was able to correctly identify all objects or words, and do so at a comfortable pace. Although the time to learn this complement of tasks varied among the group, no single servicemember took longer than three hours.

For dynamic tasking, each servicemember learned to catch a ball rolled from across a table (Figure 14). Each participant then exited the training room and walked through hallways and doorways. Using either a white centerline stripe on the floor or a safety orange runner with a black centerline stripe providing a high contrast guidance cue, each servicemember was able to walk comfortably without any other means of assistance. We then moved outside the building, where black painted stair edges allowed each individual to walk up and down steps unassisted. Upon reaching the lower level parking lot, the servicemembers were able to follow parking lines and avoid static objects, such as automobiles (Figure 15). To enhance perception of foot position, we fitted battery powered white LEDs to the top of each participant's shoes (some shoe colors lacked contrast with the floor, pavement or stairs).

Other tasks, such as reading an eye chart, playing tic-tac-toe, or trying to identify foods or facial characteristics were added as we progressed and individuals sought more challenging assignments. One servicemember (a former U. S. Army sniper) managed to read a standard Snellen eye chart at an acuity level of 20/80, while another identified that his infant son's hair was tousled from the visually substituted sensation on his tongue. Interestingly, since the child had been born post-deployment, it was this servicemember's first "visual" perception of his son (Figure 15).

Figure 15: Dynamic and ad-libbed BP-WAVE II activities performed during technology demonstrations with recently blinded servicemembers. *left to right, top to bottom*, walking down stairs, navigating office spaces, locating open parking stalls, noticing infant's hair, and reading eye charts to 20/80, evaluating TTI for peripheral tactile cues.

Today's servicemembers rely on the Internet for many social and educational activities and loss of vision severely restricts this experience as the Internet is designed for those with sight, favoring images over textual information. To address these concerns, IHMC integrated the BrainPort® with eye/head tracking equipment to demonstrate that a direct connection between the tactile interface and a computer graphical display can provide a superior qualitative experience by bypassing the limitations of cameras (e.g., glare, changing lighting conditions, focus and unintentional movements of the head). We prototyped three methods of tactile computer interactions that mimic sighted interactions (Figure 16).

Figure 16: Direct computer tactile (BrainPort®) interface demonstrations. *left*, participant prepares to use eye/head-tracking apparatus to determine point of gaze despite the users' prosthetic eyes. The software determines if the participant is looking at the screen and returns a 100-200 pixel sample of the screen image; *right*, When the user touches the screen, the system automatically switches to providing the subsection of the screen image underneath the fingertip to the tongue.

All of these participants mastered the entire suite of sensory substitution tasks in less than 8 hours total training time, significantly faster than civilian congenitally blind individuals or those who have been blind for many decades. This indicates that previous sightedness provides a reference when interacting with common objects and that brain plasticity likely fades as the individual learns alternative mechanisms of coping with their blindness.

Mobility Assistance Exoskeleton

We demonstrated the passive dynamic MAE to one servicemember (Air Force) who had TBI effects following an intracranial bleed from a ruptured arteriovenous malformation. Following a three-month coma, this individual awoke unable to speak and with a left sided hemiplegia. Two months following the coma he reacquired speech and by the time he arrived for his demonstration, had learned to walk again. However, he required a cane and ambulated slowly and deliberatively to ensure that he positioned his weak, paretic leg appropriately to support his weight on each step. Following a ten-minute training session with the passive dynamic MAE prototype on an indoor ambulation course, this individual gained sufficient confidence in his gait that he was able to walk at a normal pace with cane after doffing the MAE (Figure 17).

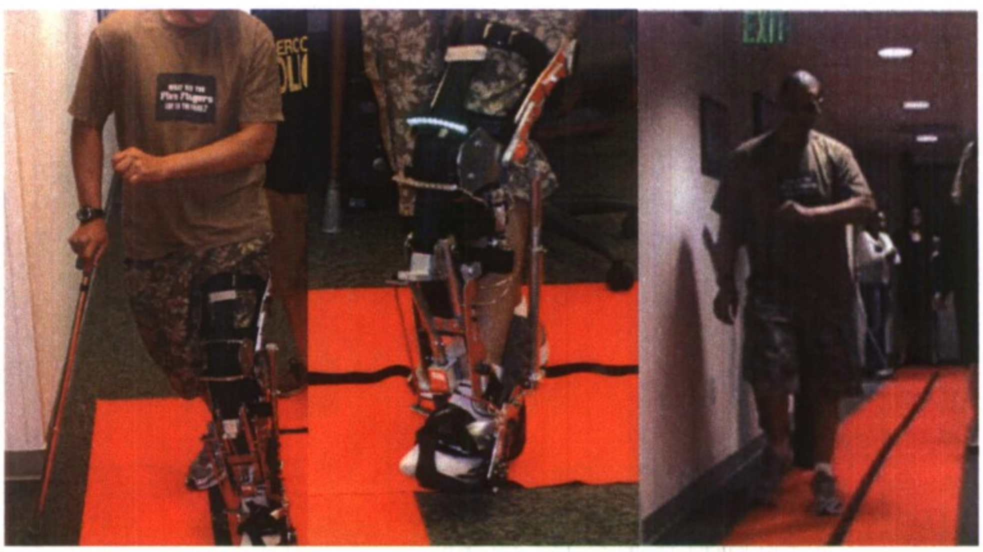

Figure 17: *left*, Hemiplegic servicemember using passive dynamic MAE; *right*, Walking unassisted without MAE, cane or assistance at near normal pace

After completing the ambulation course with his cane, he set it down and walked the course without it at a near normal pace. This was the first time he had walked unassisted since his injury. We believe that his slow gait was due to uncertainty in the stability of his foot plant on each step as a result of the diminished sensation and strength available in his left leg. By ensuring that his weight would be supported on each step, the MAE may have allowed him to place greater trust in his existing cerebellar gait patterns and believe that his normal hip swing would place his foot in the proper position for the next step, even if he could not perceive its position accurately.

Balance Rehabilitation

We are supporting ongoing studies using Wicab, Inc., BrainPort® Balance Devices by leasing or loaning BrainPort® units to the Atlanta Veterans Affairs Hospital and the Naval Medical Center-San Diego for use in their research protocols for balance retraining during recovery from traumatic brain injury (TBI). Combined, they have recruited 20 participants into their protocols which are ongoing and separate from this project. Conversations with the principal investigators of those protocols have indicated that the BrainPort® balance substitution training appears well tolerated and effective.

Public Engagement

Demonstrations were provided for able-bodied interested military and civilian individuals at IHMC. These included a project overview, goals and technology demonstrations for Commander U.S. Army Medical Command/ Acting The Surgeon General, MG Gale Pollock, and Commander, Naval Hospital Pensacola, CAPT Kevin Berry. A local television channel news report of the event, which was also supported by Wicab, Inc., is available at: http://www.ihmc.us:16080/araj/Movies/wearTV3BrainPort20070816.mov. In addition, a number of clinicians (neurologists, otolaryngologists, orthotists, etc.) participated in shortened demonstrations to help them understand the novel technologies. Technology demonstrations were also provided for two local civilians with partial vision loss due to stroke and one profoundly blind individual at their request after they learned of the technologies. One paraplegic individual provided a subjective evaluation of the powered dynamic MAE, but lacked sufficient upper body strength to participate in an actual demonstration.

e. Major Problems/Issues

We were not able to develop our initial contacts at Walter Reed Army Medical Center and the National Naval Medical Center due to changes in personnel; however, we developed alternate military contacts to provide demonstrations to wounded servicemembers during this project.

Initial attempts to provide wide field of view for peripheral vision substitution centered on identification of appropriate high resolution cameras and wide angle or panoramic lenses. These efforts were stymied by the weight and bulk of the optics as well as the amount of computation power required to process full screen video. The current IR emitter/detector approach is much more efficient computationally, and will work in the dark (the blind often do not turn on the lights in a dark room), but the late switch to this concept prevented us from completing the prototype before the end of the project.

f. Technology Transfer

Wicab, Inc., has developed a production model BrainPort® for vision substitution that utilizes the 25x25 arrays and is now available for investigational use.

ForeThought Development, LLC, is currently developing a new version of the VideoTact with significantly reduced size and weight. This will use only currently available components and transition to surface mount components. The new VideoTact will fit under the user's clothing and operate completely wirelessly.

g. Foreign Collaborations and Supported Foreign Nationals

Three foreign nationals, Cecilia Aguero (France), David Lecoutre (France) and Elsa Fouragnan (France), supported this project as graduate student assistants. All were Masters candidates in Cognitive Engineering from the Institut de Cognitique, Universite de Bordeaux-II, participating as research assistant interns as part of their curriculum and worked on developing sensory substitution systems including software coding and development of training paradigms.

Jerryll Noorden (The Netherlands), Hian Kai Kwa (Singapore), Victor Ragusila (Canada) were mechanical engineering research associates who helped design, fabricate, test and evaluate the rotary series elastic actuators and the mobility assist exoskeletons.

h. Productivity

a. Refereed journal articles: None
b. Non-refereed significant publications: None
c. Books or chapters: None
d. Tech reports: None
e. Workshops/ conferences:

Raj A. K. & Cameron, J. (2008) Sensory Substitution Technologies for TBI. Naval Hospital Pensacola Traumatic Brain Injury (TBI) Seminar. Pensacola, FL, 13 March.

Kwa, H. K., Noorden, J. H., Missel, M., Craig, T., Pratt, J. E., & Neuhaus, P. D. (2009) Development of the IHMC Mobility Assist Exoskeleton. IEEE International Conference on Robotics and Automation. 2556–2562.

f. Patents: None
g. Awards honors: None

Acronyms:

ADL:	Activities of Daily Living
AMI:	Adaptive Multi-Agent Integration
CAD:	Computer-Aided Design
CG:	Center of Gravity
DOF:	Degree of Freedom
FPGA:	Field Programmable Gate Array
GUI:	Graphical User Interface
IHMC:	Florida Institute for Human and Machine Cognition
IOD:	Intra-Oral Device
IR:	Infrared
JNI:	Java Native Interface
LED:	Light Emitting Diode
LLC:	Limited Liability Company
MAE:	Mobility Assist Exoskeleton
MG:	Major General
ONR:	Office of Naval Research
PC:	Personal Computer
PCI:	Peripheral Component Interconnect
PIM:	Process Integrated Mechanism
RSEA:	Rotary Series Elastic Actuator
SSI:	Sensory Substitution Interface
TBI:	Traumatic Brain Injury
TCP/IP:	Transmission Control Protocol/Internet Protocol
TDU:	Tongue Display Unit
TSAS:	Tactile Situation Awareness System
TTI:	Tactile Torso Interface

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