**1. Introduction**

Brain Computer Interface is a technique of and the recent development in Human Computer Interface that involves creating a direct connection between the brain and a device, mostly mechanical that is to be controlled by the brain. The field of Brain Computer Interface mostly aims at making lives of disabled persons better by allowing them to control mechanical objects as a representation of their own body such as a bionic arm. BCI is an emergent technology that compensates for the shortcomings of traditional Human Computer Interface like requiring physical interaction by reading the waves produced by the different parts of the brain and using them as control signals. BCI has several potential applications like

* Allowing games to be played only by simulating it in the brain
* Enabling social applications to capture reactions and feelings
* Enabling partially or fully disabled persons to interact with several real-world objects
* Getting more information on how the brain and human nervous system works

One of the task of Brain Computer Interface is to study incoming sensory stimuli from peripheral nerves and how they cause voluntary or non-voluntary actions in the body. The human nervous system chiefly consists of the brain and spine, where the brain is responsible for highly complex tasks that require high levels of integration like thinking, learning, speech recognition, change of emotions and reactions in varied scenarios as well as vegetative and involuntary actions like respiration and cardio-vascular activities. The spine serves as the pathway for messages out of and into the brain and generally is responsible for generating reflexes.

Recent studies however make BCI generally go beyond as a tool of communication and involves studying healthy people and construct a model that can be used in many scenarios from hands-free gaming to rehabilitation. Brain Computer Interface however needs experts to deal with it considering its complexity which becomes the reason for its inability to be used in the real world.

The increase in the complexity of BCI techniques is because of the following factors-

1. *Low BCI signal strength –* Brain signals that need to be extracted have very less strength and need amplification.

1. *Low data transfer rate -* The rate of transfer of data is very slow which makes it suffer from giving fast response
2. *High error rate -* The small signal strength and low transfer rate form the reason of making a BCI application susceptible to variability and hence increase its error rate
3. *Inaccurate classification –* BCI requires acquiring signals from certain points on the brain. However, these signals have high interference and makes classification inaccurate*.*

This report aims at providing the basics of Brain Computer Interface including the anatomy of the human brain, various control signals and acquisition and classification of those signal and the various methodologies that are employed to realise a real world Brain Computer Interface.

**2. Functionality of Brain**

The brain is the most vital organ in the human body as it forms the nerve centre and is responsible for almost any voluntary or involuntary function in the body. It does an array of complex jobs from receiving information via stimuli and various senses such as smell, sight, taste and hearing, processing the received information appropriately and sending the result in the form of a meaningful message. The brain does active functions like coordinating the movement of hands and legs, processing information received from the eyes and ears, thinking, speech as well as passive jobs like breathing, maintaining body temperature and heart rate, secreting hormones etc.



Figure 1 The 5 basic parts of the human brain

The human brain has 5 basic parts –

* **Cerebrum**

It is the largest part of the brain and is located directly under the surface of the skull. It generally does the job of initiating complex actions, memory, language processing and speech production and reasoning through logic. The sensors are generally placed on the scalp to record activity in outermost part of cerebrum called cortex. It has two hemisphere each of which is dominant for specific abilities. The cerebrum also contains the thalamus which directs information to parts of cortex.

* **Cerebellum**

The coordination of all the movements is done by the cerebellum and hence it cooperates closely with the structures of the Cerebrum

* **Medulla Oblongata**

The medulla Oblongata connects the brain with the spinal cord and controls involuntary functions such as respiration. Furthermore, a huge number of peripheral nerves pass through the Medulla Oblongata.

* **Diencephalon**

It forwards information to other areas of the brain and also contains the hypothalamus that controls the body temperature, the water balance of the body and maintains an optimum condition for working of all the cells.

* **Mesencephalon**

It controls vigilance and the sleep-wake rhythm of the body

The functions of the brain include –

*Motor Control -* The [motor system](https://en.wikipedia.org/wiki/Motor_system) of the brain is responsible for the [generation and control](https://en.wikipedia.org/wiki/Motor_control) of movement. Generated movements pass from the brain through nerves to [motor neurons](https://en.wikipedia.org/wiki/Motor_neuron) in the body, which control the action of muscles. The motor cortex of the brain is responsible for all types of gross movements.

*Sensory* - The [sensory nervous system](https://en.wikipedia.org/wiki/Sensory_nervous_system) is involved with the reception and processing of [sensory information](https://en.wikipedia.org/wiki/Sense). From the skin, the brain receives information about [fine touch](https://en.wikipedia.org/wiki/Touch), [pressure](https://en.wikipedia.org/wiki/Pressure), [pain](https://en.wikipedia.org/wiki/Pain), [vibration](https://en.wikipedia.org/wiki/Vibration) and [temperature](https://en.wikipedia.org/wiki/Temperature) and processes this information. This information is handled by the somatosensory cortex.

*Cognition* **–** It can be said as everything that the brain does. In simple language cognition can be described as gaining information and reacting to it through senses, experience and knowledge. It includes attention, problem solving, memorizing, judgement and basically anything a human being is capable of.

*Regulation* **-** The [hypothalamus](https://en.wikipedia.org/wiki/Hypothalamus) in the [diencephalon](https://en.wikipedia.org/wiki/Diencephalon), is involved in regulating many functions of the body. This includes [neuroendocrine](https://en.wikipedia.org/wiki/Neuroendocrine) regulation, regulation of the [circadian rhythm](https://en.wikipedia.org/wiki/Circadian_rhythm), control of the [autonomic nervous system](https://en.wikipedia.org/wiki/Autonomic_nervous_system), regulation of fluid and food intake, regulation of breathing rate and maintaining state of homeostasis.

*Language Processing* – Language Processing is another important functions of the brain. This includes auditory or visual input of a speech or picture, processing the language in them and giving the appropriate output.

**4. Neuroimaging Methods**

Neuroimaging, also called brain imaging is the employment of various methods to image the structure of the nervous system and its functions. Since brain lies in the center of the nervous system, it is also called brain imaging. Brain Computer Interface includes getting signal from the brain and then using them as control signals, however there are various types of signal that comes out of the brain owing to the huge amount of parallel processing done. Hence neuroimaging includes getting appropriate information from the brain usually in the form of electric or magnetic fluctuations.

Neuroimaging is generally divided into two types –

*Structural Imaging* – This type of imaging provides information about the brain’s anatomical structure and hence is useful in diagnosing certain diseases like tumour or brain injury. This includes popular techniques like Magnetic Resonance Imaging(MRI), Computerized Axial Tomography(CAT) and various others that usually image the complete structure of the brain to identify a problem.

*Functional Imaging* – Functional neuroimaging is generally concerned with the measurement of an aspect of brain function. It is usually done to study the activity in certain areas of the brain that is a result of a mental function. Functional imaging provides images of the brain as patients complete tasks, such as solving math problems, reading, or responding to stimuli such as auditory sounds or flashing lights. The areas of the brain that are involved with completing or responding to these tasks “light up,” giving researchers a visual 3-D view of the parts of the brain involved with each type of task.

Some of the popular neuroimaging techniques used are

*Electroencephalography(EEG)*

EEG is the recording of electrical activity through the scalp due to firing some of the neurons in the brain. These electrical activities are recorded over a short period of time through multiple electrodes located on the scalp directly on the cortex. EEG is considered as the most common method for brain signals recording because it has high temporal resolution, easy to use, safe, and affordable.

*Electrocorticography (ECoG)*

Electrocorticography (ECoG) is used to measure the electrical activities of the brain through an invasive procedure, where the skull of the subject is removed and the electrodes are placed directly on the service of the brain. Since the electrodes are placed directly on the skull, the spatial resolution of the measured signals is much better than EEG due to close recording of the neuronal activity. However, the usage of ECoG is very limited as it is almost impossible to be used without a critical surgery and possesses the risk of formation of scar tissue.

*Magnetoencephalography(MEG)*

Magnetoencephalography (MEG) is used to identify and analyse the magnetic field of the brain from the outside of the head by using a detector made of conduction copper or superconducting quantum interference devices. MEG becomes very important for patients with epilepsy or brain tumours by helping to identifying regions with normal brain function in such patients. At the same time, MEG works on the magnetic waves instead of electrical waves; therefore, it could provide a complementary information to EEG. MEG also captures signals with good temporal resolution and very good spatial resolution. Therefore, MEG needs special type of sensitive sensors to detect neural activity that generates very small magnetic fields.

*Functional Magnetic Resonance Imaging(fMRI)*

fMRI is one of the non-invasive techniques that is used to measure the variation of blood oxygen level during the brain activities. fMRI produces high spatial resolution that makes it suitable for identifying the active regions in the brain. However, the fMRI time resolution is very poor, ranges from 1s to 2s. In addition, it suffers from poor resolution with head movements and might produces artefacts.

*Single photon emission computed tomography(SPECT)*

SPECT or SPET is a nuclear tomographic imaging that it is based on gamma rays. The desirable image is generated based on tracking the gamma rays injected in the bloodstream of the patient and emitted by radionuclides. It needs specific chemicals to be bind with certain brain tissue which allows concentration on the radionuclides in the region of interest of the body. SPECT devices can produce 3D information that later can be constructed as 3D image of the monitored part of the brain. In addition, it has spatial resolution of about 1 cm and several seconds as time resolutions.

*Positron Emission Tomography(PET)*

Positron Emission Tomography (PET) is used to observe metabolic processes in the body and it is similar to SPECT; however, in PET a pair of gamma rays is emitted due to radionuclides injection in the patients. In other words, this radionuclide emits positrons that interacts with the electrons located in the monitored/canned area. This interaction generates the gamma rays. Using these gamma rays, an image can be constructed. Unfortunately, PET has high operating cost which makes it not preferable to be used.

**5. Signal Types in BCI**

Any BCI application would require signals captured from the brain to communicate with a device. The brain possesses some amount of neural activity as it communicates with neurons. These neurons have dendrites and axons acting as inputs and outputs respectively. These neurons when fired after getting an input generate some amount of electrical activity. These electrical activities over time generate signals that can be recorded. These signals can be categorized into two classes – Spikes and Field Potentials. Spikes are action potentials of individual neurons when they are fired and is best achieved through invasive techniques. Field potentials are recorded through EEG and are a measure of the combined neuronal activity of a group of neurons recorded through electrodes. These EEG signals can be classified into 5 different types of signal based on their frequency ranging from most active to least active where high frequency represent the brain is highly active and the lowest frequency waves represent the brain is least active. The brain constantly transitions between these 5 frequencies depending on the activity currently being done.

* **Delta**

Delta waves are within the lowest frequency range of signals that are generated when the brain is least active that is when a person is sleeping. They usually range from 0.5 – 3.5 Hz , hence are the slowest waves and have the highest amplitudes among the other signals. It is normally generated during slow wave sleep(SWS) which is the 3rd stage for non-rapid eye movement sleep and gets its name from the slow delta waves which are predominantly more during such type of sleep. The delta waves are generally used to aid in measuring the depth of sleep. Too much delta may lead to severe attention deficit hyperactivity disorder(ADHD) and too little of these waves may lead to inability to rejuvenate the brain and feeling tired.

* **Theta**

The theta waves fall in the frequency range of 3.5 – 7.5 Hz and often form a thin line between sleep and awake. It is generally charaterized by daydreaming and is produced when a person is usually in a state of non-arousal like meditation. When doing repetious jobs like bathing, grooming, walking the brain normally disengages from them and that is when these waves are produced. Theta waves when produced too much can lead to hyperactivity and impulsiveness and can lead to depression when produced too little.

* **Alpha**

The alpha waves form the transition between consciousness and relaxation. While theta waves are produced when the person is in a relaxed state, alpha waves indicate that a person has just completed a task in consciousness and is ready to relax. They usually have frequency in the range of 7.5 – 12 Hz. Too much of alpha waves lead to inability to pay attention and excessive relaxing whereas too little can lead to insomnia, stress and OCD.

* **Beta**

Beta waves are the most dominant waves in a person through out the day and represent consciousness. When a person is giving a speech, debating, or even socializing, these high frequency waves are produced. These waves lie in the range of 12- 30 Hz. Too much of these waves can lead to severe anxiety disorders, incease in adrenaline levels and too less of these waves can lead to poor cognition and difficulty in socializing.

* **Gamma**

Gamma waves are the highest frequncy waves falling in the range of 30 Hz and above. They are usually associated with tasks that require highest amount of information processing and concentration. Learning new things, problems that involve critical thinking etc lead to production of gamma waves. When gamma waves of high frequency are produced, all the senses are said to be bound to perception which is usually the case while learning new materials. Too little gamma waves are characterized by learning disabilites and too much of gamma leads to excessive stress and hyperactivity.

* **Mu**

Mu Waves are a type of oscillating electrical rhythm within the brain. In particular, they occur in the sensorimotor cortex, which is the area of the brain associated with coordinating muscle motion and the perception of one’s muscle and joint muscle. It repeats at a frequency of 7.5–12 [Hz](https://en.wikipedia.org/wiki/Hertz), and are most prominent when the body is physically at rest. Unlike the [alpha wave](https://en.wikipedia.org/wiki/Alpha_wave), which occurs at a similar frequency over the resting [visual cortex](https://en.wikipedia.org/wiki/Visual_cortex) at the back of the scalp, the mu wave is found over the [motor cortex](https://en.wikipedia.org/wiki/Motor_cortex), in a band approximately from ear to ear. A person suppresses mu wave patterns when he or she performs a motor action or, with practice, when he or she visualizes performing a motor action.

**6. Control signals used in BCI**

BCI involves extracting signals from the user’s brain and use them as control signals so control signals form a crucial part of executing a BCI application. While some control signals are easy to identify and extract, some require extra pre-processing to be interpreted. Generally, control signals used in BCI can be categorized into Evoked Signals and Spontaneous signals. Sometimes, hybrid signals may be used which is an appropriate combination of the two types of control signals.

* **Evoked Signals**

Evoked signals are the brain’s response to an external stimulus and are usually involuntary. These stimuli can either be specific to sensory, cognitive or motor event. However, since evoked potentials are related to external stimulus, it may be uncomfortable and stressful for the subject.

Evoked signals can be further divided into auditory evoked potentials, visual evoked potentials and somatosensory evoked potentials.

Evoked signals are Event Related Potentials that are phase locked to a stimulus. For auditory evoked potential that stimulus is sound. They are small electrical voltage potentials generated in response to sounds like different tones or music. Somatosensory evoked potentials find clinical use as they are used to assess a patient’s spinal cord during a spine injury. Visual evoked potential finds widespread use in BCI as they are potentials generated when a person is subjected to visual stimulus like flickering images. The most used evoked potentials are Steady State Visual Evoked potential and the P300 signal.

*Steady State Visual Evoked Potential* - SSVEP signals are provoked by usually repetitive visual stimuli. The visual stimuli such image flickering generates SSVEP at the visual cortex that has the same frequency of the flickering image. SSVEP could be further classified based on the type of modulation into time modulated VEP (t-VEP) BCIs, frequency modulated VEP (f-VEP) BCIs, and pseudorandom code modulated VEP (c-VEP). In t-VEP, the flash sequences of the different targets to different stimulus should be orthogonal or near orthogonal to each other to ensure reliable identification of the target. T-VEP has a low information transfer rate which is almost less than 30bits/min. However, there is no need for user training. f-VEP depends on flashing each target with unique frequency; this generates evoked responses with the same frequency. f-VEP has high information transfer rate, generally 30-60 bits/min. Again, f-VEP does not require any kind of training. Lastly, c-VEP uses pseudo-random sequences that determine the duration of ON and OFF. Here, the information transfer rate is very high in which it could be more than 100 bits/min. However, the subject must be trained first. One of the common application of the SSVEP is the graphical user interface with some buttons on it where each button is having certain frequency. When the subject focuses on one of the buttons the brain generates the equivalent frequency that can be used, for instance, to control the button click.

*P300 –* P300 signal is generally associated with decision making as it depends on a person’s reaction to a stimulus. It is an EEG signal that appears after almost 300ms when the subject is exposed to infrequent or surprising task. This signal is usually generated through “odd-ball” paradigm where the user is requested to attend a random sequence of stimuli with one is less frequent than the others. When this rare stimulus is relevant to the subject, it triggers the P300 EEG signals. The P300 however does not require any subject training but it requires repetitive stimuli which might lead to tiring and inconsistency to the subject.

* **Spontaneous Signals**

Spontaneous signals are the signals generated by subject voluntarily without any external stimulations. Unlike Evoked Potentials, these signals are induced by performing an action. Most of the well-known spontaneous signals are the Motor and sensorimotor rhythms, Slow Cortical Potentials (SCP), and Non-motor cognitive tasks.

*Motor and sensorimotor rhythms*

Motor and sensorimotor rhythms are the rhythms that are related to motor actions such as moving arms. These rhythms come from over the motor cortex with frequency bands located at μ (≃ 8-13 Hz) and β (≃ 12-30 Hz). The amplitude of these rhythms could be controlled by the subject. However, the control of these sensorimotor rhythms is done by one of two methods - Operant Conditioning and Motor imagery.

In operant conditioning, the subject can voluntarily change the amplitude of his/her sensorimotor rhythms through long training. It is up to the subject to choose his/her mental strategy that suits him/her. However, the training could last for weeks or months. After that, the μ and β rhythms at different positions can build up as a control signal.

Motor imagery, is the translation of the subject motor intention into control signals through motor imagery states. For instance, the left hand movement may generate EEG signals that accompany with the μ and β rhythms, decrease in specific motor cortex area. Different applications could be used according to the motor imagery rhythms such as controlling a mouse or playing a computer game. With new Artificial Intelligence techniques, the subject might not need any training; however, it is always better to have some training before using the motor imagery systems.

*Slow cortical potentials (SCP)*

SCP is an EEG signal that belongs to a frequency below 1Hz. It is a low frequency potential detected in the frontal and central parts of the cortex. SCP is a very slow varying, positive or negative wave of the cortical activity that may last from milliseconds to several seconds. The subject can control generation of such signals using operant conditioning. Therefore, subject has to undergo long training. Currently, SCP is not preferred by many of the researchers and replaced by Motor and sensorimotor rhythms.

*Non-motor cognitive tasks*

Non-motor cognitive tasks mean that cognitive tasks are used to drive the BCI. Many of the tasks could be performed such as music imagination, visual counting, mental rotation, and mathematical computation.

**7. Categorization of BCI**

BCI can be classified according to dependability, invasiveness, and synchronization. In terms of dependability, the BCI is categorized as dependent and independent while in terms of invasiveness it could be divided into invasive BCI, non-invasive, and semi-invasive BCI. In the final category, the BCI could be synchronous or asynchronous.

* **Dependent BCI and independent BCI**

The dependent BCI requires certain level of motor control from the subject while independent BCI does not require any control. Dependent BCI could help the subject to do things more easily such as playing video games and moving wheelchair. On the other hand, subject with severe disabilities would need an independent BCI where no motor control is needed.

* **Invasive BCI, non-invasive, and semi invasive BCI**

BCI is classified to invasive, non-invasive, and partially invasive according to the way of the brain activity is measured. In invasive BCI, the microelectrodes are implanted in the brain, to capture neural spikes from a region, during neurosurgery for example in Electrocorticography (ECoG). In this case, the signal might be produced with high quality but prone to scar tissue build-up over time and the signal might get lost. In addition, once the invasive technologies have been planted, it is not possible to move it to measure other parts of the brain. On the other hand, in non-invasive BCI, the signals are recorded without any penetration on the scalp. The signals in this case could be in low quality, however, non-invasive BCI is preferable due to its ease of use and low cost as well as no surgery being required. In partially invasive BCI, the electrodes are implanted underneath the skull on top of the brain. The signals produced may be of lower quality but the issue of scar tissue developing as in case of Invasive BCI is solved.

* **Synchronous and asynchronous BCI**

BCI system is called synchronous when the user interaction with the system is done at certain period. In other words, the system must impose certain constraints on the subject to interact with it at certain period. Otherwise, the system will not be able to receive the subject signals. On the other hand, in asynchronous BCI or as it is called self-paced, the subjects can perform mental tasks at any period of time and the system will react to their mental activities. Therefore, the subject is not imposed with any constraint.

**8. Pre-processing Techniques**

**8.1 Feature Extraction**

Power Spectral Density

Fast Fourier Transform

CSP form hilbert transform

Discrete Wavelet Transform

Median Filtering

Empirical Mode Decomposition (Uni and Bi)

Auto Regression

Blind Source Separation using Independent Component Analysis

Cross correlation

**8.2 Feature Selection**

Genetic algorithm based

t-statistics

Inheritable bi-objective combinatorial genetic algorithm

Jensen Shannon divergence using NN methodologies

Covariance matrix adaption Evolution strategy

**8.3 Classification**

Linear Discriminant Analysis

Bayesian Linear Discriminant Analysis

K-Nearest Neighbours

Hidden Markov Model

Support Vector Machine

Logistic Regression

Fisher’s linear discriminator

**9. Dimensionality Reduction**

**10. Summary**