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Applying Brain Machine Interfaces to Aircraft Control: Potentials and Challenges

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Abstract

Brain machine interfaces (BMI) have already successfully been used in laboratory control tasks. A next important step is to apply them in an operational context. A European research project investigates brain controlled aircraft flight, where manual inceptors are replaced by electroencephalography electrodes. Evidently, this immense paradigm shift in how pilots interact with aircraft not only promises some advantages over the established approach, such as a broadened access to aviation, but also entails a number of challenges that will have to be tackled. To provide intuitive handling qualities, which undoubtedly is of great importance, the whole pilot aircraft interface needs to be adapted to this novel control method.

This paper analyses the potentials of brain controlled aircraft flight, studies the resulting implications for flight control system design and points out possible ways of solving the occurring challenges. The absence of haptic and proprioceptive feedback from mechanical inceptors is discussed and important BMI characteristics are presented. The theoretical study of this topic led to the design of a flight controller and subsequent pilot-in-the-loop experiments in a flight simulator, where some of the potentials and challenges of the concept became visible.

1 Introduction

Airplanes, like all other machines and tools, have always been operated manually. It is natural for us humans to communicate and to interact with our environment by physical means. In engineering terms, we use our muscles as actuators and our senses, most notably sight, hearing, touch, proprioception and the vestibular sense, are our sensors.

A brain machine interface (BMI) or brain computer interface (BCI), is a type of neuroprosthesis that enables its user to communicate with a machine by mere brain activity modulation. Thus, the neuromuscular system, including the muscles as our actuators, is bypassed. Not using hands and feet to control a machine also means that touch and proprioception, although unimpaired, do not feed information on the control inputs back to the brain.

At the same time, brain machine communication is unidirectional. The BMI itself does not provide any feedback to its user. Feedback, however, is essential in the process of learning how to use new tools and even after a skill has been automated, feedback is necessary to be able to correct residual errors. You can learn how to use a screwdriver with your eyes closed, only relying on touch and proprioception, but you cannot learn how to drive a screw using a BMI controlled screw driver without any feedback.

Obviously, bypassing our natural actuators and some of our sensors has a huge impact on how we interact with our environment. Applying BMI to the control of vehicles, like airplanes, results in an immense paradigm shift that comprises technological and regulatory challenges as well as a considerable societal impact.

BMI research is still quite young and most experiments are still being performed in a laboratory environment. The tasks presented to the subjects normally are designed to assess whether the user intention is correctly classified, to prove that only brain signals contribute to the BMI, or to validate certain other assumptions. While it is undisputable that this approach is necessary to improve our knowledge about brain processes and BMI technology, it is also essential to step out of the laboratory and assess BMI performance under real world conditions. This paper and the experiments described by Fricke et al. (2014) and Zander et al. (2014) aim at advancing application-driven development.

2 State of The Art in Brain Machine Interfaces

BMIs process electroencephalography (EEG) measurements of the brain's electrical activity in real time to detect brain patterns that reflect the user's intent (Graimann et al., 2010).

EEG measurements can be taken either invasively with one or more intracranial electrodes, or non-invasively with electrodes placed on the user's scalp. Invasive systems usually offer a better signal quality, but they come with all the disadvantages of brain surgery. Hence, most research activities use non-invasive systems, which are also by far more suited for a broad application of BMIs.

Two types of EEG electrodes can be placed on the user's scalp. Wet electrodes, which are still more common, are normally mounted on a cap or assembled as a net. An EEG cap can comprise as much as 256 electrodes, thus achieving a high spatial resolution. Beneath each electrode, the user's skin is prepared by light abrasion and an electrolyte gel is applied to reduce impedance. This set-up process takes some time, depending on the number of electrodes used. After the cap is removed, the subject's hair is still full of gel. Wet electrodes offer a better signal quality than dry electrodes (Popescu et al., 2007). Dry electrodes, however, are far easier to handle. They can be mounted on a headset-like structure that the user simply puts on his head. Dry electrodes are already being distributed by commercial vendors, but some still have robustness problems (Brunner et al., 2011).

Although EEG technology emerged as early as in the 1920s, it was not before 1964 that the first BMI was described (Graimann et al., 2010). It then took another four decades of slow progress in BMI research, until a veritable boom set in that led to successes in controlling prostheses (Pfurtscheller et al., 2000; Müller-Putz et al., 2005), cars (Autonomos Labs, 2011), quad copters (LaFleur et al., 2013) and simulated airplanes (Fricke et al., 2014). In part, this was due to the fact that BMI signal processing, which generally comprises feature extraction and classification algorithms, requires an amount of computer performance that has not been available or affordable earlier.

Today, many different BMI strategies exist, each having its advantages and disadvantages. It is, however, common to all of them that they classify the user's intention only with a certain degree of reliability, rarely exceeding 80% (Fricke et al., 2014). Not many systems provide control in more than one degree of freedom simultaneously.

3 Applying BMI to Aircraft Control

3.1 Long-Term Vision

Obviously, the fact that BMIs allow humans to control machines without performing physical movements makes them a valuable tool for the physically disabled. Hence, this kind of application has been playing a central role in BMI research since its dawn. Spelling machines have been conceived and implemented (Graimann et al., 2010), brain controlled prostheses and wheelchairs have been investigated (Müller-Putz et al., 2005; Graimann et al., 2010) and a BMI controlled exoskeleton has been designed to make paralyzed people walk again (Nicolelis Lab, 2014). Along this line of development it is imaginable that also vehicles like cars and airplanes could, in the (far) future, be brain controlled by physically disabled pilots, whose mobility would thereby be increased. With body ergonomics becoming less important, access to aviation would be broadened.

Of course, BMIs can also be used by people who today are considered physically fit to fly an airplane. By using a BMI instead of manual inceptors, they would have their hands free for other activities.

Another long term vision is that by using a combination of brain control, an adequate flight control system and maybe additional feedback systems, flying could become more intuitive or easier. Thus, flying could become an automated skill in much shorter time. With the flying skill automated, the pilot's ability to multitask is much greater. Flying is safer. A level of familiarity that, today, pilots can only achieve by dozens of hours of manual flight, could then be reached after only a couple of hours. This is interesting especially for the general aviation sector, where accident rate is comparably high due to the pilots' lack in experience (Li & Baker, 2007). If familiarity with flying is gained faster, training time could be reduced. Finally, a suitable brain control system could offer similar benefits of workload reduction as an autopilot, while keeping the pilot in the loop.

3.2 The Absence of Mechanical Inceptors

Obviously, the absence of a direct mechanical link between pilot and aircraft, resulting from the replacement of mechanical inceptors by a BMI, has a tremendous impact on airplane handling. One resulting advantage is that biodynamic coupling phenomena like roll ratchet are eliminated. Moreover, pilot strength and body ergonomics do not limit brain control inputs. Less importance of body ergonomics is one of the benefits identified earlier. In fact, much controversy exists over acceptable control force magnitudes (N.N., 1997), given that a force that is considered strong by one pilot might be considered weak by another.

However, control forces are often deliberately designed to limit the control input amplitude or frequency. In fly-by-wire systems, for instance, this limitation is normally implemented as a high damping of the mechanical inceptors. Inceptor movements thus require increasing force with increasing speed. This is not possible in the case of brain control. As a result, raw brain control inputs can be excessive both in amplitude and frequency. Therefore, they must be filtered and limited within the flight control system. It is equally important to make the pilot aware of these limitations, since it is known that insufficient awareness of active limitations in the control system, especially in actuation rate and magnitude, is a contributor to pilot induced oscillations (PIOs; McRuer, 1995).

Inceptor forces and displacements also provide important cues on the airplane state, which significantly contribute to the pilot's situational awareness. For instance, pilots normally perceive static longitudinal stability of the airframe as longitudinal speed stability. Increasingly forward longitudinal inceptor displacement or force is required to maintain level flight as trim speed increases. Thus, proprioception can contribute to airspeed awareness. Similarly, sufficient stick free manoeuver stability, also referred to as stick force per g, prevents the pilot from unintentionally overstressing the airplane by applying excessive control inputs.

Neither of these cues can be provided to the pilot by a BMI. Obviously, many of the resulting problems can be solved by implementing protection mechanisms within the flight control system. This approach, however, makes the behavior of the controlled system less transparent to the operator. Active protections might be misinterpreted as reduced control effectiveness, which in turn might be tried to counter by more aggressive control inputs that further aggravate the situation. The pilot could also be confused by the airplane's behavior and lose control.

A possible way to solve some of the issues related to missing tactile and proprioceptive feedback from inceptors is to provide the missing information by other means. In the cockpit environment, the visual channel is already heavily used and the aural channel is generally used for communication (crew and air traffic control), annunciation and warning signals. Some minor feedback could indeed be presented visually or aurally, but it would also make sense to reintroduce feedback in the tactile channel. Vibrations on the pilot's body have already shown to be helpful in navigation and control tasks (Jansen et al., 2008; van Erp & Self, 2008). Tactile displays could be used to provide feedback on brain control inputs and aircraft states that are otherwise difficult to perceive.

3.3 Dynamic Characteristics

When mechanical inceptors are used, the pilot intention first needs to be translated to a limb movement by the neuromuscular system. The inceptor displacement or the force applied to it is then transformed into a command signal. When using brain control, the combined dynamics of neuromuscular system and inceptor, which incorporate lags and time delays, can be neglected.

However, a BMI introduces new dynamics. Time-consuming signal processing can lead to a time delay between brain pattern generation onset, i.e. user intention, and a corresponding change in BCI output of up to 1 second (Fricke et al., 2014). Moreover, due to the currently low reliability of BMI outputs, bandwidth is quite low. Hence, BMI control systems tend to be sluggish.

Large time delays have shown to result in significant pilot lead generation, which is accompanied by increased workload, i.e., degraded handling qualities. At the same time, pilot-vehicle crossover frequencies decrease with increasing time delays, augmenting the PIO risk (Hess, 1984). Lags, on the other hand, generally introduce less phase lag but have the additional undesirable feature of suppressing high frequency inputs, thus making the system response sluggish.

Decreasing time delay and increasing bandwidth therefore constitute major challenges of BMI technology. When designing a BMI control system, choosing command variables suitable for the expected bandwidth is of great importance.

3.4 Technological, Regulatory and Societal Challenges

For BMI technology to be actually applicable to airplane control, it will have to improve in ease of use and performance.

The ease of use can already be increased by utilizing dry EEG electrodes. Furthermore, brain pattern generation strategy must be intuitive. Using the motor imagery strategy, the pilot could, for instance, have to imagine a movement of his feet to initiate a right turn. This obviously is not practical. BMI strategies that are more intuitive already exist, but often lack performance.

Desired BMI performance can be characterized by simultaneous control of multiple degrees of freedom and the ability to intentionally produce various command intensities. Increasing the reliability of BMI outputs and thereby the BMI bandwidth is probably the biggest challenge. Although Graimann et al. (2010) expect that "substantial improvements in bandwidth are feasible", it is uncertain whether it will ever be comparable to that of mechanical inceptors. Another issue is that BMIs will have to be robust with respect to changes in the user's brain state, for example due to stress or high workload. Some of these technological challenges may be overcome as computing power increases.

Reliability also plays a crucial role if such a system would ever have to be certified, but it is by far not the only issue. Making the software algorithms employed for BMI signal processing compliant to aerospace standards would be difficult. Moreover, established handling qualities requirements (e.g., from EASA CS) are not applicable to, or unsatisfiable by a BMI controlled airplane. For instance, all requirements on control forces and inceptor displacements are void. However, even today's fly-by-wire transport airplanes do not comply with every paragraph of the certification specifications, when it has been shown that an equivalent level of safety is ensured.

Regulations reflect some, but not all societal concerns. While an invasive BMI might be certifiable, many pilots would probably not accept to use one. Moreover, BMI users might worry about what else can be detected in their EEG signal, apart from their control intentions. Although veritable thought-reading is probably far more futuristic than brain controlled aircraft flight, it is a valid concern that EEG recordings might be misused. Whether pilots will one day accept EEG systems just like they accepted the cockpit voice recorder will have to be seen.

4 Results from First Experiments

For first pilot-in-the-loop experiments with BMI control by Fricke et al. (2014), a flight controller had been designed that provides turn rate control. A command pre-filter ensured that BMI inputs to the flight controller were not excessive. The bank angle was limited to 30°.

Some pilots did not have control, whereas others accomplished the tasks surprisingly well. Without the bank angle limitation, every pilot would have reached an upset attitude at least once. Subjects reported that they had to concentrate a lot on brain pattern generation. Some said that their visual attention was focused on the brain signal feedback, which was shown on the primary flight display. This made it difficult for them to perceive other information, like for example the target heading, visually.

For those pilots who performed well with BMI control, the time delay did not compromise controllability. They reported that they countered it by anticipating the next control input. This kind of lead generation obviously increases workload.

Those who volunteered for the experiments accepted the whole BMI system well but found that the bulky EEG cap with gel electrodes not suitable for everyday application.

5 Conclusions and Perspective

Given the current state of the art in BMIs and the immense technological and regulatory challenges, brain controlled aircraft flight may only become a reality in the far future. Less safety critical BMI applications like brain controlled computer games might become increasingly popular in the nearer future. Assuming the performance of brain control will one day equal that of manual control, it is still not sure whether the possible benefits will outweigh the problems inherent to BMI, notably the missing haptic and proprioceptive feedback of control inputs, or if these problems could be solved.

However, other types of BMI might find their way into vehicles like airplanes in the near future. So-called passive BMIs can monitor the pilot's state and thereby detect drowsiness or even unintended behavior of the aircraft. They can also sense whether the pilot actually perceived a visual or aural warning message.

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