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Brain-Machine Interfaces for Space Applications

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Abstract—**In human space flight, astronauts are the most precious "payload" and astronaut time is extremely valuable. Astronauts operate under unusual and difficult conditions since the absence of gravity makes some of simple tasks tedious and cumbersome. Therefore, computer interfaces for astronauts are generally designed first for safety and then for functionality. In addition to general constraints like mass, volume, robustness, technological solutions need to enhance their functionality and efficiency while not compromising safety. Brain-machine interfaces show promising properties in this respect. It is however not obvious that devices developed for functioning on-ground can be used as hands-free interfaces for astronauts. This paper intends to address the potential of brain-machine interfaces for space applications, to review expected issues related with microgravity effects on brain activities, to highlight those research directions on brain-machine interfaces with the perceived highest potential impact on future space applications, and to embed these into long-term plans with respect to human space flight. We conclude by suggesting research and development steps considered necessary to include brain-machine interface technology in future architectures for human space flight.**

I. Introduction

While the high versatility of human sensorimotor system allows for a large range of elaborated motor behaviours, its performances are strictly bounded to the physical conditions it has been adapting to over its evolution. In particular, our perception and planning of movement depend on the identification of the gravity axis. Situations of perceived annihilated gravity (i.e. orbital microgravity) therefore inevitably affect human's sensory-motor system [1]. The subsequent losses of performances are so important that, from certain perspectives, humans operating in microgravity are in a similar situation to people affected by motor disabilities on Earth [2]: both have, for different reasons, a deficit in the performances required to accomplish their motor tasks. On Earth, disabled people can take advantage of assistive systems, which are technologies designed to fill the gap between user's residual abilities and required ones. The answer to the reduction of physical and mental ability suffered by astronauts can hence be addressed (and it already partially is) with assistive technologies, once they are redesigned for functioning in space.

The required assistive technologies for astronauts are, essentially, computer interfaces, robotic hands, and robotic arms. Most of them are already technologically well developed, but are still lacking in operability. In fact, the reduction in sensorimotor performances affects the use of any kind of physical interface as well [3]. The adoption of natural interfaces [4] could enhance the communication and control abilities of humans in space, allowing to fully focus on the task instead of on the interface use.

Natural interfaces, with respect to traditional ones, exploit natural human communicative channels and hence allow intuitive and universal use without elongated training sessions. Natural interfaces commonly are based on, and integrate, speech recognition, gesture recognition, facial expression recognition, and gaze tracking. However, their usefulness for severely disabled people and – in an analogue way - for astronauts has constraints. Gesture and facial expression recognition efficiency is affected by the inability for the impaired user to perform within strict tolerances, while speech recognition reliability presents extreme challenges when implemented in spacecraft environments [1], where the background noise can be as high as 64 dBA for the air conditioning to 100 dBA for vent relief [5]. Gaze tracking alone tends to lack precision and the ability to permit the control of complex systems.

While not yet as mature as some of the mentioned options, brain machine interfaces (BMIs) are instead virtually independent from the user's physical abilities, by accessing the user's intentions at a higher level, where they naturally origin: in the brain. They predict directly the user's motor intentions, not related with users' abilities, by monitoring the activity of neurons (individually or in networks) and translating these signals into actions. Since they are expected to operate in principle very similar in space and on Earth, BMIs could assist astronauts by helping them to perform in space as efficiently as on the Earth.

II. Microgravity Exposition Effects On Human Brain

Exposition to micro-gravity causes some very specific differences in the way the human brain behaves [6]. As the

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brain is the main element of BMIs, any changes due to short time or long-time exposition to "space environments" have to be taken in consideration in the specific design and set up of BMI for space applications. For example, the main brain rhythm, the alpha, and the main motor cortical rhythm, the mu, show important modifications in their power spectrum, which result significantly increased with respect to ground measurement, when recorded during prolonged microgravity exposition (i.e., during EEG session with astronauts in the International Space Station - ISS) [7]. It was proposed that these adaptive changes would result from a coherent cortical drive from the thalamus coincident with a lack of other input due to the general reduction in tactile and proprioceptive feedback under microgravity [8].

Similarly, the distribution of basic EEG rhythms appears to reflect some adaptive changes in brain activity during long exposures to microgravity. NeuroCog ESA virtual navigation experiment, performed both on ground and on board the ISS, showed that the initial presentation of a virtual 3D tunnel was differently accompanied by a power increase in the theta and in the alpha bands, while a power increase in the alpha, beta and gamma bands occurred during the whole task in weightlessness [9].

A first step towards appreciating the effects of microgravity on BMI operations was done during a 2007 parabolic flight campaign of the European Space Agency (ESA). During parabolic flights the human body experiences repetitive short exposures to micro and macro-gravity. Two subjects, both male, in their 20s, with prior BMI and no microgravity experience, were EEG recorded on ground (calibration sessions) and on the parabolic flights during three gravity conditions (1G, as on Earth; 2G, double weight; and 0G, microgravity). Subjects were asked to mentally move a virtual blue balloon on a computer display to its left or right. The mental tasks corresponding with the left and right movement directions were, respectively, left hand movement imagination, and words association; the balloon was artificially moved by the system with a 30% error rate (the same as usually associated with BMI operation), regardless of the subjects' EEG. Even though this approach did not allow subjects to actually operate the BMI system, it permitted to record the EEG activity associated with the two different mental states that could be compared with the one recorded during on ground sessions. An online classifier for parabolic flight session prepared on on-ground data could not have predicted the potential effects of the extreme gravity changes and noisy environment of parabolic flights. The off-line analysis computed for the two subjects achieved a mental-task classification accuracy between 72% and 79% [10], and demonstrated that the relevant brain activity features related with the tasks remained almost unaltered by the three gravity conditions (Fig.1), despite the stress, noise and novelty of parabolic flight. The results are certainly circumscribed to the particular experimental protocol, and need to be confirmed with further experiments with online controlled BMI systems in parabolic flights, and to be compared with the results coming from experiments on subjects during long exposure to microgravity, i.e. on humans on the ISS.

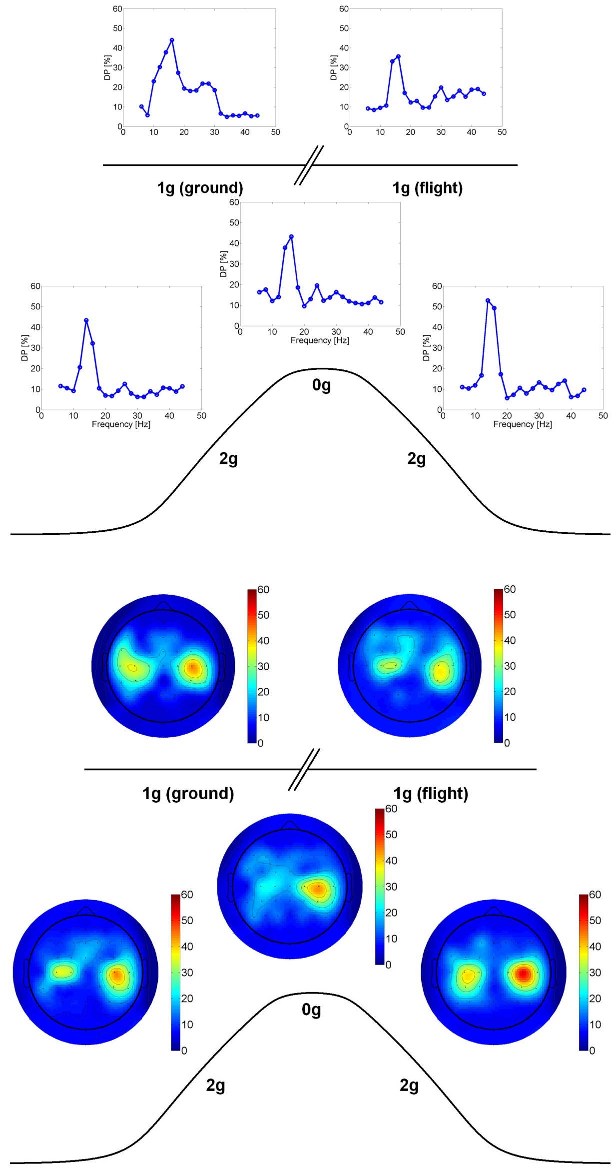

Fig. 1. Typical BMI features, as degree of relevance of EEG frequencies (first two on the top) and EEG electrodes (last two in the bottom). Those better associated with the two brain tasks were found to remain stable during all the three different gravity conditions. (Courtesy of J.R. Millán, adapted from [10]).

III. BMIs For Space Applications

Some potential uses of brain-machine interfaces (BMIs) for space applications [11], [12] have already been demonstrated in ground experimental labs, like general purpose computer interfaces, replacing the use of mouse and keyboards in dedicated environments [13], systems for use with off-the-shelve software [14], systems optimised to interface with domotic environments [15].

However, these systems have been originally conceived and implemented to restore part of the lost abilities of people seriously affected by different kinds of motor paralysis clinical perspectives on BMIs see [16]) and are not tailored to facilitate astronaut operations [17]. It is not evident that these same BMI devices can be used as hands-free interfaces for human space flight: for example, in order to avoid the production of brain activities which would interfere with the signals used by the BMI, astronauts would need to avoid postural movement, even those necessary to keep a stable position in microgravity conditions. BMIs for space applications would hence need to be first of all adapted in order to optimise the multitasking capabilities of the subject. The first generation of BMIs specifically designed for space applications is likely to be based entirely on noninvasive brain-imaging techniques. This is primarily because of the high risks still associated with neurosurgery, which make implementation on healthy subjects unacceptable. On the other hand, the research in the field of invasive brain-machine interfaces made substantial progress, and invasive systems are expected to play a crucial role in the future of BMIs [18]. At the same time, the promising results with the recent electrocortical BMI systems operated by patients who, for clinical reasons, already have implanted cortical electrodes [19], opened a new possible approach to pursue research on invasive interfaces on humans in the near future.

IV. Future Manned Space Programmes – Planned Or Envisioned

Almost 40 years after the last humans have ventured beyond low Earth orbit and landed on the lunar surface in 1972, renewed interest in such mission has led to the announcement of human space exploration plans for returning to the Moon and eventually reaching Mars before the mid of this century [20], [21]. The traditional space faring nations with human space exploration programmes, the United States (US) and Russia, have been joined by China that has recently become the third country with an independent capability to launch humans into space. A similar programme has been announced by India so that by 2020, there could be four independent, possibly competing human space exploration programmes. Private enterprises are also taking the first steps into human space flight. Private sub-orbital space flight has been successfully demonstrated and several commercial companies based on business plans centred on what is generally called "space tourism" are advancing the field. At time of writing, at least one private company has already arranged for the "visit" of space tourists in the ISS and has announced an ambitious lunar mission [22]. There are observable, stable research trends that favour the introduction of more human-centred research in human space flight. Most of the current life sciences research related to human space flight is performed within the European Programme for Life and Physical Sciences and Applications (ELIPS) Programme of ESA [23], dedicated to life and physical research on the ISS and especially to take full advantage of the unique opportunities provided by the European Columbus laboratory onboard the ISS.

V. Next Steps Towards BMIs For Space Applications

Future BMI systems for space applications will have to be able to operate continuously in reduced gravity conditions, allowing for multiple tasks to be performed concurrently with the BMI protocol execution. While current non-invasive BMI systems have reached a maturity that makes their consideration to support astronaut activities a concrete possibility, the current state of the art devices are however not directly applicable to human space exploration and exploitation activities. Hence, additional research driven by space requirements is necessary. A step by step approach with clear possibly uncritical and simple tasks would not only put BMIs to real space world tests but also facilitate their acceptance among astronauts. Because of the singular and difficult to simulate conditions in which astronauts operate, it is crucial to involve astronauts from the earliest discussion and development stages as to identify in detail those situations where astronauts may benefit from using BMIs [18]. From this application bouquet, a set of possible BMI systems might be selected to be tested and their protocols refined first in short-time microgravity exposition experiments, such as parabolic flight campaigns. Benchmark tests [12], [24] need to be implemented in order to assess the fitness level between systems and their target applications. Once the best BMI systems are identified, these would undergo long-term microgravity exposition tests, i.e. onboard the ISS. Apart from evaluating the effective usefulness of such systems in the accomplishment of specific astronauts' tasks, it remains very important to assess the effects of microgravity conditions on the use of BMIs once long-term neural adaptations have happened in astronauts' brains [25]. It is predictable that the effects of brain adaptation will differently affect the performance of different signal-processing techniques, as well as of different interface technologies, and it is crucial for the future of BMIs in space that those differences will emerge.

VI. Conclusion

Developments of technologies and knowledge required to design brain-machine interfaces are happening at a great pace. These are driven by terrestrial applications and in particular targeted biomedical research. While of interest, such achievements are not directly applicable to microgravity operations where the specific tasks and the unique environment are not considered by the mainstream research efforts on BMI. As a consequence, important research steps are still needed to prove the potential of BMI for human space flight with the early involvement of the final users (astronauts) and space experts. These steps are necessary to construct a critical set of data which will eventually allow for a matching between BMI systems performances and their related applications' requirements, paving the road towards the very first complete design of BMI for space applications. At the same time, the results of the December 2007 ESA parabolic flight campaign suggest that it is at least possible for a subject with prior BMI experience to achieve stable performances of EEG modulation during short-time exposures to micro-gravity. The logic next steps are parabolic flight experiments with online controlled BMI systems and the further comparison with long duration microgravity exposure data.

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