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Quadcopter control using a BCI

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Abstract. The paper presents how there can be interconnected two ubiquitous elements nowadays. On one hand, the drones, which are increasingly present and integrated into more and more fields of activity, beyond the military applications they come from, moving towards entertainment, real-estate, delivery and so on. On the other hand, unconventional man-machine interfaces, which are generous topics to explore now and in the future. Of these, we chose brain computer interface (BCI), which allows human-machine interaction without requiring any moving elements. The research consists of mathematical modeling and numerical simulation of a drone and a BCI. Then there is presented an application using a Parrot mini-drone and an Emotiv Insight BCI.

1. Introduction

The brain computer interface (BCI) technology make possible manipulation of an embedded system or computer using signals generated by brainwaves. A characteristic of BCI system can capture brain signals generated by neural activities, it can recognize differently neural activity patterns, and also can transform them in useful commands that can be applied to control a machine or a device. BCI are most commonly applied in prosthetic limbs, exoskeletons, robotics, autonomous vehicles, virtual keyboard and computer games [1].

From the point of view of the way the signal is acquired, a BCI system can be classified as invasive and noninvasive, depending on how the EEG biosensors are placed [2]. Noninvasive BMIs, typically named brain – computer interfaces (BCIs) are based on electroencephalography (EEG) to record the brain activities using a series of biosensors disposed on the scalp able to measure the potential generated by electrical activity of billions of cortical neurons. Our study is focused on noninvasive BCI.

Quadcopters, on the other hand, can be used in academic environment by researchers to test or to evaluate innovative new ideas from different research fields such as: real time systems, robotics, flight control theory, navigation. There is a wide range of advantages in using quadcopters as multilateral test platforms. They are relatively inexpensive, are produced in a wide range of sizes and shapes, it presents a simple mechanical design that can be understood even by persons without extensive experience in the field to build them and ensure their maintenance. Due to the interdisciplinary approach necessary to operating a quadcopter, a large number of academics from different area of science are engaged together both in the phase of elaboration and design and also in the phase of improvement the system stability and performance. Quadcopter projects are obviously based on collaboration of many researchers from the field of computer science, electrical and mechanical engineering [3].

Emotiv Insight, used to acquire the signals from the brain, is recently produced in 2015 by Emotiv and represents a novel technology in domain of brainwear device for signals acquisition by electroencephalography (EEG) and Brain-computer Interface principles.

Figure 1. Emotiv Insight Headeset Overview

Emotiv Insight headset shows a number of functional features:

- ergonomic, elegant and intuitive design, is very light,
- it offers great freedom of movement as it allows wireless communication (2.4 GHz frequency) between the headset and computer or between the headset and other embedded system Bluetooth module embedded via intelligent Bluetooth module integrated (BLE 4.0),
- enables 3D visualization of the whole brain activity signal offering through 5 biosensors for electroencephalogram EEG and two reference biosensors for noise cancellation/disturbances due to movement,
- presents 9-axis motion sensors (gyroscope 3 axis motion accelerometer, 3-axis motion and 3-axis magnetometer motion) for accurate detection of the position and head movement,
- provide support for platforms and applications: Windows, OSX, Linux, Android, iOS,
- sampling rate of 128 SPS (samples/second),
- frequency response: 1-43 Hz,
- resolution: LSB 0,51uV,
- Lithium-Polymer Battery: 5V 480mAh, which provides a lifetime of up to 4 hours,
- programming languages and development environments supported: C ++, C #, VB. NET, Java, Python, Matlab Unity.

The types of measurements allowed the headset:

- Raw signal,
- Mental Commands (conscious thoughts),
- Facial expressions - facial mimicry,
- Measurements of performance of the brain.

Emotiv Insight enables:

- Measurement of key performance indices of the brain: attention, concentration, involvement, interest, excitement/enthusiasm, affinity, relaxation, stress,
- Measurements of motion sensors - emulating a virtual mouse based on the parameters obtained from sensors with 9-axis motion [4].

In this paper, remote presence was implemented to control a quadcopter Parrot Rolling Spyder by the Emotiv Insight BCI device.

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1.1. Emotiv Insight BCI

The Emotiv Insight dispose to a system compose by five sensor that are projected to acquire and measure the key activity from the entire functional areas of the cortex. Emotiv Insight represent the first and only device available on the market that can covers **the entire key areas of the cerebral cortex**. The Emotiv Insight detects activity in the frontal cortex (responsible for executive functions), the parieto-temporal cortex (responsible for auditory function, spatial interaction /coordination), and the parietal-occipital cortex (responsible for visual function).

Principal key characteristics of the Emotiv Insight's Scientific design: dynamic brain-computer interface interactions with more degrees of freedom for controlling physical and virtual objects; accurate identify of mental states and emotion such as engagement, excitement, focus, meditation, relaxation and stress; possibility to build brain activity models in real-time based on spatial resolution; a deeper perspective on specific patterns of an individual's brain activity [5].

1.2. Parrot Rolling Spyder

Parrot Rolling Spider is a small sized drone with a compact design controlled by smartphone. It can flies both indoor and outdoor with a remarkable speed and stability. Due to the fact it benefit by ultra-light weight, Rolling Spider can achieve a complete and half turns in one single step; fitted with a pair of wheels, it can fly between the floor and ceiling or even on the walls; comes with a propellers cutout functionality to prevent collision with room objects and possess same flight stability as AR. Drone even if it is 6 times lighter thanks to an autopilot system based on a 3-axis gyroscope and a 3-axis accelerometer. Pressure sensor for flight altitude control. Ultrasonic sensor for precision detect flying near the ground. A vertical camera with a frame rate at 60 fps that can measure the speed based on images compared in real time. It is based on an ultra-sophisticated technology of fusing data received from sensors that makes Rolling Spider one of the most stable drone in the world. It benefit from an inedited take-off mode when the drone is in a state of free fall: the engines start at a drop detection. The Rolling Spider also allow users to take capture snapshots from the aerial views thanks the ingenious way of placing the mini-camera at the bottom of the drone [6].

2. Application

EMOTIV 3d Brain Visualizer is an application designed for Emotiv Insight BCI headset that acquire the brain electroencephalography (EEG) signals through EEG biosensors and shows on screen in real time a 3d cartography of entire neural activity according to the four major brainwave frequency bands: Delta, Theta, Alpha and Beta. User can adjust the sensibility of EEG signals acquisition through a intensity slider or can use default settings (auto-intensity) to obtain detailed information of neural stimuli in different brain regions. Delta wave (1 Hz to 4 Hz) - is the slowest frequency range. It can be measured in adults during drowsiness and deep sleep state [7]. Theta wave (4 Hz to 7 Hz) – may be seen in drowsiness, arousal or meditation [8]. Alpha wave (7 Hz to 14 Hz) – it can be measured on both side of the brain in the posterior regions of the scalp and shows a high amplitude during the relaxation and during eyes closure [8]. Beta wave (15 Hz to about 30 Hz) - it can be measured on both side of the brain but is more pronounced frontally. It is closely related to motor behavior and it shows a significant attenuation during active movements. [8].

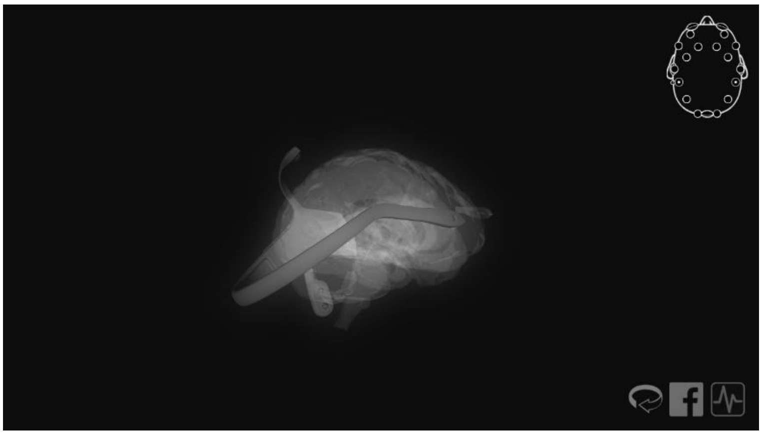

Figure 2. Overview of EMOTIV 3d Brain Visualizer

Humanoid robot controlled by BCI System could be represent a first step to develop in not far away future of an exoskeleton controlled by brain that which can be used for both military and civil purposes. Based on a BCI headset and a camera used to record a video clip of a training session for a mental task, an humanoid robot can be controlled directly by brain signals using electroencephalogram (EEG) principle by simply thinking to „turning right", „turning left" or „walking forward" [9].

Figure 3. Humanoid robot controlled by BCI System [9]

BCI for human measuring level of fatigue can be useful for drivers and aircraft pilots and for this reason it is a research line that must be promoted in the field of BCI, it is safe and effective method to prevent accidents due high workload. In order to detecting the mental state with a high accuracy up to 90% it is necessary to implement in BCI system besides electroencephalogram electrodes (EEG) both electrooculogram sensors (EOG) for estimating mental workload in tasks with high visual attention [10] and also heart rate sensors (HR) due the fact that the installation of drowsiness state is closely linked to the decrease in heart rate and the increase of blink rate [10].

Figure 4. BCI monitoring session based on EEG at flight simulator [10]

3. Software

EEGLAB is an open source Matlab toolbox for processing electroencephalography (EEG) and magnetoencephalography (MEG) signals and other electrophysiological data event-related. EEGLAB toolbox has been developed by Arnaud Delorme and Scott Makeig at the Swartz Center for Computational Neuroscience, Institute for Neural Computation at the University of California San Diego based on a set of Matlab functions for processing and visualization EEG data developed in 1997.

EEGLAB provides a standalone graphical user interface (GUI) that allows user to interact with EEG data without the need for running a Matlab syntax [11]. The user graphic interface integrates a powerful tools that provides a large number of functions placed into three individual layers for processing EEG signals (artifact rejection, filtering, epoch selection and averaging) for analysis in time or in frequency of EEG data, for independent component analysis (ICA), for event-related statistics and for data visualization (scrolling, scalp map and dipole model plotting, plus multi-trial Event-related potentials (ERP)-image plots). EEGLAB provides a programming environment that allows user to store, access, measure and manipulate the single-trial and/or averaged EEG data and display it hierarchized according to the number of EEG communication channels provided by BCI equipment [11].

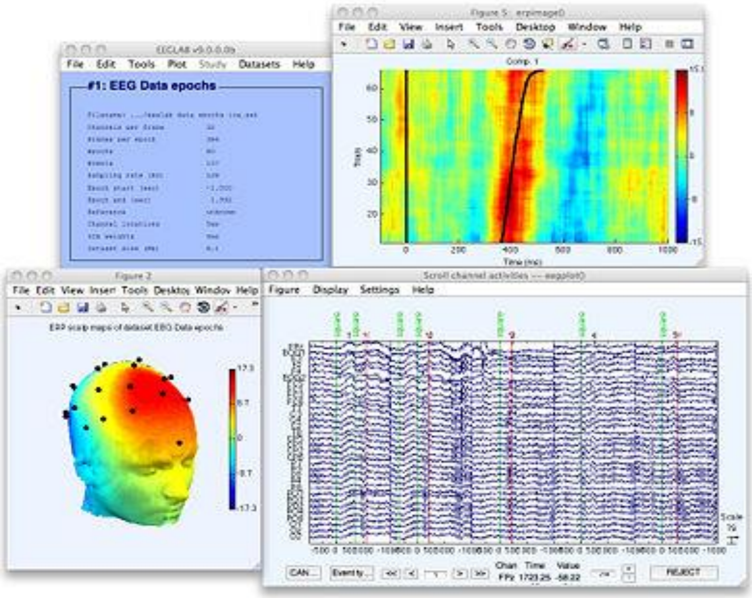

Figure 5. Overview of EEGLAB Toolbox

BCI2000 is an open source development platform for BCI systems designed to use for research or educational purposes with applicability in the field of biomedical engineering projected since 2000 by Gerwin Schalk and Dennis McFarland at the Wadsworth Center of the New York State Department of Health in Albany [12]. BCI2000 was projected in modular form using techniques of object-oriented software design in C++ and for this reason it can be implemented on any programming language and it offers support for any development environment (e.g. Matlab or LabView) [11].

BCI2000 presents a series of basic functionalities: real-time capability - acquiring and processing brain signals at high sampling rate with minimal latency, EEG data recording, removing artifacts and noise sources (e.g. interferences generate by eye blinks or eye movements), spatial filtering, offline data analyses [12].

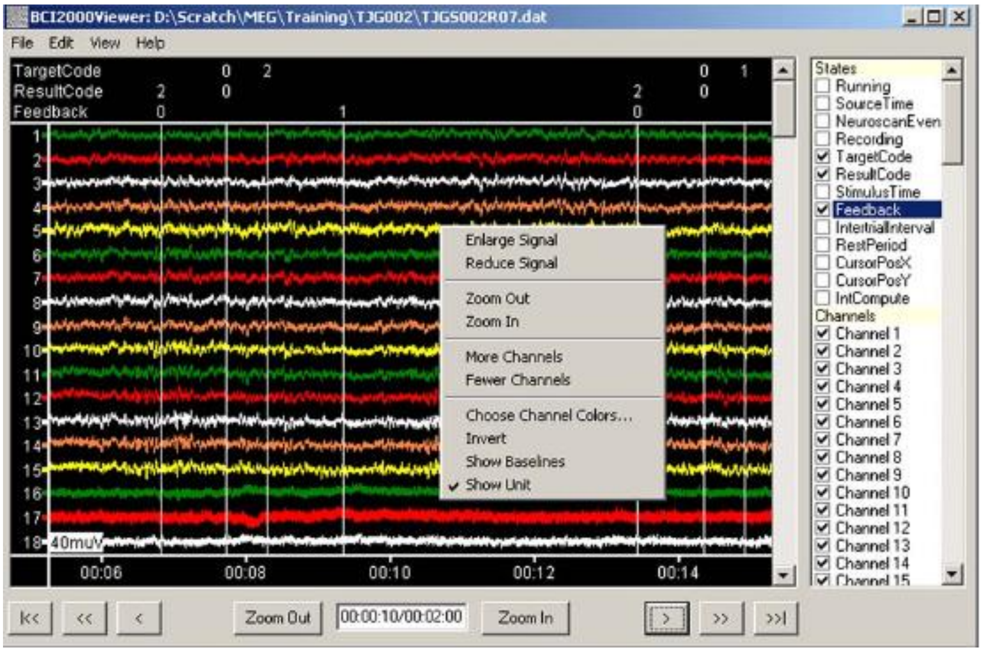

Figure 6. BCI2000 Viewer Interface [12]

Emotiv Xavier TestBench is a software development kit (SDK) designed by EMOTIV Inc., a pioneer in the field of Brainwear® Wireless EEG Technology, used to loading, displaying and analying in real time the electroencephalogram (EEG) signals aquired from EEG biosensors. Beside EEG data Emotiv Xavier TestBench can display the contact quality status with head surface for each EEG biosensors in part, an frequency analysis of the EEG signal for each communications channel based on Fast Fourier Transform (FFT) with the corespondency brainwave frequency bands (Delta, Theta, Alpha, Beta) [13] and the data received from gyroscope, accelerometer and magnetometer that are a part of Emotiv BCI headset. The user can save recorded data in European Data Format file (.edf). The EDF data previously saved can be converted into Comma-separated Value format (.csv) to be analyzed into EEGLAB toolbox.

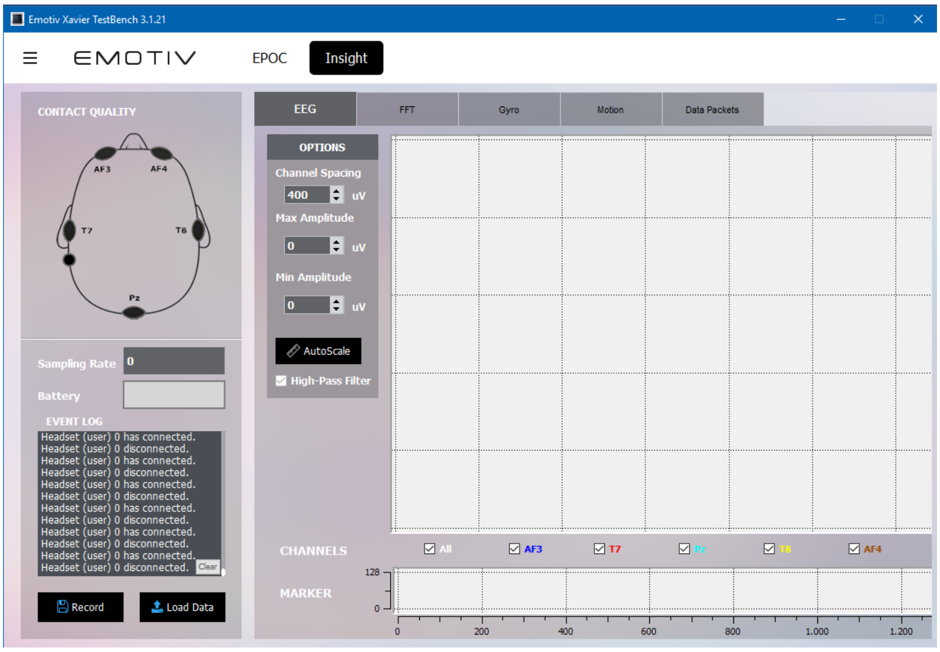

Figure 7. Overview of Emotiv Xavier TestBench SDK

Parrot mini-drone controlled by brain

The system developed in this paper aims to implement a BCI interface based on Emotiv Insight BCI headset with we can control a quadrotor Parrot mini-drone only using brain signals without requiring any moving elements.

The placement of EEG biosensors on Emotiv Insight headset corespond with 10-20 International System standardized. The number of electrodes are grouped in odd for the right hemisphere and even for the left hemisphere. The letters represent the placement of electrodes in function to lobes position: F for frontal, T for temporal, C for central (it is only for identification purposes because the central lobe not exist), P for parietal and O for occipital [14], [15].

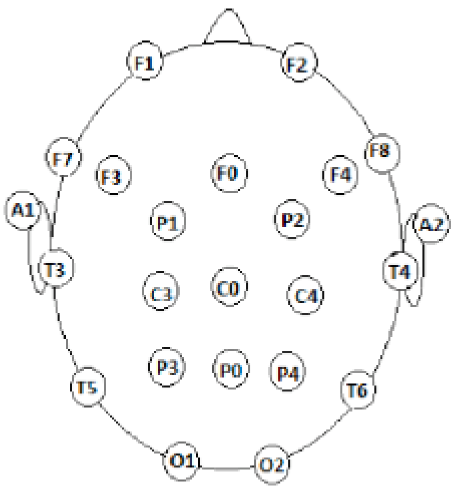

Figure 8. Electrode Placement according to the International 10-20 System [14]

The quadcopter Parrot mini-drone that we use provides 6 degree of freedom (3 degree of freedom is reserved for translational movements and other three for rotational movements) that are obtained by coupling the rotation and translation movements.

We apply the direction cousine matrix to determine quadrotor movements equation from the ground to a fixed point:

$$R_{ZXY} = \begin{bmatrix} C_\phi C_\theta & C_\phi S_\theta S_\Psi - S_\phi C_\Psi & C_\phi S_\theta C_\Psi + S_\phi S_\Psi \\ C_\phi S_\theta & S_\phi S_\theta S_\Psi + C_\phi C_\Psi & S_\phi S_\theta C_\Psi - C_\phi S_\Psi \\ -S_\theta & C_\theta S_\Psi & C_\theta C_\Psi \end{bmatrix} \#(1)$$

where:

- $S_\phi = Sin(\phi), C_\Psi = Cos(\Psi)$, etc.;
- R = matrix transformation;
- Φ = Roll angle;
- θ = Pitch angle;
- Ψ = Yaw angle.

Based on Lagrange approach we can determinated the dynamic model of the drone. Using the force and moment balance theory we can write the equations of motion as follows:

$$\left.\begin{aligned} \ddot{x} &= u_1(Cos\phi Sin\theta Cos\psi + Sin\phi Sin\psi) - \frac{K_1\dot{x}}{m} \\ \ddot{y} &= u_1(Sin\phi Sin\psi Cos\psi - Cos\phi Sin\psi) - \frac{K_2\dot{y}}{m} \\ \ddot{z} &= u_1(Cos\phi Cos\psi) - g - \frac{K_3\dot{z}}{m} \end{aligned}\right\} \#(2)$$

where:

- x: represent the forward position related to the axes of the earth;
- y: represent lateral position related to the axes of the earth;
- z: represent vertical position related to the axes of the earth
- K_i: represent the drag coefficients of the four motors

In the following, based on the fact that the drag force is insignificant at a low speed and considering that the center of gravity should be at the intersection of the axes between the four motors we assume that stability increases as angular acceleration becomes less susceptible to forces once the center of gravity moves up or down. Another way to increase the stability can be realized by targeting of rotor forces to the center of the quadrotor body frame. This will reduce the effects of pitch and roll and also the vertical thrust. For convenience, we will define the inputs to be:

$$\left.\begin{aligned} U_1 &= (Th_1 + Th_2 + Th_3 + Th_4)/m \\ U_2 &= l(-Th_1 - Th_2 + Th_3 + Th_4)/I_1 \\ U_3 &= l(-Th_1 + Th_2 + Th_3 - Th_4)/I_2 \\ U_4 &= C(Th_1 + Th_2 + Th_3 + Th_4)/I_2 \end{aligned}\right\} \#(3)$$

where:

- U_1: correspond to vertical thrust developed by the 4 rotors
- U_2: represent the pitching effect;
- U_3: represent the yawing moment;
- U_4: represent the Rolling effect;

– Th_i: represent the thrusts force developed by four rotors;
– I_i: represent the inertia intervals in relation to the axes

In this paper we also developed a simulation in real time of Parrot Rolling Spider quadcopter behavior in development environment Matlab-Simulink based on some estimation and control modules that we found in a Matlab toolbox designed by the Massachusetts Institute of Technology (MIT). Based on designed estimation and control algorithms, Matlab-Simulink can generate automatically an embedded C-code that can be load onto the drone for test it's behavior in real-life.

In next figure is presented the Simulink model of drone 's dynamics, sensor system and compensator.

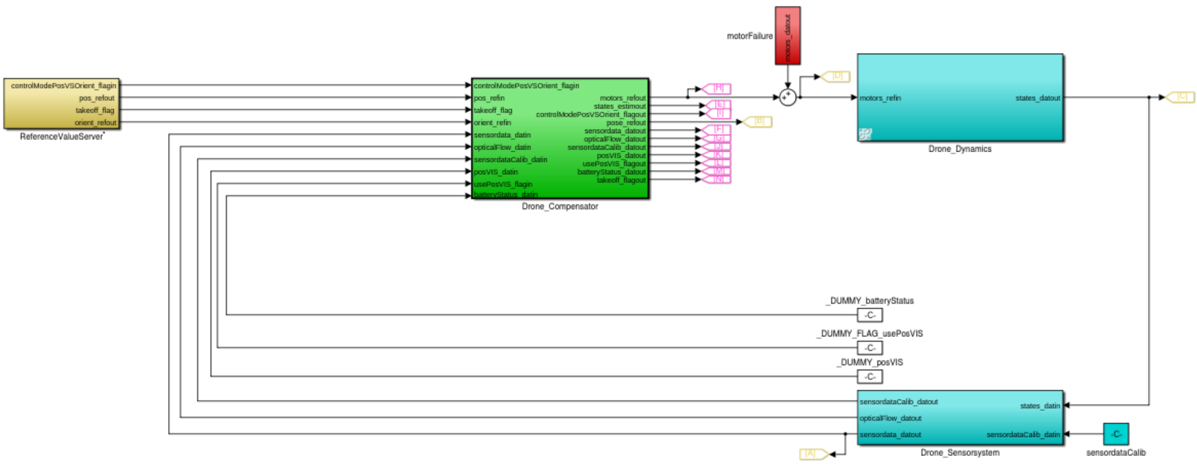

Figure 9. Simulink model of drone 's dynamics, sensor system and compensator

In Figure 10 and Figure 11 is presented the plot of data from simulated flight.

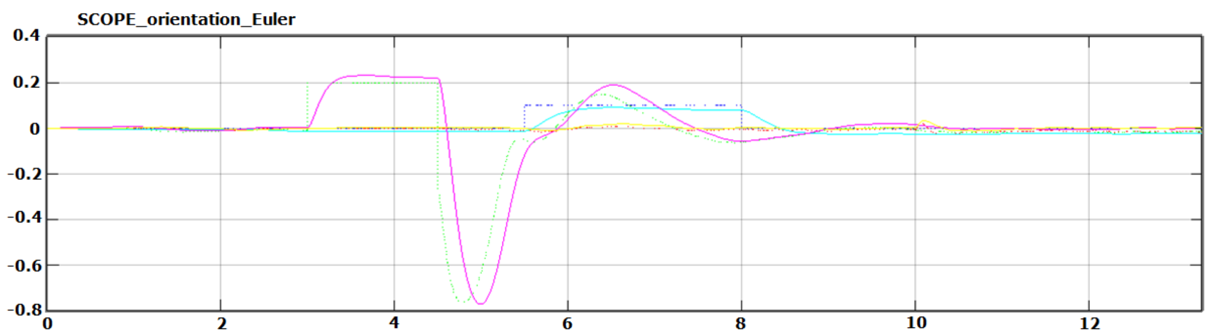

Figure 10. Simulated result for Euler Orientation

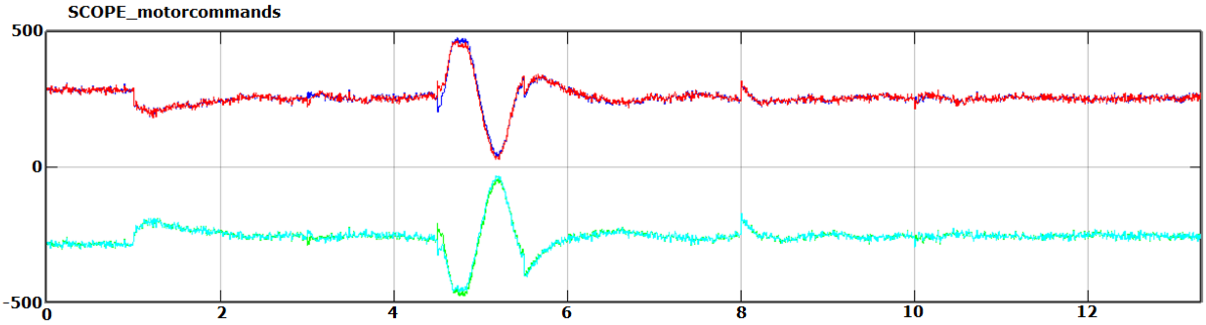

Figure 11. Simulated result for motor commands

The model developed by Simulink also gives us the opportunity to extract the actual flight data from the quadcopter and to analyze them offline, data that can then be compared to the model simulated by us.

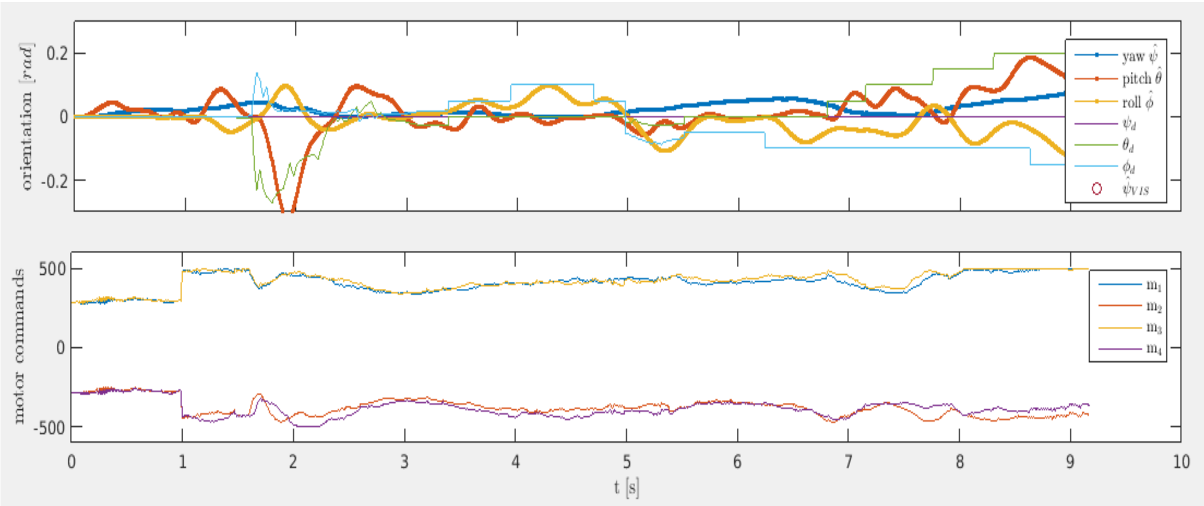

Figure 12. Result from real flight data for Euler orientation and motor commands

Based of inertial XYZ-world coordinates of the drone's center of mass and euler rotations angles (roll rotation about x axis, pitch rotation about y axis and yaw rotation about z axis) obtained by mathematical model and in accordance with simulated model, we also developed a 3d animation of the behavior of the drone in Simulink 3D Animation as presented in Figure 13.

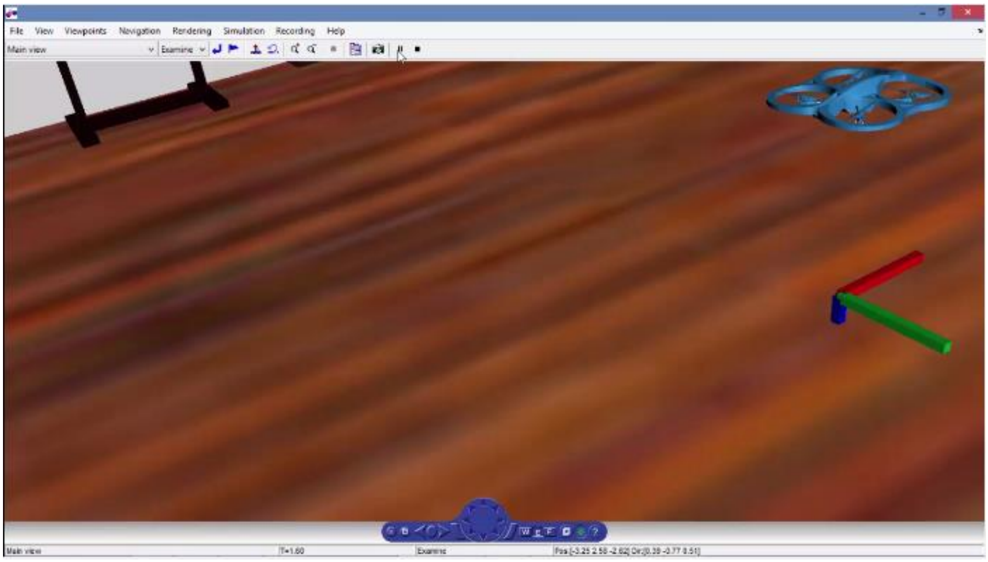

Figure 13. Simulink 3D Animation for take-off the drone

In order to create a BCI connection between the Emotiv Insight headset and the Parrot Rolling Spider Quadcopter we use the Emotiv Xavier Control Panel interface which based on the movement of a virtual object (mental tasks), acquires the EEG signals from the BCI headset and converts them into computer binary code for computer.

We train 4 distinguish mental task one for each direction in which we propose to use the quadcopter:

- lift mental task (fig.14) for take-off the drone at 1.1 meters altitude and up to 0.2 m/s
- drop mental task for decrease altitude with 0.2 m/s
- right mental task for pitch movements with 0.05 degrees on the right side
- rotate left mental for pitch movements with 0.05 degrees on the left side

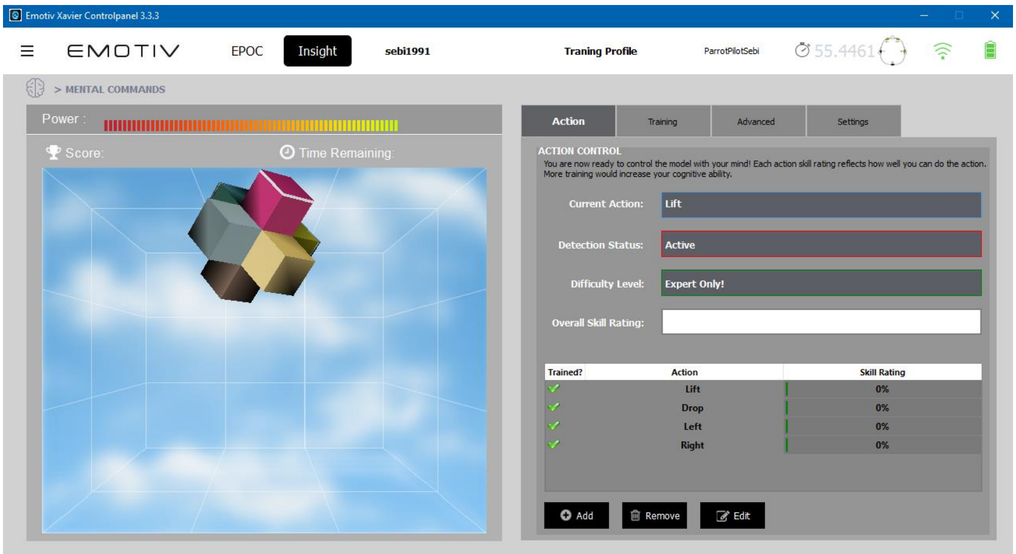

Figure 14. Emotiv Xavier Control Panel interface for Lift mental task

During on the training and execution sessions of mental task we need to maintain a good level of attention and focus key factors that correspond to a high level of beta brainwaves on frontal cortex.

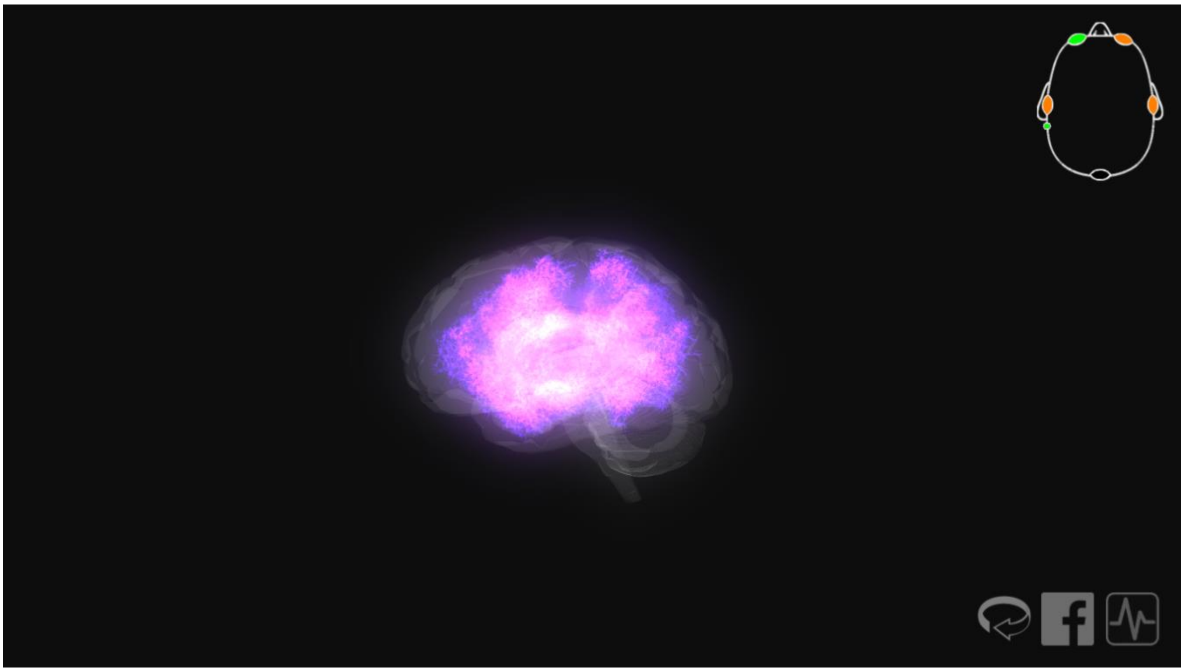

Figure 15. EMOTIV 3d Brain Visualizer Beta brainwave activation for Lift mental task

To convert the binary code into sequences of keystroke we use the Interface Emotiv Xavier EmoKey that after connect to the Interface Emotiv Xavier Control Panel based on logical rules (Mapping EmoKey) defined by us (I correspond to mental task lift, K to drop, A to right, D to left , and R to reset the angle of pich and roll).

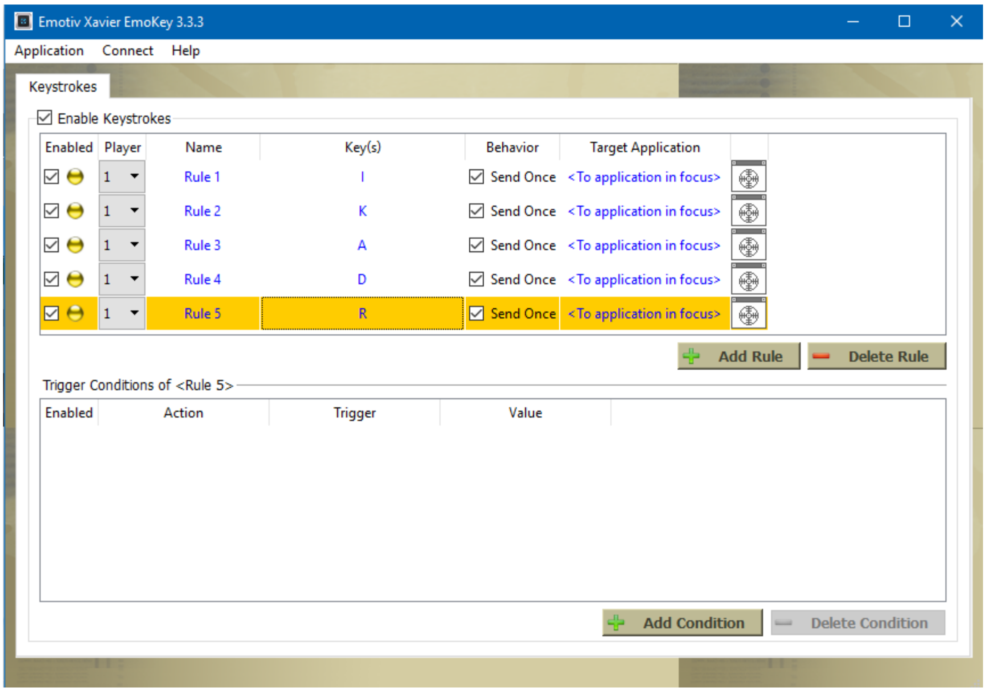

Figure 16. Interface Emotiv Xavier EmoKey

We also analyzed in development environment Matlab based on **Emotiv Xavier TestBench** development kit and EEGLAB toolbox the distribution of EEG signals for each of the five EEG channels provided by BCI headset Emotiv Insight corresponding to Lift mental task.

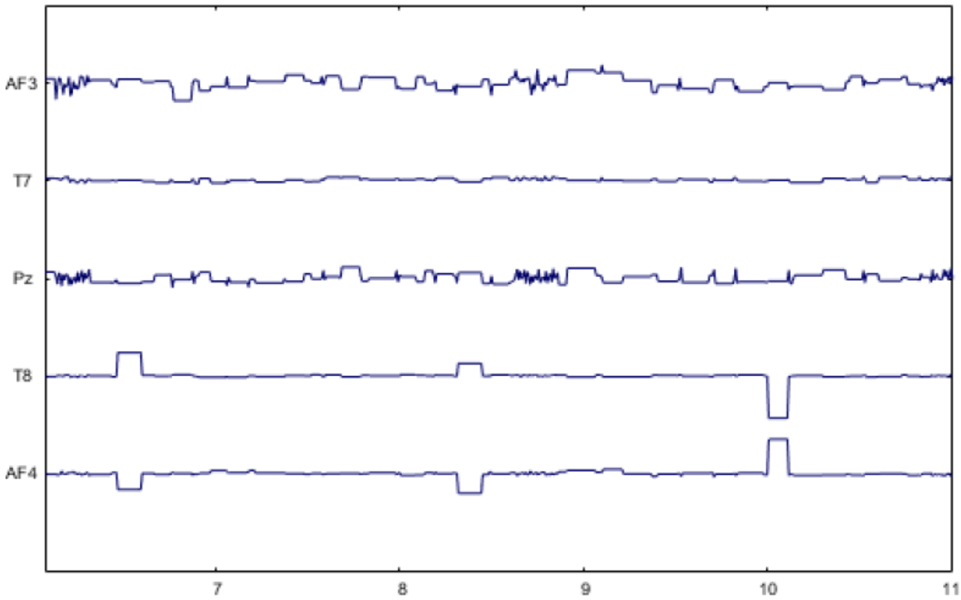

Figure 17. EEGLAB EEG Signals Plot for Lift mental task

In Figure 18 is presented the plotting of spectral analysis of the brain activity for every data channel. Each colored trace corresponds to a particular area of the brain with a distribution of power between 6Hz and 22Hz and with parieto-temporal cortex predominance.

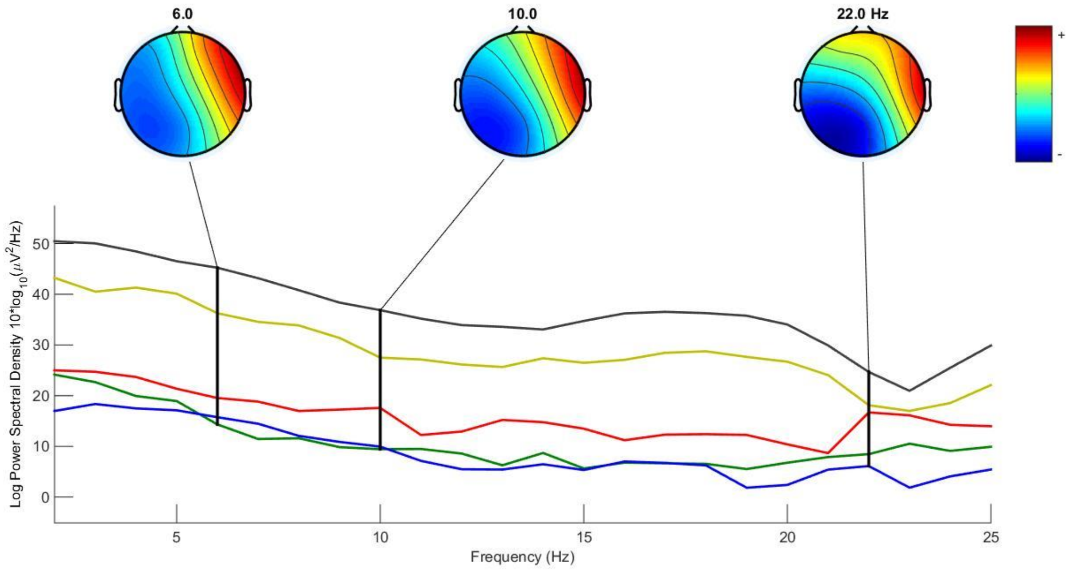

Figure 18. EEGLAB Spectral Analysis for Lift mental task

In Figure 19 is presented the diagram of brainwaves for Lift mental task obtained from analysis of AF3 data channel corresponding to the frontal cortex responsible for concentration and eye movements.

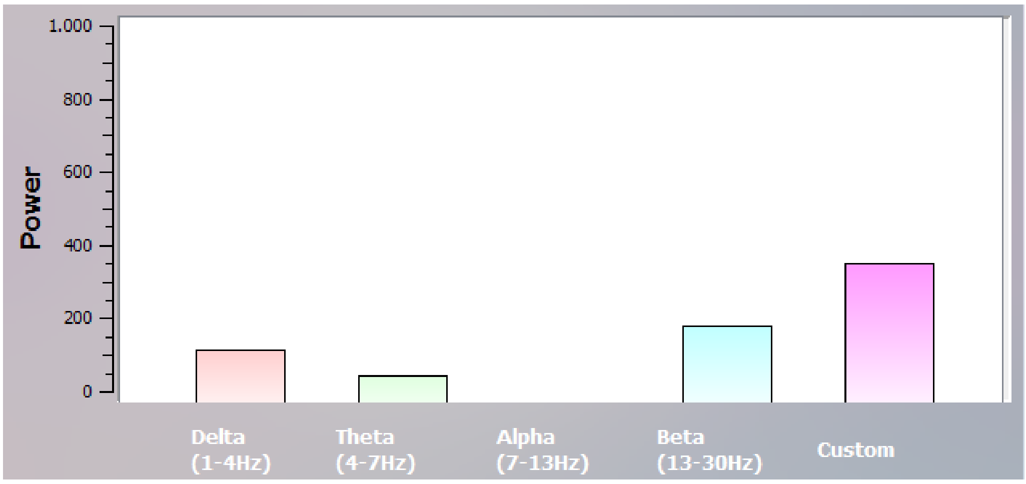

Figure 19. Emotiv Xavier TensBench SDK Brainwawes analysis of Lift mental task

4. Conclusions

Brain-computer interface represents a relatively new and reliable technology that can have appliance in major areas of activity and that can simplify human machine interaction by eliminating physical controls. Drone on the other hand also presents a wide variety of applications from monitoring and surveillance to civilian purposes.

Through this research, we proposed an unconventional method of controlling a drone directly by the brain signals acquired through a BCI system. To achieve the proposed objective we developed the mathematical model and we simulated the functioning in development environment Matlab-Simulink for the quadcopter Parrot Rolling Spider and EEGLAB toolbox for the Emotiv Insight BCI headset. We also developed a 3D animation of the quadcopter behavior in Simulink 3D animation environment based on the algorithms studied.

Further we implemented the unconventional drone control interface based on 4 mental task and we programmed the quadcopter.

Figure 20. BCI-Parrot Rolling Spider system implementation

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As further developments we propose to build our drone with a 3D printed structure, together with implementation of a GPS receiver as a safety method to prevent loss of control in case of loss EEG signals due to bad detection or due to imperfect contact of the biosensors with the skin of the head.

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