Master's Thesis

A Hybrid BCI Approach: Coupling EEG and IntegraMouse®

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Abstract

Within this Master's thesis a hybrid brain computer interface has been implemented. The goal was to combine the benefits of an EEG-based brain-switch and an assistive technology device called IntegraMouse® to control a computer. The system was developed for people who are hardly able to use the sipping and puffing function of the IntegraMouse® due to suffering from disease or disabilities. In the implemented system there are different modes to control the mouse cursor on the screen. In main mode the mouse cursor movement should be controlled by the IntegraMouse®, the click impulse should come from the EEG-based brain-switch instead. Due to decreasing of the quality of this click impulse the system should switch to a mode where the IntegraMouse®-click is used. When the mouse cursor movement turns unusable, due to uncontrolled shaking for example, the system can be changed to a mode where a *Radar Mouse* is used.

First an interface for the USB mouse device was integrated to a data acquirement system called TOBI SignalServer. Then a Matlab/Simulink model was designed which actually process the input signals to the output signal. This model is called *Fusion*. It contains miscellaneous methods for evaluating the quality of the input signals. Based on these, the optimal control mode used for the hybrid BCI can be determined. Fisher's linear discriminant analysis (LDA) was used to compute the parameters for the EEG-based brain-switch. Finally the accessibility platform QualiWorld was controlled with the obtained signal. Therefore visual feedback for the user was provided.

Finally, the whole system was tested by a test person. After this verification measurement a study on 4 participants was performed. The execution of all relevant tasks was performed well, therefore the implemented BCI system can be operated by a user.

Kurzfassung

Im Rahmen dieser Masterarbeit wurde eine hybride Hirn-Computer-Schnittstelle (BCI) entwickelt. Ziel war es, die Vorteile von einem durch EEG angesteuerten Gedanken-Schalter und einem assistivem Unterstützungsmittel namens IntegraMouse® zu kombinieren um damit einen Computer anzusteuern. Das System wurde für Personen entwickelt, welche die Saug- und Blasfunktion der IntegraMouse® auf Grund von Krankheiten oder Behinderungen nur sehr schwer ausführen können. Im implementierten System gibt es verschiedene Modi um den Mauszeiger am Bildschirm zu kontrollieren. Im Hauptmodus sollte die Mausbewegung durch die IntegraMouse® gesteuert werden, der Klick hingegen sollte vom Gedanken-Schalter ausgelöst werden. Bei Verschlechterung der Qualität dieses Klick-Impulses sollte in einen Modus gewechselt werden der IntegraMouse®-Klicks verwendedt. Bei schlechter Mausbewegung kann in einen Modus mit Radar-Maus umgeschaltet werden.

Zuerst wurde eine neue Schnittstelle für die via USB angeschlossene IntegraMouse® in das Datenerfassungssystem namens TOBI SignalServer integriert. Daraufhin musste in Matlab/Simulink ein Model erstellt werden, welches die verschiedenen Eingangssignale zu den entsprechenden Ausgangssignalen verarbeitet. Im Weiteren wird dieses Model *Fusion* genannt. Es bietet verschiedene Methoden die die Qualität der Eingangssignale bewerten. Dadurch wird der passende Modus bestimmt in dem das hybride BCI betrieben wird. Mittels Fishers Linearer Diskriminanzanalyse (LDA) wurden die Parameter für den Gedanken-Schalter ermittelt. Dann wurde die Software QualiWorld mit dem Kontrollsignal angesteuert. Diese bietet somit visuelles Feedback für den Benutzer.

Zum Schluss wurde das komplette System mit einer Testperson auf korrekte Funktionalität getestet, danach wurde eine Studie mit 4 Teilnehmern durchgeführt. Die Ausführung aller relevanten Aufgaben ist gut gelungen, das implementierte hybride BCI-System kann also erfolgreich von einem Anwender bedient werden.

Statutory Declaration

I declare that I have authored this thesis independently, that I have not used other than the declared sources / resources, and that I have explicitly marked all material which has been quoted either literally or by content from the used sources.

Eidesstattliche Erklärung

Ich erkläre an Eides statt, dass ich die vorliegende Arbeit selbstständig verfasst, andere als die angegebenen Quellen/Hilfsmittel nicht benutzt und die den benutzten Quellen wörtlich und inhaltlich entnommene Stellen als solche kenntlich gemacht habe.

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Danksagung

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Graz, im August 2011 Bettina Kaltner

Contents

1 Introduction

Scientists have, for many years, pursued the goal of controlling machines solely by thoughts. A well-performing implementation of such concepts would be a breakthrough in medical practice. Severely paralyzed patients and locked-in patients for example would regain possibilities to communicate and handle their environment on their own (for further information on locked-in syndrom see [1]). Systems realizing such concepts today are generally known as brain-computer interfaces (BCI) [48]. Commonly, they are realized using non-invasive methods to gain brain signals, which means that no surgeries are needed for measurement. [30] outlines important issues of non-invasive BCI-systems and gather information on related articles. However, accomplishments in this range of science are far apart from being good enough to get by. Regarding this, there is the idea of implementing hybrid BCIs which are not confined to one single method of collecting signals, but combine different ones [32]. Certainly, to satisfy the term BCI, there has to be at least one kind of brain signal used. A specific implementation of such hybrid BCIs is the method discussed in this Master's Thesis: signals obtained by electroencephalography (EEG) combined with an assistive technology device called IntegraMouse® (Lifetool, Linz, AT).

1.1 Brain-Computer-Interface (BCI)

Definition: 'A Brain-Computer Interface (BCI) is a non-muscular communication channel for connecting the brain to a computer or another device' [51].

Therefore, a BCI offers a direct connection between the brain and the external environment and can transform thoughts into control signals. A BCI system is always an online system, so that the person can interact with the environment in real-time.

In [48], Jacques J. Vidal mentioned the idea of implementing BCI systems for the first time. Then the idea was to evaluate the feasibility and practicality of using brain signals when establishing communication between men and computer. At the same time, he wanted to provide a new tool to study neurophysiological phenomena which ensure control or even production of observable neuroelectric events.

Since then, research in this field made great strides. Millán et al. [29] and Dornhege [9] outlines evolution and current trends in BCI systems. Pfurtscheller et al. [35] describes the state of the art at the Graz-BCI.

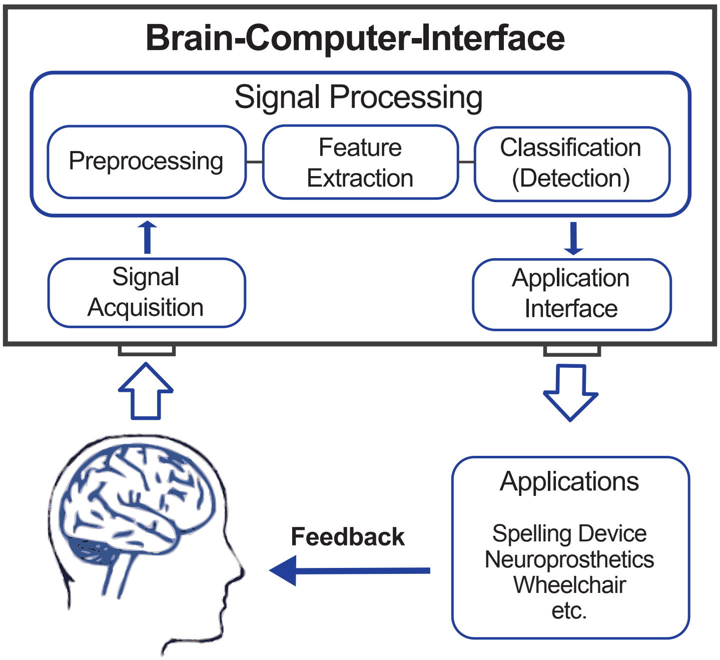


Figure 1.1: Components of a BCI (adapted from [16]). Data is acquired from the brain via any brain signal measuring method. After preprocessing, features are extracted and classified. The control signal is sent to any application via an application interface which feeds back the current performance to the user.

The principle components of a BCI are shown in Figure 1.1. The basic idea is to collect information from the brain by using any kind of brain signal and brain signal measuring method, and then process it appropriately so that the received signal can be used to control applications and devices afterwards. Therefore, the data gets preprocessed (by filtering for example), then some features are extracted. Some often used features are band power, adaptive autoregressive (AAR) parameters and calculation of common spatial filters [34]. According to those features classifications or decisions can be done. After this procedure the obtained signal can be used to control an application. To close the loop, different kinds of feedback tell the user if the computed control signal is correct.

For further background information, [9] and [51] discusses considerable aspects concerning all components of a BCI, associated possibilities, current standards and key issues for future work.

1.2 Brain Signals and their Measurement

1.2.1 Recording

There are different kinds of methods to record brain activity. To begin with, they can be divided into invasive and non-invasive ones. Non-invasive methods acquire data directly from the scalp, so the whole measurement system is outside the body. The electrodes to measure the signals are farther away from the signal source then, therefore the signals become less strongly. This means that larger electrodes are needed to distinguish between signal and noise. Thus they average dendritic currents over a large population of cells. Even if this method serves acceptable temporal resolution that is needed to observe changes in neuronal activity, spatial resolution which determines the precise position of active sources in the brain is low. Due to filtering in the skin and skull, there is limited bandwidth as well. Besides, electrodes on the scalp are very susceptible to artifacts. They can be caused by muscle or eye movements for example. Using invasive methods, there are parts of the measurement system inside the patient's body, which include surgery. Intracortical electrodes are the best choice concerning bandwidth, time- and spatial resolution but carry also highest medical risk regarding foreign bodies directly in the cortex. Less invasive methods are epidural or subdural electrodes where the cortex remains untouched. All these invasive methods use significantly smaller electrodes which can be placed more selectively. Naturally this increases the spatial resolution. However, surgeries are always related to risks that must be weighted. Figure 1.2 illustrates the difference between invasive and non-invasive methods [45].

Next, one can subdivide into direct strategies which measure the electrical or magnetic activity, and indirect metabolic ones which use extra parameters, such as the level of oxygenated and deoxygenated haemoglobin for example. In general, indirect methods have a worse temporal resolution. Figure 1.3 shows different methods and their spatial/temporal resolution [2, 47].

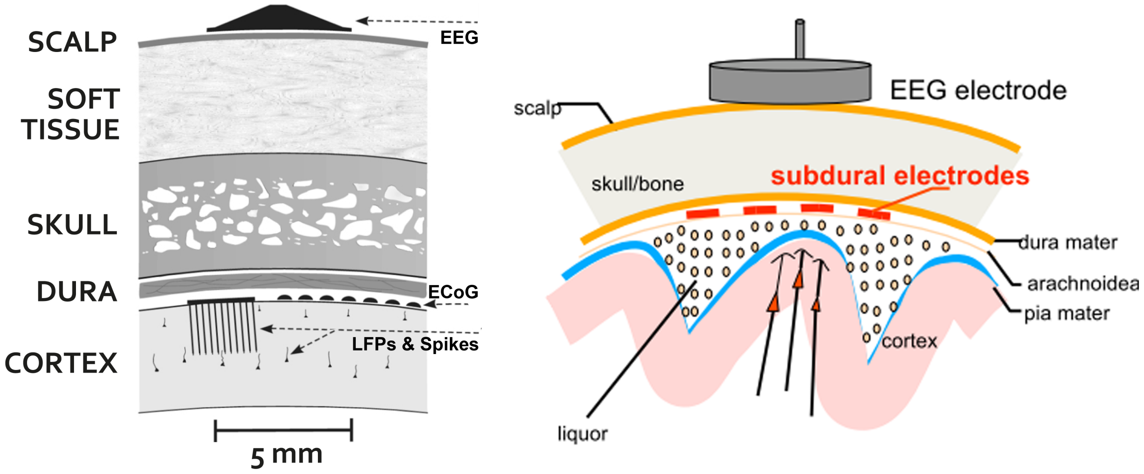


Figure 1.2: Different invasive and non-invasive methods to measure electrical brain activity. (adapted from [5] and [52]).

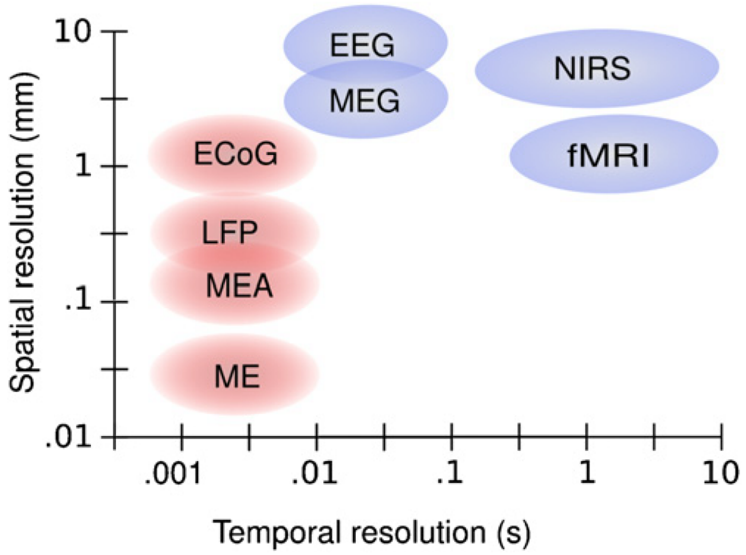


Figure 1.3: Relations between different measurement methods for brain signals used in BCI systems concerning spatial and temporal resolution (taken from [47]). Non-invasive methods (in blue) like electroencephalography (EEG), magnetoencephalography (MEG), near-infrared spectroscopy (NIRS) and functional magnetic resonance imaging (fMRI) are compared to invasive ones (in red) as electrocorticography (ECoG), local field potential (LFP) recordings, micro-electrode array (MEA) recordings and microelectrode (ME) recordings.

1.2.2 Technologies to record signals

- **Electroencephalography (EEG):** the electrical activity of the brain is measured directly on the scalp. The graphical representation of the recorded brainwaves is called the electroencephalogram. This method averages dendritic currents over a large population of cells and measures the variation in voltage over time [7]. The temporal resolution amounts to less than 0.01 s, the spacial resolution accounts for about 1cm [47]. It is one of the cheapest methods and is suitable for mobile usage due to sparse and light equipment.
- **Magnetoencephalography (MEG):** This method is related to EEG, it measures the changes of the magnetic field around the head caused by bioelectrical brain activity. Compared to the magnetic field of the earth, this fields are very small $(10fT - 1pT)$. Therefore extremely sensitive instruments called superconducting quantum interference devices (SQUIDs) are needed [44]. Due to the size of the equipment, this method can only be used stationary. [20]
- **Functional Magnetic Resonance Imaging (fMRI):** fMRI measures the level of the haemoglobin concentration in the blood. It is associated with neural activity due to differential magnetic properties of oxygenated and deoxygenated hemoglobin. Compared to MEG, the equipment needed is even larger and therefore only stationary as well. This method has a promising spatial resolution but the temporal resolution is poor. When using fMRI for a BCI system, bit rate is limited in this way. To utilize this method for a BCI system at all, the Turbo-BrainVoyager [15] ensures a real-time analysis and dynamic visualization of fMRI data sets [49].
- **Near-infrared Spectroscopy (NIRS):** this is an optical and non-invasive method. Similar as fMRI, it uses properties of hemoglobin in the near-infrared spectrum (light with a wavelength of 700-1000 nm). Since the light pierce through the skullcap only to a limited extend because of absorption, one can use this method only near the top of the cortex. Nevertheless, it is a cheap and portable alternative to fMRI when keeping in mind that it is limited to the surface [7].
- **Electrocorticography (ECoG):** names an invasive method, therefore surgery is needed. A grid of electrodes is implanted either subdural or epidural, where the trend is towards epidural [45]. The cortex itself remains unharmed. The activity of a group of neurons is observed. The obtained signal has a respectable signal-noise-ratio as well as good temporal resolution [47]. Regarding BCI systems, these properties shorten training times that are needed to adapt the system to its user [7].

- **Cortex implants:** best results are observed when planting the measuring system directly into the cortex. Known methods are single micro-electrodes (ME) and micro-electrode arrays (MEA) which are sets of up to several hundreds ME's. According to the total number and positioning of those, one can observe single or multi-neuronal spikes as well as local field potentials (LFPs). The spiking activities and synaptic currents of local groups of neurons are reflected. However, operating directly in the cortex carries a greater risk than ECoG. Certainly, such implants have best temporal resolution as well as very persuasive spatial resolution [47].

1.2.3 EEG Signals

For EEG recording, there are several different brain signals that can be used for BCI systems. These signals can be differentiated into evoked signals which are time- and phase-locked to an event and related to an external stimulus, and induced ones where not the phase but the power is time-locked to the stimuli. Averaging can be used to analyse these signals also known as evoked potentials. When using induced signals, the power in particular frequency bands must be computed to get useful characteristics [47].

(Spontaneous) Oscillations

- **Event-related Desynchronization (ERD):** Observing the EEG, there is an decrease of band power in relation to a reference interval. This decrease is caused by desynchronisation of a group of neurons due to a specific brain activity. [47]
- **Event-related Synchronization (ERS):** As opposed to ERD, in ERS there is an increase of the amplitude of the band power in relation to the reference interval. This is due to synchrony within a group of neurons. [47]

A special case of such an ERS that is utilized in this Master's Thesis is the so-called **beta rebound** (or beta ERS). Pfurtscheller et al. [33] investigated this phenomenon for different types of motor imagery. This beta rebound is a short-lasting burst of beta oscillations in motor areas, after an active, passive and imagined movement [33]. Keinrath et al. [22] already have shown that just the illusion of movements cause similar post-movement synchronisation as active or passive execution of the same movement.

Event-Related Potentials (ERP)

- **Slow Cortical Potentials (SCPs):** they appear as slow changes in amplitude (100-200μV) and last a few seconds. SCPs were one of the first potentials used in BCI systems. However, due to the slow appearance there is a limitation in bit rate then. [3]
- **Evoked Potentials (EP):** EP arise as response to an extern stimulus. This stimulus can be any sensory stimulus such as visual, somatosensory, auditory or olfactory. [42]
- **Steady-State-Evoked Potential (SSEP):** similar to EP the SSEP arise from a stimulus. It appears as sinusoidal signal with constant frequency and phase and is the response to sensory stimuli at a rate higher than 6 Hz. Such a stimulus may be a flickering light for example. However, the stimulus need not be visual, it can be auditory or somatosensory as well. [42]
- **P300:** this potential appears as a large positive component in the ERP about 300 ms after a rare task-relevant stimuli. This scenario is also called odd ball paradigm. An example is the task of counting the sighting of a certain digit appearing in a series of any other digits. The P300 is located on the centro-parietal scalp and is maximal over the midline scalp sites. Also here the stimulus can be visual, auditory or sensorial [10].
- **N400:** with a latency of about 400 ms, N400 appears as a negative peak in ERP and is caused by semantically incongruent sentences [10].

1.3 Hybrid-BCI (hBCI)

As already mentioned, there are many different methods to set up a BCI system. Each method just using one single concept of recording brain data, each one with its advantages and disadvantages. So, there is the idea of combining different methods to gain better performance for the whole system. However, the term “hybrid BCI” describes not only combinations of different kinds of BCI systems, but also a combination with any other system. It is just important that there is at least one method involved which utilizes brain signals, so that the whole system still satisfies the four criteria defining a normal BCI [32]:

1. The system should utilize signals associated to brain activity. They have to be recorded directly from the brain.
2. At least one subsystem must record brain signals that can be intentionally modulated. Therefore electrical potentials or magnetic fields can be used as well as hemodynamic changes.

3. The hBCI must remain an online system with real time processing and yielding a communication or control signal.
4. To inform the user of the control performance as well as of failure or efforts, a feedback must be offered by the system.

All along, the hBCI has the goal to improve performance, there should always be a benefit in combining systems. Such a benefit could be the possibility to use more classes for classification at the same time for example, or providing easier and less exhausting usage of the system.

Currently, there exists a large European integrated project called 'TOBI: Tools for Brain-Computer Interaction'. It aims to improve the quality of life of disabled people and the effectiveness of rehabilitation by developing practical technology for brain-computer interaction [46]. Non-invasive BCI systems based on EEG signals should be combined with existing assistive technologies and rehabilitation protocols. This Master's Thesis is developed within this project.

1.4 Assistive Technology Device

Definition: "Assistive technology device means any item, piece of equipment, or product system, whether acquired commercially off the shelf, modified, or customized, that is used to increase, maintain, or improve the functional capabilities" of disabled people [11].

Therefore, any device or other solution meant to help physically, mentally or emotionally impaired people rates among assistive technology. An assistive technology device is described as a frequently used item that helps those people to perform daily actions, tasks and activities in an alternative way [25].

According to Cook [8], one can distinguish between soft and hard technologies. Hard technologies are components which can be purchased ready to use and can be combined to assistive technology systems. Soft technologies describe human areas which may be decision making, strategies, training, concept formation, etc. They are very important for successful assistive technology systems, but also hard to acquire because they are highly dependent on human knowledge rather than tangible objects. Furthermore, assistive technologies can graduate from minimal to maximal technology, which means that there are differences in the grade of support. People with respiratory problems may for example be able to walk on their own in their homes but need a wheelchair to move along far distances. Maximal technologies are often called replacement technologies. One can also distinguish between general and specific technologies as well as between commercial and custom technologies. These differences is reflected in the price of the device of course.

Regarding physically disabled people, an important aspect is also the measurement of physical capabilities. Price and Sears[38] outline that it is important to define methodologies to evaluate a person's physical capability to use computer technologies. Those methodologies must be objective, quantitative as well as repeatable. In the course of this research [38], for example, a performance-based functional assessment tool was developed and evaluated, namely the Performance-Based Functional Assessment for Computer Technology (PB-FACT). Further, Choia and Spriglea [6] compare current methods of evaluating prototypes in usability of assistive technology products.

1.4.1 Universal Design

Important in the context of assistive technology is also the issue of a universal design. This term is defined by the Center for Universal Design at North Carolina State University as " the design of all products and environments to be usable by people of all ages and abilities, to the greatest extend possible" [37].

Preiser and Ostroff [37] also points out the seven Principles of Universal Design:

1. **Equitable Use:** The same means of use have to be provided for all users. If it is not possible to provide identical means, they should at least be equivalent. Segregating and stigmatizing of any users must be avoided. A power door at a store for example is convenient for shoppers pushing shopping carts as well as for persons using a wheelchair.
2. **Flexible in Use:** Choices in method of use and adaptabilities should be provided. This can be implemented by a computer using different input options (mouse, trackball, sip-and-puff switch,...) or if the font size of a software can be adapted.
3. **Simple and Intuitive Use:** Unnecessary complexity should be avoided, consistency with language skills, expectations and intuitions should be provided. Therefore, meaningful icons and figurative illustrations of adaption possibilities are better than plain text alone.
4. **Perceptible Information:** For presentation of essential information different and redundant modes can be used: verbal, pictoral, tactile, audible, etc. so that people with any sensory limitations can still gain the information.

5. **Tolerance for Error:** The design should minimize hazards and avoid unintended or accidental actions. Therefore it can provide warnings and arrange elements to minimize errors.
6. **Low Physical Effort:** A minimal fatigue should be achieved gaining highest efficiency and comfort. This implicates for example neutral body positions during usage.
7. **Size and Space for Approach and Use:** All components should be in comfortable reach for standing users as well as for seated ones. Accommodate variations in hand and grip size are also helpful. Open-loop door handles for example do not need grasping.

1.5 IntegraMouse®

An illustration of the IntegraMouse® is shown in Figure 1.4. It is an assistive technology device as described previously and should allow physically disabled people (e.g. through cervical spinal cord injuries) to operate a computer mouse without using their arms. The mouthpiece serves as a little joystick and is sensitive to minimal movements. There are only $15g$ axial force or $0.1mm$ of movement needed to cause a reaction. Clicking is supported by sipping and puffing through the mouthpiece. This is realized by a membrane inside the IntegraMouse® that causes pressure gradients in the control unit. Short sipping corresponds to the left click, slight puffing is linked to the right mouse click. In respect of the computer connection, it serves as a common USB-linked mouse. The IntegraMouse® is certified to MPG (Medical Devices Act) [28, 27].

Figure 1.4: IntegraMouse®.

1.6 QualiWorld

QualiWorld is a platform of QualiLife AG [39] related to the concept of ‘Accessibility’. QualiLife aims to provide products that allow people with various physical disabilities to use information technology and multimedia. There are solutions for different degrees of disability, starting from the audience of elderly and first time users, which only need simple and intuitive applications, right up to fully paralyzed persons. The software should help those people to execute daily activities like writing e-mails for example. However it just supports Windows®-use.

The user can control the software with a mouse device, by keyboard or by speech. There are several different mouse methods serving diverse possibilities for indirect selection:

- **Normal Mouse:** the mouse cursor acts as a usual one.
- **Auto Click:** the usual cursor movement is combined with an automatic click after a predefined time interval of standstill. The user can configure all predefinitions via the program settings.
- **Auto Scan:** clickable surfaces are highlighted sequentially. The user must only click in the right moment.
- **Manual Scan:** this mode is similar to Auto Scan, only that the sequential highlighting is controlled by a second mouse button or click device.
- **XY Mouse:** this mode operates like a coordinate system. A horizontal line is scanning the screen until the user clicks. Then a vertical line appears to define the second coordinate.
- **Radar Mouse:** this method is similar to the XY Mouse, only that it utilizes polar coordinates. The first line turns clockwise around the center of the screen, then again after the first click the right position along the selected line is determined by the second click.
- **Direction Mouse:** this method offers a small window with 8 buttons with directional arrows sequentially highlighted. They define, in which direction the actual cursor moves. The first click activates the movement, a second one stops it. To perform an actual mouse click, there is a 9th button in the center of the grid.
- **Tracking Mouse:** this method tracks any movement of the user and utilizes it for navigation through a standard webcam.

All those mouse cursor methods can be activated via the settings menu or just by pressing the Funtion Keys F1-F7 and F12. Therefore these keys are reserved and cannot be used otherwise.

Besides, the application offers word prediction, abbreviations and diverse keyboard layouts and macros to ease keyboard usage. For speech control, it provides text-to-speech functionality and also voice commands and dictation. To ease the understanding of information on the screen it provides a screen reader which reads all visible texts aloud [41].

1.7 Motivation and Related Work

By now, there are plenty of prototypes proving principal functionalities of BCI systems [29]. Such prototypes include brain-controlled wheelchairs, keyboards or computer games for example. They are meant to improve quality of life of disabled people but still can't be brought out of the lab and into real-world applications in most cases. On the other hand, the continual progress in assistive technology (AT) promises high potentials in meeting the needs of people with physical disabilities [8]. However, there are still many people who cannot fully benefit from the current AT devices according to limited access. Often the extent of limitation varies over the day or is dependent on a person's daily constitution. So, on good days there are remaining functionalities which may be ignored by a BCI system but could be used as additional control possibilities. As a result, a hBCI system, using BCI technology as well as an AT device, appears to be the optimal solution to provide a control more stable and adaptive to the users momentary condition and serves a usage as easy as possible. Besides, a combination of different signal sources can make the system more independent of disorders of each single one, just through avoiding the bad source by switching to the better one [26].

The IntegraMouse® is an AT device which is easy to use and compatible to all operating systems because it acts as a usual USB-linked mouse. It is ideal for people who suffer from major limitations in movement but still are able to move the head or at least the mouth slightly. This might be applicable for persons with cervical spinal cord injuries for example. The problem is that there are often impairments of the lung connected with spinal damages as well (see [43]), which means that the sipping and puffing functions of the IntegraMouse® are difficult and exhausting for the patients. Pfurtscheller and Solis-Escalante [36] have already proved that using the beta rebound of an imaginary foot movement is an easy and efficient method to realize an EEG-based brain-switch. Therefore there is the idea of combining the IntegraMouse® with such an EEG-based brain-switch that takes over the click functionality of the mouse. [31] shows that an asynchronous brain switch can be set up in short time by just using one EEG-channel.

A similar current project realizing a hBCI combined by BCI and AT devices is [24]. It aims to combine an EEG-based brain-switch and a shoulder joystick to control an artificial limb.

1.8 Objective

The goal of this Master's Thesis is to create an online hybrid BCI, composed of an EEG-based brain-switch and the IntegraMouse®. The system should allow a user to control the mouse cursor of the accessibility platform QualiWorld using two different selection modes offered by QualiWorld, namely *Normal Mouse* mode and *Radar Mouse* mode. Principally there are four different scenarios in which this hBCI should be used. First one can navigate in *Normal Mouse* mode and use either the EEG-based brain-switch or the click impulse of the IntegraMouse® to trigger the mouse click on the screen. In these two cases, the xy-coordinates of the IntegraMouse® are used for the cursor movement. On the other hand there is the possibility to navigate in *Radar Mouse* mode. Again the mouse click can be supplied by either the EEG-based brain-switch or the IntegraMouse®. Furthermore, an evaluation module for all provided input signals should be realized. According to the determined qualities of EEG, mouse movement and clicking, the system should decide which control scenario would be most qualified in the current situation.

The EEG-based brain-switch itself will be realized using the beta rebound of a brisk imaginary foot movement. All needed signals should be collected via the TOBI Data Acquisition Module [4] where the interface for a mouse device must be implemented first. Next, a Matlab/Simulink model called *Fusion* has to be implemented which combines the different (redundant) input signals into consistent output signals. Therefore the needed qualities are computed first. On the basis of these qualities the *Fusion* should decide which signals can be used and then switch to the corresponding control mode. In a last step the control signals should be sent to QualiWorld. According to the selected mode, either the *Normal Mouse* method or the *Radar Mouse* method should be activated, then either the mouse cursor or the radar bar should be controlled by the obtained signals.

Summarized, the aims of this Master's Thesis are as follows:

- First the IntegraMouse® has to be integrated into the TOBI Data Acquisition Module. Therefore a new interface for a mouse device has to be implemented that acquires the data from the mouse device and also blocks the default drivers of the operating system.
- To use the EEG signals for the click function an EEG-based brain-switch has to be created. It should be based on a Fisher's Linear Discriminant Analysis (LDA) [19] classifier and use the logarithmic bandpower of the EEG signal which is obtained

by Laplacian derivation. Once the optimal LDA weights and frequency bands are configured for the subject, there should be a simple threshold-function which can be applied to the preprocessed EEG signals.

- In a next step a Matlab/Simulink model called *Fusion* shall be created which models the quality management of the input signals, chooses the right operating mode and serves all data that is needed to be send to the QualiWorld application. It contains a body of rules with different evaluation mechanisms for the different input signals.
- Then, QualiWorld has to be configured, so that the QualiWorldAPI provided by QualiLife can be used. When this is done, a module has to be created which takes the data from the *Fusion* and converts it to predefined XML-strings (Extensible Markup Language, for further information on XML see [21]) which have to be send via a uDP socket to the QualiWorldAPI so that the *Fusion* is able to communicate with QualiWorld.
- In an verification measurement functionalities of the whole setup should be tested with one subject. Therefore a little tool should be prepared, which provides a repeatable and static click pattern. This tool should promt the user to move the mouse cursor over the screen and perform clicks at specified locations. All operating modes should be tested in this measurement.
- When the verification measurement worked fine, within a study the principle should be proved. Therefore measurements with 4 participants will be performed. Especially the mode switching functionality dependent on the current mode and the qualities should be tested.

2 Methods

2.1 System Overview

The goal of this Master's Thesis is to provide a system that allows the user to control a computer using a combination of IntegraMouse® and an EEG-based brain-switch only. Figure 2.1 gives an idea of how the usage of this hybrid BCI might look like.

Figure 2.1: System setup consisting of the user wearing the EEG-cap, the IntegraMouse® and one single PC running the Qualiworld application as well as the Simulink model of the *Fusion* and the SignalServer.

Regarding the hardware of the system, the main components of the system are:

- the IntegraMouse®
- the EEG measurement setup

The following software components are implemented and used as part of the system:

- the SignalServer which collects all input signals and sends them to the client
- the EEG-based brain-switch module which generates clicks from the EEG signal

- the *Fusion* which computes and evaluates the qualities of the signals, determines which control scenario will be best the choice and then switches the control mode and signals accordingly
- the Qualiworld-Controller which converts the control signals into required XML-strings and sends the packages to the QualiWorld application
- QualiWorld which receives the control signals and provides visual feedback for the system.

Generally QualiWorld should be controlled either in *Normal Mouse* mode or in *Radar Mouse* mode. The main difference between these two modes is the usage of the xy-coordinates. One time the control signal must consist of xy data as well as click information, otherwise only the click information is needed. Figure 2.2 and Figure 2.3 show these two selection modes.

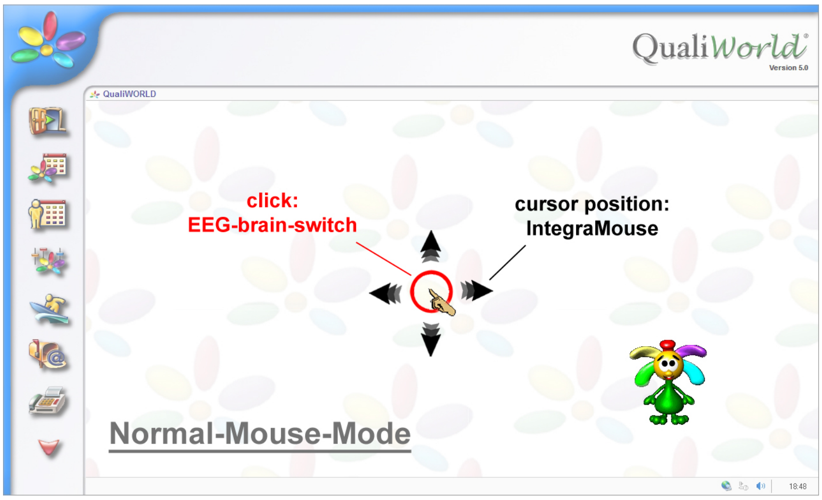


Figure 2.2: *Normal Mouse* mode. The cursor gets moved according to the xy-data of the IntegraMouse®, clicking is elicited by eighter the EEG-based brain-switch or the sipping funtion of the IntegraMouse®.

After data acquisition via the SignalServer the available signals are the xy-coordinates and the click inpulse of the IntegraMouse® as well as the EEG data from which the clicks of the EEG-based brain-switch are generated. Now the *Fusion* has to decide which control scenario is the appropriate one. Therefore the quality of the xy-coordinates, the quality of clicks triggered by the EEG-based brain-switch as well as by the IntegraMouse®, and the quality of the EEG signal itself has to be evaluated. The system always starts in *Normal Mouse* mode combined with the EEG-based brain-switch. When the *Fusion* is running, there are two different switching cycles. The first one refers to the movement

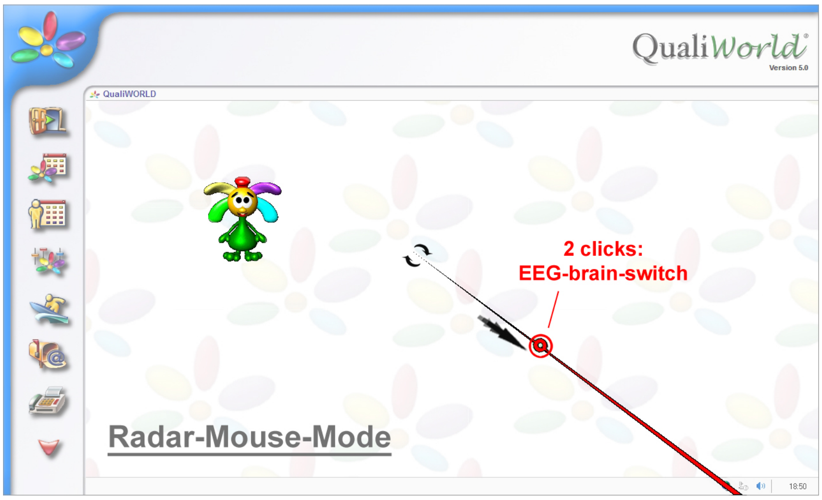


Figure 2.3: *Radar Mouse* mode. There is no cursor movement, the position on the screen is indicated by the radar system: the first click defines the direction of the line outgoing from the center of the screen, a second click determines the exact position along the line and causes the real mouse click. Again, clicking is elicited by eighter the EEG-based brain-switch or the sipping funtion of the IntegraMouse®.

of the mouse cursor. When the quality of the xy-coordinates is lower than 20%, the system jumps to *Radar Mouse* mode and stays in this mode as long as the quality has not recovered to 50%. Then the system returns to *Normal Mouse* mode. The second cycle is related to the mouse clicks. When one of the qualities regarding the EEG-based brain-switch decreases under 20%, the system switches to IntegraMouse®-click. It remains in this mode as long as the quality of this click method is higher than 20%, otherwise it returns to the click information of the EEG-based brain-switch.

Figure 2.4 shows how all components of the hybrid BCI work together. Principally it is possible to run the whole system on a single PC. However, if it is desired, each one of the three main modules (SignalServer, Qualiworld and the MATLAB/Simulink-model of the *Fusion*) can be run on an extra PC, one must only adapt the corresponding IP-adresses so that the modules can communicate with each other by sockets.

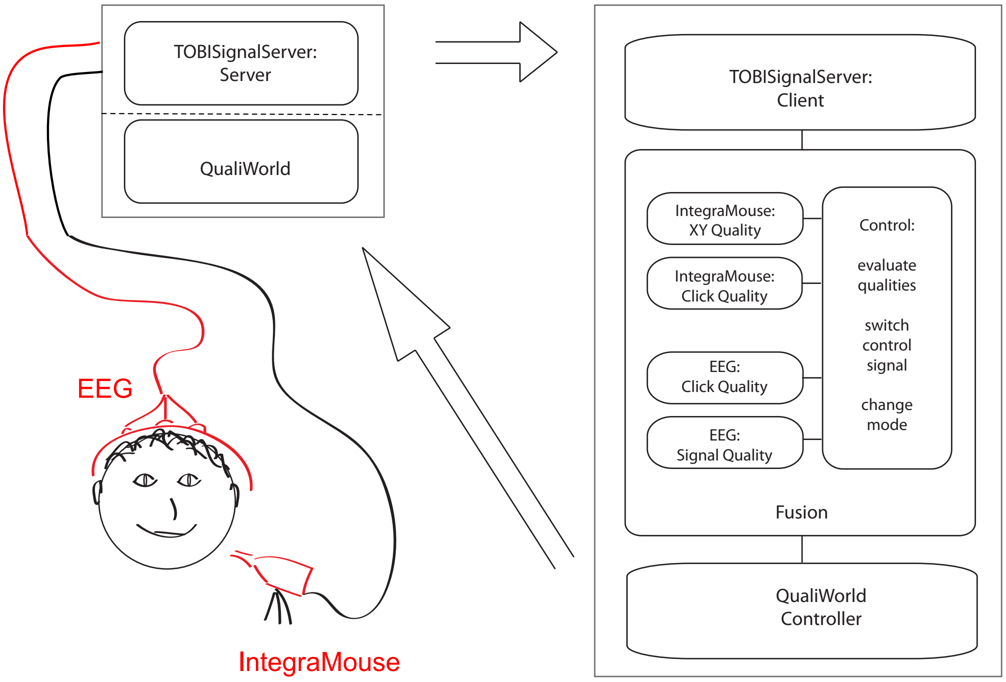


Figure 2.4: Principle of the hBCI system. The SignalServer acquires the EEG-data as well as data from the IntegraMouse® and sends the information to the client. The *Fusion* computes the control signal and the appropriate mode by determination and evaluation of the signal qualities. The Qualiworld Controller transmits the signals to the QualiWorld application where the mouse cursor is controlled in the right mouse mode.

2.2 Implementation

2.2.1 IntegraMouse®

The IntegraMouse® in general as well as its functionalities are already described in section 1.5. Technically, the IntegraMouse® serves as an ordinary computer mouse device that is connected via USB. It supports plug and play. Figure 2.5 shows all components of the IntegraMouse®. The sipping and puffing into the mouthpiece cause changes in the air pressure which are transmitted to the controller via a membrane. Figure 2.6 shows the opened IntegraMouse® and illustrates this membrane and the control unit. The controller converts these changes in air pressure into electric signals.

Also the movements of the mouthpiece acting as a little joystick are perceived in the controller. At the distributor box there is a reset button to calibrate the joystick. This is necessary because the IntegraMouse® can be placed in any vertical angle. If there is not a reset of calibration via this button every time the position changes, there would be a permanent offset on the joystick causing unwanted movements. The internal reset button can be linked to any other button by using the connection jack for the extern reset button.

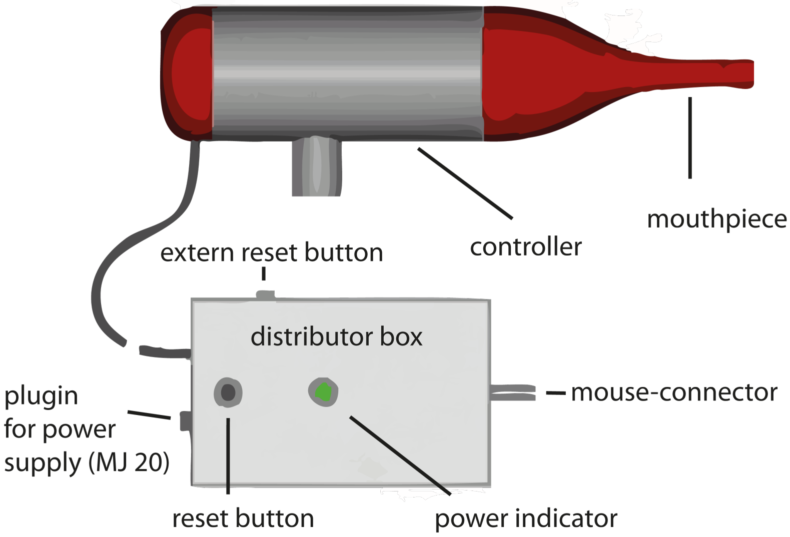


Figure 2.5: The IntegraMouse® composed of mouthpiece, controller, distributor box with reset button, and mouse connector.

Figure 2.6: Opened IntegraMouse® showing the control unit and the membrane placed between mouthpiece and controller.

To use the IntegraMouse® within the hybrid BCI system, the signals of the device have to be collected, recorded and then processed. Therefore the SignalServer is used. However, until now there is no mouse device support implemented. Therefore the integration of the IntegraMouse® into the SignalServer is done within this Master's Thesis.

2.2.2 SignalServer

Generally, the TOBI signal server is designed to provide a uniform data acquisition and distribution system to feed hBCI systems with a standardised signal format [4]. Therefore, it should support as many sorts of signal inputs from hardware devices or biosignals as possible. The idea is to acquire all predefined inputs, pack them into defined packages and send them to the client in uniform format. Client-sided, someone can easily use these normed packages. To declare which signals are to be collected, someone must merely adapt a configuration file according to the signals needed for processing. The SignalServer is available for Debian based systems as well as for Windows XP/7.

Taken from the user manual [46], the following hardware has been supported when this Master's Thesis has been started:

- g.USBamp (Windows only)
- g.Mobilab
- g.BSamp
- BrainProducts Brainamp series (Windows only)
- generic joysticks
- software sine generator

Since the implementation of the SignalServer is not finished yet, [46] provides information on new hardware support and extensions.

The SignalServer should be used to establish communication with the IntegraMouse® and acquire data. Since the IntegraMouse® acts as a generic mouse, general support for mice can be used instead of a specific solution. However, by now, there has been no interface for mouse device input yet, therefore the SignalServer has to be extended to establish communication with the IntegraMouse® first.

Therefore, within this Master's Thesis the SignalServer project is extended by:

  - LifeTool IntegraMouse®
  - Generic mouses

For integration one important aspect has to be regarded, the consideration of a multi mouse usage. When plugging in a new standard mouse device, any operating system recognizes it and automatically couples it with the mouse cursor instantly. However, the mouse device intended to be used in the hBCI should not interfere with a possibly already existing main mouse device. This is especially important, when the hBCI uses the mouse device input for any other purpose than controlling the mouse cursor. Then naturally the signal from the new mouse device should be decoupled from the cursor so that the cursor can be controlled by the main mouse without interference of the hBCI. A schematic overview of this problem can be seen in Figure 2.7.

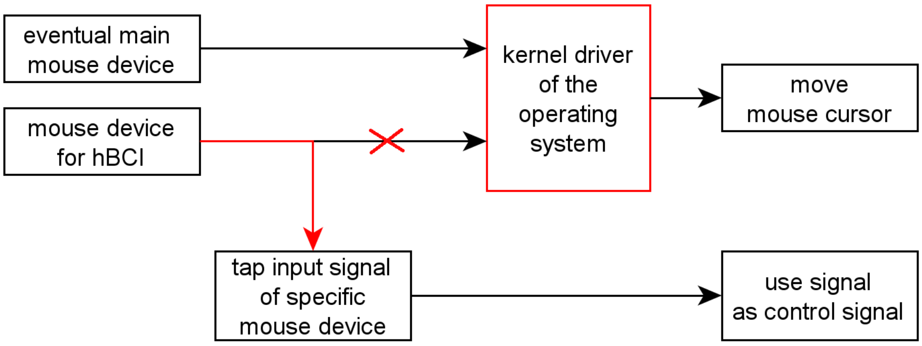


Figure 2.7: The input signal of the mouse device used for the hBCI must be decoupled from the kernel driver of the operating system.

Regarding the changes that have to be made, it is important to understand the following substructure of the code concerning the hardware access shown in Figure 2.8. There is a general class `HWAccess` that owns the object `data_packet` and an arbitrary number of objects of class `HWThread` which are of type `master` or `slaves`, depending on their running mode. For any supported hardware device there exits an extra subclass derived from the superclass `HWThread`, containing the needed variables and functions to acquire the specific data. The setup telling which devices should be used by the SignalServer and how they are configured must be inserted to the configuration file `server_config.xml` which is coded in XML format.

The acquired data is collected in the data packet which has the structure shown in Figure 2.9. The first subsection of the data packet header is reserved for the flag. This flag defines what kind of data is saved in this packet. There are predefined flags for each data type (EEG, EMG, EOG, Buttons, Joystick,...). Later the packets are submitted

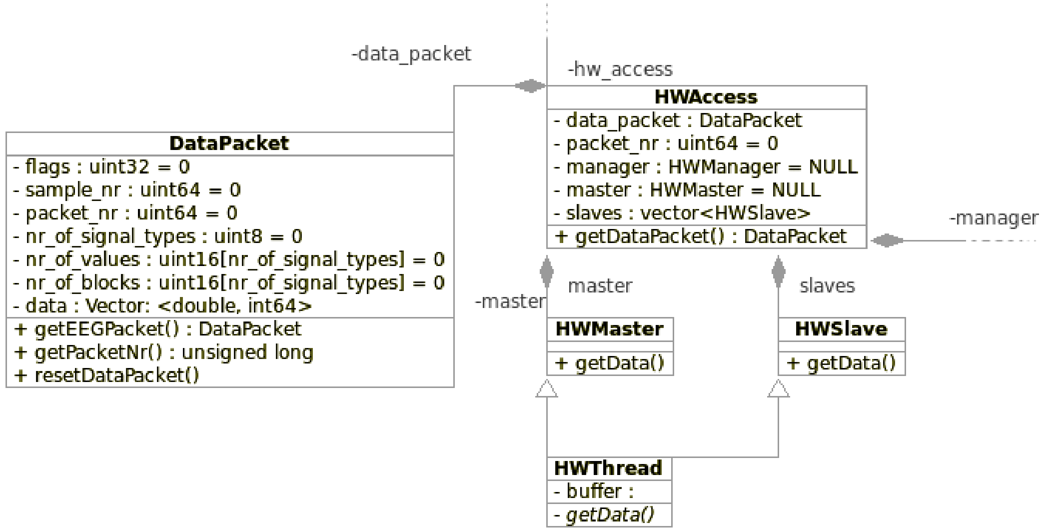


Figure 2.8: Class diagram for all subparts of the SignalServer concerning the hardware access.

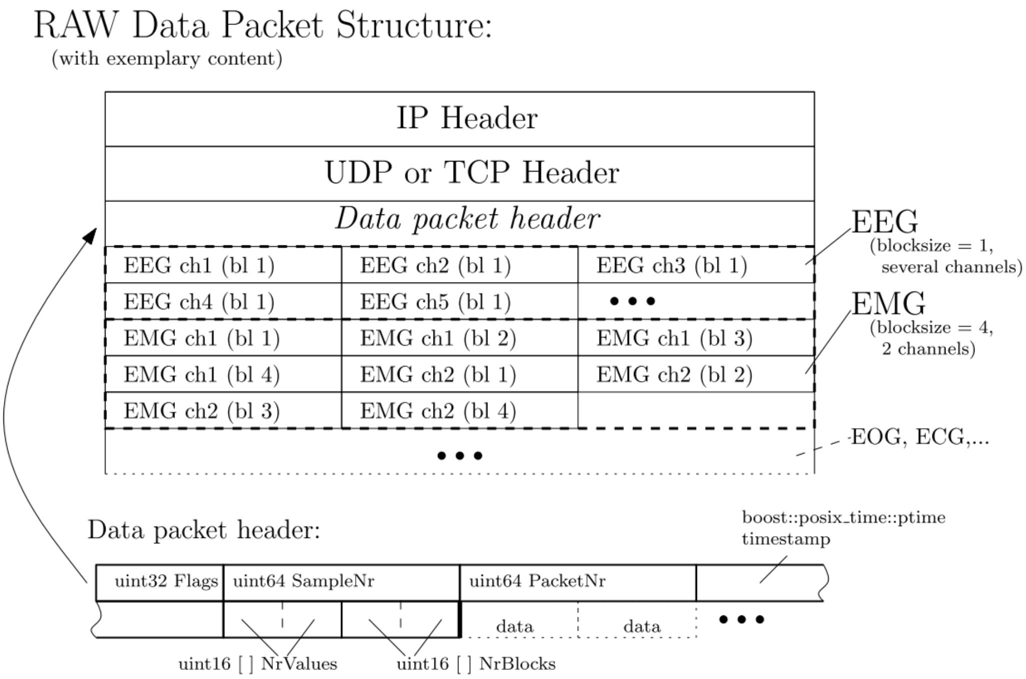


Figure 2.9: Structure of a data packet which is sent to the SignalServer client(Taken from [4]).

in the order of this predefinition. For the implementation of mouse device support, two new flags are introduced as well as a new hardware identifier:

```
#define MOUSE     5
...
#define SIG_MOUSE 0x800
#define SIG_MBUTTON 0x1000
```

The newly defined `SIG_MOUSE` packet is used to send data concerning the movement of the mouse device. It contains two values, one for the x coordinate and one for the y coordinate. The `SIG_MBUTTON` packet belongs to a mouse click and consists of three button values, each containing a 1 if the button is held and 0 otherwise.

For the needed code extension also a new class has to be created. It is called `MouseBase` and is derived from `HWThread`. In this new class all functions concerning the data acquisition from the mouse device are implemented. The next step is to look for a C++ library that offers possibilities to retain signals directly from the USB port before they are tapped by the operating system. Unfortunately there could not be found any solution that is platform independent because driver management and hardware support are handled completely differently on Windows than on Linux. The best solution found is `libusb` [14]. It is not platform independent and originally was implemented for Linux but at least provides a truncated counterpart called `libusb-win32` that works for Windows systems. Now, depending on the used operating system, there are two different libraries used for the functionality acquiring data. Therefore an additional subclass called `Mouse` is introduced, that is derived from the basic class `MouseBase`. `MouseBase` contains all mouse device functionalities that are platform independent and therefor remain the same on Windows and on Linux. However, for the class `Mouse` there are two different source files (`mouse_win.cpp` and `mouse_linux.cpp`) as well as two different header files (`mouse_win.h` and `mouse_linux.h`) provided. These files contain the code for the platform dependent parts of the class. So, according to the running operating system, via `#ifdef`-directives the right file shall be compiled. In the basic class there are the functions setting up the class and filling the data packet, in the derived class there are the functions to block or free the kernel and to acquire the data from the USB port. A detailed listing can be seen in the class diagram in Figure 2.10.

Linux Version

The linux version of the used C++ library is called `libusb-1.0`. It offers methods to detach the input signal from the kernel driver and open an extra interface to the

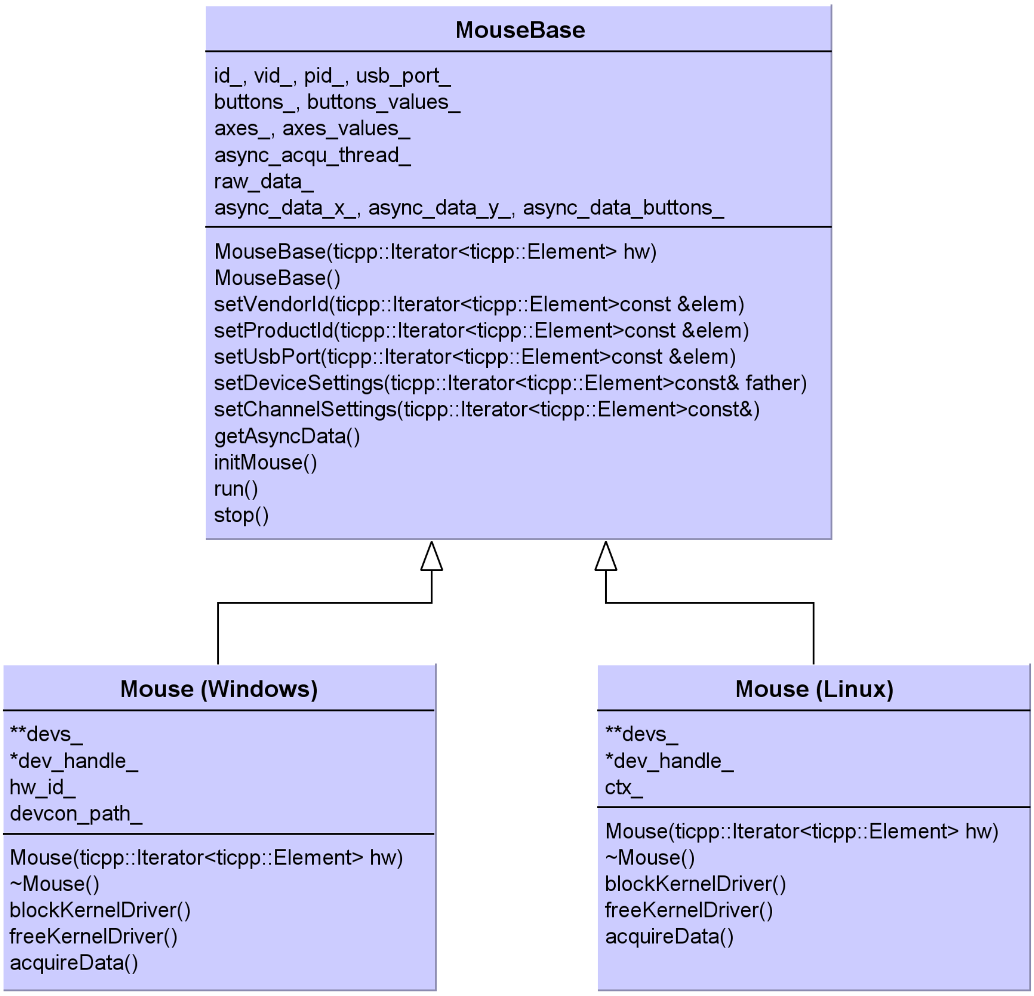


Figure 2.10: Class diagram of the basic mouse class and its subclasses, containing different implementations for Windows use or Linux use.

USB port. Via this interface signals from the mouse device are read and can be used afterwards. The library blocks the operating system automatically from using this signal. The new class is created in the SignalServer C++ project using the Qt development environment. It implements the USB port access, reads in the data from the mouse device and brings the data into a format that can be sent to the client. Therefore the vendor ID (VID) and the product ID (PID) as well as the used usb port number (`bEndpointAddress`) of the respective mouse device are needed. If usage of a mouse device is desired when starting the SignalServer, there must be a entry in the configuration file containing this data. These informations can be obtained by using the command `‘lsusb -v’`.

Windows Version

Even if there is a win32-version provided, it is nowhere near as adequate as the original library. The main functionalities to connect to the device and to acquire data from this connection are served. Therefore the mouse device can be linked to the SignalServer and data can be used for means of the hybrid BCI. `libusb-win32` is used to perform these tasks. However, it is not possible to detach the kernel driver with `libusb-win32`, which means that the decoupling of the cursor movement cannot be done with this library. Therefore the ‘Windows Driver Kit (WDK)’ from the Windows Driver Foundation is used in addition [50]. It provides a tool called ‘devcon’ which allows to work with the drivers utilized by Windows. So it is possible to disable the current mouse driver for the desired mouse device and load another one. In this case at first use of a device a new driver for this particular mouse device has to be created using the ‘libUSB-Win32 INF-Wizard’ (included in the ‘libusb-win32 Filter Driver’ downloaded from [14]). This driver is loaded as actual driver every time the SignalServer is starting.

On Windows the Microsoft Visual Studio project of the SignalServer is used for implementation. When acquiring data from the mouse device via the SignalServer, again there must be an entry in the configuration file containing the vendor ID (VID), the product ID (PID) and the number of the used usb port (`bEndpointAddress`), they can be read using the application called ‘Test (Win) Program’ which is also included in the ‘libusb-win32 Filter Driver’. Additionally the path of the installation of the devcon-tool must be enterd to the configuration file (normally it is `‘C:\WinDDK\7600.16385.1\tools\devcon\ia64\devcon.exe’`).

2.2.3 Implementation of the EEG-based brain-switch

Using the beta rebound to trigger the mouse click

As proved in [36], the beta rebound is a reliable method to be used for an EEG-based brain-switch. As shown in [31], even by applying just a the bandpower of an one-channel EEG, a good task performance is reached. Therefore, in this Master's Thesis this method is used to generate the mouse click triggered from the EEG-based brain-switch. The task performed by the user to initiate a click is a brisk imaginary foot movement which should last for less than 1 sec. Every time the user imagines the task, a beta rebound is initiated which can be detected as an Event Related Synchronization (ERS) in the EEG. For the online computation of the click a threshold function is used. To set up the appropriate threshold for the specific user, a training run has to be performed. In this run the task has to be accomplished 20 times, randomly alternated by a second task (also 20 times) where the subject does nothing. Using the obtained EEG data, it is evaluated at which time interval as well as in which frequency band the relative difference in power is maximized between the two tasks. Using LDA, the optimal threshold is computed. The exact strategy is described as follows.

Measurement Setup

The EEG is recorded using sintered Ag/Ag Cl electrodes in combination with a standard cap to fix the electrodes at the desired position. They are placed in a manner that a Laplacian derivative can be obtained from the center Cz according to the 10-20 system. Therefore the 4 surrounding positions are used which are FCza, C1a, C2a and CPza. Equation 2.1 shows how the Laplacian L of channel Cz is computed when S is the matrix containing the EEG data:

$$L_{Cz} = S_{ch3} - \frac{1}{4}(S_{FCza} + S_{C1a} + S_{C2a} + S_{CPza}) \tag{2.1}$$

The electrodes are assembled monopolarly with a left mastoid reference. The ground electrode is mounted on the right mastoid. The electrode impedance is kept below 5 $k\Omega$. Figure 2.11 illustrates the electrode placement. Furthermore, the EEG signal is amplified by the biosignal amplifier g.BSamp (g.tec medical engineering GMBH, AT [18]). The following settings are chosen for amplification: High pass is 0.5 Hz and low pass is 100 Hz. Also a notch filter is used in order to suppress the 50 Hz noise from the power line. A sensitivity of $100\mu V$ is chosen. The continuous signal is sampled with $fs = 512\ Hz$.

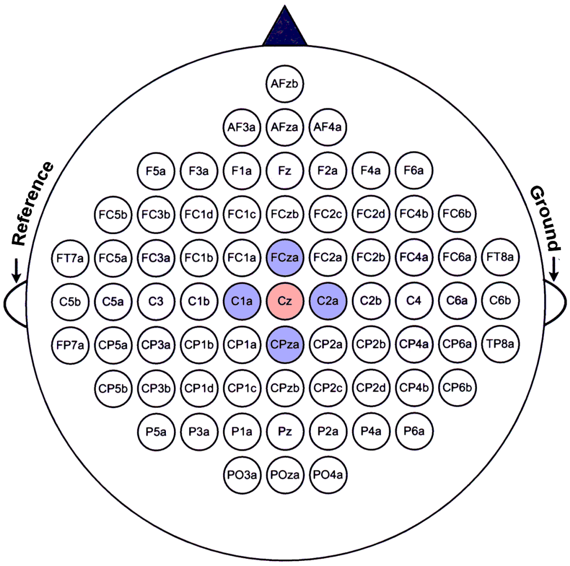


Figure 2.11: Positions of the electrodes. A Laplacian derivative over Cz is used.

Paradigm to set up the classifier used for the threshold

For the setup a standard paradigm with two different classes is used. In the paradigm there are two different tasks which represent the two different classes. The first task is to perform a brisk movement of both feet that lasts less than $1s$ and is linked to the cue showing an arrow pointing to the bottom. This task should initiate the beta rebound. The second task is to do nothing, linked to the cue with the arrow pointing to the top. In this case no beta rebound should appear at all. Every run of the classifier setup consists of a randomized sequence of 40 trials with a total number of 20 iterations of each task. The subject sees a black screen where a green fixation cross appears to indicate that a new task has started. The cross lasts 8 s, during this time the subject must be concentrated and should try to avoid producing artifacts. At second 2, a beep gets the subject's attention and then from second 3 to 8 the cue with the arrow related to the task is presented. Now the subject has to perform the appropriate task for $1s$. Between the trials there is a random pause for 2 s to 3 s. There is no kind of feedback provided. Figure 2.12 shows the paradigm.

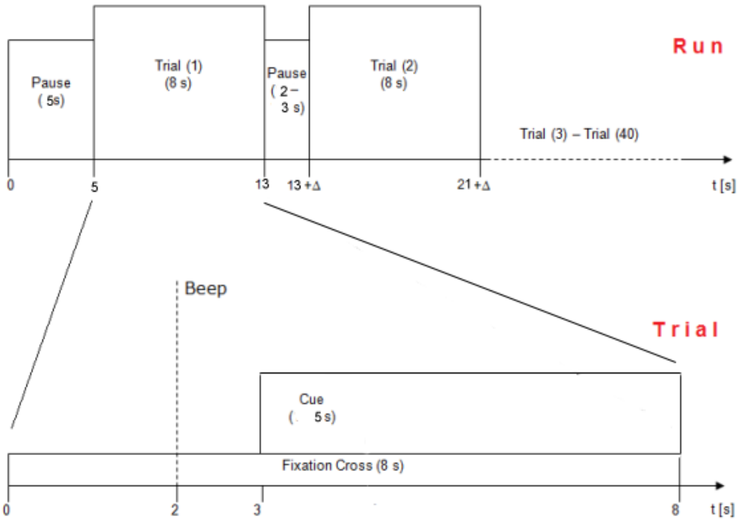


Figure 2.12: The paradigm used for the classifier setup. 1 run consists of 40 trials (20 each class), each trial shows the fixation cross for 8s with a beep at second 2, and a cue from seconds 3 to 8. During this cue the task is shown and has to be performed by the subject. Between trials there is a random pause Δ for 2s to 3s.

Time-frequency maps - ERD(S) maps

ERD(S) (Event Related (De)Synchronization) maps are an offline method to visualize changes in synchronizations of a group of neurons during tasks [17]. Therefore, recorded EEG data of the repeatedly executed tasks are needed. The utilized feature extracted from the EEG data is the stepwise shifted band power for all frequencies. For each frequency band the logarithmic band power is computed and averaged over all trials. Then a reference interval is determined. The ERD(S) map shows the relative increase or decrease of the band power compared to the corresponding band power of the reference interval. Figure 2.13 displays the ERD(S) map of a beta rebound after a brisk imaginary foot movement (for a Laplacian derivation over C_Z). First, one can see a power decrease, followed by a significant power increase.

For considerations in this thesis, the frequencies between $6Hz$ and $40Hz$ are divided into bands of $2Hz$ width which are shifted for $1Hz$ each time. Next, the optimal frequency band has to be searched. In a 10x10 fold cross validation, separability of the two different tasks is tested by means of LDA (see Section 2.2). Therefore, time segments with 0.5s length are observed for each frequency band. For each time segment, the classifier is computed. This way, the best time segment as well es the optimal

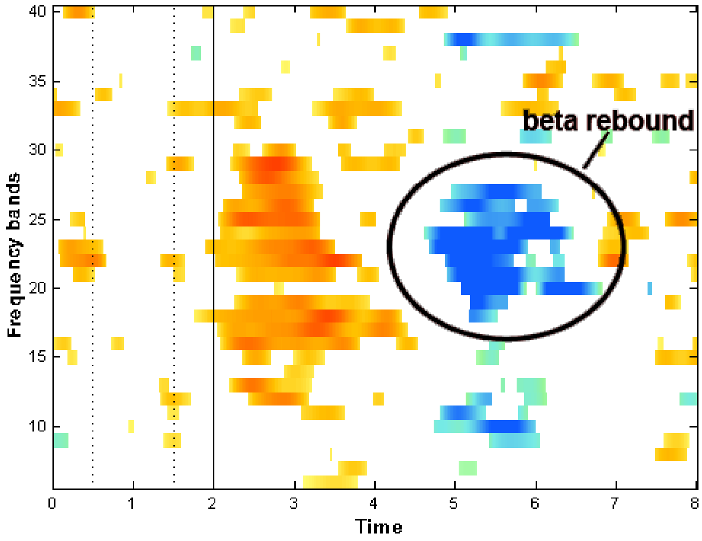


Figure 2.13: ERD/ERS map showing a beta rebound for a brisk imaginary foot movement (Laplacian derivation over C_Z and frequency bands of 2 Hz each). The color red indicates significant power decrease (ERD) and blue significant power increase (ERS).

frequency band is determined by finding the classifier with best accuracy.

Fisher's Linear Discriminant Analysis (LDA)

Originally, LDA was developed in 1936 by Sir R. A. Fisher when calculating taxonomic problems. It is a simple method to classify data that can be separated linearly. For computation of the classifier the covariance matrix $\Sigma_{1\ 2}$ is used. Given the means of the 2 different classes μ_1 and μ_1, the weight vector w and the discriminant D are calculated as shown in Equation 2.2:

$$w = (\mu_1 - \mu_2)^T \Sigma_{1\ 2}^{-1} \tag{2.2}$$

$$D(x) = w^T x \tag{2.3}$$

The sign of D determines to which class data sample x belongs [12, 13, 23].

This method is one of the most frequently mentioned ones concerning classification of EEG data. For further information as well as a description of usage see [19] for example.

Determination of the parameters used in the *Fusion*

For the online application, a simple threshold function is used. Therefore the previously determined optimal frequency band as well as the computed LDA weights are used. First the logarithmic band power (logBP) for the corresponding frequency band is calculated from the input signal. When w_0 is the bias and w_1 the weight obtained by the LDA classifier,the click C for time t is computed as shown in Equation 2.4:

$$C(t) = w_0 + logBP(t) * w_1 - threshold \begin{cases} > 0 & \Rightarrow click \\ \leq 0 & \Rightarrow no\ click \end{cases} \tag{2.4}$$

To determine a proper threshold, the LDA weights are applied to the already recorded offline data. It is important that only the data from the trials refering to the feet movement task are used. For this LDA output, the mean μ and the standard deviation σ over all trials of this task are computed. Threshold th is calculated as in Equation 2.5:

$$th = \mu - 2\sigma \tag{2.5}$$

2.2.4 *Fusion*

The *Fusion* aims to combine the different input signals into consistent output signals. Figure 2.14 shows the flowchart of the *Fusion*:

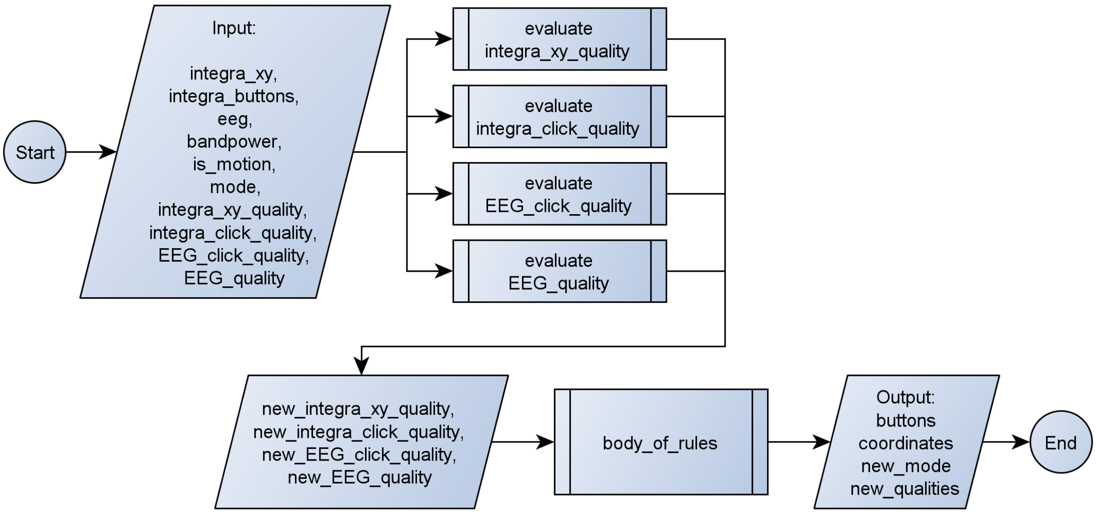


Figure 2.14: Flowchart of the *Fusion*.

The fusion of the different input signals depend on the current mode. This mode can be switched according to the current qualities of the input signals. The *Fusion* module determines the qualities of the different signals and decides whether the actual control mode is the best choice or if switching the mode would be better. There exist four different modes combining the available input signals with the used QualiWorld control modes:

Mode 1: *Normal Mouse* (IntegraMouse® coordinates) + clicks from the EEG-based brain-switch
Mode 2: *Normal Mouse* (IntegraMouse® coordinates) + clicks from the IntegraMouse®
Mode 3: *Radar Mouse* + clicks from the EEG-based brain-switch
Mode 4: *Radar Mouse* + clicks from the IntegraMouse®

The *Fusion* consists of four different quality evaluation mechanisms for the input data, and a control block. These modules are designed to handle the choice of the appropriate mode. The four sub functions of the quality measurement are the xy-motion quality of the IntegraMouse®, the click quality of the IntegraMouse®, the click quality of the EEG-based brain-switch and the quality of the EEG signals themselves. These qualities are composed of quality-decreasing criterions regarding the properties of the associated signals and a constant recovery over time which increases the quality again. If qualities of the current mode become low, this implies that quality decreasing behavior outdoes the predefined recovery over time, which results in unintended control impulses or lack of controllability of the system. Then the mode must be changed. When properties of signals and events are not needed for the current mode, the user does not pay attention to them and there is also no feedback preserved for these input methods at that time. Therefore, their qualities are not evaluated either. For example, if *Radar Mouse* mode is active, IntegraMouse® coordinates do not matter, these signals are ignored and the only activated evaluation machanism for this quality is recovery over time. So if the user moves the IntegraMouse® unintentionally while clicking in *Radar Mouse* mode, this has no impact on the system.

2.2.5 Body of rules

This module collects all quality informations, interconnects them and selects the appropriate control mode then. As described previously, there are 4 different control modes. They can be divided into 2 groups, namely the one concerning only the click information and the other that concerns motions. These groups are independent of each other and are treated consecutively.

Notation: All constant values that are used in the *Fusion* for thresholds or time intervals are observational and are adapted to obtain reasonable results in a short measurement run. When using the system in a longterm run, most values need to be adapted to the user (see also Section 4.1 of the Discussion).

At first the qualities of the clicks are compared. If the qualities corresponding to the current button mode decrease under a certain threshold (20%) a change of mode is considered. However, the actual execution of this switch depends on the quality of the complimentary mode (which is the click quality of the IntegraMouse® in case of EEG mode and the click quality of the EEG-based brain-switch combined with the quality of the EEG signals otherwise). The changeover is only executed, when it is reasonable, so that the system would profit from the change and the quality of the new mode would promise better control results. If quality is above a fixed threshold (50%) then the switch proceeds, otherwise the current mode is kept until the complementary quality recovers long enough. This mechanism prevent the system from multiple switching in a short time interval end gives the user the chance to recover as well. Figure 2.15 shows the flowchart of this procedure.

Next, the body of rules evaluates the qualities of the movement. Here the system switches from one of the *Normal Mouse* navigation modes to the corresponding *Radar Mouse* navigation mode and otherwise. Similar to the mechanism rating the qualities of clicking, the switch happens the moment that the signal quality of xy-coordinates of the IntegraMouse® decreases the threshold (again 20%). Since the *Radar Mouse* mode is more time-consuming than the navigation with xy-coordinates, the system aims to switch back automatically as soon as the patient's ability to control the mouse movement has recovered. To give the user the time to revocer, the quality of the xy-coordinates has to recover to more than 50%, then there is a change in mode again. This time interval can be adapted by the user himself, just by changing the constant value for the percentage of recovery per second in the configuration file. As a result, the user need not stay in *Radar Mouse* mode until any quality becomes bad, but only as long as it takes the quality of the *Normal Mouse* mode to recover. Figure 2.16 shows the flowchart of this procedure.

Until this moment all possible output control signals computed from the input signals are available. According to the determined optimal control mode, the according control signals are interconnected to the output.

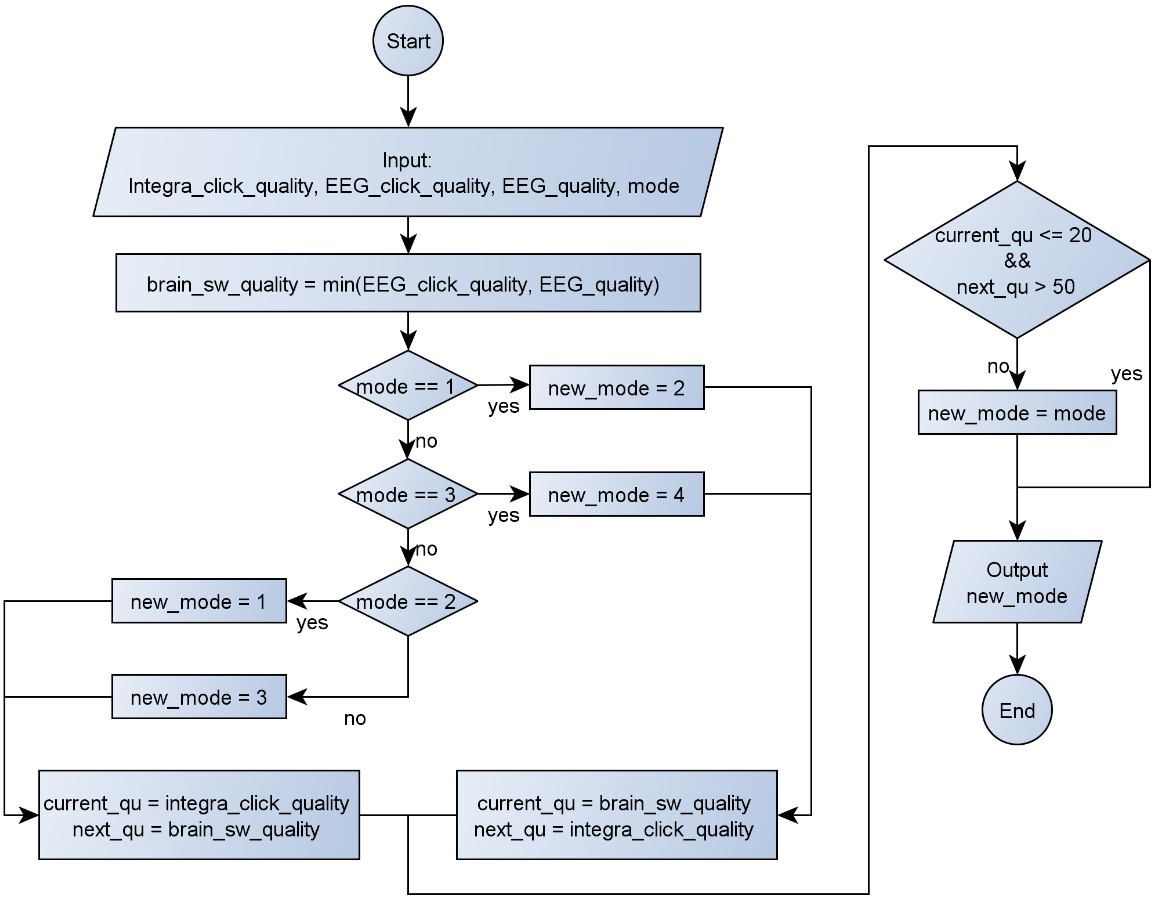


Figure 2.15: Flowchart of the mechanism that changes the control mode with respect to the click qualities.

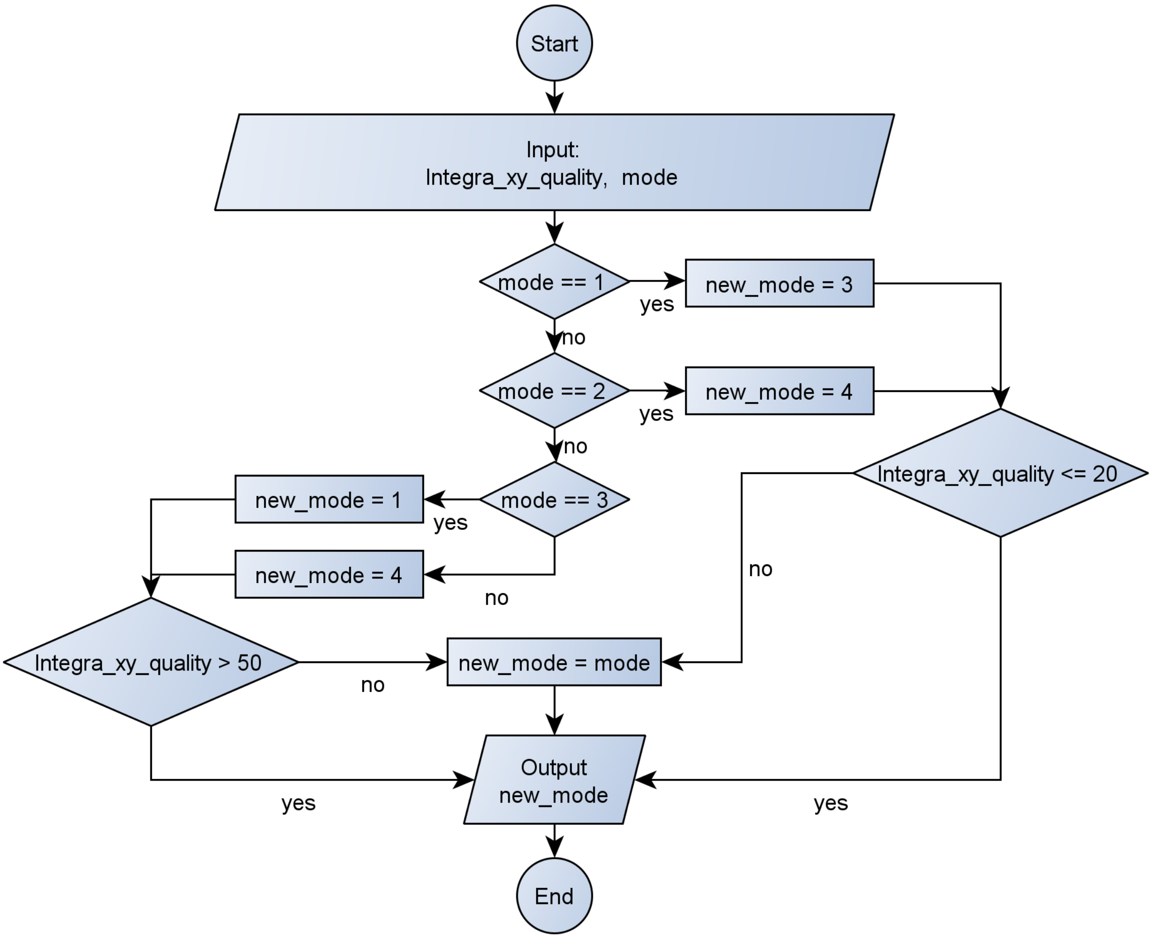


Figure 2.16: Flowchart of the mechanism that changes the control mode with respect to the quality of the xy-coordinates.

Signal quality of xy-coordinates of the IntegraMouse®

This mechanism examines if there are any problems concerning the joystick movement of the IntegraMouse®. In case of spasm for example, the coordinates are not reliable any longer. When the displacement is too small because of weakness, such that the mouse cursor would be trapped in one area of the screen, the signal cannot be used either. To evaluate these disorders there are 3 different quality decreasing mechanisms implemented. Figure 2.17 shows a flowchart containing these evaluations.

Weak movement is detected when the absolute sum over the derivative of the passed x-/y-values during the last two seconds does not exceed the constant threshold $window\_resolution/40$ (this constant as well as all other constants used in the descriptions for the quality evaluations are predefined in the ini-file of the Simulink model for the *Fusion*). This implies that the absolute movement of the mouse curser is too sparse.

Uncontrolled movement appears when there are more than 5 changes of direction in the x-/y-coordinate during a time window of 3s. Therefore changes in the sign of the derivatives are used.

The Cursor sticking in one corner is assumed if one of the coordinates remains at the maximum-value. The resolution of the screen is utilized for the limits.

Click quality of the IntegraMouse®

This mechanism examines if there are any troubles concerning the clicks of the IntegraMouse®. Figure 2.18 shows a flowchart containing these evaluations.

Motion with simultaneous clicking is rated as unintended and therefore penalized. If there is a change in x or y detected in combination with an active button, then there is a decrease in quality and the click is not transmitted to the QualiWorld application.

Multiple clicking is also associated as unwanted. If there are more than 3 clicks within the passed 5s, quality decreases.

Only right clicks without any left clicks in between may provide an indication of problems with the left click which is the main click by default. The user may not be able to puff due to weakness or may have any kind of seizure in this scenario. Therefore more than 2 right clicks in a row lead to a decrease in quality.

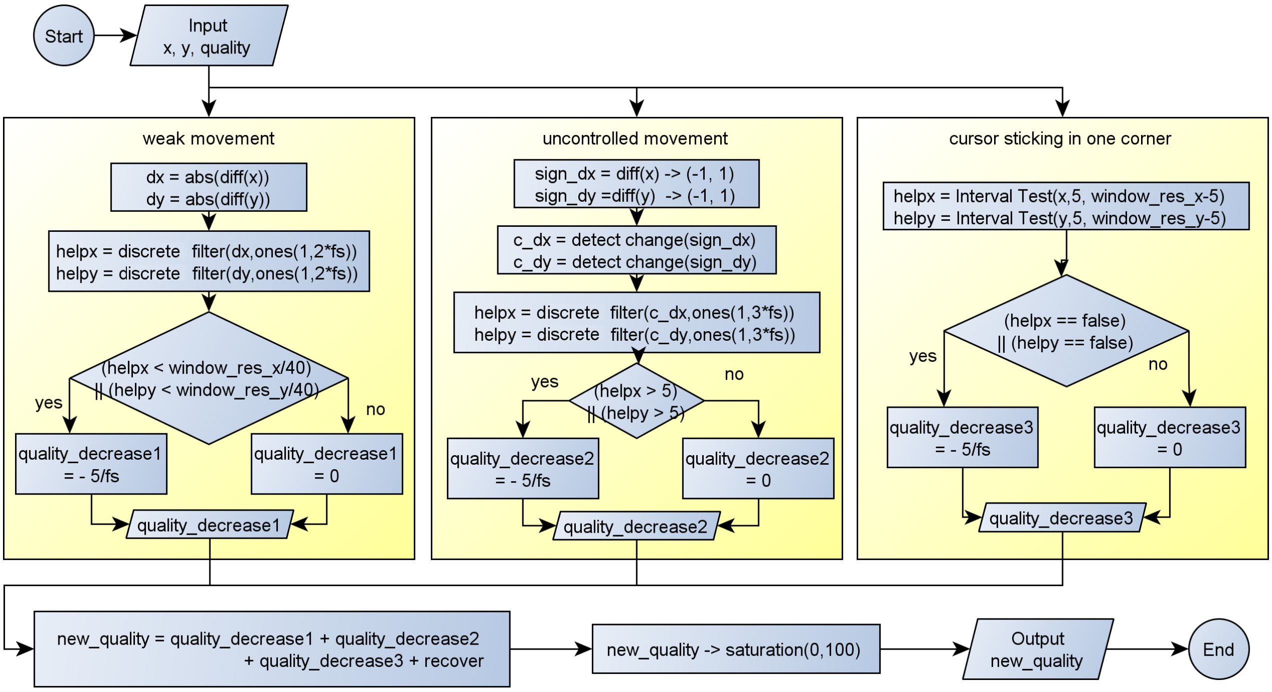


Figure 2.17: Flowchart of the mechanism that evaluates quality of the xy-coordinates.

No click for a long time is detected by counting the samples between clicks. If there is no click for 10 s or longer, then quality is scaled down.

Click quality of the EEG-based brain-switch

Equivalent to the IntegraMouse® click, also the EEG-based brain-switch click is checked. There are the same functionalities supported, with the exception that there is no right-mouse-click provided and therefore mechanisms concerning a right click are removed. The only difference in methods is that the time intervals of toleration are longer, for multiple clicking the latest 10 s of the signals are observed and there is not a penalty until 20 s without a click passed by. A flowchart of those evaluations is shown in Figure 2.19.

Quality of the EEG signals

To evaluate this quality, the EEG itself is observed as well as the behavior of the resulting band power which is utilized for the EEG-based brain-switch. There are four

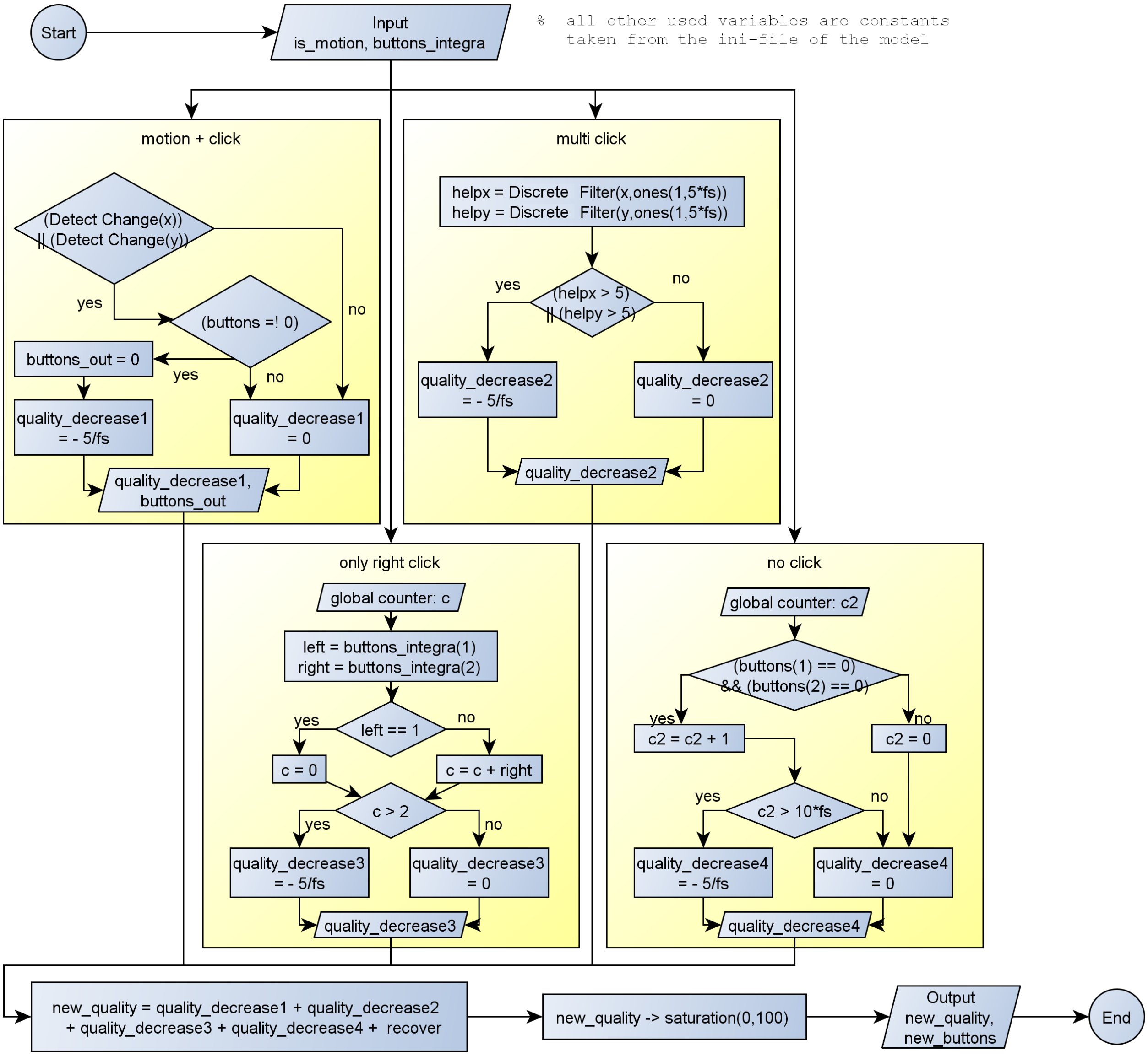


Figure 2.18: Flowchart of the mechanism that evaluates quality of the click initiated by the IntegraMouse®.

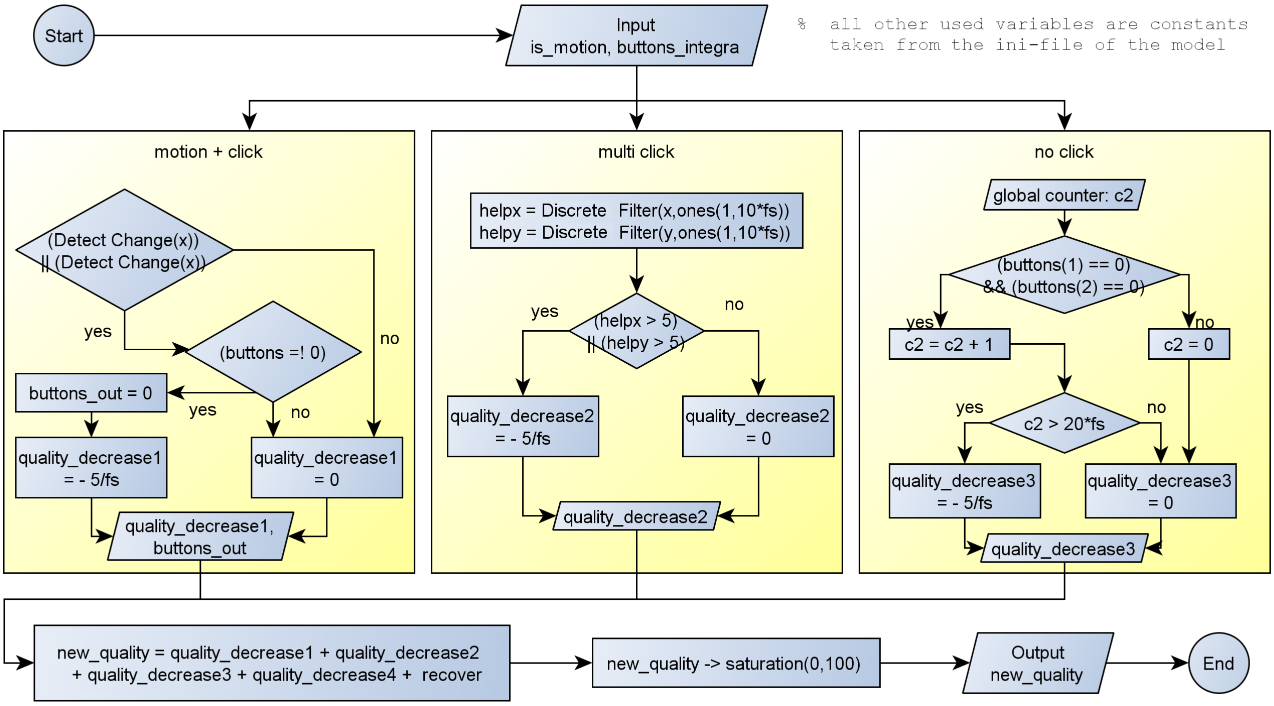


Figure 2.19: Flowchart of the mechanism that evaluates quality of the click initiated by the EEG-based brain-switch.

different mechanisms which can also be seen in the flowchart shown in Figure 2.20:

The band power remaining on a constant level is checked by adding up the samples of the derivative of the band power for the latest 3s. If this sum does not exceed $(max\_amplitude - min\_amplitude) * 0.1$ then the absolute change of the signal is too low .

The amplitude of the band power is rated abnormal when the sample value of the band power exceeds the maximum value for the amplitude. Also a minimum value is examined. If the band power falls under this minimum, quality is decreased.

The amplitude of the EEG is too large when its absolute value exceeds the predefined constant for the maximum value set in the ini-file.

The amplitude of the EEG remaining on the maxima or oscillating between them is determined by averaging the absolute values of the signal for the last 3s. If this value is higher than a threshold, quality is decreased. Therefore the highest possible value for the EEG signal is predefined in the ini-file of the model. To include also oscillating behavior, a variance of 20% is allowed, therefore this constant is multiplied by 0.8 and is used as threshold then.

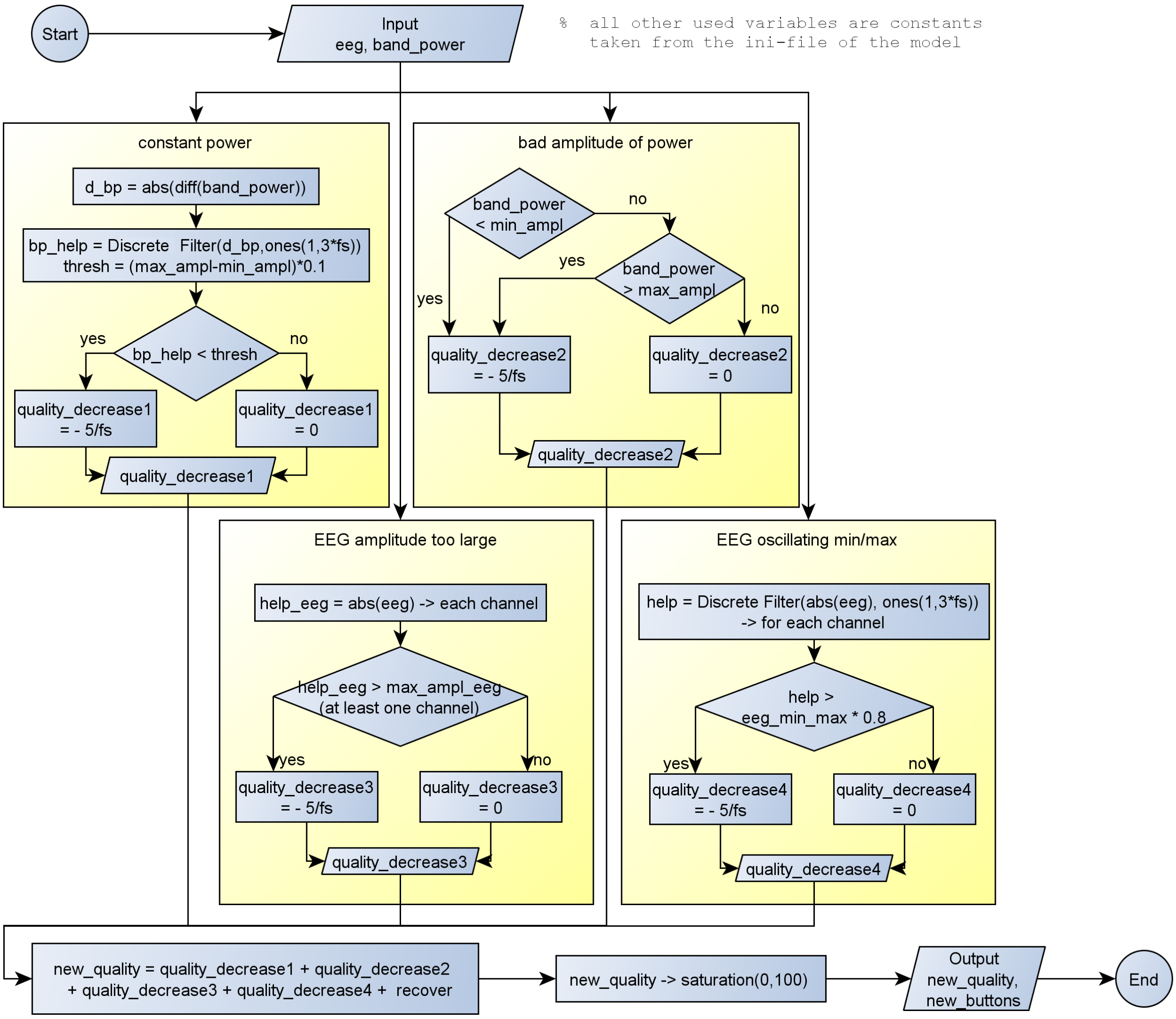


Figure 2.20: Flowchart of the mechanism that evaluates quality of the EEG signals.

Reset-functionality for the mode and the qualities

There is a reset function implemented in the model of the *Fusion*, which can be activated by a manual switch. If the switch is toggled to 1, the mode and each quality is set to the value entered in the corresponding constant blocks. This state is kept as long as the switch points to 1. When it is switched back to 0, the *Fusion* proceeds normally starting from that set state. This functionality is helpful for holding a certain state, utilized for example for testing issues and to adapt qualities to a specified szenario as well as for the case when suppression of the mode switching functionality is wished.

2.2.6 QualiWorld API

This API provides external control of the QualiWorld application. Therefore any software can communicate with the application and send individual control commands originating from any other application [40]. Generally, this communication happens via UDP sockets by means of XML message exchange . It is important to know, that there is a change in the Windows registry needed to use this API at all. Therefore a new key in the registry has to be defined at the following position:

`‘HKEY\_LOCAL\_MACHINE\SOFTWARE\QualiLife\QualiWorld\API’`

The key API should be of type `DWORD` with value 1 and hexadecimal format. Further on the QualiWorld software needs to be updated to version 5.0.73 or newer. Now the system is set up and any application can communicate with QualiWorld. To this purpose, Qualiworld now has two different ports opened, one to receive its commands and one to send its messages back. The messages that QualiWorld receives through its input port are called Commands, whereas the messages it sends back via its output channel are called Notifications. The communication on these ports are unidirectional. The default IP address used in QualiWorld is ‘127.0.0.1’ serving the ‘command port 10001’ and the ‘notification port 10000’. These settings can be changed via the QualiWorld software at ‘Settings –> Mouse –> BCI Options –> Transport’.

For the communication between the Simulink model for the *Fusion* and the QualiWorld application three different XML messages are used. All of them are Commands, the Notification port is not required. The following XML code performs a left-click at the current mouse cursor position:

```
<?xml version="1.0" encoding="utf-8" ?>
<QWMessage>
<Command Name="MouseEvent" Value="LeftClick" />
</QWMessage>
```

To set the mouse cursor to the right position, the following code snipped is used:

```
<QWMessage>
  <Command Name="MouseEvent" Value="MouseMove">
    <PosX>256</PosX>
    <PosY>484</PosY>
```

```
  </Command>
</QWMessage>
```

These two commands can be combined to the following command, then a left-click on a certain position is performed:

```
<?xml version="1.0" encoding="utf-8" ?>
<QWMessage>
   <Command Name="MouseEvent" Value="LeftClick">
     <PosX>200</PosX>
     <PosY>360</PosY>
   </Command>
</QWMessage>
```

Changing the mouse cursor mode is very simple. Since there are fixed shortcuts provided for switching this mode in QualiWorld, only a key event command is needed:

```
<?xml version="1.0" encoding="utf-8" ?>
<QWMessage>
<Command Name="KeyEvent" Value="F6" />
</QWMessage>
```

Table 2.1 taken from [40] shows all possible mouse cursor modes and the associated function key. Note that these keys are permanently assigned and cannot be used otherwise therefore.

Table 2.1: Different mouse cursor modes and their associated function keys.

Function Key	Mouse Method
F1	Normal Mouse
F2	AutoClick Mouse
F3	AutoScan Mouse
F4	ManualScan Mouse
F5	XY Mouse
F6	Radar Mouse
F7	Directional Mouse
F8	APIScan mouse
F12	Switch on/off the Face Tracking mouse

2.3 Verification

Within the process of verification, in a first step all methods and procedures that are not related to the processing of the EEG data are tested. Especially the proper functioning of the evaluation for the quality of mouse movement and the IntegraMouse® clicking is examined. When those modules of the system are proved right, a verification measurement with only one subject is performed. This measurement shall confirm the correct behavior of the whole system, including also the mechanisms end procedures concerning the EEG data now. When the whole system is working well, after this verification a study with 4 participants is performed.

2.3.1 Testing without EEG data

When the implementations of all modules of the system is finished, all functionalities are tested. At first the functionalities regarding the use of the IntegraMouse® are evaluated. Therefore no EEG data is needed and the system is run with an sine-wave generator instead of real EEG signals. This testing is done by myself without any subject. The SignalServer is started with the IntegraMouse® connected, the *Fusion* is only used in modes where no EEG data is needed. In this setup the quality evaluation of the movement of the IntegraMouse® as well as the clicking in *Normal Mouse* mode and *Radar Mouse* mode are verified. Each of the following scenarios is simulated: Weak movement is simulated by just tipping on the mouthpiece of the IntegraMouse® slightly, for uncontrolled movement the mouthpiece is moved along all axes randomly and very quickly. The Cursor sticking in one corner is tested for all edges and corners of the screen. It is checked if motion with simultaneous clicking is suppressed, and how the system acts on multiple clicking, only right clicks and no click at all. Moreover, it is controlled if the right signals are forwarded to the QualiWorld application and if the desired actions are performed. Then the switching between modes is examined. Therefore, the *Fusion* is started with different presetting of all qualities and the current mode. Then, by simulating bad behavior of movement and/or clicking, the reaction of the system is observed.

2.3.2 Testing with EEG-based brain-switch

In a next step, a real measurement is performed to verify functionalities of the whole setup, using the complete hybrid BCI with the EEG-based brain-switch as well. Now, usability of the implemented system is tested by one subject only. Therefore a person experienced to the task of imaginary foot movement is chosen to control the system. The able-bodied test person is a right-handed female. The paradigm as well as the whole experiment is explained to her before beginning.

After setting up the EEG-based brain-switch as explained in Section 2.2.3 the test runs can start. The results of the first setup run have been satisfying, so there are no more training runs done. For the test setup, the QualiWorld application serves as visual feedback. At correct usage of the EEG-based brain-switch and the IntegraMouse®, the subject can see the movement and the clicks of the mouse cursor on the screen directly. For testing, two PCs are used. The first one is running the SignalServer and the Matlab/Simulink model, this one is also connected to the EEG amplifier and the IntegraMouse®. On this PC the behavior of the *Fusion* with all its quality outputs can be supervised and modified. The other one is used by the subject, it runs the QualiWorld application. For the *Fusion* model no paradigm is needed. Once started, the online model runs as long as the user wants it to. A paradigm with cues would be pointless, since it cannot be predicted how long it will take the subject to navigate through the clicking tasks and to perform the clicks.

A small test tool has been implemented to bring the clicking in a repeatable procedure. Figure 2.21 shows the surface of this tool. When the ‘Start’ button is clicked this button is disabled and button ‘1’ is enabled instead and becomes the current target to click. When ‘1’ is clicked, again this button is disabled, and ‘2’ is enabled and is the only clickable button on the screen. Therefore, no unintended clicks can cause any trouble. The subject has to start the run and then click the sequence of 20 buttons as fast as possible. After clicking the ‘end’ button, a pause is possible before starting the next run.

For the experiment, first each mode of the *Fusion* is tested on its own by suppressing the switch functionality. In the end a whole run without interfering the function of switching modes is performed. In this last run the behavior of the *Fusion* regarding the right choice of the mode is observed.

2.4 Study - Proof of Principle

After the verification measurement, a study is run with five subjects (there are results for only four subjects because one measurement was interrupted for medical issues). The subjects are all female, right-handed and between 22 and 25 years of age. All of them are experienced to the task of imagination of the movement of feet, so that it is

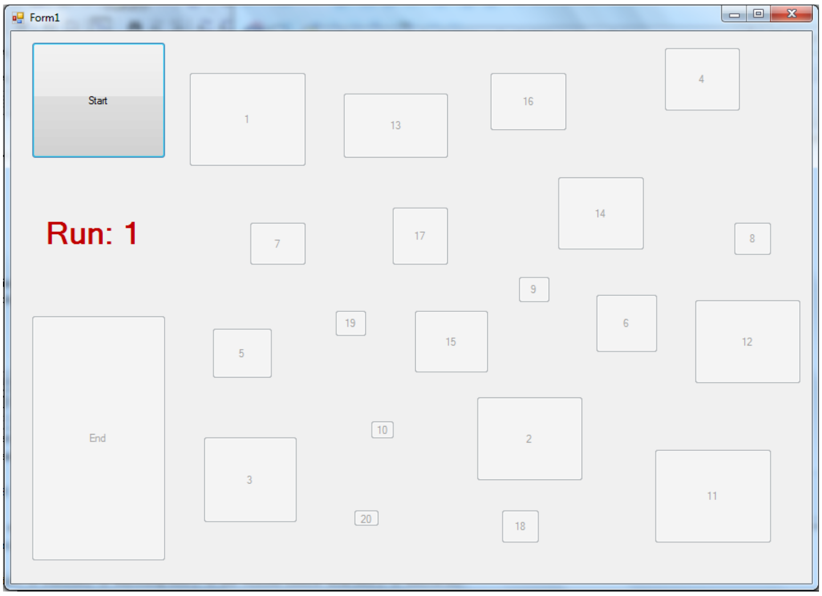


Figure 2.21: Test tool to get a repeatable procedure for clicking.

known that they all have a recognizable beta-rebound. Again, the ideal parameters for the EEG-based brain-switch are calibrated for the subject as described previously. Then the mode switching functionality of the hybrid BCI system is observed. The system setup is slightly modified to the one used for the verification measurement. There are three different possibilities to add noise manually to the signals now. There is added one source of noise for each of the two variants for clicking (EEG, IntegraMouse®) that produces multiple unintended clicks. Another noise source causes shaking of the movement of the mouse cursor. The test tool, providing the buttons, is extended with the functionality of saving the moment when a button is clicked. This information is stored in a text file called `clicktime.txt` automatically and is filed in the same directory as the test tool.

Again, the subjects are asked to click all the buttons of the test tool. When clicking button ‘10’, one of the noise sources is activated to force a specific change in mode. It is observed, if the desired switch of mode really is executed then. If the start mode is related to *Radar Mouse* mode, then the noise for IntegraMouse® XY is always activated as well. This is because of the fact, that the mechanism for switching from *Radar Mouse* mode to *Normal Mouse* mode does not depend on any changes in quality but occurs automatically after a specified time interval. For the observation this switch is unwanted, therefore the noise of the movement is on, so that the system switches back to *Radar Mouse* as fast as possible. After these observations regarding the switching behavior, there is a further run (run 7), where the subject is locked in mode 1. In this run it should be tested, if the subject can concentrate on listening to other people while using the EEG-based brain-switch. Therefore a (german) text is read to the subject until all buttons are clicked (Wikipedia: "Der Dodo"[1]). Afterward, the subject is asked 9 questions relating to the text. It is observed, how many questions are answered correct. The following questions are asked in germen in the verbal quiz:

- Welchen Namen hat der Vogel? (What is the name of the bird?)
- Kann der Vogel fliegen? (Is the bird able to fly?)
- Warum nicht? (Why not?)
- Wo gibt es heute solche Vögel? (Where can you find those birds today?)
- Wann ist diese Vogelart ausgestorben? (When ceased this bird species?)
- Warum ist die Vogelart ausgestorben? (Why ceased this bird species?)
- Wo kam die Vogelart vor? (Where lived those birds?)
- Wie groß war der Vogel? (What was the height of the bird?)
- Wie schwer war der Vogel? (What was the weight of the bird?)

Table 2.2 shows the setup for the different runs of the study. For recollection, the modes are defined as follows:

Mode 1: *Normal Mouse* + clicks from the EEG-based brain-switch
Mode 2: *Normal Mouse* + clicks from the IntegraMouse®
Mode 3: *Radar Mouse* + clicks from the EEG-based brain-switch
Mode 4: *Radar Mouse* + clicks from the IntegraMouse®

Table 2.2: Setups for the study

Run	**Start mode**	**Next mode**	**Added noise**
run 1	2	1	IntegraMouse® click
run 2	2	4	IntegraMouse® XY
run 3	1	2	EEG click
run 4	3	4	EEG click + IntegraMouse® XY
run 5	1	3	IntegraMouse® XY
run 6	4	3	IntegraMouse® click + IntegraMouse® XY
run 7	1	-	-

---

[1] http://de.wikipedia.org/wiki/Dodo

3 Results and Evaluation

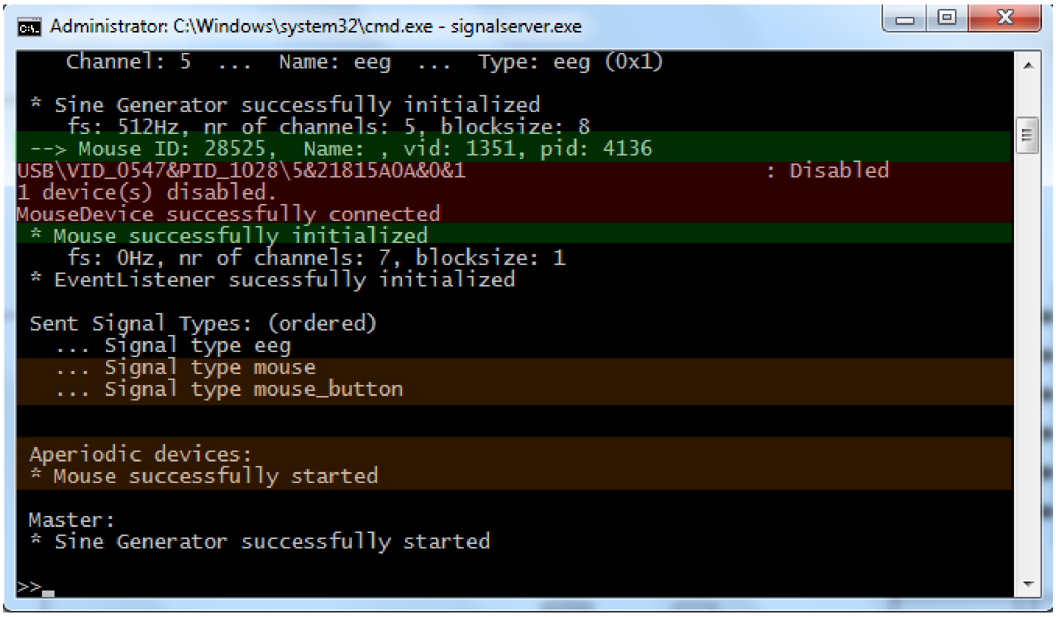
3.1 SignalServer and IntegraMouse®

The integration of the mouse device interface into the SignalServer was successful. Libusb was used for Linux as well as libusb-win32 for Windows. The following files were changed or added to the project:

`\src\hardware\mouse.cpp`
`\src\hardware\mouse_win.cpp`
`\src\hardware\mouse_linux.cpp`
`\include\hardware\mouse.h`
`\include\hardware\mouse_win.h`
`\include\hardware\mouse_linux.h`
`\include\tia\constants.h`
`\include\tia\defines.h`
`\bin\server_config.xml`
`\extern\include\libusb\libusb.h`
`\extern\include\libusb\usb.h`
`\extern\lib\libusb\linux\*`
`\extern\lib\libusb\win\*`

In the `bin` folder the folder `libusb` wasintegrated. It is needed for Windows use only. There the driver file for the used mouse device must be generated. It must be named `mouse.inf`. The rest of the files in this folder are generated automatically.

The successful implementation of the IntegraMouse® in the SignalServer can be seen in Figure 3.1. The SignalServer is running with the mouse device started. In the green highlighted section one can see when the mouse object is initialized. The red section appears only when working on Windows, it is caused by the 'devcon tool' of the WinDDK and confirms that the Windows kernel driver has been blocked. In the orange sections, one can see that the signal types `'mouse'` and `'mouse_button'` are used to send data concerning the mouse device. The server confirms also that the connection



```
    Channel: 5  ...  Name: eeg  ...  Type: eeg (0x1)

 * Sine Generator successfully initialized
    fs: 512Hz, nr of channels: 5, blocksize: 8
 --> Mouse ID: 28525,  Name: , vid: 1351, pid: 4136
USB\VID_0547&PID_1028\5&21815A0A&0&1                        : Disabled
1 device(s) disabled.
MouseDevice successfully connected
 * Mouse successfully initialized
    fs: 0Hz, nr of channels: 7, blocksize: 1
 * EventListener sucessfully initialized

 Sent Signal Types: (ordered)
   ... Signal type eeg
   ... Signal type mouse
   ... Signal type mouse_button


 Aperiodic devices:
 * Mouse successfully started

 Master:
 * Sine Generator successfully started

>>
```

Figure 3.1: Screen shot of the Widows console with the SignalServer started. The mouse device is connected successfully.

to the mouse device is started and can now be used. To enable data acquirement from the IntegraMouse®, the configuration file must include the following code:

```
<hardware name="mouse" version="1.0" serial="">
 <mode> aperiodic </mode>
 <device_settings>
 <vendorid> 1351 </vendorid>
 <productid> 4136 </productid>
 <usb_port> 130 </usb_port>
 <devcon_path>C:\WinDDK\7600.16385.1\tools\devcon\i386\devcon.exe</devcon_path>
 </device_settings>
</hardware>
```

3.2 Matlab/Simulink model for the *Fusion* and the QualiWorld controller

`FusionBCIM.mdl`, `FusionBCIM.ini` and `FusionBCIM.xml` contain the model for the *Fusion*. The complete model can be seen in Figure 3.2. It consists of the module for the SignalServer client, the module for the *Fusion* itself, the QualiWorld control module, and the reset funtionalities for the signal qualities. All input signals from the SignalServer client are saved via the `C++ DAQ Saver` as well as the output signals that are forwarded to the QualiWorld application, and the manual quality resets.For the quality reset there exits the Matlab-S-Function `set_fb.m`. Moreover, the current mode and all the qualities are saved. All data is saved to a gdf-file. The important signals stored in the signal block of the gdf-file have the order shown in Table 3.1.

Table 3.1: Structure of the signal block of the generated gdf-file.

Line	**Item**
1-5	EEG signals
7	x-coordinate IntegraMouse®
8	y-coordinate IntegraMouse®
10	left click IntegraMouse®
11	right click IntegraMouse®
13	left click sent to QualiWorld
14	right click sent to QualiWorld
15	x-coordinate sent to QualiWorld
16	y-coordinate sent to QualiWorld
17	mode
18	activation of the manual mode switch (on/off->1/0)
19	quality xy
20	quality IntegraMouse® click
21	quality EEG click
22	quality EEG
23	which mode is activated by the manual switch

In Figure 3.3 one can see the overview of the *Fusion* module. All features that were discussed previously in Section 2 were implemented successfully.

The detailed implementation of the body of rules can bee seen in Figure 3.4. One can find the two different mode switching cycles that are independent of each other, the first one concerning the clicking modes, the other one belonging to the switch between *Normal Mouse* mode and *Radar Mouse* mode. Also the selection of the right output signals can be seen.

For the establishment of the communication with the QualiWorld application, the Matlab-S-Function `qwcomm.m` has been created. When initializing the model, a UDP socket is started. The QualiWorld block of the implements the mechanism for sending changes in the output signals to the QualiWorld application.

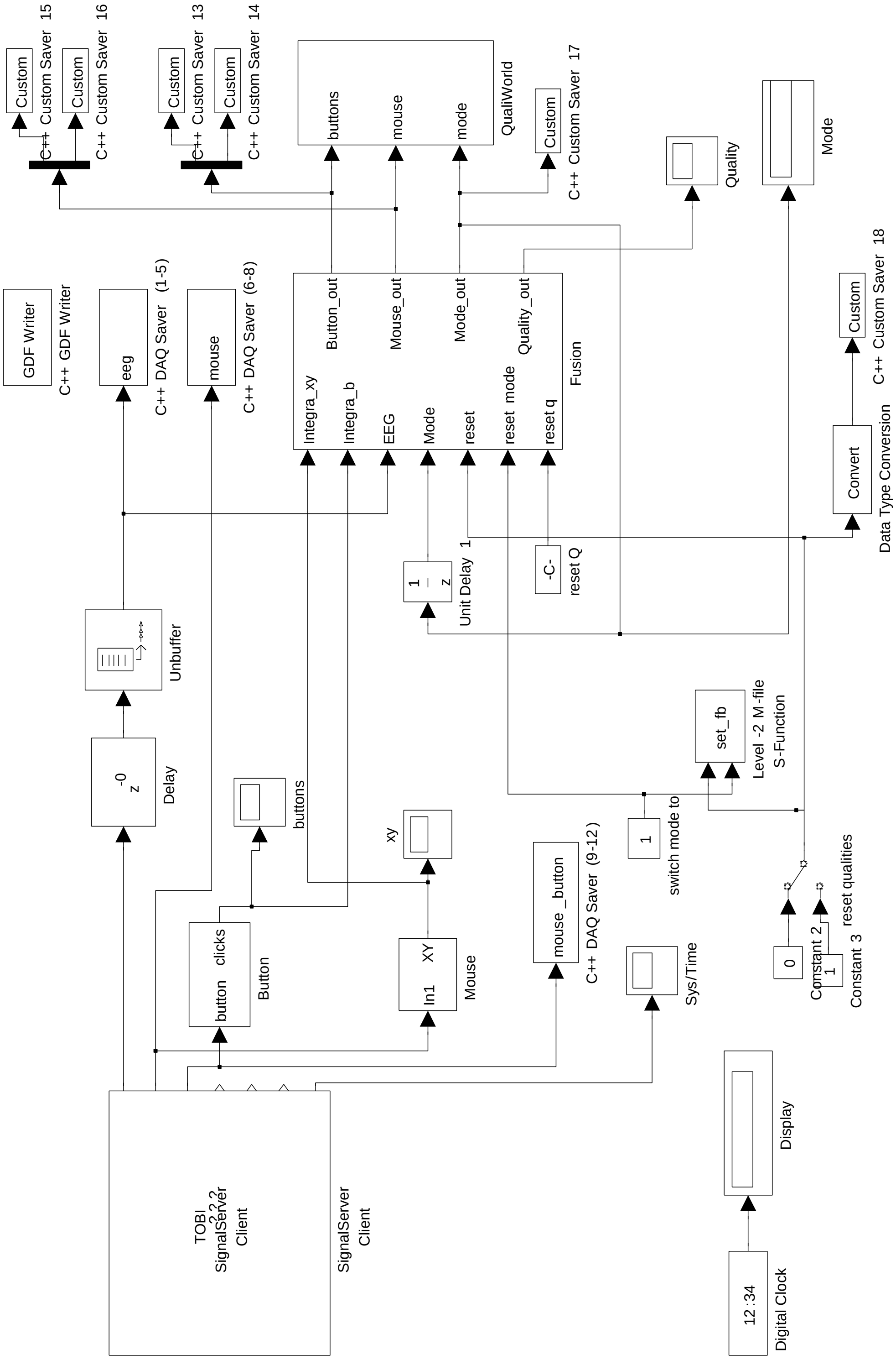


Figure 3.2: Complete Matlab/Simulink model.

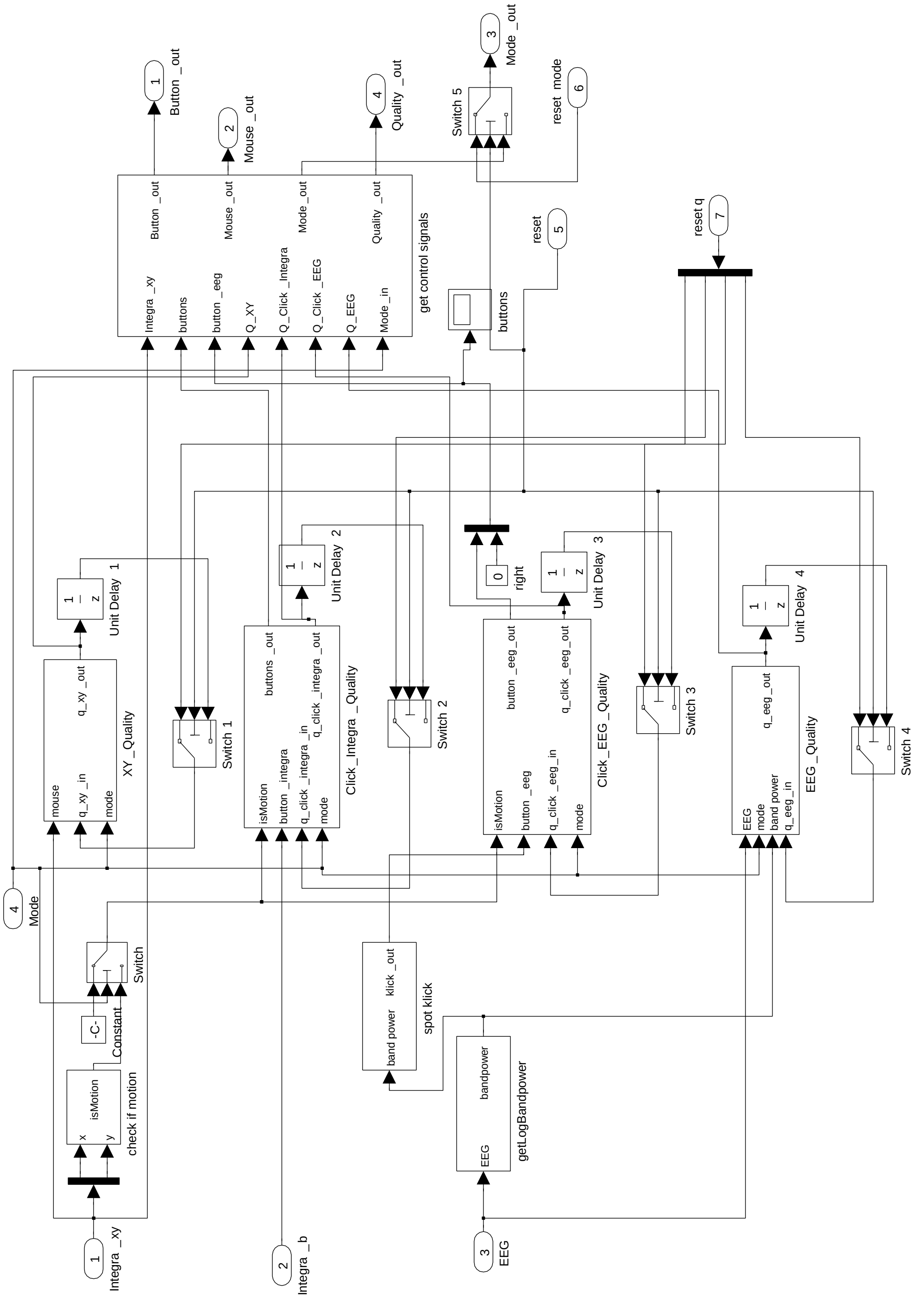


Figure 3.3: Matlab/Simulink model of the fusion module.

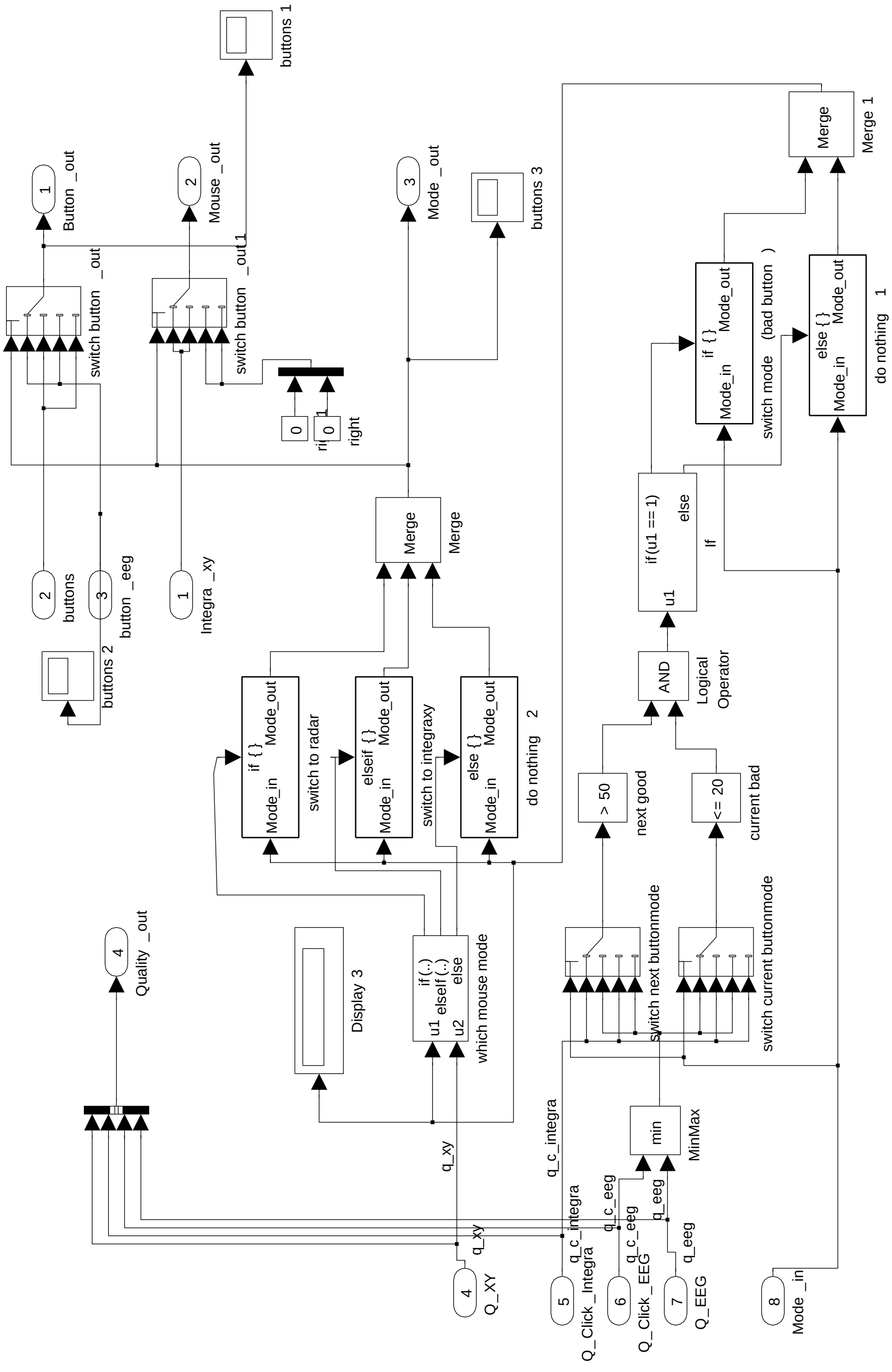


Figure 3.4: Matlab/Simulink model of the body of rules.

3.3 Parameter setup of the EEG-based brain-switch

The parameter setup is working well. It was possible to configure the EEG-based brain-switch for all subjects. Only the computed threshold was slightly too high in some cases but had been adapted in conference with the subject easily. Representatively for all other subjects, The ERD(S) combimap for the imaginary movement of the first measurement - the verification measurement (subject bi5) - is shown in Figure 3.5 (data of all other subjects can be found in the Appendix at Section A.1). The beta rebound can be seen clearly. The red line on top represents the standard deviation of the power band between $6Hz$ and $40Hz$, the blue line reflects the corresponding mean. One computed frequency band is $2Hz$ wide each.

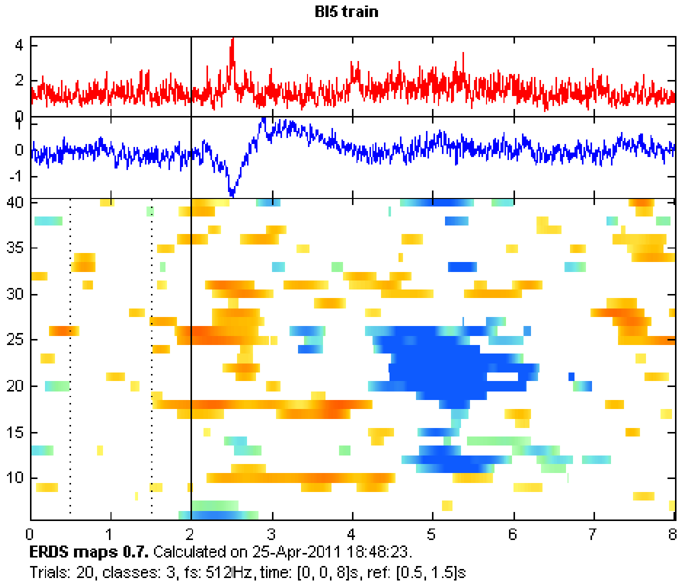


Figure 3.5: ERD(S) map of the verification measurement (subject bi5). 20 imaginations of a brisk movement of both feed are averaged (Laplacian derivation over CZ and frequency bands of 2 Hz each).

In Figure 3.6 one can see the computed LDA output of the EEG averaged over all trials for the same subject. It shows a clear maximum at the same time as the ERD(S) map indicated before. Therefore good classification results can be expected. The plotted lines are the mean LDA value ± the corresponding standard deviation. These values are used to calculate the threshold used for the parameter setup of the EEG-based brain-switch.

The following parameters are calculated for this test run:

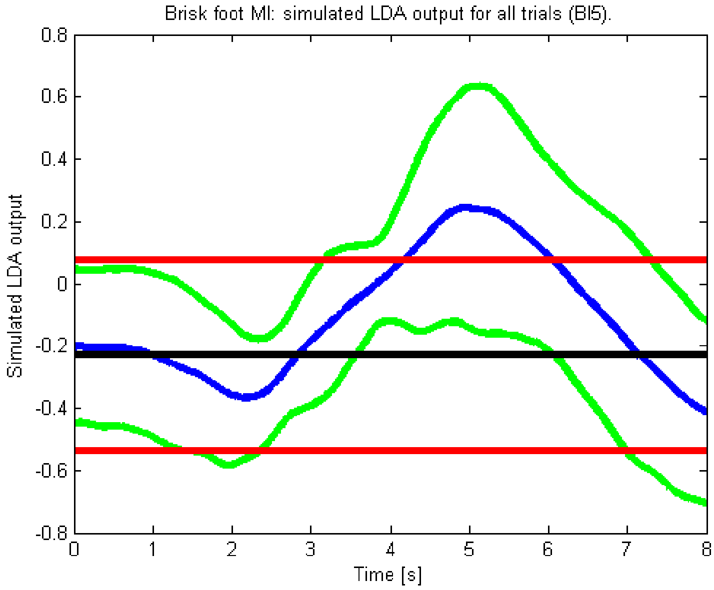


Figure 3.6: LDA output averaged over all tasks with imagination of feet movement, the used EEG data was from the setup run in the verification measurement (subject bi5). The horizontal lines are the mean LDA ± the standard deviation.

```
W = [-0.893601814030933 -0.448860555140042]
thresh = 0.320590148845728
cfr_band = [18 24]
```

By way of illustration, those parameters are applied to the same data set again that was already used for the setup. This approach shall show, how the good the estimation of the parameters works for the whole data, including also the sequences in between the tasks as well as the sequences of the contra-task. Figure 3.7 shows the results. The red line is the computed threshold, the gray areas define the trials with the target movement. Every time the blue line exceeded the threshold a click was initiated. As long as the line remains above the threshold, no new click can be initiated, the click is only triggered by the rising edge. When counting the times where the line exceeds the threshold within a gray area as true positives (TP), the gray areas without any click as false negative (FN) and the clicks outside those gray areas as false positives (FP) one gets the following values:

Table 3.2: Comparing true positives, false positives and false negatives of the triggered clicks.

TP	**FN**	**FP**	**total # of gray areas**
14	6	5	20

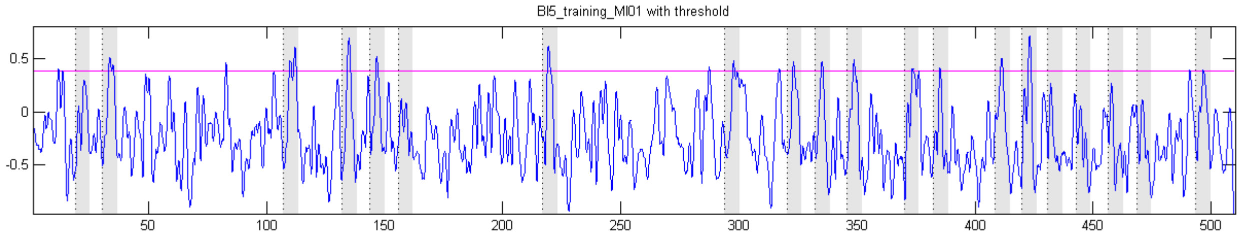


Figure 3.7: The computed parameters for the EEG-based brain-switch were applied to the whole data of the setup run of the verification measurement (subject bi5). When the signal was above the threshold (redline) a click was initiated.

3.4 Verification

3.4.1 Testing without EEG data

During implementation, each subpart of the Matlab/Simulink model was tested. Each method of the different quality measurements was examined using intentionally caused problematic inputs for all scenarios discussed in the Methods section. The quality decreasing and recovering mechanisms worked well. Also the mode switching was tested successfully by manipulating quality outputs to get configurations where a switch of mode was forced.

3.4.2 Testing with EEG-based brain-switch - verification measurement

This measurement was performed with one subject only (subject bi5). At first, each mode was tested for the length of one run with mode switching functionality suppressed. This means that the subject remained in the chosen mode, no matter how badly she performed. It was measured how long it had taken the subject to click all 20 buttons plus the start and the end button (therefore there has been a total number of 22 buttons to click at each run). Also the needed clicks were counted. Table 3.3 lists the results of this measurement and Figure 3.8 shows the corresponding diagram.

To visualize the performance, the recorded data of the movements and the click information was plotted in a xy-diagramm. This diagramm then was cross-faded over a screen shot of the test tool. By this way, the run to test mode 2 (*Normal Mouse* mode with clicks initiated by the click function of the IntegraMouse®) is shown in Figure 3.9. All 22 buttons had been clicked successfully at first try.

Table 3.3: Comparison of needed time and number of clicks for completion of one run using the differend modes (subject bi5). Each mode was tested once.

mode	**clicks**	**time [s]**	**description**
Mode 1	48	140	Normal Mouse + EEG click
Mode 2	22	90	Normal Mouse + IntegraMouse® click
Mode 3	136	512	Radar Mouse + EEG click
Mode 4	51	115	Radar Mouse + IntegraMouse® click

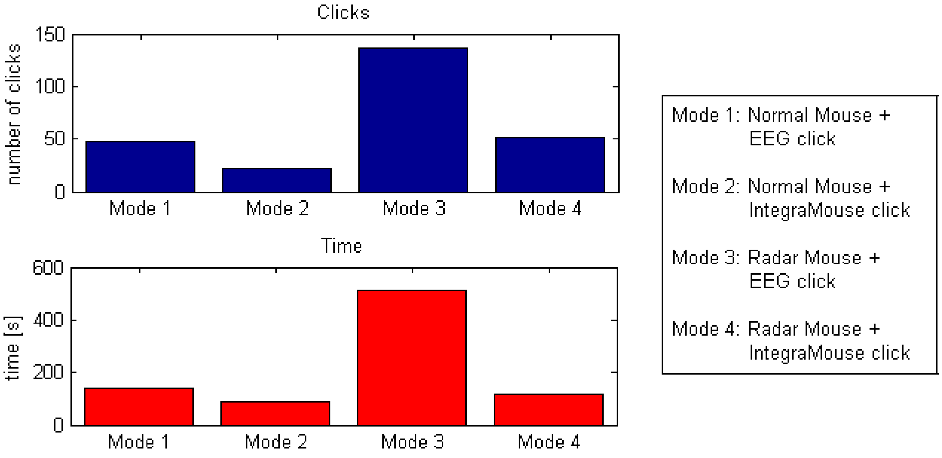


Figure 3.8: Comparison of the number of clicks needed to perform a whole run using the different modes (subject bi5). Each mode was tested once.

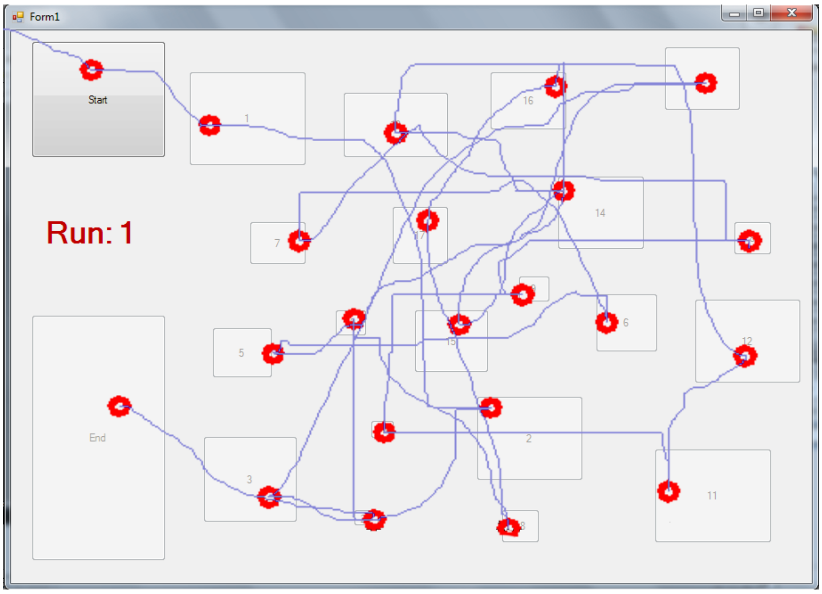


Figure 3.9: Click sequence, testing mode 2. *Normal Mouse* mode was used combined with the click function of the IntegraMouse®.

When testing mode 1 (*Normal Mouse* mode with clicks initiated by the EEG-based brain-switch) also all buttons had been clicked successfully, but often not on first try. Therefore there were more clicks. In Figure 3.10 one can see a segment of the sequence of the run testing mode 1 (*Normal Mouse* mode with clicks initiated by the EEG-based brain-switch). It presents the sequence from click at button 3 to the click at button 12. One can see that the movement is more unexact than in run 1. The subject had troubles when clicking button 10 (marked in the picture).

Due to the fact that there is no cursor movement in *Radar Mouse* mode, no informations concerning the position of the click was saved. Therefore there are no sketches visualizing the click sequence. Also in *Radar Mouse* modes the subject was able to click all 22 buttons but again not each one at first try.

At last, a run was performed, where mode switching functionality was enabled. The subject started in mode 1 and the *Fusion* was switching according to the current qualities. The subject was able to perform this run without considerable losses in quality. Thus the model has been reseted to interesting constellations of qualities manually, to force switching.

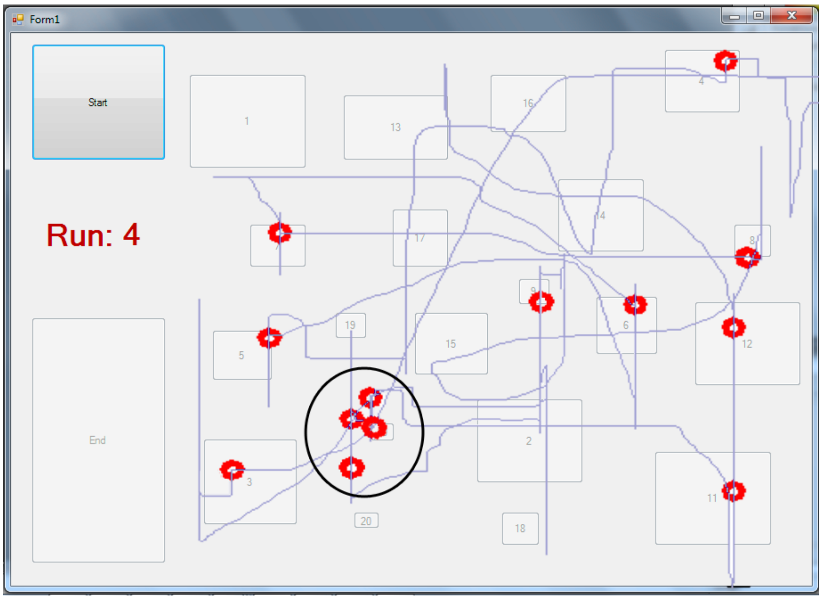


Figure 3.10: Click sequence (snipped out), testing mode 1. *Normal Mouse* mode was used combined with the click function of the EEG-based brain-switch.

3.5 Study - Proof of Principle

The computed configurations for the EEG-based brain-switch of each subject are shown in Table 3.4.

Table 3.4: Configurations for the EEG-based brain-switch.

subject code	used frequency bands	W	threshold
bc4	[17 18]	[-0.9407 -0.3392]	-0.46
bi5	[20 21]	[-0.9537 -0.3007]	-0.54
bx3	[30 31]	[-0.9788 -0.2047]	-0.27
bo2	[20 21]	[-0.9608 -0.2773]	-0.45

Representative for all measurements, in Figure 3.11 to Figure 3.16 the behavior of the qualities in the different setups are plotted for only one subject, where the behavior can be seen best (plots for all other subjects can be found in the Appendix at Section A.2). The dotted vertical line marks the moment the switch in mode was executed.

The mode in which the system was started for Figure 3.11 was mode 2 - *Normal Mouse* and IntegraMouse® click. Therefore the quality of the xy-movement as well as the quality for the IntegraMouse® click were evaluated. When the subject clicked button '10', noise for the IntegraMouse® click was added and the quality decreased (pink line).

When the quality reached 20%, a switch to mode 1 - *Normal Mouse* and EEG click - was initiated. Now the quality evaluation mechanism for the IntegraMouse® click was inactive, and there was just the recovery over time for this quality. Instead the quality for the EEG click was examined then.

When starting in mode 2 and adding noise for the mouse movement (see Figure 3.12), mode was switched to mode 4 - *Radar Mouse* and IntegraMouse® click - as soon as the quality for xy-movement (yellow line) decreased under 20%.

When starting in mode 1 and adding noise for the EEG click (see Figure 3.13), mode was switched to mode 2 as soon as the quality for the EEG click (cyan line) decreased under 20%.

When starting in mode 3 - *Radar Mouse* and EEG click - and adding noise for the EEG click (see Figure 3.14), mode was switched to mode 4 as soon as the quality for the EEG click (cyan line) dropped under 20%. For this scenario the noise for the mouse movement was activated for the whole run. This was necessary to assure that the system returns to *Radar Mouse* mode each time the quality of the mouse movement recoverd.

When starting in mode 1 and adding noise for the mouse movement (see Figure 3.15), mode was switched to mode 3 as soon as the quality for the mouse movement (yellow line) decreased under 20%.

When starting in mode 4 and adding noise for the IntegraMouse® click (see Figure 3.16), mode was switched to mode 4 as soon as the quality for the IntegraMouse® click (pink line) decreased under 20%. Again, for this scenario the noise for the mouse movement was on for the whole run.

The attended times to click all buttons are shown in Table 3.5. The time measurement started when the subject clicked the ‘Start’ button. Therefore the time line is not the same as in the previous plots for the qualities. Also the mean value over all subjects for each run can be found there. One value is missing (bx3 run 6), the subject has not been able to finish this run because there have been problems with the click function of the IntegraMouse®. The second value displayed in each cell is the time value where the additional noise was activated. The value corresponds to the moment when button ‘10’ was clicked. Figure fig:clicktimesall visualize these results.

In run 7, which included the task of listening to a text while clicking the buttons using mode 1, all subjects were able to answer most of the questions. Table 3.6 shows the results of the quiz.

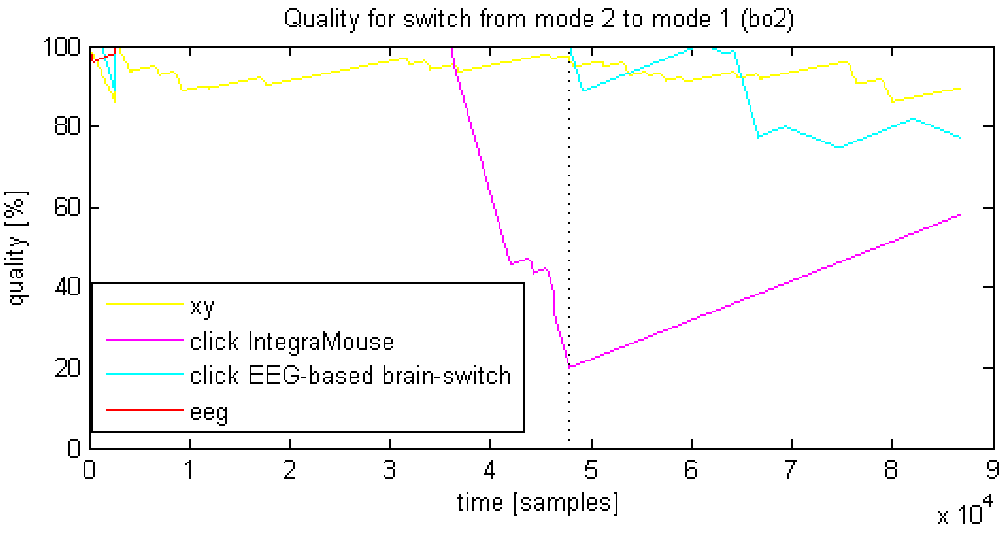


Figure 3.11: Influence of starting mode and behavior of qualities on the system: when starting in mode 2 and adding noise to the IntegraMouse® click the system switches to mode 1. The dotted vertical line represents the moment the change in mode occurs. (bo2)

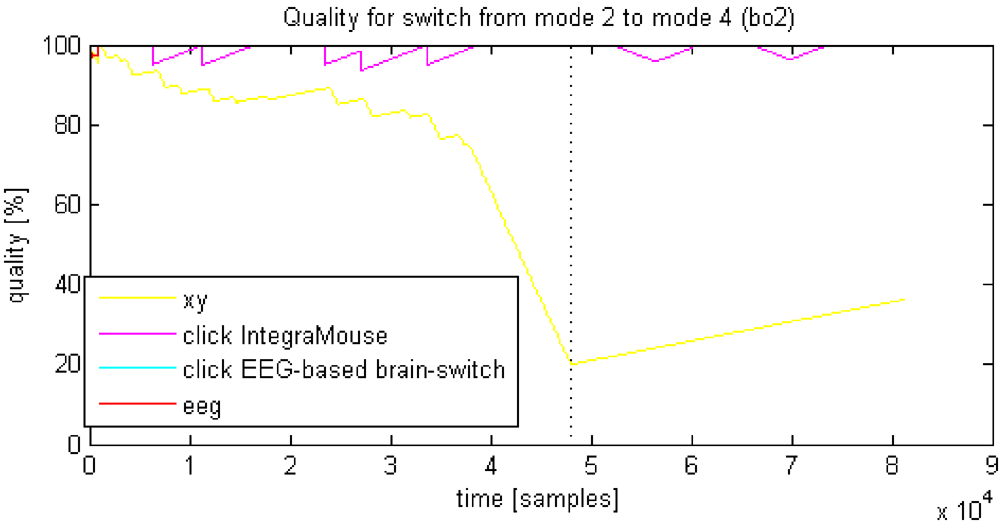


Figure 3.12: Influence of starting mode and behavior of qualities on the system: when starting in mode 2 and adding noise to the mouse movement the system switches to mode 4. The dotted vertical line represents the moment the change in mode occurs. (bo2)

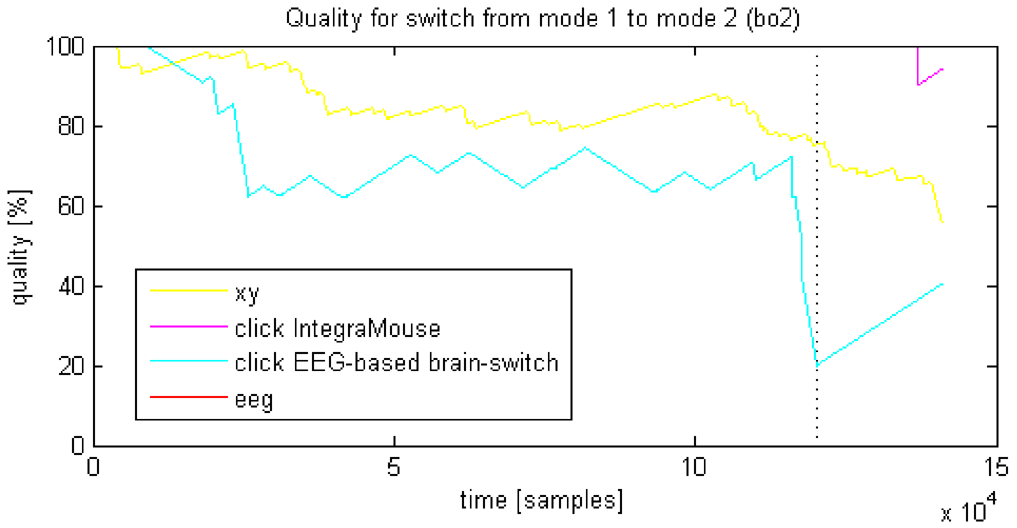


Figure 3.13: Influence of starting mode and behavior of qualities on the system: when starting in mode 1 and adding noise to the EEG click the system switches to mode 2. The dotted vertical line represents the moment the change in mode occurs. (bo2)

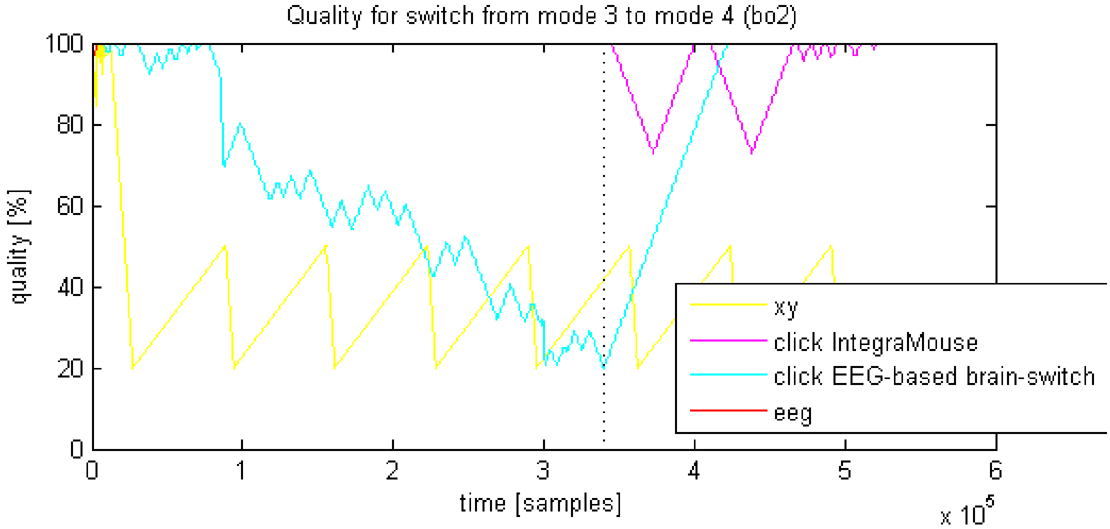


Figure 3.14: Influence of starting mode and behavior of qualities on the system: when starting in mode 3 and adding noise to the EEG click the system switches to mode 4. The dotted vertical line represents the moment the change in mode occurs. Also the noise for the mouse movement needs to be active during the whole run to obtain *Radar Mouse* mode. (bo2)

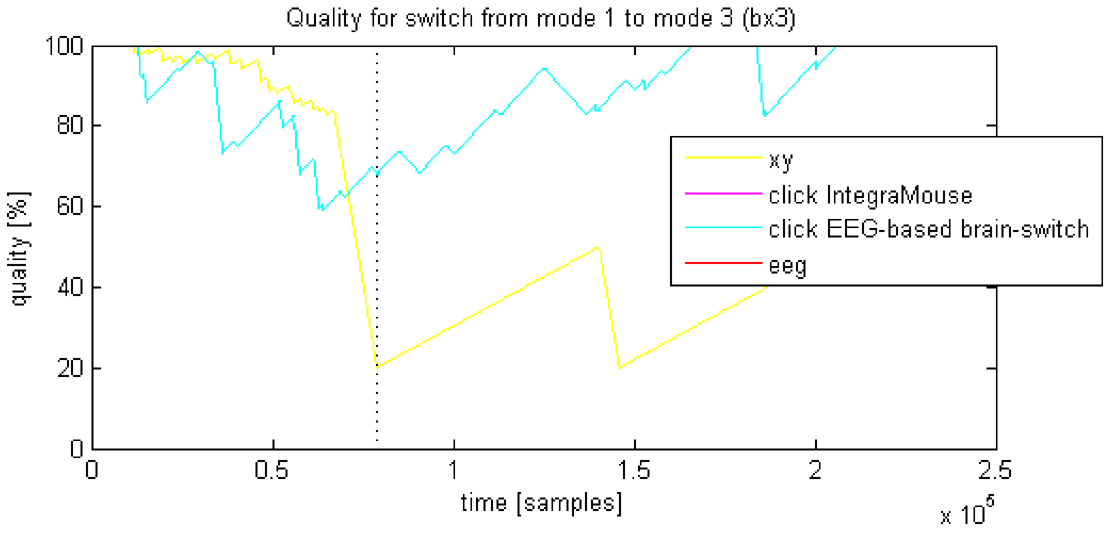


Figure 3.15: Influence of starting mode and behavior of qualities on the system: when starting in mode 1 and adding noise to the mouse movement the system switches to mode 3. The dotted vertical line represents the moment the change in mode occurs. (bo2)

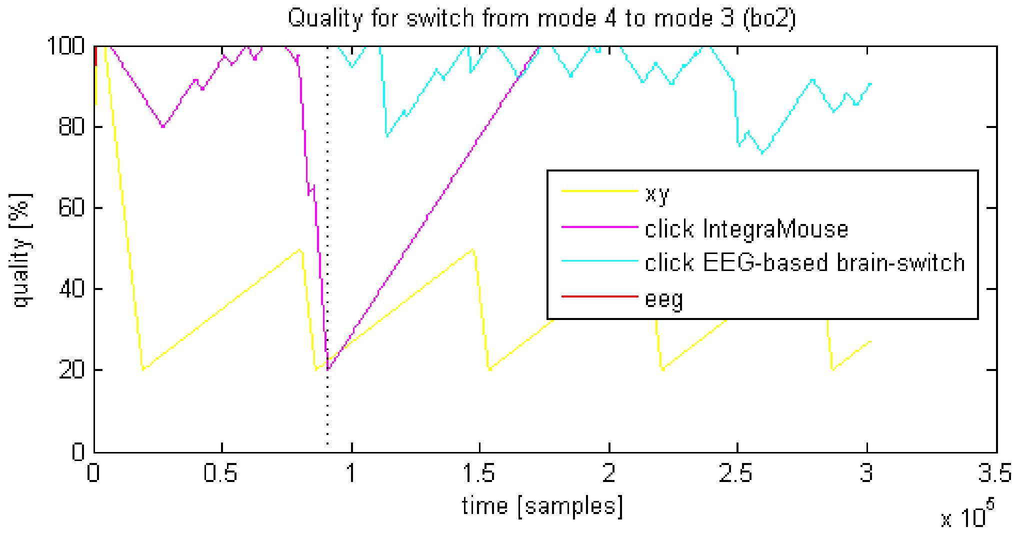


Figure 3.16: Influence of starting mode and behavior of qualities on the system: when starting in mode 4 and adding noise to the IntegraMouse® click the system switches to mode 3. The dotted vertical line represents the moment the change in mode occurs. Also the noise for the mouse movement needs to be active during the whole run to obtain *Radar Mouse* mode. (bo2)

Table 3.5: Attended time [min] to click all buttons of each run. The moment when noise is activated is in brackets.

subject code	**run 1**	**run 2**	**run 3**	**run 4**
bc4	02:26 (0:35)	05:36 (0:42)	01:59 (01:12)	07:46 (05:59)
bi5	02:45 (1:53)	05:08 (0:45)	06:49 (03:16)	07:26 (05:21)
bx3	03:11 (2:26)	01:48 (0:32)	04:02 (01:40)	16:18 (13:54)
b02	03:52 (2:54)	02:13 (0:52)	02:17 (00:57)	15:23 (13:15)
mean	03:04 (1:57)	03:41 (0:43)	03:47 (01:46)	11:44 (09:37)

subject code	**run 5**	**run 6**	**run 7**
bc4	06:05 (01:29)	12:45 (03:23)	02:58
bi5	10:06 (02:38)	06:44 (01:32)	06:12
bx3	06:18 (01:43)	-	05:56
b02	22:27 (02:32)	08:48 (01:21)	06:16
mean	11:14 (02:05)	09:25 (02:06)	05:21

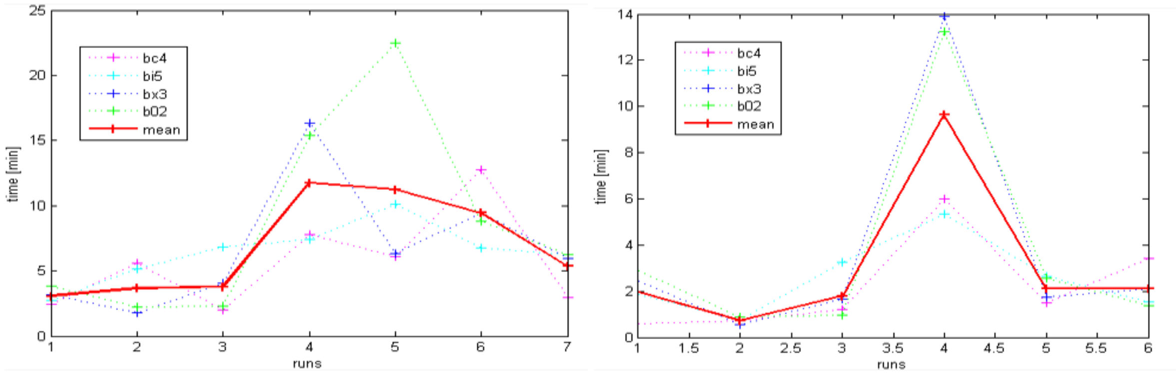


Figure 3.17: Left: Time needed to click all buttons of a run. The thicker red line is the average over all subjects. Right: Moment when noise started.

Table 3.6: Results of the quiz concerning the text read to the subjects during run 7.

subject code	**correct/total answers**
bc4	9/9
bi5	8/9
bx3	8/9
bo2	9/9

4 Discussion and Conclusion

The goal of this master's thesis has been to build a hybrid BCI system that merges benefits from an EEG-based brain-switch with those from the assistive technology device IntegraMouse®. Therefore the following main tasks has been settled:

- The integration of an interface for a USB mouse device into the SignalServer,
- the modeling of the Matlab/Simulink model for the *Fusion*,
- the establishment of a communication interface to the QualiWorld application,
- the implementation of an EEG-based brain-switch
- the execution of a verification experiment
- and the completion of a study to prove the principle.

4.1 Implementation

The integration of the mouse device interface into the SignalServer caused some troubles, because of the additional functionality to decouple the mouse device of the hybrid BCI from the mouse cursor of the operating system. Especially for Windows, a workaround had to be found to disable the automatically started Windows driver for the device. This issue was solved by using the "Windows Driver Kit". Now the signals from the IntegraMouse® (as well as signals from any other USB mouse device) can be used via the SignalServer either on Windows or on Linux. When the SignalServer is started, there is a notification that the chosen mouse device is used and therefore it's effects on the mouse cursor are blocked. When closing the server, the mouse device is reconnected again and therefore a normal usage, as designed by the operating system, is possible again.

Also the communication interface to the QualiWorld application is working as scheduled. It must be mentioned, that there is no support for an external right-mouse-click in the QualiWorld API yet. Therefore no right-mouse-click can be performed by the implemented system at the moment. Nevertheless, the related functionalities are provided in the model of the *Fusion*, therefore just an update in the communication interface is needed once there is support from the QualiWorld API.

The *Fusion* provides all functionalities described in Section 2.2.4. The constant values for all thresholds and time intervals are configured to gain the needed observations in the test runs. They are adapted to values that cause changes of mode during a short time of measurement. The measurements were carried out with healthy people. Troubles in controlling the input devices were generated by artificial noise sources. Thus, the correct behavior of the system could be proved. However, when using the system for disabled people in daily use, those values have to be changed because switches in mode will occur too often then. The most important values that should be adapted to the user's needs are accessible through the configuration file `FusionBCIM.ini`. If those possibilities of adaption are not sufficient, thresholds and time intervals have to be changed in the model directly.

4.2 Parameter setup of the EEG-based brain-switch

Since all tested subject had already participated in a study involving an EEG-based brain-switch driven by imaginary movements of both feet in the past, it was known that they are performing well at this task. Therefore, after one first run of settling in by really performing movements of the feet, just one set-up run with just the imagination of the movement was necessary to adapt the parameters. Concerning the single verification measurement with subject bi5, when applying the computed parameters and the threshold to the complete data of the setup measurement run, a good performance was reached. Most of the time there were hardly any false positives and just as little false negatives. Only in the end performance gets worse, 3 of the 5 false negatives of the whole run are among the last 4 clicks. Until the trigger for click 16, there were only 2 false negatives. Therefore, the bad performance in the end of the runs may be caused by falling concentration at the end of the setup run. Later in the test run, the subject had no trouble initiating a click by the imagination of the brisk movement of both feet. The only problem that occurred was that there often were multiple clicks initiated in a short time distance when the subject concentrated on a click. This might be caused by a threshold function where the threshold is chosen too low. However, the wasted clicks did not matter in this test setup, it would have be more disruptive if the threshold had been too high to initiate most of the clicks. Also in the study with 4 participants there were no problems in configuring the EEG-based brain-switch. Only the threshold had to be adapted slightly in some cases, when the subjects had the feeling that initiating a click was too hard. These adaptations were done on trial then.

4.3 Verification runs with one single subject (bi5)

The single verification measurement started with the single mode tests where the start mode was always locked until the end of the run. At first the subject operated in mode 2, *Normal Mouse* mode combined with IntegraMouse® click. Naturally, as the subject had no disabilities, this was the easiest one. All buttons have been clicked at first try and one could see that movements were very straight forward and smooth. The subject had more difficulties with mode 1, *Normal Mouse* mode combined with clicks initialized by the EEG-based brain-switch. The movements showed more detours than in the first run. This may be due to the fact, that activating the EEG-based brain-switch needs more concentration. But all in all the performance has been satisfying as well. Considering Table 3.3, the subject had most problems with mode 3, *Radar Mouse* mode combined with clicks initialized by the EEG-based brain-switch. According to the use of the beta rebound, there was always a delay of about a second from the time the click is initialized until the click is executed. Therefore it was especially difficult to time the two clicks needed for *Radar Mouse* mode. The smaller the buttons were, the more difficult it was to time the second click. In most cases, there were several tries needed to perform a click right.

Resuming this measurement, mode 2 would have been the best choice for the subject. But regarding that the system was designed for disabled people, interpretation of the results turns out completely different. Assuming, that the subject would have had great problems using the sipping and puffing functionality of the IntegraMouse® due to suffering of the lung for example, mode 2 and mode 4 would have been worse. Then the comparison between mode 1 and 3 is of great interest, where mode 1 had great advantage over mode 3. In all cases, the user can benefit from the hybrid BCI system. If there was no IntegraMouse® a disabled person would only be able to use *Radar Mouse* mode. Both modes concerning *Radar Mouse* mode perform worse than the *Normal Mouse* mode opposite. Otherwise, if there was no EEG-based brain-switch, the disabled user can only use the sipping function of the IntegraMouse®, which would be extremely exhausting.

Besides one has to keep in mind, that there can always be disorders or troubles with signal sources. In this case a normal BCI system would lose controllability of the system completely. In the case of this hybrid BCI, only the quality of this disturbed input source would get low. This would just cause a switch in mode, but the system would be controllable in the other modes still. Therefore any additional method to gain redundant input signals makes the system more robust against external disorders of the input signals.

One fact has to be mentioned concerning the *Radar Mouse* mode and its evaluation: There was always only one active button on the surface. Therefore the radar line only passed through the area of this single button every rotation, which means large saving of time. If there were more clickable surfaces on the screen (which is indicated by normal use) the needed time would be much higher because the radar line would have to rotate around the whole screen.

The feedback of the subject was positive. At the beginning of the experiment she found *Radar Mouse* mode confusing and, especially combined with the EEG-based brain-switch, clicking was a big challenge. But the subject adapted to the system very fast and in the end she could manage all modes easily.

4.4 Study - Proof of Principle

The goal of the study was to test and verify the mode-switching functionality of the system. Therefore 4 subjects were measured. The subjects were starting the system with a specific mode, then after 10 clicks noise was added to the signals to force a change of mode. All changes proceeded as scheduled, therefore the system was working well. Also the subjects had no difficulties to handle the changes between the different modes of controlling the system, which means that it is suitable for real use. Moreover, the last run with the listening task was performed well by all subject. This proved that the subjects were able to concentrate on other things than the imaginary foot movement during the runs.

The basic idea of this hybrid BCI system was to provide a solution for users of the IntegraMouse® that have any problems that keep them from utilizing the sipping and puffing functionality of this device. Therefore the IntegraMouse® alone is not usable for them. On the other hand, using only the EEG-based brain-switch to control the *Radar Mouse* is very time consuming. All subjects have had most difficulties in handling mode 3 (*Radar Mouse* + EEG-based brain-switch). The usage of mode 1 appeared to be far more comfortable and easier in usage. Therefore the benefit of combining the movement of the IntegraMouse® with the EEG-based brain-switch has been proved.

4.5 Future Work

To obtain a good statistical statement about usability of the system, a greater experiment is advised. However, main functionalities and usability have been proved in this short experiments. When performing more measurements a better test tool should be considered, which saves the positions of the clicks for example and provide more clickable regions.

When the QualiWorld API is updated to support right-mouse-click as well, the communication interface has to be updated.

It can also be considered to implement a function where the user can switch the mode or disable mode switching by himself. Therefore the implemented manual reset-switch can be used and modified. One must only think of a way to express the wish of a switch. Maybe with a double click to a specified area.

Concerning the SignalServer a little tool would be helpful which determine the needed configurations automatically and creates the INF-file by itself. Those settings must be done manually currently.

Appendix

A.1 Addition: Parameter setup of the EEG-based brain-switch

The following plots show the ERD(S) map and the LDA output for the setup run of each subject. The used data were all trials with the task to imagine a movement of the feet, averaged over a repetition of 20 times.

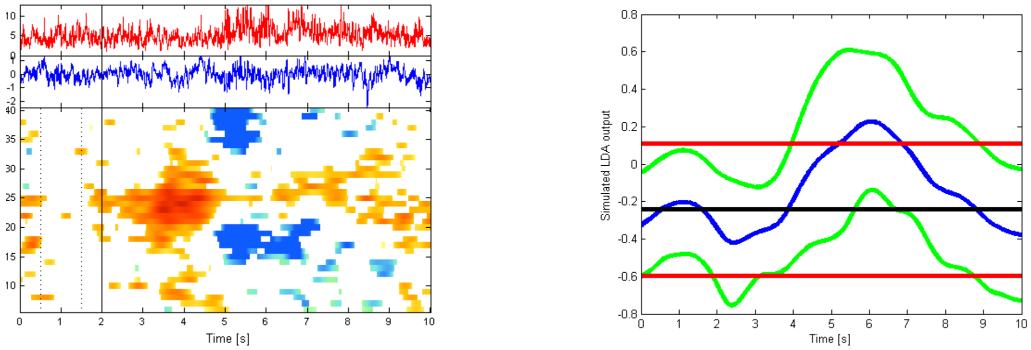


Figure A.1: Setup run of subject bc4. Left: ERD(S) map (Laplace Cz, 2 Hz-bands). The beta rebound can be seen. Right: LDA output averaged over all tasks with imagination of movement.

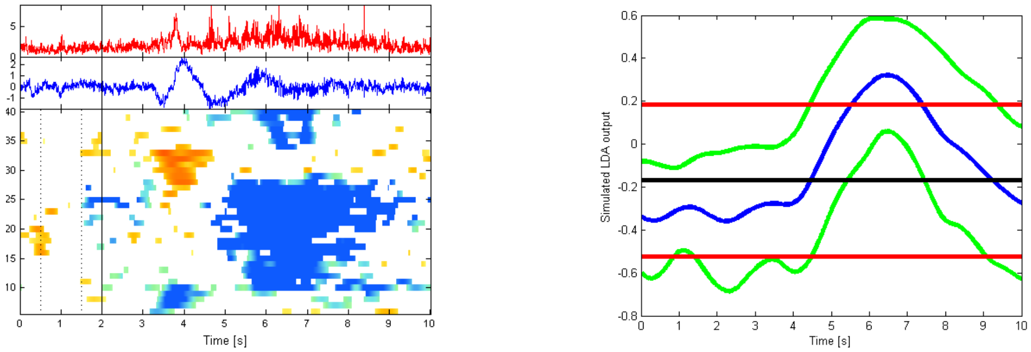


Figure A.2: Setup run of subject bi5. Left: ERD(S) map (Laplace Cz, 2 Hz-bands). The beta rebound can be seen. Right: LDA output averaged over all tasks with imagination of movement.

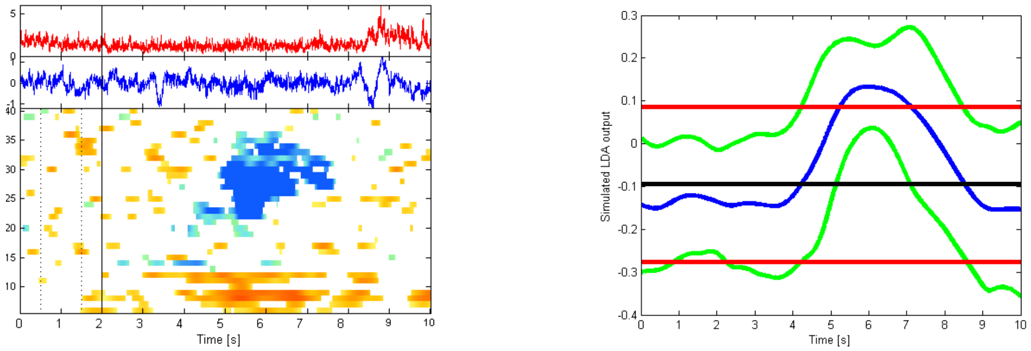


Figure A.3: Setup run of subject bx3. Left: ERD(S) map (Laplace Cz, 2 Hz-bands). The beta rebound can be seen. Right: LDA output averaged over all tasks with imagination of movement.

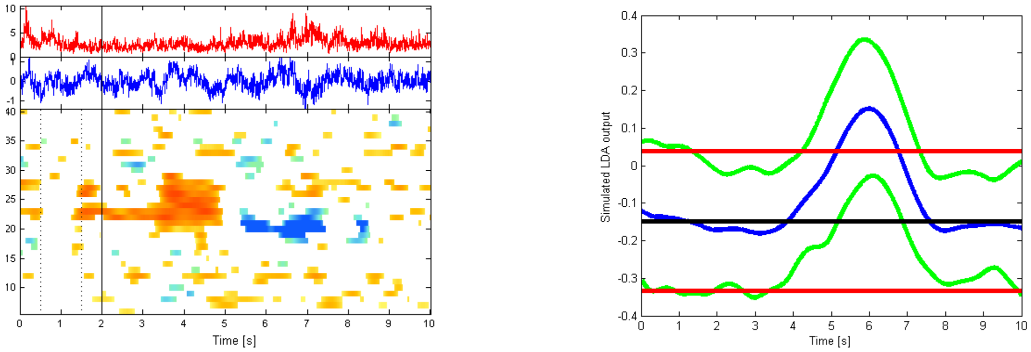


Figure A.4: Setup run of subject bo2. Left: ERD(S) map (Laplace Cz, 2 Hz-bands). The beta rebound can be seen. Right: LDA output averaged over all tasks with imagination of movement.

A.2 Addition: Study - Proof of Principle

The plots describing the behavior of the qualities and the switching of modes for all runs and all subjects can be seen in Figure A.5 to Figure A.8. In these plots all switches that occurred during a run are represented as gray dotted lines. There is a number besides each line that shows the mode it was switched to. The one black line that is thicker than the others marks the main switch which was desired to force by the added artificial sources of noise. All switches that occurred were correct. It was also possible to force the desired switch by adding the corresponding source of noise in all cases.

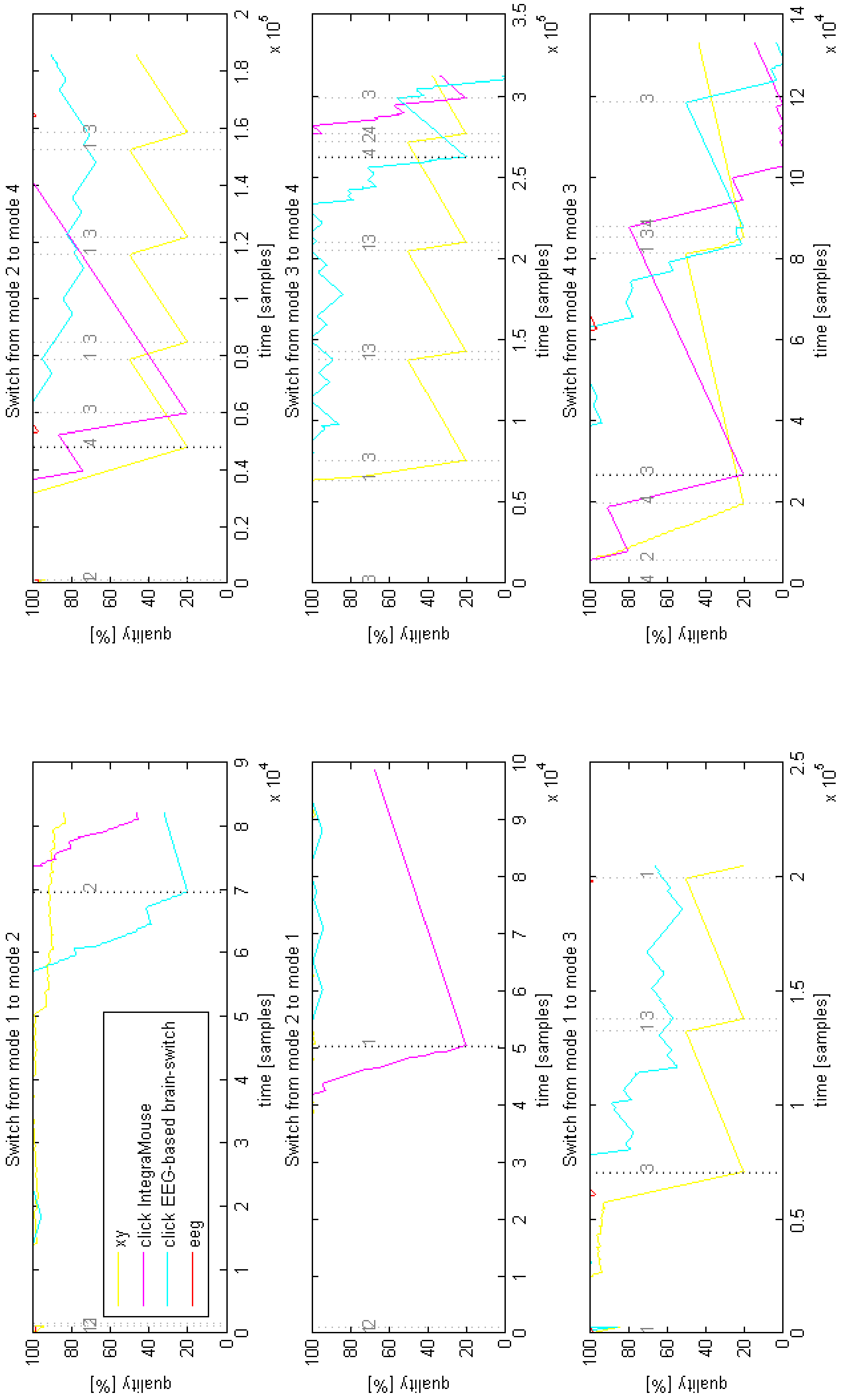


Figure A.5: Switching functionality of the system for all runs of subject bc4. The gray dotted lines represent each switch that occurs, the thicker black line marks the main switch which was forced by the added artificial source of noise. Along each line there is a number standing for the mode it was switched to.

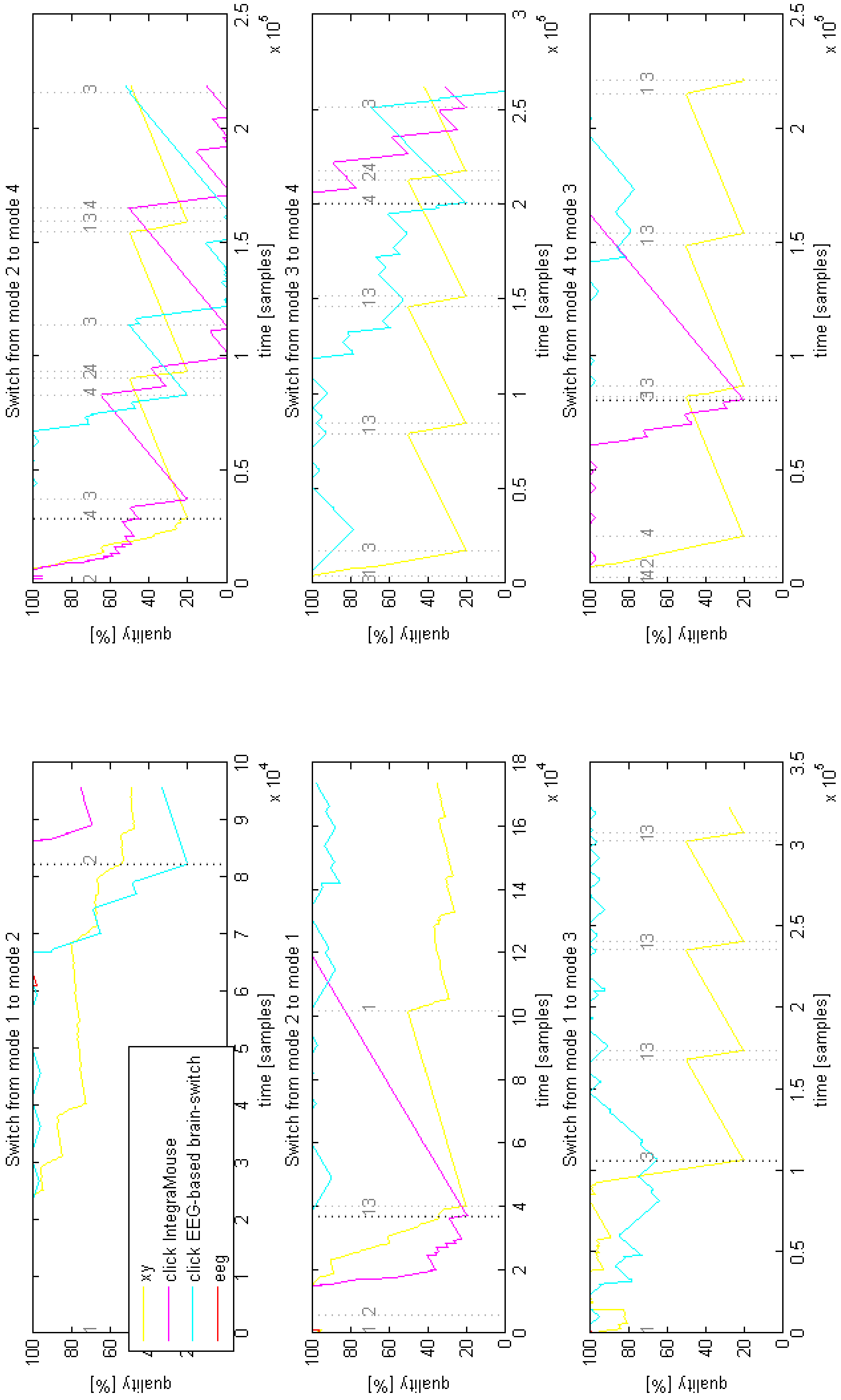


Figure A.6: Switching functionality of the system for all runs of subject bi5. The gray dotted lines represent each switch that occurs, the thicker black line marks the main switch which was forced by the artificial source of noise. Along each line there is a number standing for the mode it was switched to.

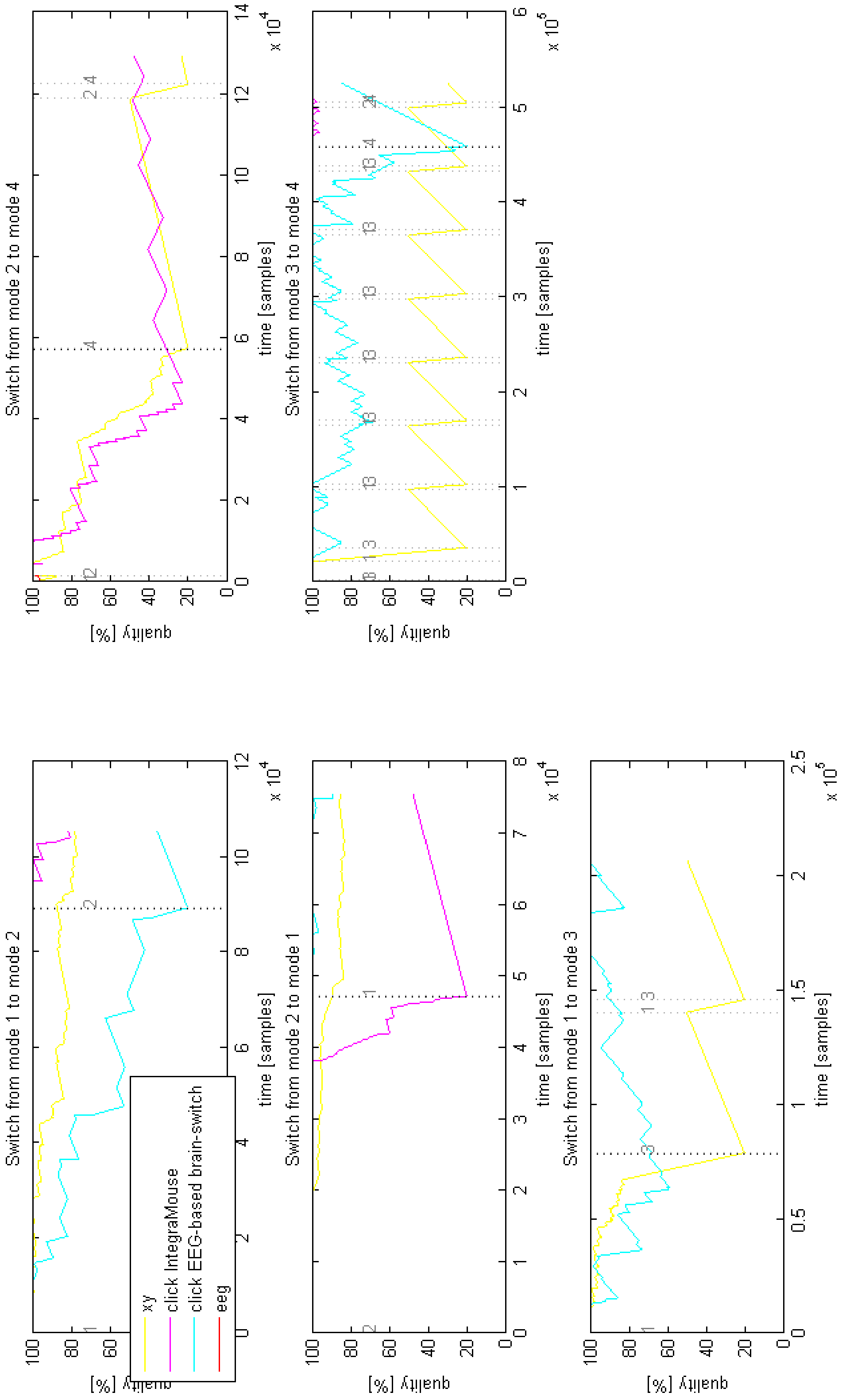


Figure A.7: Switching functionality of the system for all runs of subject bx3. The gray dotted lines represent each switch that occurs, the thicker black line marks the main switch which was forced by the artificial source of noise. Along each line there is a number standing for the mode it was switched to.

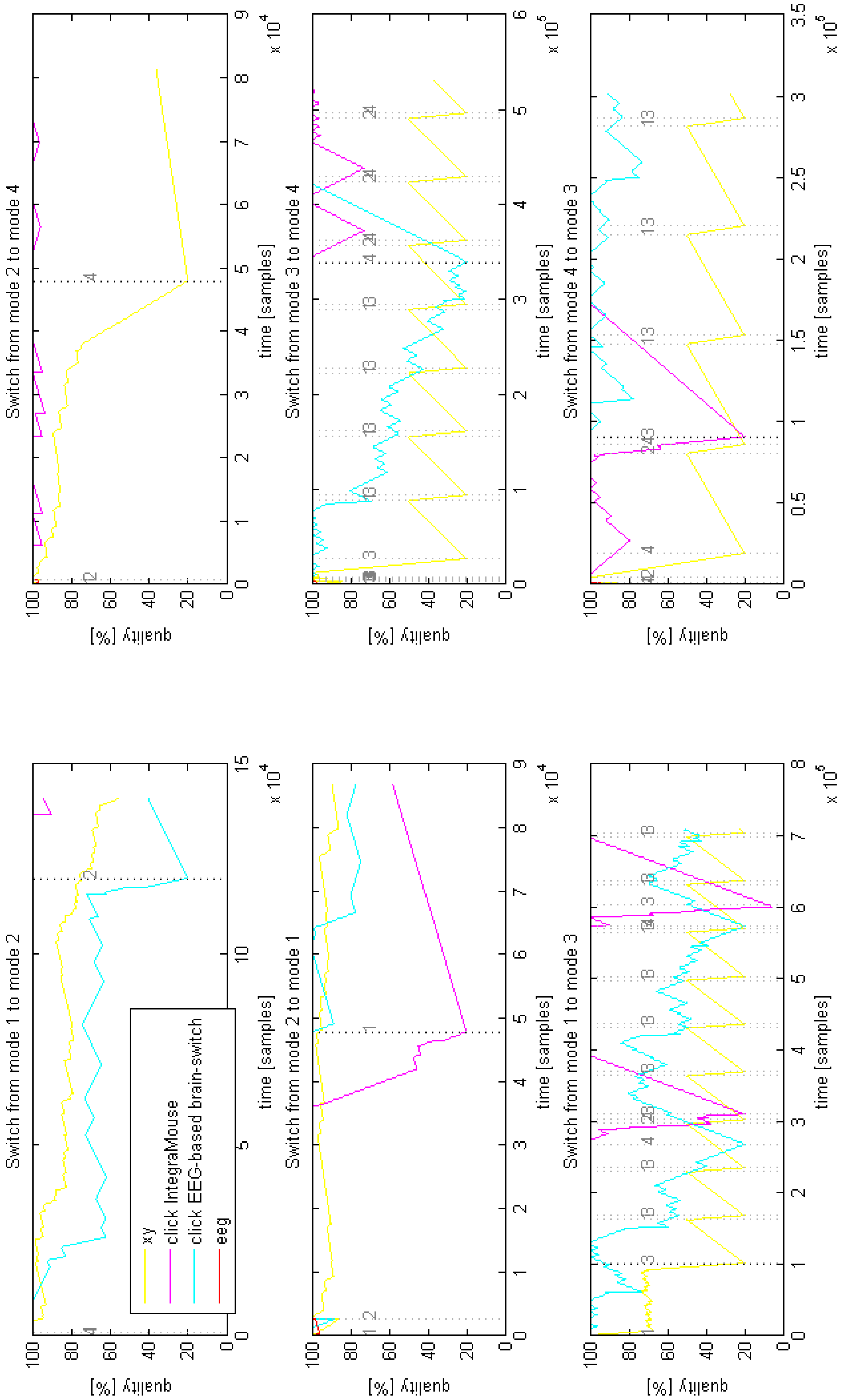


Figure A.8: Switching functionality of the system for all runs of subject bo2. The gray dotted lines represent each switch that occurs, the thicker black line marks the main switch which was forced by the artificial source of noise. Along each line there is a number standing for the mode it was switched to.

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