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Prototype of an auto-calibrating, context-aware, hybrid brain-computer interface*

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Abstract— **We present the prototype of a context-aware framework that allows users to control smart home devices and to access internet services via a Hybrid BCI system of an auto-calibrating sensorimotor rhythm (SMR) based BCI and another assistive device (Integra Mouse mouth joystick). While there is extensive literature that describes the merit of Hybrid BCIs, auto-calibrating and co-adaptive ERD BCI training paradigms, specialized BCI user interfaces, context-awareness and smart home control, there is up to now, no system that includes all these concepts in one integrated easy-to-use framework that can truly benefit individuals with severe functional disabilities by increasing independence and social inclusion. Here we integrate all these technologies in a prototype framework that does not require expert knowledge or excess time for calibration. In a first pilot-study, 3 healthy volunteers successfully operated the system using input signals from an ERD BCI and an Integra Mouse and reached average positive predictive values (PPV) of 72 and 98 % respectively. Based on what we learned here we are planning to improve the system for a test with a larger number of healthy volunteers so we can soon bring the system to benefit individuals with severe functional disability.**

I. INTRODUCTION

Electroencephalography (EEG) based brain-computer interface (BCI) systems can establish a channel of communication for individuals with severe functional disabilities (cf. [10], [5], [1]). Sensorimotor rhythm (SMR) based BCIs generate control signals based on the dynamics of oscillatory brain activity in the EEG. Such SMR based BCIs use machine learning techniques to detect decreases (event-related desynchronization, ERD, [7]) and increases (event-related synchronization, ERS) of the amplitude of specific frequency bands within the SMR, which the user can voluntarily influence by performing certain mental tasks (e.g. motor imagery).

However, modulating these brain patterns to create a reliable control signal is a skill-full action that, with traditional training paradigms, can require extensive training over weeks or even months [5]. Recent studies showed that co-adaptive online training paradigms effectively lead to high control accuracy, even in participants that could not achieve control with conventional training paradigms [9]. In the simplest case, the user can, after training, produce a one dimensional signal, that can be used to interact with the environment.

SMR based BCI systems can be complimented with other BCI or non-BCI input signals, where both signals are used either simultaneously or in a sequential manner. This by definition constitutes a Hybrid BCI [6]. Such Hybrid BCI setups can increase the number of available classes, the stability and/or speed of the BCI system. Another way to increase reliability of the interaction is to implement the concept of context-awareness, which means that the system adapts according to the current status of user and environmental variables [4].

A hybrid system of an SMR BCI and a conventional assistive technology device integrated with an optimized Graphical User Interface (GUI) to a Context-Aware Environmental Control System has the potential to vastly increase social inclusion and independence of users with severe functional disabilities, since the combination potentially brings up synergies and balances out shortcomings that the components might have in standalone configurations. This is an improvement over existing systems, which often implement only one or some of the abovementioned technologies or concepts, which we think might leave considerable potential in interaction efficacy unused. Other systems require expert interaction during calibration and are therefore more difficult to operate for non-expert caregivers.

We integrate a Hybrid BCI (SMR BCI and Integra Mouse® mouth joystick), a simulated Workload Detector, a specialized GUI based on [2] and a Context-Aware Environmental Control System in an intuitive framework that allows the user to trigger actions in the outside world. The paradigm for this first proof of concept involving 3 healthy volunteers very loosely resembles a potential real-world use-case, where we (1) auto-calibrate the SMR BCI, then (2) let the user remotely control a camera via ERD, then (3) simulate that the Workload Detector deactivates ERD and at last (4) let the user post a message on Twitter® using the Integra Mouse.

II. MATERIALS AND METHODS

A. System Architecture

Our framework mainly consists of three loosely coupled parts that we show in the Architecture Overview Diagram in Fig. 1. Block (A) User Interface, includes the hybrid system consisting of an SMR BCI, a mouth joystick and a simulated Workload Detector. The color segmentation of block (A) depicts how the parts overlaying (A.1) are needed for auto-calibration and the parts overlaying (A.2) are

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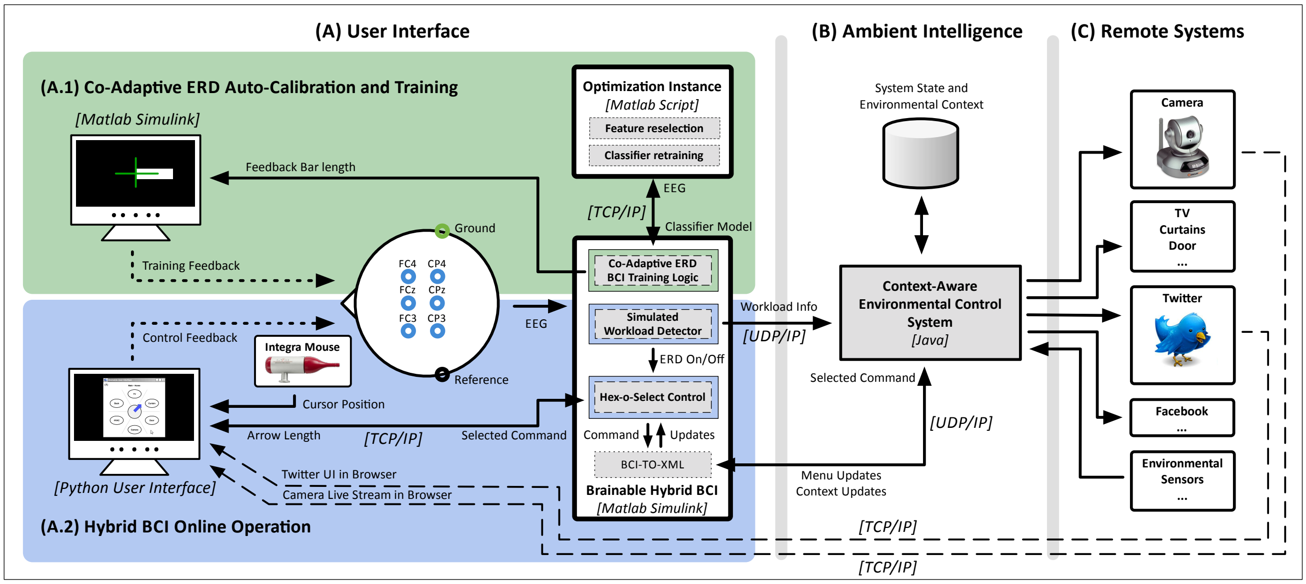

Fig. 1. Architecture Overview Diagram for the complete framework, excluding some supported input interfaces that are not the focus of this work. The framework mainly consists of three loosely coupled segments in the panels (A) User Interface, (B) Ambient Intelligence and (C) Remote Services. The components overlaying the green area (A.1) are used during Co-Adaptive ERD Auto-Calibration and Training while the components overlaying the blue area (A.2) are mainly used for Hybrid BCI Online Operation. (Twitter logo is the property of Twitter Inc., San Francisco, CA, USA).

needed for online operation. Block (B) shows the Context-Aware Environmental Control System that updates the GUI depending on the context, executes commands that the user selects and controls Remote Services in block (C) via an abstract interface called Universal Control Hub (UCH, [11]) which is based on ISO standard 24752, as promoted by the international OpenURC Alliance (http://www.openurc.org/).

B. EEG Setup for ERD BCI control

We recorded EEG at a sample-rate of 256 Hz with a bandpass filter between 0.5 and 100 Hz and a notch filter at 50 Hz. For signal acquisition we used g.GAMMAsys active electrodes, a g.USBamp biosignal amplifier and the g.HIGHspeed signal acquisition block (g.tec, Guger Technologies OEG, Graz, Austria). The positions for the 6 electrodes according to the 10/20 System for Electrode Placement were FC3, FCz, FC4, CP3, CPz and CP4. The three bipolar derivations FC3-CP3, FCz-CPz and FC4-CP4 (blue colored sensors in Fig. 1), were considered during ERD auto-calibration and one was used during online operation.

C. Co-Adaptive ERD Auto-Calibration

The system by default loads the ERD classifier configuration from the last training at startup and is then ready to use. With one double-click, a new co-adaptive online ERD training session can be started, where the user has to produce two different mental activities (right hand versus both feet movement imagery) in a cue guided training paradigm (see Fig. 2). The paradigm starts with offline data collection and then automatically calibrates and provides feedback after approximately 3 min (7 trials per class). During this online feedback operation the system continuously analyzes the data, reselects one best logarithmic bandpower feature (α, 10 to 13 Hz, or β, 16 to 24 Hz from C3, Cz or C4) and recalculates a new linear discriminant analysis (LDA) classifier whenever 5 new trials per class are available after trial based outlier rejection (see [3] for details). A total of 60 trials were collected during ERD auto-calibration procedure.

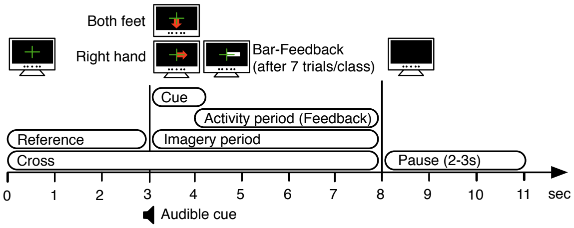

Fig. 2. The task for the user was to perform sustained right hand versus both feet movement imagery starting from the cue (second 3) to the end of the cross period (second 8). A trial started with 3 s of reference period, followed by a brisk audible cue and a visual cue (arrow right for right hand, arrow down for both feet) from second 3 to 4.25. The activity period, where the user received feedback, lasted from second 4 to 8. There was a random 2 to 3 s pause between the trials.

D. Hex-o-Select GUI and Control Logic

As GUI for our online ERD/Integra Mouse Hybrid BCI control, we use a customized implementation (see Fig. 3) based on [2]. This GUI that we refer to as Hex-o-Select displays a variable number (3 to 8) of menu items in layers that are organized in a tree structure. The menu items can represent either atomic actions or headlines that lead to sub-menu layers. The last element of every sub-menu layer is labeled 'Back' and leads to the menu-layer directly above.

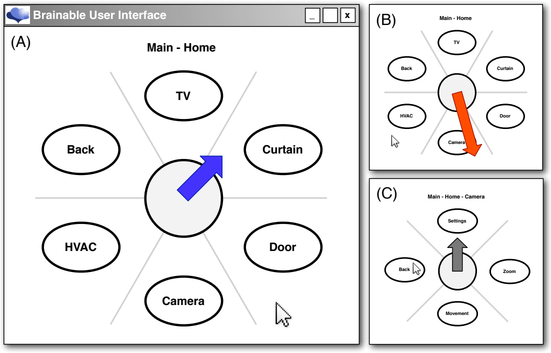

Fig. 3. The panels show different layers in the Hex-o-Select GUI (based on [2]). Arrow Mode (I) and System Mouse Cursor Mode (III) are activated in all the panels. In Panel (A) the arrow length is below selection threshold and the arrow is therefore colored in blue and rotating, whereas in Panel (B) the arrow is extended over the selection threshold and therefore colored in red and not rotating. Panel (C) shows the change to the sub-menu layer 'Camera' after a successful selection in Panel (B). The arrow is colored in black which indicates that the system is in refractory period.

The GUI is completely remote configured by the Context-Aware Environmental Control System and receives immediate updates whenever devices change their status (e.g. Twitter Logged On or Off). All this communication is mediated by the BCI-TO-XML Block (see Fig. 1 and [8]).

The GUI supports four different operation modes: (I) The arrow mode uses a one dimensional signal. In this mode, the length of an arrow can be increased by imagining right hand movement and decreased by imagining movement of both feet. The arrow is rotating at a slow pace and colored in blue when its length is lower than a certain threshold (see Fig. 3, Panel A). Whenever its length exceeds the threshold, the arrow stops rotating and turns its color to red (see Fig. 3, Panel B). The user can select the menu item in the segment where the arrow is pointing to by keeping the arrow length above the threshold for a dwell time of 3 s. After every successful activation the system would either execute an action or change to a sub-menu layer depending on the type of the item. After any activation, the arrow resets to the original position (pointing upwards), remains disabled, static and colored in black for a refractory period of 3 s.

The operation modes (II) and (III) use two dimensional input signals to guide a cursor to select items. Operation mode (II) allows for devices such as Joystick, eye-tracker or Wii-Remote whereas operation mode (III) enables the system mouse as an input device. The latter option allows to use assistive technology like the Integra Mouse but also allows an operator or care-giver to quickly interact using the system mouse. Operation mode (IV) allows for any simultaneous hybrid operation of the modes (I), (II) and (III).

E. Online Simulation of the Workload Detector

Our idea is that the system could try to detect whether the user is overwhelmed with workload and could then deactivate the ERD BCI so that no erroneous activations can be triggered. We mainly focus on testing the proposed Hybrid BCI for interacting with the Context-Aware Environmental Control System. Therefore we only simulate the functionality of the Workload Detector by having an experimenter trigger it manually at a defined point in the test protocol.

F. Mouth Joystick Setup

As the second active input signal next to ERD we used a mouth joystick (Integra Mouse, LifeTool Solutions GmbH, Linz, Austria, see Fig. 1), since it is a common assistive technology device. By moving the tip of the mouth joystick with their lips, users could freely control the system mouse cursor up, down, left and right. The tip of the joystick has the form of a small tube and the users could trigger a left-mouse click by briefly (less than 1 s) creating underpressure in the mouth piece by sucking out the air.

G. Experimental Paradigm and Evaluation

We tested our system in one session with 3 healthy volunteers (male, age 25 ± 3.5), who had previously used ERD BCIs but were not specifically trained for this experiment. The protocol of interactions was the same for every participant. First (1) the users completed the Co-Adaptive ERD Auto-Calibration and Training paradigm of our prototype (see Fig. 1, Segment (A.1)). From this we report the selected feature and the peak training accuracy from second 4 to 8 in the trial after leave-one-out cross-validation. We then start the system in Hybrid BCI Online Operation Mode (see Fig. 1, Segment (A.2)) where the GUI simultaneously runs (I) Arrow Mode based on ERD and (III) System mouse cursor mode relying on the signal from the Integra Mouse (see Section II-D).

The second step (2) concerned the ERD online operation and was divided in 3 subtasks: (2.a) 1 min idle, (2.b) actual selection of the 10 predefined menu-items in 4 layers to remote control a camera and again (2.c) 1 min idle. The camera is exemplary for a variety of supported devices, and could in practice be used by a disabled, potentially bed-bound user to perceive what happens in other localities. For the idle period the subjects were instructed to actively avoid triggering any activations. For this, we report the number of False Positive (FP, i.e. unintentional) activations. For (2.b) we report time-to-finish (TTF), False Negatives (FN, i.e. failure to trigger an activation) and Positive Predictive Value ($PPV = total(TP)/(total(TP) + total(FP))$, TP means True Positive, i.e. intentional activation).

We then (3) simulate that the Workload Detector triggers and deactivates the ERD input, so that in practice no unintentional commands could be sent by the ERD signal when the user is overwhelmed with workload.

At last (4) the participants had to select a predefined sequence of 20 menu items in 5 layers using the Integra Mouse to post the text 'Hello' to a configured account in the social platform Twitter (http://www.twitter.com). We report the same performance criteria as in step (2.b).

III. RESULTS

All three participants successfully completed the full test protocol and all systems worked as expected. We present

	(A.1) Calibration		(A.2) Online Operation							
	ERD - Calibration		ERD - Camera control					Integra - Twitter control		
	60 Trials LooCV		Idle	10 Selections			Idle	20 Selections		
	Feature	Acc. (%)	FP	PPV (%)	FN	TTF (s)	FP	PPV (%)	FN	TTF (s)
S01	α_{C3}	96.0	0	76.9	10	20:55	0	100.0	4	1:11
S02	α_{C4}	92.0	0	59.1	0	12:07	0	93.3	3	1:06
S03	α_{Cz}	88.0	2	80.0	3	10:39	1	100.0	2	1:05
Mean	-	92.0	0.67	72.0	4.3	14:33	0.3	97.8	3	1:07
SD	-	4.0	1.2	11.3	5.1	05:33	0.6	3.9	1	0:03

TABLE I

RESULTS OF THE (A.1) AUTO-CALIBRATION AND (A.2) HYBRID BCI ONLINE OPERATION PHASE.

all results in Table I. Based on the high average of 92 % over the peak training accuracies, the subjects were able to reach an average of 72 % PPV in the Hex-o-Select ERD online condition. As expected, the average PPV in the Integra Mouse condition was even higher, above 97 %.

IV. DISCUSSION

Three healthy volunteers successfully operated the prototype of our highly integrated context-aware system by means of a Hybrid BCI consisting of an SMR BCI and a mouth joystick to control a camera and to post a message on the social platform Twitter. The tested functionality is representative for a vast number of other compatible appliances (TV, Door, etc.) and internet services (Facebook, etc.).

Operating the system did not require any expert knowledge other than connecting the user and starting the system. In the beginning, the Co-Adaptive ERD Auto-Calibration and Training system successfully identified single features for the three users that led to an average peak training accuracy of 92 % after only 11 minutes of calibration. Also, the transition from cue-paced training to online ERD operation did not cause any problems. In online ERD operation, the users were able to effectively select the correct menu items using Hex-o-Select with an average PPV of 72 %. This was even though they had to orient themselves in the menu structure and were possibly distracted by the camera feedback. The number of FP activations was surprisingly low in the idle periods and the users effectively corrected their mistakes during online operation. The long TTF for Subject S02 can be attributed to the comparably high occurence of FNs, where often the time of the arrow-length being above threshold was slightly below dwell-time. Using subject-specific dwell-time or checking for the total time above threshold per segment could improve the system in this concern.

During informal interviews, subjects reported that operating the ERD BCI for 10 to 20 min was mentally straining. This supports the idea that a mechanism such as the Workload Detector that we simulated could be beneficial in combination with an ERD BCI. As expected, the control with the Integra Mouse was very fast and accurate, and only led to a low number of FNs.

The positive results of this first pilot study lead us to conclude that this system may potentially increase independence and social inclusion of users with disabilities by offering intuitive control over smart home devices and internet services. We are working to improve the efficacy of the Hybrid BCI based on what we learned here so that we can start tests on a larger number of healthy users with the aim to eventually deploy our system to create real-world benefit for users with functional disabilities.

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