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Adrijan Božinovski, Stanko Tonković, Velimir Išgum, Liljana Božinovska

Robot Control Using Anticipatory Brain Potentials

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Original scientific paper

Recently Biomedical Engineering showed advances in using brain potentials for control of physical devices, in particular, robots. This paper is focused on controlling robots using anticipatory brain potentials. An oscillatory brain potential generated in the CNV Flip-Flop Paradigm is used to trigger sequence of robot behaviors. Experimental illustration is given in which two robotic arms, driven by a brain expectancy potential oscillation, cooperatively solve the well known problem of Towers of Hanoi.

Key words: EEG-based Control, Brain Potentials Taxonomy, Anticipatory Brain Potentials, CNV Flip-Flop Paradigm, Two-Robot Solution of Towers of Hanoi Puzzle, Adaptive Interface

Upravljanje robotom pomoću anticipacijskih potencijala mozga. U posljednje vrijeme je u području biomedicinskog inženjerstva postignut napredak u korištenju potencijala mozga za upravljanje fizičkim napravama, posebice robotima. U radu je opisana mogućnost upravljanja robotima pomoću anticipacijskih potencijala mozga. Oscilacijski potencijal mozga generiran u CNV (Contingent Negative Variation) flip-flop paradigmi se koristi za okidanje slijeda ponašanja robota. U radu je prikazana eksperimentalna ilustracija rješavanja dobro poznatog problema Hanojskih tornjeva pomoću dvije robotske ruke upravljane moždanim potencijalom očekivanja.

Ključne riječi: upravljanje zasnovano na EEG-u, taksonomija potencijala mozga, anticipacijski potencijali mozga, CNV flip-flop paradigma, rješenje problema Hanojskih tornjeva pomoću dva robota, adaptivno sučelje

1 INTRODUCTION

Brain potentials have been of scientific interest since the discovery of the Electroencephalogram (EEG) [1]. Various derivatives of EEG have been studied, including frequency bands (e. g. alpha waves) and event related potentials (e.g. anticipatory potentials). Recently, interest has been expressed towards using brain signals to control various physical devices, such as home appliances, prostheses, and, in particular, robots. The control loop includes: a human subject, a brain signals capturing device, a specific brain signal recognition software, a robot interface, a robot, and a feedback (usually visual) to the subject. The first report on robot control robot using an EEG signal was given in 1988 [2, 3]. Since then, various brain signals, various types of robots, as well as control tasks, were used in EEG-based robot control. Later in the text, in a separate chapter, a short review of various efforts in the field is given.

The work presented here describes utilization of anticipatory brain potentials to control two robotic arms. The Contingent Negative Variation potential (CNV) is considered. A CNV Flip-Flop Paradigm is used to guide two robot arms to cooperatively execute the Towers of Hanoi task with three disks, referred to as the TOH(3) task. The objective of this research is to verify the hypothesis that a subject can generate an oscillatory expectancy process in the brain long enough to guide seven behaviors with two robot arms in order to solve the posed problem.

This paper is organized in 8 chapters. After this short introduction, a taxonomy of brain potentials is described, pointing out the place of anticipatory brain potentials among other brain potentials. Chapter 3 briefly describes the CNV Flip-Flop experimental paradigm. Chapter 4 describes the experimental setup of the presented research, including signal processing and robot control. Chapter 5 describes the considered TOH(3) task. Chapter 6 describes the experimental investigation, its methods and results. Chapter 7 is a discussion chapter, and it discusses the terminology in the field, as well as the related literature. Chapter 8 is the conclusion.

2 ANTICIPATORY BRAIN POTENTIALS

A taxonomy of brain potentials which includes anticipatory brain potentials was introduced in 1992 [4]. According to it, brain potentials are divided into spontaneous and event related. Event related potentials are divided into post-event (evoked), and pre-event (anticipatory). Evoked potentials are divided into exogenous (reflexive) and endogenous (cognitive). An example of a reflexive potential is the Visual Evoked Potential (VEP) and an example of a cognitive potential is the P300. Anticipatory brain potentials are divided into preparatory (showing readiness for a willing action), an example being the Bereitschaftspotential – BP [5], and expectatory (showing expectation of an event), an example being the CNV potential [6].

3 THE CNV FLIP-FLOP PARADIGM

A CNV potential appears in a so-called CNV paradigm [6]. In essence, it is a Reaction Time paradigm, in which EEG is recorded. The subject is presented with two stimuli: S1, which is short in duration and serves as a warning signal, that a next, S2, will follow, which is longer and needs to be interrupted by the user (usually by pressing a button). The user is instructed to press the button (i.e. stop S2) as quickly as possible, having been told that the subject's reaction time is measured. After averaging the EEG over several trials, a specific ramp-like shape forms between S1 and S2, which is the CNV potential. Several modifications of the original CNV paradigm have been proposed, and the CNV potential itself has been extensively studied [7]. An example of a CNV paradigm modification is the probability-driven appearance of S2 [8]. The modification of the original CNV paradigm used in this work consists in adding a feedback loop to the paradigm [4]. The flow chart of the paradigm, which is named the CNV Flip-Flop Paradigm [9, 10, 11], is shown in Fig. 1. As shown in Fig. 1, the feedback is introduced by monitoring the appearance and disappearance of the CNV potential and using that information to turn the imperative stimulus (S2) OFF and ON.

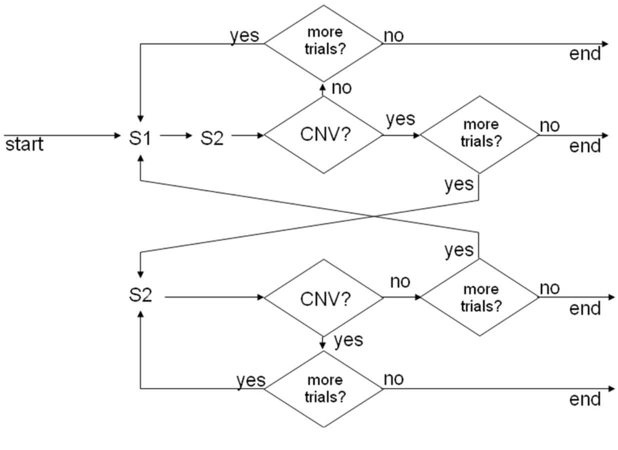


Figure 1. The CNV Flip-Flop Paradigm.

The recognition of CNV appearance would yield switching OFF the S2 stimulus, which would result in the lack of a need for the subject to react. This would eventually lead to a decline of his/her expectancy, and thus a decay of the CNV potential. The computer would recognize this and consequently turn ON the S2 stimulus again, which would in turn make the subject Owner to expect and react again, thus redeveloping his/her CNV potential, and so on.

The experiment would go on as long as there were trials available. While the subject's reaction is usually measured by him/her pressing a button, it has been shown that the CNV Flip-Flop Paradigm does not necessarily need a press button part [12]. The CNV potential is generated by an expectancy process and this means that the paradigm truly bypasses a motor organ.

We would note that the CNV Flip-Flop Paradigm is an *interactive and adaptive interface paradigm*. Both actors, the brain and the computer, mutually influence the behaviors of one another. The brain adapts its expectancy state and the computer adapts its response to the brain expectancy state, by turning the S2 signal (buzzer) ON and OFF.

4 EXPERIMENTAL SETUP

The CNV Flip-Flop paradignm is a direct bioelectric control paradigm which controls a sound generating device, namely a buzzer. In the current research, a robotic arm was added [13], and then two robotic arms, as described here. Thus, presently in the research, a brain expectatory process controls three physical devices: one buzzer and two robots. The experimental setup of this *multi-device control using a brain potential* is shown in Fig. 2.

The experimental setup is designed to show evidence of an oscillation of the expectation mental state in the brain. EEG is recorded and initially preprocessed for artifacts. The signal processing part first extracts the Event Related Potential (ERP), and then recognizes whether the brain entered the expectation state (ERP is CNV) or is not in an expectation state (ERP is not a CNV).

During the software development phase, both the programmer role and the subject role can be performed by the same person. The programmer/experimenter need not be present during the exploitation phase of the program. During the development phase he/she can observe the experiment and intervene by manually rejecting flawed experiment trials, if necessary.

In this experimental setup, two mental states trigger the three devices. The *appearance of the expectation state* (ERP has shaped into a CNV) activates a behavior of Robot1 and then (in the next trial) turns the Buzzer OFF. The *dissapearance of the expectation state* (ERP has lost the CNV shape) activates a behavior of Robot2 and (in the next trial) turns the Buzzer ON.

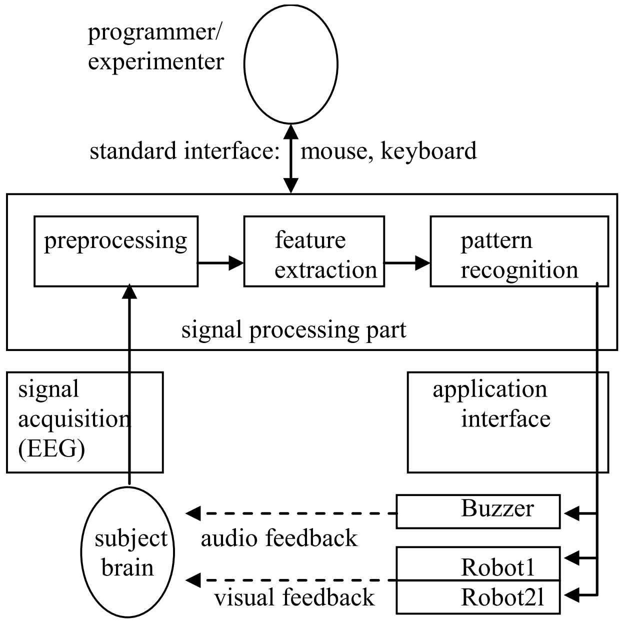


Figure 2. Experimental setup: Multi-device control using EEG signals.

4.1 Biosignal processing

After preprocessing (applying a low-pass filter with 30Hz cut-off frequency and dealing with artifacts) the signal processing parthas two tasks: to extract the relevant ERP and to recognize the appearance and disappearance of CNV.

In the CNV Flip Flop paradigm, extracting relevant ERP is a problem of extracting a time varying potential. Since the paradigm itself requires that the obtained signal oscillate between a CNV and a no-CNV pattern, a classical averaging technique is not suitable. Therefore, an incremental (adaptive) filter was used, defined as

$$ERP(0) = 0 \tag{1}$$

$$ERP(t) = pERP(t-1) + qEEG(t) \tag{2}$$

where both EEG(t) and ERP(t) are sequences containing 700 samples taken within 7 seconds of recording time, t (t = 1, 2, …, n= 700) is the experimental trial, and p and q are weighting parameters, satisfying $p + q = 1$.

The next step in signal processing is the recognition whether the obtained ERP forms into a CNV shape or loses its CNV shape. Since the expected CNV is a ramp-like signal, the pattern recognition software looks for parameters of that ramp. The parameters that are computed are the slope of the regression angle and the amplitude of the ERP just before S2. The ERP baseline is computed as the mean value from the 100 samples of the ERP signal from the beginning of the trial until the appearance of the S1 stimulus. In the research presented here only the amplitude difference was used for the signal recognition part. Using programming pseudocode notation, the appearance of CNV is computed as

```
brain state = “no expectation”;
if for three trials in a row
  $\operatorname*{average}_{t=295}^{300}(erp(t)) - \operatorname*{average}_{t=1}^{100}(erp(t)) > threshold$
then ERP is a CNV
  brain state = “expectation”
  activate Robot1 behavior;
```

For the decay of CNV, the following routine is used

```
brain state = “expectation”;
if for two trials in a row
  $\operatorname*{average}_{t=295}^{300}(erp(t)) - \operatorname*{average}_{t=1}^{100}(erp(t)) < threshold$
then ERP is not a CNV
  brain state = “no expectation”
  activate Robot2 behavior;
```

In the current research the threshold was set to be 5 μV. Note that in the above pseudocode the problem of false positives is addressed by the need of the ERP to be above the CNV recognition threshold three trials in a row, in order for the ERP to be recognized as a CNV. Conversely, the ERP needs to be below the CNV threshold two trials in a row, for the disappearance of the CNV to be recognized. In normal subjects, the CNV Flip-Flop paradigm generates an oscillation of the CNV amplitude. The CNV Flip-Flop oscillatory curve is a cognitive (expectancy) wave used as a triggering process for a sequence of robot behaviors.

4.2 Control of two robots

The device control architecture we used is shown in Fig. 3. Robot1 is activated by a CNV appearance event and Robot2 is activated by a CNV disappearance event. Both robots have predefined behaviors. Behavior-based robotics [14] is used, which is currently a widely used approach in robot control. Robots and their behaviors are triggered by a brain state recognition system, which recognizes the existence and non-existence of the brain expectancy state represented by the CNV potential.

5 THE TASK CONSIDERED

The brain expectancy wave control task that was considered is sketched in Fig. 4 and can be defined as: Given two robotic arms each with at least 5 degrees of freedom, perform a robotic solution of the TOH(3) task driven by

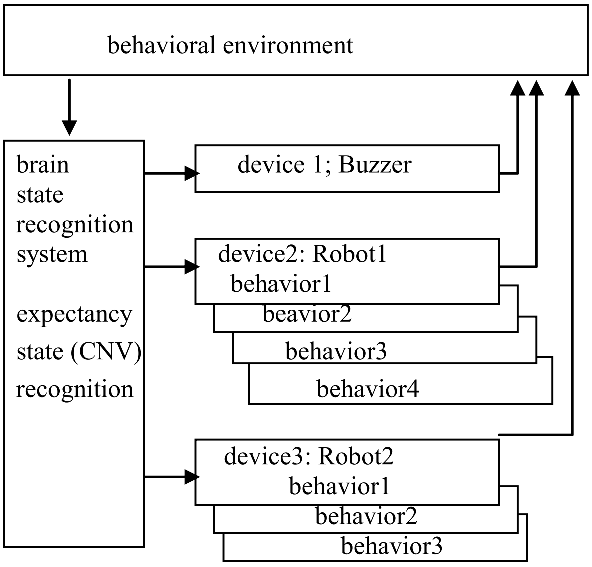


Figure 3. The behavior-based control architecture.

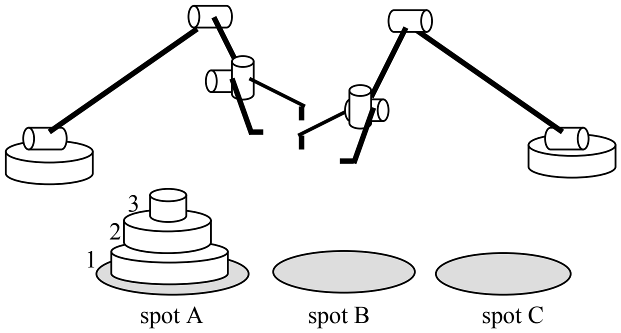


Figure 4. The considered task: the Towers of Hanoi problem to be solved by two robotic arms controlled by an expectancy oscillatory process in the brain.

the expectancy brain wave which is generated by the CNV Flip-Flop paradigm.

The Towers of Hanoi task is a benchmark problem in the literature of Artificial Intelligence and Algorithm Theory. Given a set of disks with different diameters, a *tower* is defined as a disk stack in which a smaller disk is always above a larger one. Three spots are given – A, B, and C. If the initial tower is in spot A, the task is to move it to spot C, using a “buffer” spot B. It is known that to move a tower of d disks, 2^d-1 movements of the individual disks are required. If the height of a particular disk is denoted with a number between 1 and 3 (height 1 being the bottom), the sequence can be represented as A3toC1, A2toB1, C1toB2, A1toC1, B2toA1, B1toC2, A1toC3.

Once the problem is decomposed into a sequence of robot behaviors, the CNV Flip-Flop Paradigm generates an oscillatory process that will drive two sequences of behaviors. Robot1 behaviors are activated whenever the ERP shapes into a CNV, while Robot2 behaviors are activated whenever the ERP loses its CNV shape.

6 EXPERIMENTAL INVESTIGATION

The research hypothesis for the experimental investigation is that healthy subjects will be able to carry out the oscillatory expectancy process in the brain long enough to solve the TOH(3) problem. The assumption is that it would take less than 100 trials. The subject should produce the appearance of the CNV four times and the disappearance of the CNV three times. It is assumed that the TOH(3) task gives enough achievement motivation for completing the task.

The experimental setup consists of an EEG-event recognition part and a robot behavior execution part. The event recognition part recognizes the appearance/disappearance of the brain state of expectation, while the behavior execution part activates the controlled devices.

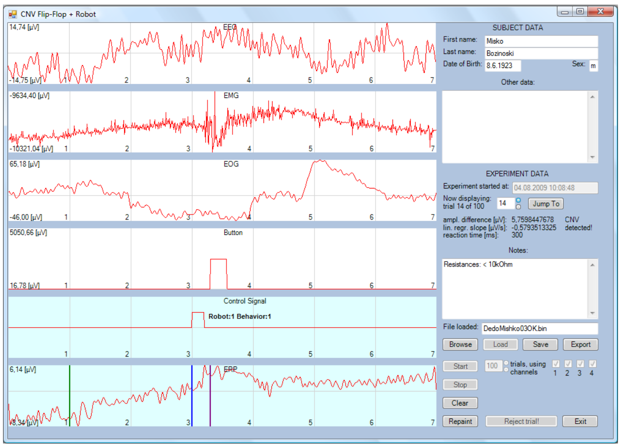
6.1 Materials and Methods

The two controlled robotic arms and the Towers of Hanoi disk set are shown in Fig. 5. Each robot is controlled by a servo controller connected to the computer by a USBtoCOM cable.

Figure 5. Experimental setup, two robotic arms and the TOH(3) disk set.

The subject is sitting and observing his/her progress towards the solution of the TOH(3) task, which gives a motivation for achievement. The EEG electrodes are placed on Cz and mastoid, while the forehead is the ground. A personal computer receives the signals and processes them. A four-channel biopotential amplifier receives the biosignal information from the subject. A USB cable connects the biopotential amplifier to the computer.

Figure 6 shows the design of the screen. The rightmost part of the screen is used for control of the experiment, including subject data and the name of the file where the experiment is stored. The screen in Fig. 6 shows six channels, out of which the first four are acquisition channels and the last two are mathematically computed channels. The first channel is the EEG acquisition channel, the second is the EMG acquisition channel from the arm pressing the button, the third is the EOG acquisition channel, and the fourth is the press-button signal acquisition channel. The sixth channel computes the event related potential extracted in the observed trial. The fifth channel displays the signal showing activation of a robot behavior.



SUBJECT DATA

First name: Misko

Last name: Bozinoski

Date of Birth: 8.6.1923 Sex: m

Other data:

EXPERIMENT DATA

Experiment started at: 04.08.2009 10:08:48

Now displaying: trial 14 of 100 14

ampl. difference [µV]: 5,7598447678 CNV detected!

lin. regr. slope [µV/s]: -0,5793513325

reaction time [ms]: 300

Notes:

Resistances: < 10kOhm

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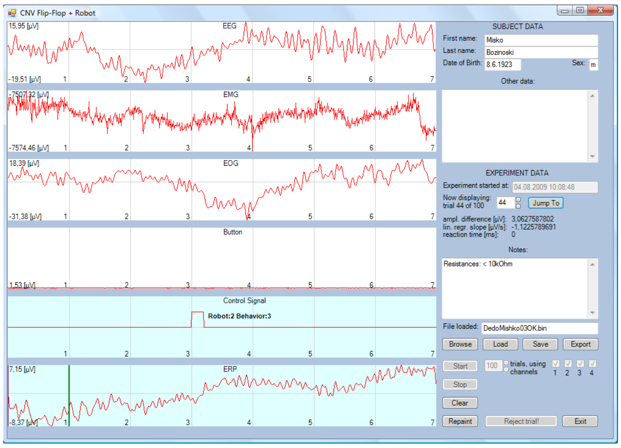
100 trials, using channels ☑ 1 ☑ 2 ☑ 3 ☑ 4

Figure 6. An experimental trial with recognized CNV appearance and activated Robot1 behavior.

Figure 6 shows an example of an experimental trial. A trial consists of seven seconds of signal acquisition, after which there is a 7-14 seconds inter-trial interval (the duration of the inter-trial is obtained randomly). At second 1, a vertical bar appears on the screen, representing S1. The vertical bar at second 3 represents the appearance of S2, if that signal is present. The reaction time of the subject is shown with the third vertical bar, if a reaction from the subject is present. The press-button signal in all its duration is shown in Channel 4, if the subject presses the button. If the CNV pattern is recognized at the time of S2, a signal for robot activation is sent, as shown on Channel 5. Thus, a robot is activated by the *expectation of S2*, *before the actual press button motor movement,* which takes place a reaction time later. Since the last component of the CNV is a readiness potential, a robot is activated by *an intent* to move.

Figure 7 shows an experiment trial where the CNV shape is lost, and the CNV recognition system activates a Robot2 behavior. In Fig. 7, there is no S2 generated and there is no press button. *Robot2 is activated solely by the recognition of the brain state of non-expectation, with no physical movement at all.*

Figures 6 and 7 emphasize two crucial features of the CNV Flip-Flop Paradigm: 1) when the CNV appears, a device is activated by the expectation state and the state of intention to move; if the paradigm does not include a press button [12], only the expectation state activates a device. 2) when the CNV decays, a device is activated upon the recognition of a non-expectation state. In both cases, a device is controlled by an EEG-only event, with no physical movement.



SUBJECT DATA

First name: Misko

Last name: Bozinoski

Date of Birth: 8.6.1923 Sex: m

Other data:

EXPERIMENT DATA

Experiment started at: 04.08.2009 10:08:48

Now displaying: trial 44 of 100 44

ampl. difference [µV]: 3,0627587802

lin. regr. slope [µV/s]: -1,1225789691

reaction time [ms]: 0

Notes:

Resistances: < 10kOhm

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100 trials, using channels ☑ 1 ☑ 2 ☑ 3 ☑ 4

Figure 7. An experimental trial in which ERP between first and the third second just lost a CNV shape so a Robot2 behavior is activated.

6.2 Results

The series of experiments described here is the proof-of-the-concept experimental illustration. A three-disk Towers of Hanoi problem requires seven behaviors to complete the task, which means that, in order for the CNV Flip-Flop Paradigm to complete the task, 4 appearances of the CNV pattern need to occur (and thus 4 movements of Robot1), and 3 disappearances (and thus 3 movements of Robot2). Each experiment lasts up to 100 trials at most; this number being less if the task is completed successfully before that. Table 1 gives summary of 12 experiments for the proof-of-the concept purpose. Each experiment on Table 1 is carried out on a separate subject.

In Table 1, the numbered columns in bold indicate the experiment identification. Under the section "Trial order number", the numbers indicate the trial number in which the corresponding EEG event and robot behavior (listed in the leftmost column) occurred. For example, in Experiment 1 the expectation state of the brain was recognized as emerged in trial 9, which was then recognized as lost in trial 15, then the CNV reappeared in trial 22, and so on. Robot behaviors followed the corresponding EEG events. The TOH(3) task was completed in 57 trials. In average, over 12 subjects, the TOH(3) task was completed in 60 trials.

Table 1. Results of series of experiments controlling two robots by an oscillatory expectancy wave in the brain

	Experiment												
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Average**
EEG event→ Robot#Behavior#	**Trial order number**												
CNV1→ Robot1Behavior1 (A to C)	9	19	15	10	6	6	11	31	7	18	17	18	14
No CNV1→ Robot2Behavior1 (A to B)	15	25	24	18	22	12	13	36	21	22	31	22	22
CNV2→ Robot1Behavior2 (C to B)	22	41	29	29	25	21	21	44	25	33	36	35	30
No CNV2→ Robot2Behavior2 (A to C)	31	45	48	40	35	32	24	50	41	40	42	42	40
CNV3→ Robot1Behavior3 (B to A)	38	60	50	52	38	36	30	55	47	46	46	45	45
No CNV3→ Robot2Behavior3 (B to C)	43	64	71	56	51	53	34	62	53	51	50	49	53
CNV4→ Robot1Behavior4 (A to C)	57	69	75	76	54	56	39	71	57	59	53	60	60

7 DISCUSSION: TERMINOLOGY AND RELATED WORK

This chapter discusses topics related to the research in the area of EEG-based control of robots. The terminology in the field is discussed first, after which a short review of other works is given.

7.1 Terminology in the field of EEG based robot control

Initial terminology used in EEG-based control of robots [3, 4] used terms "direct bioelectric communication using brain waves", "brain waves bioelectric control" and "brain wave control of a robot". The term "direct bioelectric control" was also used [15]. The considered EEG-based control task was a non-invasive real-time start/stop control of a mobile robot executing a default behavior of following a trajectory drawn on the floor.

Later, the term Brain-Computer Interface (BCI) was used for EEG-based robot control for both invasive control of a (manipulative) robot [16] and non-invasive control of a (mobile) robot [17]. In this discussion, the focus will first be on the term Brain-Computer Interface.

The term Brain-Computer Interface (BCI) was introduced by Vidal in 1973 [18], as the name of the project he worked on. He pointed out that the ultimate goal of human-machine communication is to provide a direct link between the mental processes of a human and the capabilities of a computer. The following quote describes the scope of his BCI project:

"The Brain-Computer Interface system is geared to the use of both the spontaneous EEG and specific evoked responses triggered by time dependent (visual) sensory stimulations under various conditions. In addition, other biosignals that are of interest for interfacing the physiological man and the machine are to be included later in the project.

Eye movements, muscle potentials, galvanic skin reflex, and heart rate are ready examples which hold promise for particular applications. Acoustic and somato-sensory evoked responses also need to be evaluated since the latter, in particular, affords less variability than the visual evoked responses. Of special interest also is the contingent negative variation (CNV), a slow negative baseline shift of the EEG signal that relates to expectation, attention, and arousal."

As can be seen, BCI was originally defined as an inclusive research. Vidal's challenge was object control using biosignals such as EEG, EOG, and CNV, among others.

In 1977 [19], Vidal achieved control of a graphical object on a computer screen using EEG signals. Other early responses to his challenges are: the 1988 control of text on a computer screen using the EEG P300 potential [20], the 1988 robot control using the EEG alpha rhythm [2, 3], and the 1989 robot control using EOG signals [21]. A report on both EEG and EOG robot control was also given in 1990 [15]. In 1991, the mu rhythm was used for computer screen cursor control [22] and in 1992 the CNV potential was used for computer buzzer control [4].

Contemporarily there are different understandings of the scope of BCI. Three among them are possibly the most influent: a year 2000 definition that a BCI is a communication system that does not depend on the brain's normal output pathways of peripheral nerves and muscles [23], a year 2002 definition that BCI technology gives to its users communication and control channels that do not depend on the brain's normal output channels of peripheral nerves and muscles [24], and a year 2008 definition that BCI monitors the users' brain activity and translates their intentions into actions without using activity of any muscle or peripheral nerve [25]. It should be noted that the first of the three definitions mentioned above is a definition proposed by the first international meeting on BCI, in 1999. Later definitions have slightly different views towards BCI; there are contemporary understandings that BCI is a direct brain control of devices [26], which is basically proposed in the early days of EEG based control of robots [2]. In regards to the undergoing work presented in this paper, its scope is defined as extracting meaningful information from EEG for control of external devices, robots in particular.

In regards to the BCI terminology, in this work it is understood that the following inclusion relation holds: BRI $\subset$ BMI $\subset$ BCI, where BMI is Brain-Machine Interface and BRI is Brain-Robot Interface. BCI includes control of objects on the computer screen as well as virtual devices, BMI includes control of physical devices (such as TV sets and house doors), and BRI narrows down to robots. The boundaries are fuzzy, and control of some devices (e.g. wheelchairs) might be considered either a BRI or BMI.

The control of any device is achieved by a mental state which produces a particular EEG manifestation Some examples of mental states (and their EEG manifestations) are: relaxation (alpha rhythm), alertness and computation (beta rhythm), reflexive reaction (evoked potentials), recognition (P300), expectation (CNV), and imagination of a voluntary movement, among others. All of the mentioned brain states can produce EEG patterns that can be used in the activation of a physical device.

7.2 Related work

In this section, a brief list of literature related to the work presented in this paper is given.

In this research, a cognitive brain wave is considered, which is a manifestation of an oscillatory expectancy process in the brain generated by the CNV Flip-Flop Paradigm. The first comprehensive report on this type of CNV paradigm is given in 1992 [4] and its first consideration as a BCI paradigm is given in 2005 [9, 10]. The work most related to this research is the work of Millan's group in Switzerland, which started reporting on use of anticipatory brain potentials in 2008 [27, 28, 29]. Other related work is [30].

Here, some 20th century work on EEG-based control will also be mentioned. The problem of how to extract a brain hemisphere related biosignal was considered in 1984 [31] and the alpha rhythm was proposed as a possible representation of a mental task. More elaboration on mental tasks approach was given in 1990 [32]. In 1992 a visual evoked potential (VEP) was used to control letters on a computer screen [33]. In 1993 the mu rhythm in combination with a press button was used as a BCI paradigm [34]. The alpha rhythm was again used as a mind switch in 1997 [35, 36]. An invasive approach, recording signals inside the brain, rather than on the scalp, was introduced in 1999 [37]. In 2000 the asynchronous brain control was emphasized [38].

At the turn of the century, in 2000, a report of the first international meeting on BCI technology appeared [23]. It advanced the way of thinking about BCI: "BCI operation depends on interaction of two adaptive controllers, the user's brain, which produces the activity measured by the BCI system, and the system itself, which translates that activity into specific commands". It is worth noting that the CNV Flip-Flop Paradigm is indeed a system that implemented this adaptive interaction (game) approach between the user's brain and the adaptive BCI system.

Progress in the area flourished in the 21st century. Motor imagery based EEG control was improved [39]. In 2001 a mobile robot control was reported using a combination of EEG and EMG [40]. In 2004 a mobile robot control was reported based on EEG only [17]. Research continued with motor imagery, VEP based and other types of signals [41]. A combination of functional magnetic resonance imaging (fMRI) and EEG was used in 2006 [42]. A popular robot pet such as SONY AIBO was used in 2007 [43]. In 2008 the error related potential from the brain was used [44, 45]. Wheelchair navigation was improved [46]. A new technology, the near infrared spectroscopy (NIRS) was also used [47]. A combined method, EEG/NIRS, was demonstrated by Honda, while controlling a humanoid robot [48]. In 2010 some findings suggested that spontaneous, rather than intentionally generated, brain signals should be used [49]. Recently, interest has been shown towards the modulation of brain rhythms [50], as well as eye movement related potentials [51].

As a short conclusion of this chapter, the work presented here is a unique research direction inside the EEG-based control of physical devices, particularly robots. It uses a cognitive (expectancy) oscillatory wave generated in the human brain to control several coordinated devices. The process is manifested by changing of shape of the CNV signal.

8 CONCLUSION

An adaptive EEG-based brain-robot interaction is presented, in which a cognitive expectancy wave generated by the CNV Flip-Flop Paradigm drives two robotic arms to cooperatively solve a problem. Proof of the concept is given by experimental investigation in which the two robotic arms successfully solve the well known TOH(3) problem. The experimental investigation confirmed the initial hypothesis that the TOH(3) task gives enough motivation for a healthy subject to generate and maintain an expectancy oscillatory wave in her/his brain until the task is completed.

ACKNOWLEDGMENT

Relevant to this special issue of Automatika, the authors would like to point out that the first paper on robot control using an EEG signal was published in the proceedings of a conference held in Zagreb, in 1988. A member of the team that achieved that result was a student of professor Šantić.

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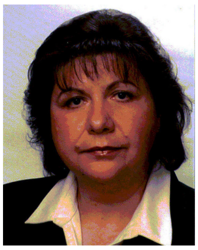
Adrijan Božinovski received his B.Sc. degree in 2002 from the Electrotechnical Faculty, University "St. Cyril and Methodius" in Skopje, Macedonia, and his M.Sc. and Ph.D. degrees in 2007 and 2010 respectively, both from the Faculty of Electrical Engineering and Computing, University of Zagreb, Croatia. He has worked as a teaching assistant at the Institute of Physiology of the Medical Faculty in Skopje from 2005 to 2007. From 2007 to 2010 he has worked as Assistant Lecturer at the School of Computer Science and Information Technology at University American College Skopje, where he has been elected Assistant Professor in 2010. His area of interest include anticipatory brain potentials, bioelectrical control of devices, signal processing, robotics, artificial intelligence, and cognition processes, and he has published about a dozen papers related to these subjects at various international conferences. He is a member of IEEE.

Stanko Tonković is a full Professor with permanent title, University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia. More than forty years of teaching experience in the fields of electronic measurements and instrumentation and biomedical engineering. With educational, scientific and professional activities he has excelled at most in biomedical engineering and technology, electronic measurements and instrumentation. He has been the head of a number of scientific and technological projects, as well as projects for industry. He is author/co-author of more than 150 scientific papers in journals or conference proceedings. Dean of the Faculty of Electrical Engineering and Computing, 1994-1998. President of Croatian Academy of Engineering, 2009 – 2013. President of the Croatian Medical and Biological Engineering Society, 2000-2009. Membership: IEEE-Senior Member, IFMBE, EMBS, EAMBES, IFAC, Croatian Medical and Biological Engineering Society, Croatian Society for Medical Informatics, Croatian Metrology Society.

Velimir Išgum received B.Sc. degree in 1971, M.Sc. degree in 1978 and Ph.D. degree in 1983 at the Faculty of Electrical Engineering, University of Zagreb. Since 1974 he has been employed at the Department of Neurology, University Hospital Rebro, Zagreb where he currently holds position as a head of the Laboratory for cognitive and experimental neurophysiology. He currently teaches at postgraduate study at the Faculty of Electrical Engineering and Computing, the School of Medicine, and the interdisciplinary scientific doctoral study Language and Cognitive Neuroscience, all at the University of Zagreb. He conducted several national and international scientific projects. He is a member of CROMBES (past president of Clinical engineering section), Croatian Society for Medical Informatics, International Society of Intraoperative Neurophysiology, and Croatian Society for EEG and Clinical Neurophysiology.



Liljana Božinovska received M.D. degree from Medical School of the University of Cyril and Methodius University in Skopje, Macedonia. She received MSc and PhD degree from the same university, where she had her residency in Neurology. She started teaching and research at the same School where in the period 1997-99 was a Vice Dean, and the Chair of the Cathedra for Physiology in the period 1992-94 and 2002-2006. Her teaching and research interest includes Neuroscience, Brain-Computer Interface, Cell Physiology, and Engineered Physiology. Among published papers her most significant works are achievement of pioneering results of controlling robots using EEG signals (1988) and using EOG signals (1989). Currently she is Associate Professor at the South Carolina State University, where she has developed Medical Physiology and Neuroscience Laboratory. She teaches Medical Physiology and Brain Science. She is a President of the Macedonian Society for Physiology, and member of the European Brain and Behaviour Society, and the South Carolina Academy of Science.

AUTHORS' ADDRESSES
Adrijan Božinovski
School of Computer Science and Information Technology
University American College Skopje
Skopje, Macedonia
email: bozinovski@uacs.edu.mk
Stanko Tonković
Department of Electronic Systems and Information Processing
Faculty of Electrical Engineering and Computing
Zagreb, Croatia
email: stanko.tonkovic@fer.hr
Velimir Išgum
Department of Neurology
University Hospital Center Zagreb
Zagreb, Croatia
email: velimir.isgum@kbc-zagreb.hr
Liljana Božinovska
Department of Biological and Physical Sciences
South Carolina State University
Orangeburg, SC, USA
email: lbozinov@scsu.edu

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