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BCI-controlled mechatronic devices, systems, and environments

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Abstract

Use of BCIs in patients with severe neurological deficits can improve their quality of life (QoL), provide them increased independence, and possibly increase effectiveness, shorten, and reduce cost of diagnosis, treatment, rehabilitation and care. Many publications have shown evidences for efficacy of BCI-based neurorehabilitation so far, including application as output devices mechatronic modules such as robots and active orthosis. The aim of this study was to investigate the extent to which the available opportunities in BCI-based control of mechatronic devices are being exploited, and discuss their perspectives and directions of further research from the engineers' point of view.

Introduction

Concept of using brain derived signals for diagnostic purposes is not new, its application for communication and control are rather at the beginning of development, especially within novel neurorehabilitation approaches. Early attempts with EEG-based brain computer interfaces (BCIs) had promising results on average 70% correct responses for letter selection in paralyzed patient [1, 2]. Many publications have shown evidences for efficacy of BCI-based neurorehabilitation so far, including application as output devices mechatronic modules such as robots and active orthosis [3, 4, 5]. Clinical BCI-based approaches concern not only more accurate diagnosis and simple communication, but whole strategies of BCI-supported motor rehabilitation including three basic strategies: substitutive strategy, classical conditioning and operant conditioning [5].

Use of BCIs in patients with severe neurological deficits can improve their quality of life (QoL), provide them increased independence, possibly increase effectiveness, shorten, and reduce cost of diagnosis, treatment, rehabilitation and care. Use of BCIs in healthy people can constitute both possibility to continuous brain training, and, if successful, tendency to overuse of BCIs even in children, constituting severe medical and ethical problem. Despite the most advanced solutions are used only in laboratory settings some commercial solutions (Emotiv, MindWave, Muse) are available to the public.

The aim of this study was twofold:

1. to investigate the extent to which the available opportunities in BCI-based control of mechatronic devices are being exploited,
2. discuss their perspectives and directions of further research from the engineers' point of view.

Processes underlying BCI-based control

BCIs are relatively novel tools established in the field of human-computer interaction (HCI). They constitute a hardware and software systems, that permit cerebral activity alone (i.e. measured activity of the central nervous systems - CNS) to control computers or external devices. They may be acquired different neurophysiological control signals (detected in brain activity in invasive or non-invasive way) that determine user intention. From engineers' point of view BCIs:

- acquire brain signal (one or more simultaneously),
- analyze it,
- translate it into command,
- command (though BCI-controlled device) causes desired actions.

The accuracy of aforementioned device action is usually controlled by the user using natural (visual, haptic) or artificial (biofeedback) feedback. Thus BCI creates additional (non–existing in the nature) non-muscular channel for relaying intention of the user to external control device. Moreover BCI-related performance can be individual feature of each user, thus it needs to be trained and corrected during BCI application. Basic phases of BCI work consist of signal acquisition, preprocessing (signal enhancement for artifacts avoiding or performance improvement purposes), feature extraction, classification, and distinct control over device procedures [5]. Proper interpretation of the intent of BCI-user is critical within aforementioned procedure – every mistake may not only cause errors, irritation to the user, but – if user is controlling mechatronic device – not obeying safety precautions, cause crash, etc.

Approximately 60% of all current BCIs is EEG-based (rather non-invasive: exogenous: P300, steady-state visual evoked potentials - SSVEPs, or endogenous: event related synchronization / de-synchronization - ERS/ERD, slow cortical potentials - SCPs), since electroencephalography is regarded as cheap and portable, with high temporal resolution and few risks to users, despite lot of artifacts, noise, and too low resolution to control prostheses with multiples degrees of freedom so far (but control of wheelchairs and basic neuroprosthesis is possible) [3]. On the other hand concurrent non-invasive approach is based on magneto-encephalography (MEG) registering (by means of magnetic induction) brain's magnetic activity. MEG-based BCI can significantly increase resolution and lower noise, but for this moment need more research and are rather expensive. Other concurrent methods, like BCIs based on electro-corticography (ECoG), intracortical neuron recording, functional magnetic resonance imaging (fMRI), and near-infrared spectroscopy (NIRS), despite potent, are still at an early stage and are far from commercialization.

There are many important CNS mechanisms underlying BCI application, including brain neuroplasticity and natural response to visual cue. Closed-loop between brain and effectors (hands, legs, artificial neuroprosthesis) can enhance changes in the CNS (neural activity) during rehabilitation. Both various technologies and brain areas may be useful, depending on the patient's health status, kind and severity of the neurological deficits (one or more coexisting), and his/her preserved functions [9].

Function of BCI within mechatronic system plays crucial role in designing it, and may decide which feature of BCI alone and whole mechatronic system is the most important: accuracy, speed (including real time applications) or usability aspects (e.g. learnability, ease of use, workload, increasing motivation, preventing frustration, etc.).

Communication

Application of BCIs in patients with severe communication disabilities (including patients with disorders of consciousness) has been widely discussed [9], see also e.g. Farwell-Donchin paradigm. In selected patients it may provide a useful additional way of re-establishing communication, usually with error rate 20-30% (after training). Depending on type of the control signal (and associated rate, accuracy, and precision), user selects a letter by means of a BCI using virtual keyboard (or the alphabet) displayed on screen. Various solutions allow for browser control or other more advanced use of computer software. Relatively novel technologies for such communication purposes are avatars in the internet-based virtual reality (VR) systems [9], which are another step toward BCI-based multimodal communication and using it within ambient intelligence (AmI) and affective computing (AC) systems.

Locomotion: BCI-based robotic wheelchair control and BCI-controlled exoskeleton

Continuous mental control of a wheelchair constitutes complex mechatronic problem. It needs co-operation between two key components of the control system:

- real-time and error-free selection of stable user-dependent features of the BCI-derived signal, and classification maximizing the separability between subsequent tasks,
- shared control system: between the BCI system and the intelligent simulated wheelchair [8].

We should take into consideration, that effective fulfilling of the real time control need not only real-time exchange of commands and responses/confirmations, but it incorporates whole process of path planning, wheelchair status control, multi-degree motion control (including at least in-line motion, turning, acceleration, deceleration, and breaking), and environmental control (including user-controlled or automatic obstacle avoidance when necessary) [9, 10]. Additionally such control should be safe and easy (incorporating usability rules). From the other side this control process, usually far from natural patterns, should not constitute too high workload for usually damaged user's CNS. Greater number of commands with increased accuracy can be provided using hybrid BCI [11, 12, 13].

Useful mechatronic training in the area of BCI-controlled wheelchair is regarded development of whole families of various BCI-controlled mobile robots, not only wheelchairs, to avoid cost-dependant mistakes in full-scale experiments. Simulated wheelchairs are also often used to measure usability and reduce workload in BCI-controlled wheelchairs.

Despite research on medical and military exoskeletons are rather popular (XOS, HAL5, ReWalk, Exo, etc.), BCI-controlled exoskeletons are rare. Relatively simple research on training useful movements (e.g. ball grasping) using occupational therapy assist suit (BOTAS) [14] showed possibility of use basic robotic suits (exoskeletons) in complex movement of BCI-assisted grasping. We should take into consideration that artificial hands with five independent fingers and active wrist are not common so far due to complicated construction and control [15]. More advanced successful research was conducted by Ramos-Murguialday [16], within BRAVO (Brain computer interfaces for Robotic enhanced Action in Visuo-motOr tasks) project [17], and MindWalker project [18, 19].

Continuous control over complex robotics devices allowing for increased patients mobility (robotic wheelchairs, exoskeletons) using BCI is possible, but needs control system balancing between BCI user intent and artificial intelligence of the moving robotic device. Safety of the user and his/her environment is the most important, thus efficient emergency switch-off should be provided.

Motor restoration and neuroprosthesis

Clinical neuroprosthetics application was divided recently into three approaches:

1. recovery (complete or partial),
2. function(s) supplementation and support,

3. function(s) replacement [20].

Lorenz et al. proposed two-stage neuroprosthetic control within the EU project MUNDUS: ERP-ERP and ERP-motor imagery (MI) interfaces have provided the best suitability so far [21]. What important according to the research by Foldes et al. [22] multimodal communication and control can be sustained. Patients may simultaneously perform both neuroprosthesis control (movement control) and other cognitive function (e.g. speaking) with only little declination in BCI-controlled movement performance. Results were as follows:

- time of movement completion: increased by 7.2%,

- percentage of targets successfully acquired: declined by 11% [22].

Aforementioned results seem to be promising. This drop in BCI-control performance need for additional research – various cognitively engaging activities can influence in various way, moreover we should take into consideration various kinds and levels of deficits, BCIs and neuroprosthesis construction, training and research methodologies, etc. Hybrid neuroprosthesis can also combine functional electrical stimulation (FES) with orthosis. We should admit that from engineers' point of view FES compensates loss of voluntary movements by intentional eliciting artificial muscle contractions. But even long-term training cannot increase features of MI-BCI performance: according to the research by Rohm et al. it ranged from 50% to 93% (average: 70.5%) after one year of training (more than 40 training sessions) [23]. This feature needs additional research; moreover we should work on more effective training procedures [24, 25, 26, 27].

Research on robotic arm control showed that EEG-BCI-actuated mechatronic devices have limited potential for self-assistance in patients with quadriplegia (without significant side effects): 33.3% of such patients were able to control the robotic arm through imagination of their movement [28].

Field of BCI-controlled robotic arms, legs, and neuroprosthesis constitute relatively novel field of research in mechatronics – there is need for novel, more effective strategies. Impact of computational intelligence (including biologically relevant control systems based on neural networks and fuzzy logic systems) to mechatronic control modules seems to be underscored. Some of aforementioned research will need interdisciplinary cooperation with specialists in medical and health sciences, and cognitive sciences.

Environmental control and intelligent environments

Traditional system for environmental control consists of i-wear and/or smart home solutions. Their control possibilities may be increased by built-in BCI-based control systems, allowing additionally for remote control of children, elderly people, and severely ill people (including patients during recovery, long-term home rehabilitation, etc.).

VR environments (VREs) are popular in rehabilitation robots (Lokomat, Reo Ambulator) and biofeedback systems for adults and children as visual cues and solutions increasing patient's motivation. This model of neuro-rehabilitation can be increased using VR-based BCI-controlled training environments achieving average training performance across subjects 77.2% (after only 10 minutes training) [29]. This implies research on training systems preparing patients toward e.g. BCI-controlled lower limb prosthesis systems.

More advanced solution is intelligent IT environment of disabled person developed by Polish scientists [30,31, 32, 33, 34]. As system open to interconnections it constitutes whole framework for integration of various solutions. From commercial point of view there would be useful to provide whole family of standarized BCI-controlled mechatronic modules similar to the LEGO Mindstorms robots used currently e.g. in the therapy for autistic adolescents.

Other BCI applications in mechatronics

Other possible applications of BCIs within mechatronic devices and systems are as follows:

- telemedical devices and systems allowing for remote assessment of the patient's status in health and disease – potential of e.g. telerehabilitation systems rapidly increases currently in long-term cardiac telerehabilitation,
- extended environment control – compared to the Google Glass technology, but BCI-based,
- concept of BCI-controlled robotic toy/companion useful e.g. in peadiatric neurorehabilitation,
- entertainment-oriented BCI, e.g. BCI-controlled games, like Mindball game,
- neuromarketing devices – measuring brain response to advertisements, despite severe ethical problems concerning this new application.

Limitations and directions of further research

Aforementioned BCI-controlled mechatronic tools are still at the beginning of their development, and need further research and evolution toward long-term effects of their application. Basic current limitations are following:

- lack of technical standards, especially concerning safe commercialization, possible cooperation with e.g. telemedical systems, etc.
- few research supporting usefulness of such systems,

- need for interdisciplinary research teams,

- many ethical (e.g. shared responsibility of human and device) and legal issues.

Actual challenges and directions of the further research in the area of BCI-based mechatronic devices and systems are as follows:

- need for progress of BCI-based rehabilitation strategies (both concerning invasive and non-invasive interfaces) and to underline future challenges [5],

- employing BCI control over mechatronic devices for real-world tasks (including activities of daily living),

- change location of research from “quiet” laboratory environment to the real world,
- decrease possible high cognitive load of the BCI user - especially in tasks concerning contiuous control like wheelchair movement,
- areas of BCIs personalization,
- risk analysis.

Conclusions

Great dream of being able to control devices and systems through thoughts now becomes the reality. It may be significantly extended using whole families of advanced mechatronic devices and systems, providing user friendly and adaptive fulfilling activities of daily living (ADLs), increased independence, and – in the most severe patients – communication through virtual and/or robotized avatars. Current possibilities are promising, but they are not fully applied topics, especially in the area of research and education of the multidisciplinary teams.

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