FIRST PILOT-IN-THE-LOOP SIMULATOR EXPERIMENTS ON BRAIN CONTROL OF HORIZONTAL AIRCRAFT MOTION

T. Fricke[1], T.O. Zander[2], K. Gramann[2], F. Holzapfel[1]

[1]Lehrstuhl für Flugsystemdynamik, Technische Universität München
85748 Garching bei München, Deutschland
[2]Team PhyPA, Fachgebiet Biopsychologie und Neuroergonomie, TU Berlin
10587 Berlin, Deutschland

Abstract

Brain computer interface (BCI) technology has been experiencing dynamic development over the past years. As a result, more and more possible applications of this technology are being investigated. One vision pursued in a European research project is brain controlled aircraft flight, where manual inceptors are replaced by electroencephalography (EEG) electrodes. Obviously, existing paradigms in flight control system design cannot directly be applied to this novel approach to aircraft control. First and foremost, adequate command variables must be identified and aircraft dynamics and the human-machine interface must be optimized for good handling.

A flight controller that provides direct control of the flight path was designed and implemented. During subsequent pilot-in-the-loop experiments with this controller in a fixed base flight simulator, the horizontal aircraft motion was controlled via a motor imagery BCI. Different operational and laboratory tasks were flown by six participating pilots with different amounts and types of flying experience as well as one participant that had only theoretical knowledge about flying. Since preliminary experiments lead to some changes of the flight control law, the following six participants performed the tasks with both the initial and the modified flight control law.

The results show that brain control of one degree of freedom of the aircraft motion is possible, in some cases even with high reliability and accuracy. They also permit qualitative and quantitative comparison between the two flight control law designs and between brain controlled flight and manual flight.

1. INTRODUCTION

Although the first BCI was described in 1964 [1], it was not until four decades later that a veritable boom in BCI research set in, leading to successes in controlling prostheses [2, 3], cars [4] and quad copters [5]. Today, many different BCI approaches exist, each having its advantages and disadvantages [6]. 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%. While this is enough to show that BCIs actually work, it is too little for the user to reliably issue commands. The easiest way to increase the reliability of a given BCI is low pass filtering. Various implementations exist, all of which compute one single command based on a multitude of single trial decisions, i.e., samples measured and classified. However, if the desired reliability is high, the system's bandwidth must be reduced dramatically. Most of the previously performed experiments therefore only enabled the user to perform one single, discrete control event every few seconds.

Spelling one single letter of the alphabet with the P300 speller BCI can take more than 10 seconds. In one of the two modes of operation of the brain controlled car [4], semi-autonomous driving, the user can decide over the direction to go at a crossroads. Communicating this binary left/right decision with the BCI takes a few seconds. These two experiments are examples of cue-paced or synchronous BCIs. Synchronous BCIs can only be used in a well-defined time frame and they prompt the user to communicate. Self-paced or asynchronous BCIs, on the other hand, let the user decide when to use the BCI and when not. In another study [5], a self-paced BCI was used to control two degrees of freedom (up/down, left/right) of a quad copter. The task given to the subjects – flying through two suspended rings – essentially was a target acquisition task with an additional element of obstacle avoidance. Hence, only little importance was given to the trajectory the quad copter took to reach a target. Plant dynamics were taken as they were and their influence on handling of the quad copter was not explored.

For the experiments described in the present paper, an asynchronous motor imagery BCI was employed which allowed the pilots to quasi-continuously control the horizontal motion of a simulated airplane. The tasks were largely similar to actual airplane operations and included both target acquisition and tracking elements. Subjects were seated in a highly realistic cockpit. The performance metrics used are based on the actual requirements that must be met in the flight test of a student pilot and allow a comparison between different plant dynamics.

2. BRAIN COMPUTER INTERFACE

The experiments described in this present paper relied on a motor imagery BCI. Motor imagery BCIs make use of the fact that when an individual imagines performing a movement of his body, neuronal activity, the event-related desynchronisation (ERD) of the motor rhythm, is similar to when the movement is actually performed. Since the localization of the ERD, which depends on the part of the body whose movement is imagined, can be identified in the EEG signal, it is possible to train a computer in distinguishing between imaginations of right hand movements "R", left hand movements "L" and feet movements "F" [7].

Prior to the flight control tasks of each subject, classifiers were calibrated to distinguish the pairs L and R, L and F, and F and R. The classifier with the best cross-validation estimate was then chosen to be used for airplane control. The brain computer interface thus allowed control over one degree of freedom. Regardless of what classifier was employed, L always was associated with a left turn of the airplane and R with a right turn. Imagining feet movements would turn the airplane left in the case of the F-R classifier and right in the case of the L-F classifier.

The BCI produced one output signal at 10Hz that was directly fed to the flight control system. Increased match of brain signals and trained patterns produced higher classifier outputs. In the absence of user intention, the average BCI output was zero. Whenever a subject reported a bias in the control, a correction of the BCI output was performed after completion of the current task. The expected online-accuracy of BCI control, estimated from the calibration data by cross-validation, was 72% in single trial averaged over participants. Three of the seven participants had 94% accuracy on average, reporting to have a feeling of accurate control. The time delay between motor imagery onset and a corresponding change in BCI output was estimated to be about 1 second. It had therefore been expected that only low bandwidth control would be possible.

3. FLIGHT CONTROL SYSTEM

The Diamond DA42, a light twin piston engine airplane, was chosen as baseline aircraft for two reasons. First, light general aviation aircraft are mostly flown manually, whereas in airline transport operations, autopilot flight prevails. It is therefore in the general aviation sector where the replacement of manual control by brain control should be investigated first. Second, the Institute of Flight System Dynamics auf Technische Universität München possesses a highly realistic flight simulator of the DA42.

Since, basically, pilots imagined left and right hand movements, it was decided that they would control the horizontal motion of the airplane with the BCI. At the same time, they were relieved from all other flying tasks. For the longitudinal motion, an autopilot and an autothrottle were implemented. They held speed and altitude, or speed and flight path climb angle. For the landing approach, a simple flare manoeuver was incorporated to give the pilots the cues they were used to in this flight phase.

Since the BCI only allowed low bandwidth control, the flight control system needed to provide high level, autopilot type control. General aviation pilots usually follow a desired flight path. For the considered aircraft and mission, the primary task in the horizontal motion is to acquire and hold given headings or tracks. In order to stay close to the conventional airplane reaction to control inputs, the rate of rate of turn was chosen as a command variable. Hence, the current turn rate would be held in the absence of control inputs. An advantage of this type of control is that no command is needed during prolonged turns. On the other hand, it requires a higher BCI bandwidth than, for example, a rate of turn control.

The output of the BCI was passed through a command shaping element and a command pre-filter, before being fed to the χ controller that had been designed for the horizontal motion. The command pre-filter was of second order to create the desired $\ddot{\chi}$ command system. The command shaping element was basically linear, but also comprised a dead zone that was tuned during the preliminary experiments. This dead zone was meant to facilitate users to neither command a left or right turn.

This setup differed from other BCI experiments in that the relatively unreliable single trial decisions were directly fed to the controlled system. The command pre-filter merely represented the low pass dynamics of the airplane as a physical system. These low pass dynamics ensured that, as long as the majority of BCI outputs was correct, the airplane moved to the direction intended by the pilot.

A bank angle protection limited the bank angle to 30°. This limit was reduced at low heights above ground, so that during landing, a wings level attitude was ensured at touch down. Another feature of the flight controller was the path straightener – a function similar to a wings leveller – which returned the airplane to straight flight when turn rate and command input were small. Similarly, when turn rate was close to standard turn rate and the command input was small, the flight controller acquired and held standard turn rate.

4. EXPERIMENTAL SETUP

4.1. Simulator Setup

The week-long test campaign was conducted in one of the flight simulators at the Institute of Flight System Dynamics of Technische Universität München. The Diamond DA42 flight training device is a fixed-base flight simulator built with original aircraft components to achieve a highly realistic cockpit environment. Aircraft flight dynamics and systems are accurately replicated. The three-channel external visual system projects the simulated outside world on a 180° cylindrical screen.

The two displays of the Garmin 1000 integrated flight instrument and avionics system were turned off. Instead, a research display had been fitted to the cockpit, which made it possible to provide visual feedback that had been specifically tailored for the experiments. All in all, visual cues were exclusively presented by the simulated outside view, the research display and the four standby instruments (airspeed indicator, attitude indicator, altimeter and magnetic compass). FIG. 17 shows the cockpit as it was set up for the experiments.

The appearance of the research display was chosen to be similar to the Garmin primary flight display usually used in this simulator or airplane: the entire background was devoted to an artificial horizon, whereas attitude indicator, airspeed indicator, altimeter and heading indicator formed the standard T arrangement in the foreground. Vertical speed was displayed next to altitude and lateral acceleration was presented by a moving bar below the bank angle indicator. The display was complemented by a flight path angle indicator, an indication of the autothrottle target speed (below the airspeed indication), a horizontal situation indicator (HSI) and, in the case an instrument landing approach was flown, a glide slope indicator. Current turn rate was shown by an arc around the compass rose. FIG. 1 depicts the display in its basic configuration, i.e., without any task related elements.

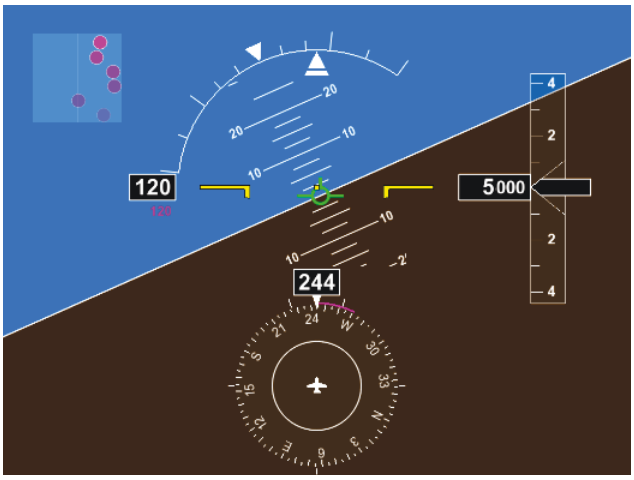

FIG. 1. Basic configuration of the research display

In the top left corner of the display, the brain signal after command shaping was shown to the pilot by a series of left and right moving balls. The uppermost ball represented the current command, whereas the movement of each following ball was delayed by 0.2s with respect to the preceding one. Thus, the pilot could perceive a command history of 1s.

The display also showed task-related elements. During tasks 1 and 2, a heading bug was shown (see FIG. 2). The heading bug was green when the heading error was in the desired range, yellow when the error was adequate and red otherwise.

FIG. 2. Heading bug

During task 3, a course deviation bar indicated the deviation from the (offset) localizer track (see FIG. 3). Again, if the deviation was within the desired range, the course deviation bar was green, whereas it was yellow when the deviation was adequate and red otherwise.

FIG. 3. Course deviation indicator

4.2. Participants

Participants were chosen to have various backgrounds of flying experience. Six out of the seven participants had experience as pilot. Participants 3 and 4 were private pilots who practiced flying as a leisure activity. Participants 1 and 5 had a private pilot license (PPL) when the experiments took place, but also underwent training for the airline transport pilot license (ATPL), thus having additional experience in flight and navigation procedures trainers (FNPT) and jet airplanes. Participant 2 was an airline transport pilot, usually flying the Embraer E-Jet and participant 6 was a former Panavia Tornado pilot. Participant 7 had no piloting experience. He was merely familiar with the theory of flight and knew how to read the relevant aircraft instruments. TAB 1 lists age, license and approximate flying experience of the participants.

Pilot No.	Age	Licence	Experience [h]
1	23	PPL	100 + 60 FNPT
2	30	ATPL	4300
3	29	PPL	120
4	52	PPL	270
5	26	PPL	120 + 70 FNPT
6	32	n/a	1100
7	27	none	none

TAB 1. List of participants

None of the participants had ever used a BCI before the experiments. In this paper, the term pilot refers to every participant, although not all of them were actual pilots.

4.3. Tasks and Performance Metrics

The pilots were confronted with three different tasks that were designed to cover various levels of difficulty and to allow performance assessment in the time and frequency domain. An effort was made to design tasks that are similar to actual airplane operations. The first two tasks were flown with good outside visibility, whereas during task 3, outside visibility was zero above 500ft above ground level (AGL) and 10km below 500ft AGL.

4.3.1. Task 1 – Turns

The task was to acquire and hold target headings given by the heading bug on the research display's HSI. TAB 12 shows the sequence of steps, which has been selected to be random-appearing with an equal number of left and right turns. Another two steps were added for initial familiarization with the task. Each step $\Delta\Psi$ was accompanied by an acoustic signal. Time between heading changes Δt accounted for acquisition with standard turn rate as well as for turn initiation, turn termination and about one minute of tracking (equation (1)), resulting in a total task duration of about 15 minutes.

$$\Delta t = \Delta\Psi \cdot \frac{1s}{3°} + 63s \qquad (1)$$

This task comprised two sub-tasks: heading acquisition and heading tracking. To acquire a target heading, pilots were advised to turn with standard rate of turn. Desired tracking performance was defined as a heading error of less than 5°, which equals to the heading tolerance defined in [8] for an instrument rating flight test. A heading error of less than 10° is required for private and commercial pilot license flight tests [8] and therefore was considered adequate tracking performance.

To quantify heading acquisition performance, a turn rate index (TRI) has been defined that relates the average turn rate to the standard turn rate (equation (2)). Average turn rate was defined as the heading bug step size $\Delta\Psi$ minus 5°, divided by the time to reach the desired region t_d minus 2.5s to account for reaction time and turn initialization.

$$\text{TRI} = \frac{\Delta\Psi - 5°}{t_d - 2.5s} \cdot \frac{1s}{3°} \quad (2)$$

Furthermore, overshoot was defined as the value of the heading error at the time at which the turn rate first becomes zero after the heading reached the desired region. Overshoot could therefore be negative, but not smaller than -5°.

Tracking performance is analysed and quantified between the first time the desired region of the current target was reached and the next target change. Performance measures are the root mean square of the heading error e, defined by equation (3), error variability as a measure of the amount of oscillation (equation (4)) and maximum absolute error.

$$\text{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} e_i^2} \quad (3)$$

$$\text{VAR} = \frac{1}{N-1}\sum_{i=1}^{N-1} |e_{i+1} - e_i| \quad (4)$$

Since the tracking phase was started as soon as the heading entered the desired region, maximum heading error could not be smaller than 5°.

4.3.2. Task 2 – Heading Bug Tracking

Again, the task was to follow the heading bug on the HSI. This time, however, the heading bug oscillated about the initial heading. The forcing function was a sum of 10 sine waves, as described by equation (5), and thus random appearing.

$$f(t) = \sum_i A_i \cdot \sin(\omega_i \cdot t) \quad (5)$$

TAB 2 lists the frequencies and amplitudes of the forcing function components. Frequencies were chosen to be integer multiples of 1/300Hz, as the task duration was set to 300s (5 minutes).

Frequency [Hz]	Frequency [rad/s]	Amplitude [°]
1/300	0.0209	5
2/300	0.0419	5
3/300	0.0628	5
4/300	0.0838	5
7/300	0.147	5
12/300	0.251	5
21/300	0.440	0.5
34/300	0.712	0.5
57/300	1.19	0.5
95/300	1.99	0.5

TAB 2. Forcing function components

Desired and adequate performances were defined like in task 1. The RMS of the heading error (equation (3)) was used as a performance metric. In addition to that, the results of this task can be used to estimate the bandwidth of the pilot-BCI-flight controller-aircraft system.

4.3.3. Task 3 – Offset Localizer Tracking

The aircraft was positioned at a distance of 7NM to the runway threshold and 1NM to the left of the extended runway centreline. Its heading intersects an offset localizer track at an angle of 45°. This offset localizer track differs from the actual localizer track (i.e., the runway centreline) by one dot on the course deviation indicator (CDI, see FIG. 3), which is the half scale deflection and corresponds to approximately 1.3°. Throughout the approach, glide path and airspeed were automatically controlled to provide the cues of a normal landing approach.

The task was to first intercept the offset localizer, then track it. As there were no outside visual references, it was not apparent to the pilot that the localizer was offset. However, since pilots generally flew this task twice, they were told that the localizer could be offset to the left or to the right, or not at all. When the aircraft descended below 500ft AGL, the runway became visible. The pilot was instructed to then ignore his navigation instruments and to continue the approach only by outside visual references. Since the first part of the approach had been offset, the pilot was forced to conduct a sidestep manoeuver. After that, he had to track the runway centreline and touch down as close to it as possible. The simulation ended just before touchdown. FIG. 18 depicts a schematic of this task, which took about 5 minutes.

Obviously, this last task, which required the pilot to follow a given ground track, was considerably more difficult than the previous ones. Apart from its objectively high level of difficulty, it put pilots into the stressful situation of an instrument landing approach. The sidestep manoeuvre finally required the pilots to operate quite aggressively, i.e., with high gain.

Performance was analysed separately for localizer tracking and the sidestep manoeuver. Like in the requirements for a successful instrument rating flight test [8], adequate performance for localizer tracking was defined as half scale deflection of the deviation indicator, i.e., 1 dot on the CDI (see FIG. 3). Desired performance was chosen to be 0.5 dots on the CDI.

Desired centreline tracking performance was chosen to be 27ft or 8.23m, like required by [9] for automatic landing systems. Adequate performance was 23m, an estimate of half runway width minus half wingspan.

For both localizer and centreline acquisition, overshoot was defined as for heading acquisition in task 1. RMS, VAR and maximum error were evaluated for both parts of the task as well. Due to the definition of the tracking segments, maximum localizer and centreline error could not be smaller than 0.25dots and 8.23m, respectively.

5. RESULTS

5.1. Manual Flight as a Reference

To be able to properly assess the pilots' performance with brain control, manual flight will serve as a reference. Although performance with brain control differed a lot from pilot to pilot, it was not expected to see significant differences between pilots in manual flight. Therefore, only two pilots were selected to fly the tasks manually, a few months after the brain control experiments. One of the pilots (age 27, PPL) did not take part in the brain control experiments and the other one was pilot 7. Indeed, their performance was very similar.

In the longitudinal motion, the same configuration of autopilot and autothrottle was used for manual control as for brain control. In the horizontal motion, however, the bare aircraft was controlled manually. Lateral centre-stick inputs corresponded to aileron deflections and pedal inputs deflected the rudder. The bare airplane was chosen because it was known to have adequate handling qualities. Using, for example, a control law from the brain control experiments for manual flight would have been possible, but handling qualities could have been inadequate, thus deteriorating the task performance.

FIG. 4 shows the sequence of turns flown manually by pilot 7 and TAB 3 lists the quantified performance indices. Note that turn no. 1 starts at approximately 190s in FIG. 4, the first two steps being dedicated to familiarization only.

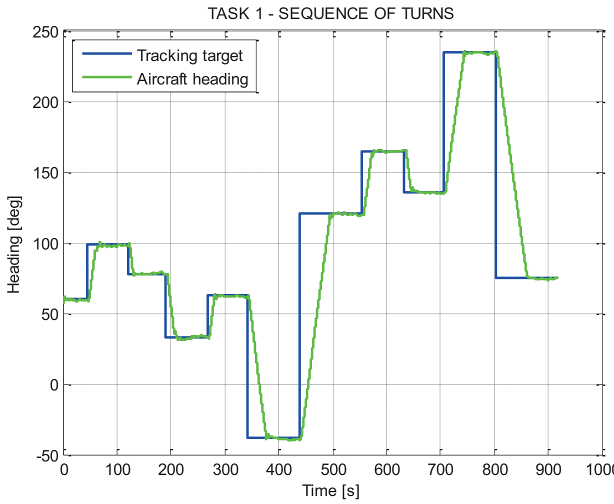

FIG. 4. Task 1, manual fight, pilot 7

Turn No.	Acquisition TRI [-]	Acquisition Over-shoot [°]	Tracking RMS [°]	Tracking VAR [°]	Tracking Max. Error [°]
1	1.12	-2.53	1.41	$4.23 \cdot 10^{-3}$	5.00
2	1.01	0.90	0.97	$2.68 \cdot 10^{-3}$	5.00
3	1.01	0.26	0.96	$3.36 \cdot 10^{-3}$	5.00
4	0.96	-1.54	1.13	$3.30 \cdot 10^{-3}$	5.00
5	0.94	-1.11	0.92	$3.09 \cdot 10^{-3}$	5.00
6	0.88	-0.80	0.98	$3.49 \cdot 10^{-3}$	5.00
7	0.91	0.51	1.00	$3.39 \cdot 10^{-3}$	5.00
8	0.94	-0.58	0.88	$2.65 \cdot 10^{-3}$	5.00
Mean	0.97	-0.61	1.03	$3.27 \cdot 10^{-3}$	5.00

TAB 3. Task 1 performance, manual flight, pilot 7

The TRI values show that the pilot was generally able to turn at the standard rate of turn. Overshoot and maximum tracking error always were within the desired region.

FIG. 5 shows the recording of the manually flown heading bug tracking. The RMS error was 3.69° and the bandwidth of the pilot-aircraft system was estimated to be 0.400rad/s, as can be seen in FIG. 6.

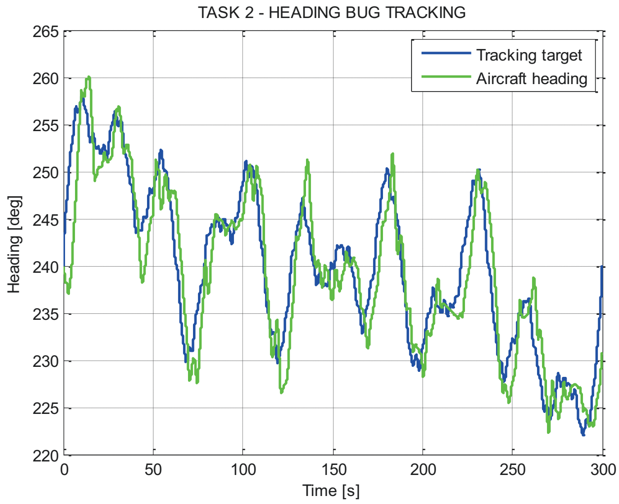

FIG. 5. Task 2, manual flight, pilot 7

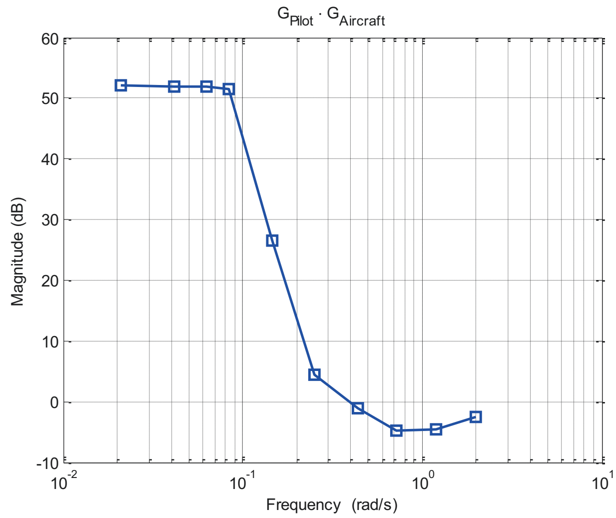

FIG. 6. Frequency domain analysis, manual flight, pilot 7

Finally, FIG. 7 shows the localizer acquisition and tracking and FIG. 8 depicts the sidestep manoeuvre. TAB 4 lists the corresponding performance metrics.

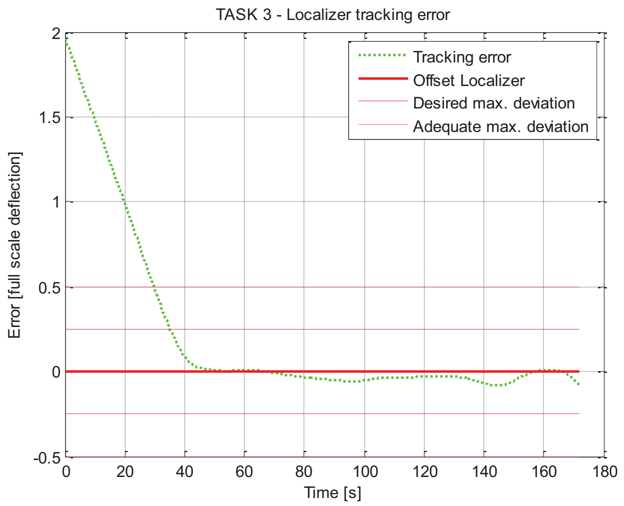

FIG. 7. Localizer tracking, manual flight, pilot 7

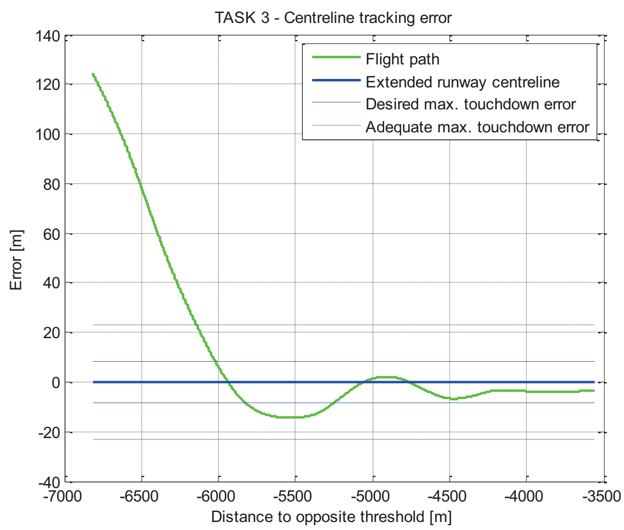

FIG. 8. Centreline tracking, manual flight, pilot 7

	Localizer Tracking [Full Scale Defl.]	Centreline Tracking [m]
Overshoot	-0.0038	14.27
RMS	0.0498	7.10
VAR	$4.26 \cdot 10^{-5}$	$1.23 \cdot 10^{-2}$
Max. Error	0.25	14.27

TAB 4. Task 3 performance, manual flight, pilot 7

It can be seen that localizer acquisition and tracking performance were excellent and that, although the sidestep manoeuvre produced a large overshoot, touchdown occurred close to the centreline.

5.2. Preliminary Experiments

Pilot 1 was invited for one and a half days of preliminary experiments, which permitted to find control system configurations that best enabled him to control the airplane with the BCI.

First, the flight control system was set up as described above. This $\ddot{\chi}$ command configuration will be referred to as control law A. The subject was able to initiate turns, but did not succeed in terminating them, thus flying in circles. A small amount of positive spiral stability was introduced, which seemed to allow better performance. It was then decided to try to use a different command pre-filter, creating a $\dot{\chi}$ command system called control law B. Although performance in all three tasks was not objectively better, control law B received better pilot comments.

It was therefore decided to test both control laws. A variation of task 1 (turns) with a different sequence of target headings was implemented for initial training and BCI tuning. Hence, each following pilot was supposed to fly training and all three tasks first with one control law and then with the other. Some started with control law A, others with control law B.

5.3. Main Test Campaign

During the main test campaign large differences in performance between pilots became evident. Pilots 4 and 6 did not have control. They flew in circles and performed undirected manoeuvers, respectively. Pilots 2 and 5 generally did not perform well. However, they sometimes managed to acquire and track a heading target. Pilot 2 was rather successful when training with control law B, but completely lost control during landing approach, when he seemed to be stressed and quickly got frustrated. Pilot 3 performed amazingly well in all tasks. He even managed to land the airplane on the runway. He was therefore invited for a second session on the following day, where he performed equally well. Pilot 7 achieved a similar performance. All pilots reported that they had to concentrate a lot with this type of control.

Using the recordings of pilots 3 and 7, the influence of the flight control law on airplane handling can be analysed. First of all, it can be said that both configurations were controllable by those pilots.

FIG. 9 and TAB 5 show how pilot 3 performed with control law A. The targets were generally reached in a very short time. Most TRI values are considerably greater than 1. Strong oscillations can be observed. This is also reflected by high VAR values. For only two targets, the maximum error was in the adequate range. Compared to manual flight, RMS error is much greater. Its mean value is approximately 9 times as high.

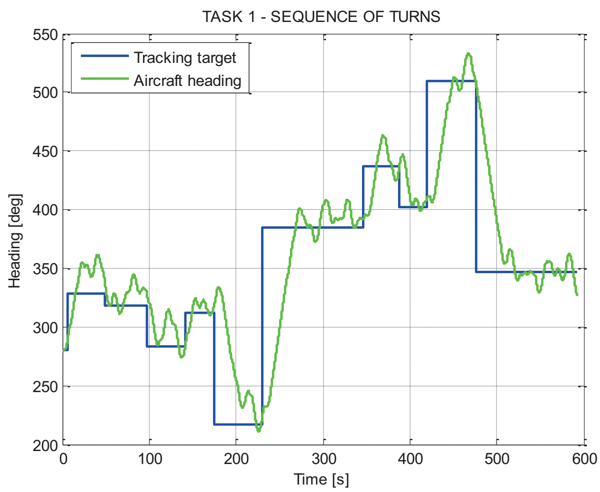

FIG. 9. Task 1, control law A, pilot 3

Turn No.	Acquisition TRI [-]	Over-shoot [°]	Tracking RMS [°]	VAR [°]	Max. Error [°]
1	1.60	-1.66	16.71	$2.48 \cdot 10^{-2}$	31.68
2	1.77	12.16	7.00	$1.94 \cdot 10^{-2}$	12.16
3	0.69	5.73	4.19	$3.02 \cdot 10^{-2}$	8.47
4	1.49	16.30	11.63	$2.20 \cdot 10^{-2}$	23.64
5	1.17	25.91	14.42	$2.93 \cdot 10^{-2}$	25.91
6	0.73	-1.38	4.07	$1.61 \cdot 10^{-2}$	7.33
7	1.24	3.45	12.01	$2.76 \cdot 10^{-2}$	23.30
8	1.26	6.98	7.72	$2.17 \cdot 10^{-2}$	20.27
Mean	1.24	8.44	9.72	$2.39 \cdot 10^{-2}$	19.10

TAB 5. Task 1 performance, control law A, pilot 3

Task 1 flown by pilot 7 with the same control law can be seen in FIG. 10 and TAB 6. Here, a similar performance of fast acquisition and oscillatory tracking can be observed.

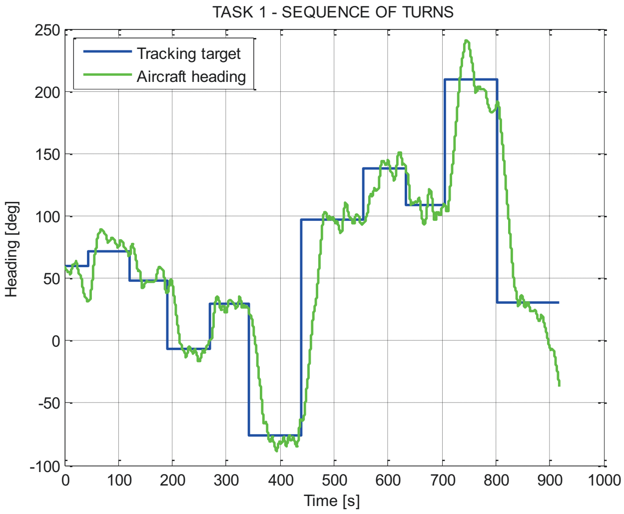

FIG. 10. Task 1, control law A, pilot 7

Turn No.	Acquisition TRI [-]	Over-shoot [°]	Tracking RMS [°]	VAR [°]	Max. Error [°]
1	0.64	2.17	4.34	$1.13 \cdot 10^{-2}$	10.32
2	1.25	5.96	3.65	$1.28 \cdot 10^{-2}$	8.01
3	0.99	5.30	6.19	$1.51 \cdot 10^{-2}$	12.93
4	1.37	6.25	5.23	$1.31 \cdot 10^{-2}$	13.46
5	0.48	6.15	6.39	$1.54 \cdot 10^{-2}$	12.82
6	1.40	-0.63	7.63	$1.73 \cdot 10^{-2}$	15.54
7	1.30	31.25	18.88	$1.65 \cdot 10^{-2}$	31.25
8	1.49	2.41	25.21	$1.44 \cdot 10^{-2}$	66.84
Mean	1.11	7.36	9.69	$1.45 \cdot 10^{-2}$	21.40

TAB 6. Task 1 performance, control law A, pilot 7

For control law A, mean values of the performance indices of pilot 3 and 7 are comparable. Pilot 7, however, achieved slightly lower VAR values and generally reached the target with a lower amount of overshoot.

FIG. 11 and TAB 7 show the performance of pilot 3 with control law B.

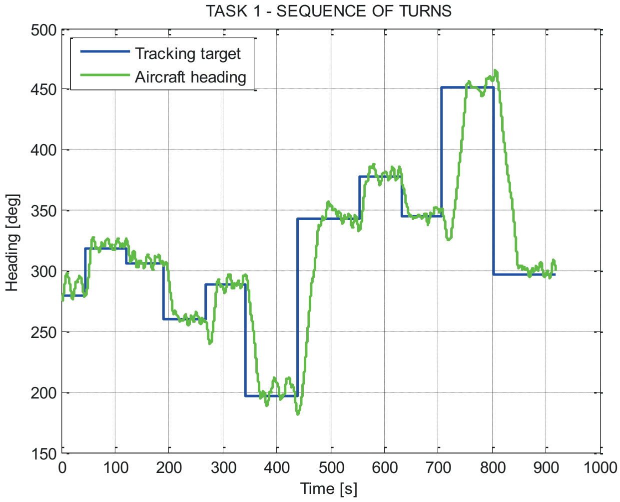

FIG. 11. Task 1, control law B, pilot 3

Turn No.	Acquisition TRI [-]	Over-shoot [°]	Tracking RMS [°]	VAR [°]	Max. Error [°]
1	0.91	-4.23	3.17	$1.20 \cdot 10^{-2}$	7.18
2	0.49	3.63	4.40	$1.55 \cdot 10^{-2}$	9.30
3	1.32	2.10	8.20	$1.72 \cdot 10^{-2}$	15.82
4	1.23	1.62	6.03	$1.50 \cdot 10^{-2}$	13.89
5	1.64	-4.11	4.78	$1.52 \cdot 10^{-2}$	9.43
6	0.91	-0.20	3.51	$9.35 \cdot 10^{-3}$	7.71
7	0.72	2.94	4.81	$1.03 \cdot 10^{-2}$	9.03
8	1.00	-4.35	5.65	$1.43 \cdot 10^{-2}$	12.94
Mean	1.03	-0.32	5.07	$1.36 \cdot 10^{-2}$	10.66

TAB 7. Task 1 performance, control law B, pilot 3

With control law B, pilot 3 achieved much better values in all performance metrics than with control law A. TRI is generally closer to 1 and overshoot always is in the desired range. RMS error is almost halved when compared to control law A. Maximum error is in the adequate range for four targets. Finally, FIG. 12 and TAB 8 depict how pilot 7 performed with control law B.

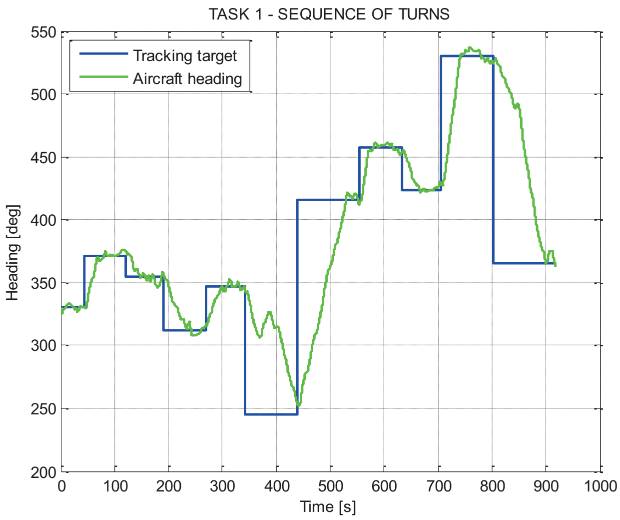

FIG. 12. Task 1, control law B, pilot 7

Turn No.	Acquisition TRI [-]	Over-shoot [°]	Tracking RMS [°]	VAR [°]	Max. Error [°]
1	0.36	-0.82	3.51	$8.40 \cdot 10^{-3}$	6.54
2	0.38	0.28	2.59	$8.66 \cdot 10^{-3}$	5.69
3	Did not reach target.				
4	0.59	6.03	3.67	$1.15 \cdot 10^{-2}$	6.03
5	1.03	-3.25	2.65	$6.29 \cdot 10^{-3}$	5.86
6	0.35	-4.65	2.73	$5.32 \cdot 10^{-3}$	7.18
7	1.01	2.11	3.96	$7.53 \cdot 10^{-3}$	6.97
8	0.55	0.27	6.23	$1.41 \cdot 10^{-2}$	10.10
Mean	0.61	0.00	3.62	$8.82 \cdot 10^{-3}$	6.91

TAB 8. Task 1 performance, control law B, pilot 7

At around 370s, pilot 7 briefly lost control, which is why target 3 was not reached. Overshoot values are generally good, but TRI values are quite low. RMS error and VAR values are low as well. Every target reached was tracked with a maximum error in the adequate range, or only slightly greater.

TAB 9 summarises the previous results. Control law B clearly enabled better tracking performance. For pilot 7, this came at the cost of strongly reduced agility, shown by a low mean TRI.

Control Law	Pilot	Acquisition Mean TRI [-]	Mean Over-shoot [°]	Tracking Mean RMS [°]	Mean VAR [°]	Mean Max. Error [°]
A	3	1.24	8.44	9.72	$2.38 \cdot 10^{-2}$	19.10
A	7	1.11	7.36	9.69	$1.45 \cdot 10^{-2}$	21.40
B	3	1.03	-0.32	5.07	$1.36 \cdot 10^{-2}$	10.66
B	7	0.61	0.00	3.62	$8.82 \cdot 10^{-3}$	6.91
M	7	0.97	-0.61	1.03	$3.27 \cdot 10^{-3}$	5.00

TAB 9. Task 1 summary and control law comparison (M = Manual flight)

Clearly, a difference in performance between brain control and manual control remains. Nevertheless, both pilots performed surprisingly well with control law B.

FIG. 13 and FIG. 14 show how pilot 7 performed with control law B in task 2. All other runs of task 2 revealed considerably worse performance, regardless of pilot or flight controller. It must be said, however, that task 2 can be considered more difficult than task 1.

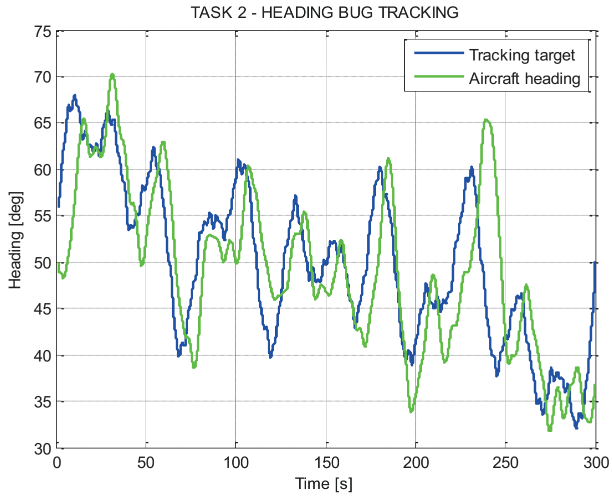

FIG. 13. Task 2, control law B, pilot 7

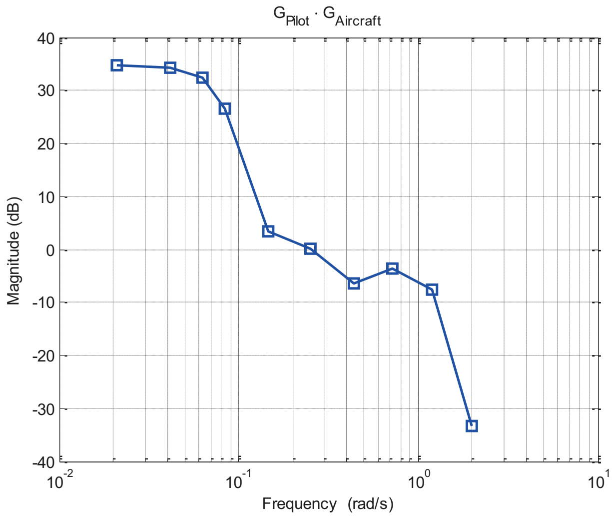

FIG. 14. Frequency domain analysis, control law B, pilot 7

The numerical performance indices of this run, as well as for all other runs of pilots 3 and 7 are given in TAB 10.

Control Law	Pilot	RMS [°]	Bandwidth [rad/s]
A	3	17.17	0.239
A	7	17.71	0.230
B	3	69.95	0.119
B	7	6.61	0.256
Manual Flight	7	3.69	0.400

TAB 10. Task 2 summary and control law comparison

It can be seen that RMS error and bandwidth correlate. Evidently brain control does not reach the performance of manual control. Interestingly, both pilots performed similar with control law A, but very differently with control law B.

Task 3 was rarely successfully accomplished, even by pilots 3 and 7. Some approaches ended near the runway, but only two touch downs occurred on it. As an example, FIG. 15, FIG. 16 and TAB 11 show a successful landing of pilot 3 with control law B.

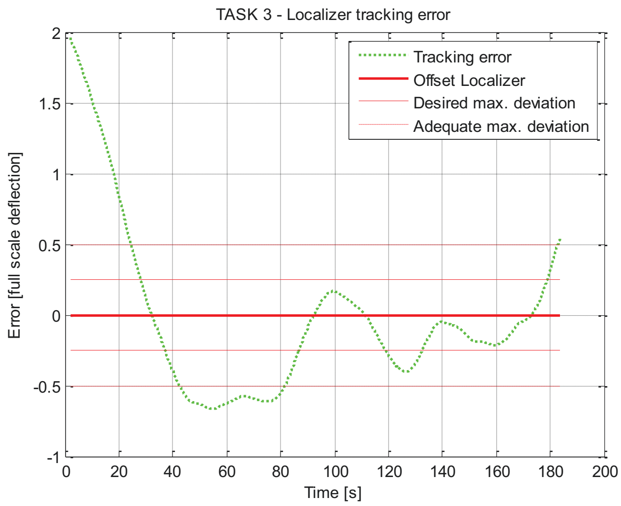

FIG. 15. Localizer tracking, control law B, pilot 3

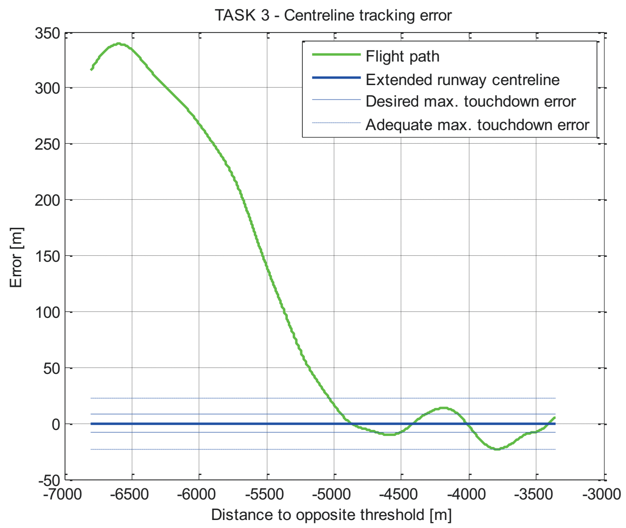

FIG. 16. Centreline tracking, control law B, pilot 3

	Localizer Tracking [Full Scale Defl.]	Centreline Tracking [m]
Overshoot	0.6627	10.29
RMS	0.3588	11.39
VAR	$2.35 \cdot 10^{-4}$	$3.54 \cdot 10^{-2}$
Max. Error	0.6627	23.05

TAB 11. Task 3 performance, control law B, pilot 3

In both cases, tracking performance was generally adequate. Compared to manual control, considerably more oscillations occurred and when the runway centreline was reached, the airplane was closer to the threshold.

6. CONCLUSIONS AND PERSPECTIVE

It was shown that it is possible to control the horizontal movement of a light airplane with a motor imagery BCI. Not all pilots had control, but two performed surprisingly well. Manual control still enabled better performance with far less workload, but the results nonetheless encourage to conduct more experiments, for example to assess how learning affects the pilots' performance or to investigate the application of other BCIs to airplane control.

7. ACKNOWLEDGEMENTS

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APPENDIX

FIG. 17. Cockpit configuration for the experiments

	Familiarization		Turns for Evaluation							
Heading bug step	40° right	20° left	45° left	30° right	100° left	160° right	45° right	100° right	30° left	160° left

TAB 12. Sequence of heading bug steps of task 1

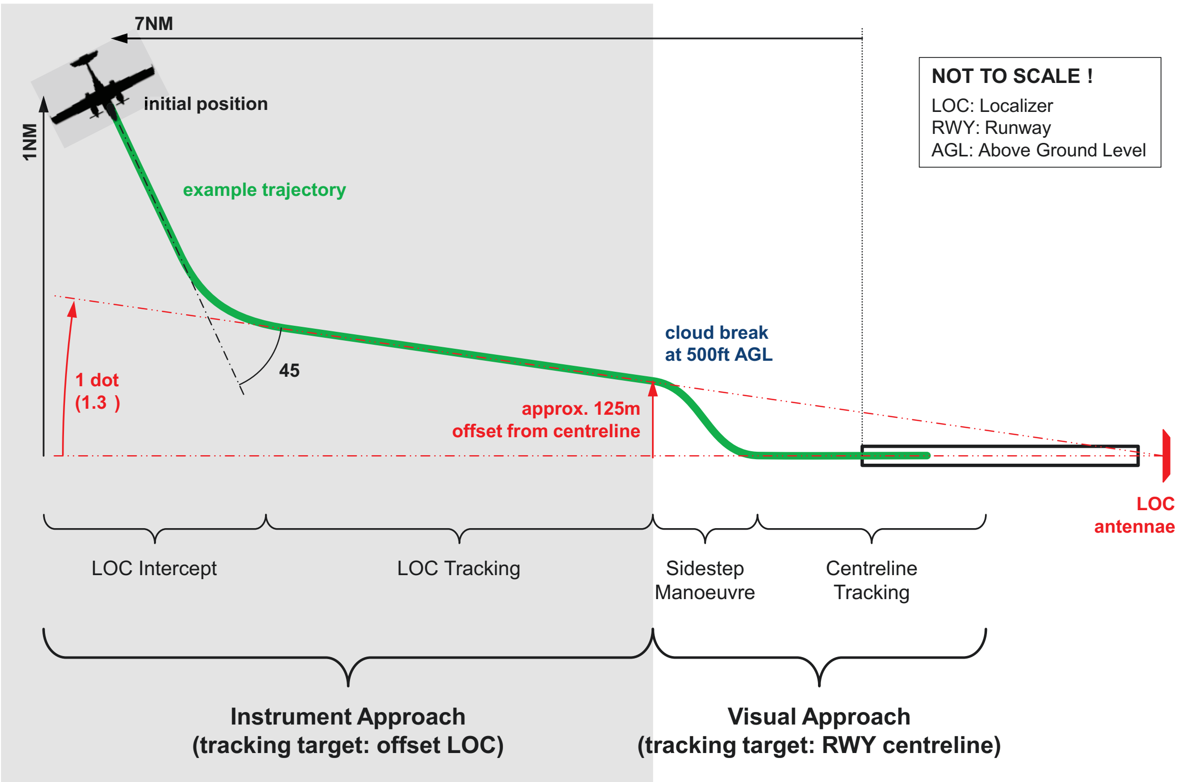

FIG. 18. Schematic of task 3