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The Thought Translation Device: Structure of a multimodal brain-computer communication system

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Abstract – **The Thought Translation Device (TTD) is a Brain-Computer-Interface (BCI) which successfully enabled totally paralyzed patients to communicate by using their brain potentials only. An extended version of the TTD has been developed running on any MS-Windows PC and its architecture is described. A variety of filter modules (temporal and spectral filters, classifier, etc.) can be combined in a configurable order for on-line processing and feedback of physiological data. Statistical analysis methods are implemented for online and offline classification of SCP and spectral EEG data. As many patients suffering from Amyotrophic Lateral Sclerosis (ALS) in its final stage no longer have the ability to focus a computer screen, the TTD is now able to present all information necessary for brain-computer communication by voice and sound as well as visually. The TTD is currently used for various studies with paralyzed and comatose patients, patients with epilepsy and children with attention deficit disorders.**

Keywords - **Brain Computer Interface (BCI), Slow Cortical Potentials (SCPs), EEG-feedback**

I. INTRODUCTION

Healthy people as well as completely paralyzed patients can learn to self-regulate physiological signals such as their electroencephalogram (EEG). Birbaumer and group showed, that self-regulation of slow electrocortical potentials (SCPs), defined as the part of the EEG below one Hz, can be trained by a feedback device. The Thought Translation Device (TTD) was developed as a feedback device which enabled people to respond by voluntary SCP changes and to use these responses to control their environment (switch electronic devices) or spell words and write messages. It was the first BCI which enabled several patients suffering from Amyotrophic Lateral Sclerosis (ALS) - a neuromuscular disease leading to a complete paralysis (locked-in syndrome) - to communicate using their (SCPs) only [1].

The TTD in its first version consisted of several MS-DOS based programs written between 1997 and 1999 and required two computers. One program, the *Slow Wave Translator* [2], acquired and filtered the EEG and displayed it graphically for the human operator. The SCP response was classified into binary decisions and sent to one of the other (application related) programs running on a second computer and showing all feedback-related information to the user. During training, the user-to-be is prompted to produce SCP shifts of predetermined polarity (task). Therefore, a *training program* displayed the task, the result of the response, the SCP-signal for feedback and a smiling face for reinforcement of correct responses (i.e. the result meets the task). Each answer is given in a *trial* comprising a phase for preparation and a phase for producing the brain response; an uninterrupted sequence of trials makes a *run*. For verbal communication after successful training, the training program was replaced by the *Language Support Program* (LSP). The LSP enables the user (patient) to select single letters with binary decisions [3]. As a third application, a brain-signal controllable *internet browser* program was connected to the Slow Wave Translator. It allowed for navigating the web with binary brain responses [4]. That program extracted the URL-links from a web page and arranged them in a dichotomic decision tree similar to the letter selection in the LSP. To overcome the limitations of the previous TTD system (restricted portability and extendability), it had to be reprogrammed for the use in a single MS-Windows PC or notebook promoting its application in the patient's home. Connecting a second monitor allows to present feedback to the user while the operator supervises data processing and statistical online analysis. The use of a PCs' multi-medial abilities to provide visual and auditory feedback, task, and result presentation was another goal. Scientific functions such as statistical data analysis in the time and frequency domain or offline simulation of feedback scenarios with previously recorded data should also be supplied. Besides SCPs, other EEG signals and differing paradigms can be used for brain-computer communication, such as μ-rhythm desynchronization while imagining hand or foot movements [5], [6]. Therefore, a modular concept was required allowing different programmers to easily add extensions, new filter methods, and applications to the TTD.

II. METHODOLOGY

A. Basic considerations

The goals described above can be achieved with the help of various development tools. A very efficient but also expensive way to implement a large variety of signal filters offers the use of MatLab® in combination with SimuLink® for on-line data processing as realized by the group of Pfurtscheller [7]. The disadvantage of this approach is that

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the expensive MatLab environment has to be installed on every system. Modern C++ programming environments also allow rapid prototyping by providing powerful components to develop a condensed and user-friendly program. The code of MatLab routines can also be integrated in C++ programs. We favored Borland's C++-Builder and developed an extendable program structure as described below.

Schalk, Hinterberger, McFarland and Perelmouter developed a BCI programming standard, called the BCI2000 standard [8], (http://www.bci2000.org). One goal of this standard was to obtain compatible systems, where components can be easily exchanged and shared between research groups. Thus, all data acquisition modules, filter modules, feedback- and application modules programmed in accordance with this standard can be used in every BCI2000 compatible BCI. In addition, a common file format for storing the EEG signal, associated status information, and the parameters was defined enabling other Labs to read every BCI data set for off-line analysis. A BCI2000 framework [8] allows to distribute single modules on different computers interacting by socket communication, which might be necessary for scientific purposes. The TTD can be regarded as a compact clinical BCI system. It is compatible with the data storage format and the parameter handling of the BCI2000 standard. The sub-modules have been designed to be easily transferred into the BCI2000 framework also.

B. The TTD architecture

The software architecture with the most important functional modules of the TTD is depicted in Fig. 1. On the left, a collection of the currently available data sources and signal processing filters, including modules for statistical analysis and the presentation of feedback, is listed. Each module is programmed as a C++ object, derived from generic classes. The filters are derived from a generic filter class, the signals from a generic signal class. The program structure will be explained in four steps necessary to set up an experiment:

1. *Load a filter configuration:*

A feedback controlled BCI receives an EEG-data flow which is transmitted through different signal processing filters or modules. They transform the EEG into a suitable feedback signal and classify it into responses which operate an application (e.g. a spelling device). After startup, a set of signal processing modules requested for a specific experiment has to be activated from a collection of available filters (Fig. 1, left; all signal processing modules are referred to as "filters"), arranged in a sequential list and repetitively processed at run-time. Each filter receives a signal from an arbitrary previous filter, applies its algorithm to the signal, and provides an output signal that can be used as an input for any later filter. The soft-wiring of the filters is organized by a global filter list object. Each filter carries a label consisting of two characters. After loading a configuration from a file, each activated filter receives a variable for its output signal with the same label, which can serve as an input for a later filter.

2. *Setup parameters:*

When activating the filters, each one sends all its parameters to a global parameter container. This enables the user to configurate the whole system in one setup menu or load a complete setting from a parameter file containing a list of parameters. The parameters are also stored in the file header of the EEG data for reconstruction of a feedback process. Parameters can also be shared amongst different filters (e.g. the sampling rate is important for various filters) [7].

3. *Selection of a signal source:*

The incoming signal can be obtained from a hardware device supplying a physiological data stream. Some EEG amplifiers transmit already digitized data in a specific data format only. For three of such devices, data acquisition modules have been written. Other amplifiers are equipped with an analog output. These amplifiers can be directly connected to a 16-bit A/D converter (we use DAS-series boards from Measurement Computing being available for desktop PCs and notebooks). Data can also be read from an existing TTD data file. In the standard setting, the EEG signal is sampled at 256 s^{-1}. For a smooth feedback cursor movement, an update rate of 16 s^{-1} is sufficient. This can also be the repetition rate for processing the filter list resulting in 16 samples being transmitted block-wise from the data source (signal *DS*).

4. *Start a run:*

Once the system is configured and a data source is selected, the system can be started in a passive mode, i.e. the main loop is continuously processing the active filters but without storing data nor starting a feedback trial. In this mode, EEG acquisition and impedances can be checked. A visual interface allows scientists to visualize the output signals of all filter modules. To each sample, a number of status bits (states) containing permanently changing information about the system, are attached. States indicate, e.g. in which phase of a trial the system is, whether feedback is currently provided, or whether an artifact has been detected. Each module can support and change states. Status bits form a global state vector, which is stored in the EEG-data file with each sample (for details, see BCI standard [8]). A start-command initiated by the operator instructs the *Run Manager* which triggers the state responsible for starting a trial. The *Task Manager* is part of the presentation module and defines the task for each trial during training.

C. The SCP feedback configuration

The configuration displayed in the center of Fig. 1 shows the signal flow for SCP feedback mode described here. The digitized EEG is sent to the data storage module and to the first filter in the list, the *Calibrator* converting the signal into μV units. Each signal channel carries the potential between two electrodes according to the amplifier setup. A spatial filter transforms this hardware channel configuration to the channels of interest by a matrix transform. A common electrode configuration uses Cz-(A1+A2)/2 (international 10/20-system) as feedback channel and the vertical

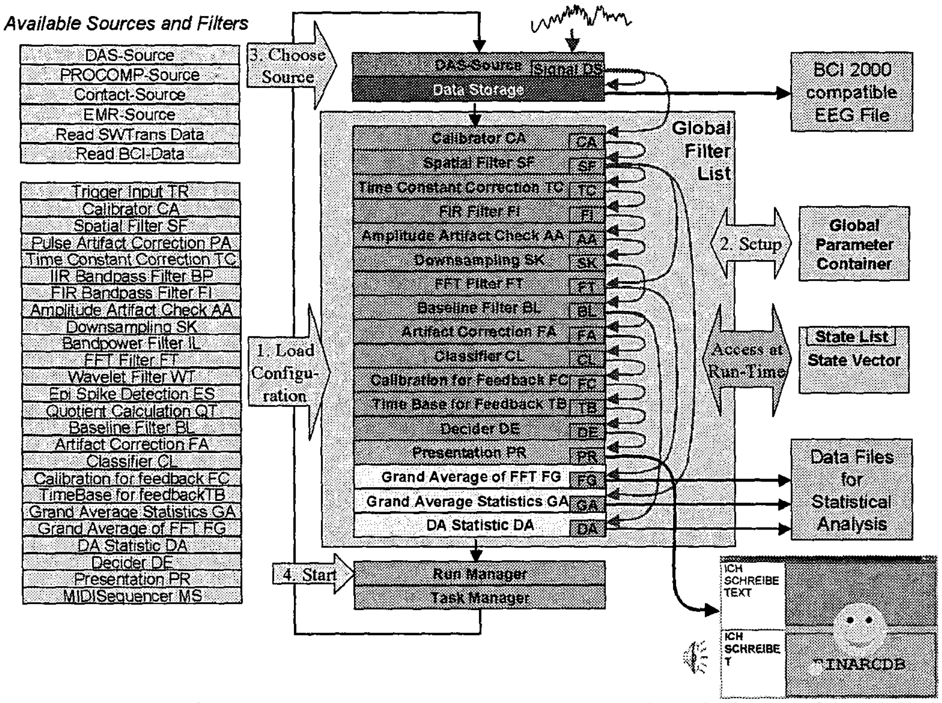

Fig. 1: The schematic displays the main functional modules of the TTD and how they are connected to each other. One of six available data sources (top six rows) can be chosen. In the center, the main processing loop is depicted, containing the data sources and storage modules, the global filter list, and at the bottom modules for organizing the time schedule of the experiment. The filter list contains all signal processing modules loaded as a sub-set of the available filters at the left. The output signal of each filter (labeled with two characters) can, in a soft-wired fashion, serve as an input for any following filter. All modules add their parameters to a global container where they are administrated from a setup menu. At run-time, filters have access to additional status information which changes permanently. The presentation module presents visual and auditory stimulus elements necessary for various applications. The user screen of the spelling application is shown at the bottom right. The upper left window displays the text to be copied in a spelling training procedure, the window below presents the text already spelled. For choosing a letter sequence, the feedback cursor has to be moved into the corresponding box. The smiling face reinforces the user or patient for a correctly chosen target.

electrooculogram (vEOG) as a channel for artifact control. The time constant correction will simulate a quasi-DC behavior of the signal within a trial, which is usually high-pass filtered with a cut-off at 0.01 Hz [2]. The FIR (finite impulse response) filter is capable of realizing band pass filters. For the low-pass filtering of SCPs, it performs a moving average of an 0.5 s window. Afterwards, the amplitude changes within a trial are checked for being in a defined valid range of 200 µV for the SCP channel and 800 µV for the vEOG channel. Signals exceeding this range will lead to an invalid trial. The following down sampling reduces the 16 samples per channel in the signal *AA* to one element in signal *SK* (see Fig. 1). An online fast Fourier transform (FFT) is carried out only for supervision of the EEG spectra by the operator. After the baseline, which usually is defined by the SCP amplitude immediately before the start of the feedback, has been subtracted from the SCP signal, a correction of EOG-artifacts is carried out according using the algorithm described in [9]. A classifier, performing a linear discriminant classification (Fishers' discriminant) may be optionally used for subjects with stable responses [10]. The SCPs, possibly weighted by the classifier, are then scaled with respect to the range of the screen coordinates. For showing different decision options, the screen is subdivided into target areas into which the feedback cursor may be moved. Using the targets' positions, a decision module (*Decider*) will calculate the result.

D. The presentation module

The presentation module presents all user-relevant information to the user of the TTD. It also provides applications such as a spelling and answering system for communication or stimulus presentation for studies with event-related potentials. The presentation module is designed in a "model-view" concept, where "models" contain the logical structure of an application and "views" only display visual or play auditory stimuli (Fig. 1, bottom right).

For the various applications, a set of models is available containing a model for the feedback training, for the selection of visual or auditory stimulus elements, and for the spelling procedure. The most complex model is the *spelling-model*. It provides a flexible decision tree which offers the user single letters or sets of letters to be selected or rejected by the classified brain responses [3]. To speed up the communication process, the spelling-model also contains a dictionary, suggesting whole words after only a few letters of a word have been spelled.

Various visual and auditory elements necessary for the feedback and communication process are provided by a set of views. The feedback cursor, displayed by a *feedback view*, (yellow circle or any arbitrary bitmap) can move two-dimensionally across the screen. For patients who can no longer focus their eyes on a computer' screen, feedback can alternatively be given by varying the brightness of the whole feedback-screen. For auditory feedback, one dimension is coded as the pitch of a MIDI instrument. The target areas are shown by *target views*. Selectable letters are also displayed in the targets. In the training mode, computer defined tasks are signalized by a red highlighted target. Results are indicated by blinking of the corresponding target. In auditory mode, the target options are given by voice before the feedback starts. The result is told to the user after the decision is made. Other views are available for displaying artifacts, number of correct results, or the reinforcing smiley face. A *stimulus view* allows the presentation of pictures, movies and sounds for event related studies. Text frames are used to show the already spelled text and/or the text to be copied in a spelling training.

III. APPLICATIONS

The TTD is currently used for a variety of physiological experiments around BCI research and EEG feedback: In one study, a comparison of visual, auditory and combined (visual and auditory) feedback for the learning process in SCP self-regulation was carried out [11]. Another study investigates the activated brain area during voluntary SCP control by running the TTD synchronized with functional MRI. For this, an online pulse artifact correction filter (*PA*) has been developed. Studies demonstrating a reduction of epileptic seizures by teaching patients to voluntarily produce positive cortical potential shifts can be executed with the TTD[12]. The feedback of epileptic spikes has also been realized by a neural network classification algorithm included in the TTD (*Epi Spike Detection* filter) [13]. In a feedback training with hyperactive children (ADHD-syndrome), the effect of SCP-regulation versus Beta/Theta-regulation is studied by feeding back either slow potentials or the ratio between the power of the Beta and Theta band of the EEG. Several patients with ALS were successfully trained for SCP self-regulation. The described structure of the TTD also allows the realization of various event-related EEG paradigms which do not need feedback but timed visual or auditory stimuli. Also various diagnostic paradigms [14] for evaluating cognitive abilities of completely locked-in patients were transferred to the TTD.

IV. CONCLUSION

A software structure of a BCI is presented, which has been successfully implemented and serves as an experimental platform for many applications in BCI research but also for a variety of other physiological feedback studies or diagnostic experiments. The TTD is presently used in several clinical studies involving EEG feedback and its self regulation for therapeutic purpose or communication.

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