MINDWALKER: A BRAIN CONTROLLED LOWER LIMBS EXOSKELETON FOR REHABILITATION. POTENTIAL APPLICATIONS TO SPACE.

ESA/ESTEC, NOORDWIJK, THE NETHERLANDS / 12 – 14 APRIL 2011

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ABSTRACT

MINDWALKER [1] is an EC FP7 funded project which aims at researching, designing and prototyping technologies for the seamless control of a lower limbs exoskeleton, relying on BNCI (Brain Neural Computer Interfaces) technologies. It promotes a non-invasive approach minimizing the cognitive load of the user for controlling the system.

This paper first introduces the MINDWALKER projects, its challenges and solutions being considered. Then the paper presents a perspective of how related technologies, which primary application field deals with the rehabilitation of spinal cord injured (SCI) subjects, may be considered for applications in the space domain.

1. INTRODUCTION

A lack of mobility often leads to limited participation in social life. The purpose of MINDWALKER is to conceive a system empowering lower limbs disabled people with walking abilities that ultimately let them perform their usual daily activities in the most autonomous and natural manner.

MINDWALKER is a 3 years EC FP7 funded project primarily addressing the condition of Spinal Cord Injured (SCI) adult patients (caused e.g. by an accident). Section 2 further introduces MINDWALKER, with a focus on the main research areas. Section 3 provides more insight regarding Brain Neural Computer Interfaces (BNCI) for robotics control applications. Then section 4 introduces perspectives of possible applications in space oriented domains, and manned spaceflights in particular. Then section 5 and 6 are respectively the conclusion and acknowledgment.

2. THE MINDWALKER PROJECT

2.1. Research areas and methodology

The project involves three main different fields of expertise (Fig. 1. below):

1. Non invasive BNCI technologies,
2. Exoskeleton mechatronics and control technologies,
3. Virtual Reality (VR) simulation for training technologies.

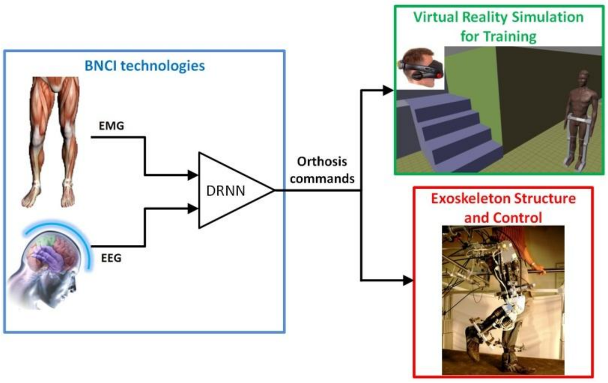

Figure 1. MINDWALKER three main objectives

MINDWALKER main purpose is to research, develop and integrate needed technologies in the three areas above, and to eventually demonstrate a prototype of BNCI controlled lower limbs exoskeleton to empower SCI patients with walking ability. An important concern is to preserve most cognitive capabilities available for everyday life activities, and therefore to minimize the required mental load to control the lower limbs exoskeleton.

After multiple, iterative integration steps, the developed technologies will be assessed and validated with the support of a formal clinical evaluation procedure. This will allow measuring the strengths and weaknesses of the chosen approaches and to identify improvements required to build a future commercial system. In addition, in the last months of the project, the resulting system will be progressively experimented in everyday life representative environments and situations, ranging from simple activities at home to eventually shopping and interacting in dynamic environments like e.g. a crowded street.

2.2. Dry Electroencephalography (EEG) Cap

Brain computer interfaces technologies rely on the acquisition, processing and interpretation of brain electrical signal. In the case of non-invasive approaches, an EEG cap is used for that purpose. Most EEG caps require lengthy preparation, due to the positioning of wet (conductive gel) electrodes. For a 128 channels cap (very usual amount), this may take 1 to 2 hours for experienced people.

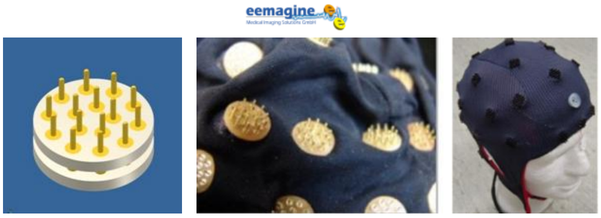

Figure 2. Dry electrodes EEG cap early prototype
(Credit: eemagine Medical Imaging Solutions GmbH)

The project includes the design and development of a lightweight, dry electrodes [2] EEG cap (Fig. 2 above) allowing fast and convenient don-on/off, that can be used on daily basis by users. This dry EEG cap is expected to allow suitable acquisition of EEG signals, before this signal is further processed through the BNCI chain in order to translate it into kinematics control signal.

2.3. BNCI Processing Chain

The BNCI processing chain is one of the most challenging part of the MINDWALKER project: it aims at translating EEG signals into an exploitable control signal for the lower limbs exoskeleton.

It relies for that purpose on spatial and temporal signal pre-processing, before feeding in a Dynamic Recurrent Neural Network (DRNN) [3]. In the baseline approach, the DRNN is trained with pre-processed EEG datasets covering various walking patterns, and provides kinematics angles that the exoskeleton's joints should match.

As a complementary approach, arms muscles electrical signal (EMG) [4] as an input to the DRNN is additionally considered as a backup option, should EEG based approach not be fully exploitable with the developed prototype and aimed demonstration scenarios.

2.4. Lower Limbs Exoskeleton Development: Approach and Challenges

A novel lower limbs exoskeleton system [5] (Fig. 3) is being designed and prototyped in the frame of the project. It should be able to support the weight of an adult having complete lower limbs disabilities, and to dynamically maintain the stability of the wearer. For that purpose, the control approach relies on the biped robots originating limit cycle walking [6] paradigm, which requires much lower power levels than e.g. zero momentum point control strategy.

Figure 3. Lower limbs exoskeleton early model
(Credit: TU Delft)

A low level model based controller continuously ensures the overall system's (user + exoskeleton overall structure) balance while walking, relying on proprioceptive sensors. Additionally a high level controller (supervisor) makes use of exteroceptive sensors (laser range-finder, time-of-flight camera and Kinect are evaluated) to obtain a short term 3D model of the frontward environment. This environment model allows checking and, when deemed necessary, inhibiting or adapting BNCI originating control requests in case of risky situation (obstacles, uneven terrain, etc).

2.5. VR Training Environment (VRTE)

Having such an exoskeleton system used by SCI patients requires progressive familiarization and training: a VR setup is being designed (Fig. 4. below) to support users experiencing the sensations of controlling the exoskeleton through the BNCI interface. It features an immersive setup with 3D visual feedback, and an actuated seat allowing complementary vestibular feedback, to enhance the immersion feeling. Scenarios can be authored by medical staff, and biological parameters can be monitored during the trials. The VR setup is to be evaluated along with the exoskeleton structure, the EEG cap and the BNCI processing means, in the last year of the project to the Santa-Lucia Foundation (Italy) which is specialized in spinal cord injuries and neuromotor rehabilitation.

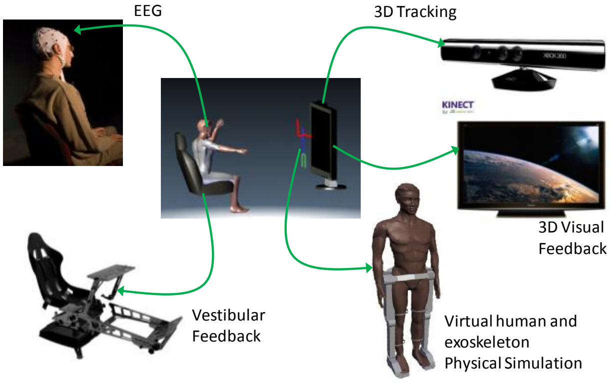

Figure 4. VRTE early setup

Besides, the VR Training Environment also contributes to the research work on EEG signal translation into kinematics signal. The purpose it to experiment various stimuli generation (visual, aural, other...) related to human gait, as a way to better identify promising and relevant EEG patterns to take into account as input to the DRNN.

3. BNCI TECHNOLOGIES FOR ROBOT CONTROL: STATE OF THE ART AND CHALLENGES

3.1. BNCI Background and Challenges

Brain computer interfaces consist in exploiting brain signal (or other biological signals, like EMG) as a mean to control a device (computer or other).

Brain computer interfaces research field, though initiated in the 70s in the US, significantly expanded since the mid-90s with setups successfully demonstrating EEG-based recognition of patterns in a group of distinguishable patterns (aka. classification – for instance arrow direction selection on a screen, or EEG self-paced key typing [7]).

In the case of non-invasive BNCI, brain signal interpretation is a very tough challenge, due to multiple factors:

- The difficulty to acquire exploitable signal, due to the noise originating from nearby face muscles activities, and surrounding electromagnetic sources, in particular.
- The difficulty to identify relevant signals in the huge amount of available data (64 to 256 channels in the case of usual EEG acquisition, with sampling rates up to 4,000 Hz).
- The difficulty to sort out relevant signals from artefacts caused by acquisition conditions (vibrations, cap movement, etc.).

A number of mathematics tools, along with adequate experimental protocols allow mitigating some of those concerns. However BNCI experiments often require numerous trials and much time for outcomes debriefing. Additionally, ethical review protocols should be followed for most BNCI related experiments, adding to the burden.

Invasive BNCI implies the insertion of electrodes in the grey matter of the brain, and consequently allows collecting high quality EEG signal.

Partially-invasive BNCI (aka. electrocorticography) involves electrical activity measurements in the same manner as with EEG, though beneath the skull. It however does not require electrode insertion in the grey matter, as done with invasive approaches.

3.2. Event Related BNCI Approaches

The most usual approach to non-invasive BNCI (called P300) relies on the analysis of Event Related Potentials (ERP) in the EEG signal. The main limitations with classical P300 BNCI setups are (1) the signal integration and processing time, that may require up to tens of seconds before identifying that a control request has been issued, and (2) the mental effort required by the subject to successfully trigger such control requests, even after lengthy training.

This approach has nevertheless been successfully applied to rehabilitation robotics in order to control a robotic wheelchair in orientation [8].

Another Event Related non-invasive BNCI approach, based on functional Magnetic Resonance Imaging (fMRI), has been demonstrated by the Honda firm as a mean to control Asimo [9] (arm or leg single motion) with a good success rate. The Honda setup for fMRI experiment is however quite large as shown on Fig. 5.

Figure 5. Honda fMRI based BNCI for Asimov robotic platform control (Credit: Honda Research Institute)

3.3. Brain Signal to Kinematics Approaches

As a more challenging, but more promising path to everyday applications, continuous conversion of brain signals to control signal is an appealing alternative.

Invasive BNCI to kinematics has been successfully demonstrated in 2005 with a quadriplegic patient for the control of an artificial hand. This implied the implantation of a 96 electrodes chip (BrainGate [10]) on the surface of the subject's motor cortex. Furthermore, a partially-invasive device has been engineered one year later, as a less risky substitution to the invasive one. Several patients already benefited from this partially invasive implant so far, as part of clinical experiments

Figure 6. Dexterous kinematic control of a robotic arm and hand by a monkey through a BNCI setup (Credit: Pittsburgh University - Motorlab).

Making use of a similar approach with electrodes implanted in the brain of a rhesus macaque, Nicolelis & al. (Duke University) recently demonstrated [11] the kinematic control of an anthropomorphic robotic arm by the monkey, with manipulation tasks like grabbing fruits and bringing them back to the animal. Nicolelis team further investigated such an approach for bi-pedal robot control [12]. Similar research has been carried out at Pittsburgh University by Schwartz & al., with impressive results [13] (Fig. 6).

MINDWALKER also investigates such continuous conversion of brain signal to kinematic signal, however with non-invasive brain signal acquisition (EEG based). This in fact makes the problem even more challenging, due to the difficulty of collecting and exploiting EEG signals, as explained earlier. This however avoids the implantation of a brain chip in the user's brain and associated risks and inconvenience. This moreover allows broadening the spectrum of applications beyond rehabilitation robotics – e.g. considering potential space oriented applications, as introduced in the next section.

3.4. Main MINDWALKER Competitor Technologies

A small number of lower limbs exoskeleton platforms got a lot of media coverage in the last few years.

Figure 7. Top left: ReWalk (Argo); top right: eLEGS (Berkeley Bionics); bottom left: REX (Rex Bionics); bottom right: HAL 5 (Cyberdine).

These platforms may in some extent be considered competitors to MINDWALKER technology, though they differ by their approach and aimed performances.

ReWalk [14] has been the first medical oriented lower limbs exoskeleton with media coverage. It senses and exploits upper body movement to trigger and pace the walk. It requires the subject to use crutches.

eLEGS and REX have been advertised in the same time frame (both in 2010). eLEGS [15] perceives and interprets movement intentions, and is presented as a lightweight device, though requiring crutches as well. It is a direct ReWalk competitor. REX [16] is a joystick controlled, crutch-less platform, that does not rely on BNCI technologies. It is significantly heavier and larger than the other platforms.

HAL 5 [17] is not originally a rehabilitation exoskeleton, although rehabilitation applications are now being considered. The lower limbs part of the exoskeleton exploits legs EMG signals for control.

MINDWALKER concept is more ambitious in the sense that (1) the system is expected to be controlled relying primary on EEG signals (therefore without assumptions regarding the possibility to capture legs EMG – which may not be always available with SCI patients) and (2) the lower limbs exoskeleton platform should allow dynamic balance while walking, without the use of crutches.

4. MINDWALKER TECHNOLOGIES RELEVANCE IN SPACE SCENARIOS: POTENTIAL APPLICATIONS

4.1. Astronauts After-landing Condition Mitigation

After long duration missions in microgravity condition (typically, after 6 months long mission to the ISS), once back on Earth, astronauts often suffer during a few days of vestibular perception issues and other biological perturbations ranging from slight losses of balance to fainting. Lower limbs exoskeleton technologies could help mitigating some of those effects, and help preventing falls. The system would have to adapt to the pace of the recovery, and accordingly adapt the required magnitude of the provided support, until full recovery. For such applications, a lower limbs exoskeleton like the one being prototyped in MINDWALKER with dynamic balance capability would be a strong asset. The EEG based control approach, though possible, may be substituted in this context with legs EMG signal acquisition as control signal input. Both approaches performances may anyway be worth being further investigated.

4.2. In-space, Astronaut Health Deconditioning Mitigation

Human body in microgravity is subject to a number of biological effects such as fluid shifts, muscle losses and bones deconditioning. The latter is a major concern, as its effects are difficult to mitigate and take time to recover after a mission (it is actually not clear whether resulting condition can be fully recovered). As a countermeasure, in-orbit regular physical exercise (several hours per day) is made mandatory for all flying crews. Exoskeleton systems along with immersive virtual reality environment would be appealing setups to perform such countermeasure exercises. Forces feedback provided by a lower limbs exoskeleton suit could help simulating gravity condition and contact forces with ground.

In addition, an immersive virtual reality environment could provide visual feedback and possibly (should the training setup allow it) vestibular feedbacks. Such a setup could be exploited in preparatory phases to landing on a planetary surface, or in preparation to the return to Earth (with the aim of minimizing adversarial effects and recovery time).

4.3. Robot Control

As an interesting application of BNCI technologies in the space domain, the control of mobile or manipulator robotic platforms is an appealing one. We present below possible applications that could bring interesting operational benefits.

4.3.1. EEG based dexterous manipulation

Most missions toward the ISS require the use of a manipulator arm. The ISS is equipped (or being equipped) with several robotic arms, such as: the Canadarm 2 and its Dextre extension, the Kibo’s JEMRMS arm, and the European Robotic Arm (ERA). These teleoperated arms allow manipulation of huge payloads, as well as performing some assembly tasks, with control from inside the space station (IVA). Their control by astronauts however requires proficient capabilities with manipulator robotics system (as part of the “generic robotics training” (GRT) astronauts lessons), and relies on interfaces such as joystick and traditional switches and buttons panels, along with visual feedback.

Brain computer interfaces could be exploited along with rich visual feedback. The setup could consist of a dry EEG cap interface as developed in MINDWALKER, with a BNCI processing chain mapping arm control ideation to the actual control of the target robotic arm. A 3D, augmented visual feedback (e.g. with delineation of important areas, distance indications, etc.), or alternatively a pure VR rendering could come in addition. This approach may be exploited to perform robotic arm control with minimum need for arms movements, and could therefore fit setups with limited available room. As a trade-offs, such a BNCI setup however could not provide the user with force feedback.

4.3.2. Mobile robotic planetary exploration with telepresence

Humanoid robots are complex systems, that have only been recently considered (e.g. Robonaut [18]) for actual applications in space, due to their greater mechanical complexity (compared to e.g. rover platforms).

They are however appealing due to their potential versatility and capacity to make use of human-designed tools and facilities. “Centaur like” manipulator platforms (i.e. bi-manipulator mobile rovers) have been investigated in several ESA [19] and NASA [20] studies.

The control of such humanoid robotic platforms could be achieved through BNCI, assuming adequate visual feedback (possibly augmented, in the same manner as for ISS robotic arm control). The EEG based control could then cover both the locomotion and the manipulation tasks. MINDWALKER approach to EEG translation into lower limbs kinematic control for walking could accordingly be exploited and extended for the navigation of a bi-pedal humanoid robots as well as for various manipulation tasks, in a planetary exploration setup.

5. CONCLUSION

We provided in this paper an introduction to the MINDWALKER project, stressing the challenges associated to its main research objectives. The technologies that are expected as outcomes of this project may have, individually or combined, various potential space oriented applications.

EEG based kinematic control is one of the most challenging research activity in MINDWALKER, which, depending on performances and constraints of use (electromagnetic, etc), may find numerous applications both for space and non-space domains.

Lower limbs exoskeleton structures may find shorter term interest in space applications as a mean to help fighting adversarial effects of microgravity for astronauts, both onboard as a countermeasure, and on ground as a mitigation.

Finally, immersive virtual reality, besides being a great asset to training, may also find applications for users awareness building in operational situations where pure visual feedback is poor or unworkable (due e.g. to light conditions) – in particular when controlling a robotic platform.

6. ACKNOWLEDGEMENT

MINDWALKER is supported by EU research program FP7 under project contract #247959 for Accessible and Inclusive ICT. The MINDWALKER project is coordinated by Space Applications Services.

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