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An OpenViBE-Based Brainwave Control System for Cerebot

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***Abstract*—In this paper, we develop a brainwave-based control system for Cerebot, consisting of a humanoid robot and a Cerebus™ Data Acquisition System up to 128 channels. Under the OpenViBE programming environment, the control system integrates OpenGL, OpenCV, WEBOTS, Choregraph, Central software, and user-developed programs in C++ and Matlab. The proposed system is easy to be expanded or upgraded.**

Firstly, we describe the system structures for off-line analysis of acquired neural signals and for on-line control of a humanoid robot via brainwaves. Secondly, we discuss how to use the toolboxes provided with the OpenViBE environment to design three types of brainwave-based models: SSVEPs, P300s, and mu/beta rhythms. Finally, we use the Cerebot platform to investigate the three models by controlling four robot-walking behaviors: turning right, turning left, walking forward, and walking backward.

I. Introduction

Control of physical devices, such as wheelchairs and manipulators, via brainwaves will play an important role in helping disables in their daily life [1]. A variety of methods are able to acquire brain signals either invasively or non-invasively, such as electrocorticography (ECoG), electrocorticography (EEG), functional magnetic resonance imaging (fMRI), et al. An invasive method uses electrodes implanted over the brain cortex (requiring surgery) to record actions of neurons. It has higher spatial resolution, broader bandwidth, higher characteristic amplitude, and less vulnerability to artifacts or ambient noise. The works [2]-[4] propose and review directly employing cortical neurons to control a robotic manipulator.

The invasive methods face substantial technical difficulties and involve clinical risks because surgeons are needed to implant the recording electrodes in or on the cortex, the devices must function well for long periods, and they risk infection and other damage to the brain. A non-invasive method commonly used in applications is to record electroencephalogram (EEG) signals from electrodes placed on the scalp. It's easy to use, requires inexpensive equipment, and has relatively high temporal resolution, so the non-invasive methods have been applied to controlling varieties of robots through directly employing brain signals. Millan et al. use noninvasive EEG signals recorded over sensorimotor areas to give two human users control of a mobile robot [5]. Pfurtscheller et al. train a tetraplegic patient to control a hand orthosis with EEG recorded over the sensorimotor cortex [6]. Müller-Putz et al. train a patient to modulate EEG using motor imaginary and control an implanted neuroprothesis [7].

Compared with manipulators and mobile robots, humanoid robots are more advanced as they are created to imitate some of the same physical and mental tasks that humans undergo daily [8], but control of humanoid robots is much more challenging. Humanoid robots are being developed to perform some complicated tasks like personal assistance, where they should be able to assist the sick and elderly, and dirty or dangerous jobs. However, for people with severe motor disabilities it is important to establish augmentative communication with humanoid robots for personal assistance. Bell et al. describe a humanoid robot controlled by a human operator's P300 response [9]. Li et al. present a mind-controlled humanoid robot platform — Cerobot [10]-[11].

In this paper, we develop a brainwave-based control system for Cerebot, consisting of a humanoid robot and a Cerebus™ Data Acquisition System up to 128 channels. The proposed system is easy to be expanded or upgraded so that it makes the Cerebot platform flexible to investigate different brainwave-based models for control of the humanoid robot behavior. This paper describes the system structures for off-line analysis of acquired neural signals and for on-line control of a humanoid robot via brainwaves, discusses how to use the toolboxes provided with the OpenViBE environment to design a brainwave-based control system, and reports the investigation of three types of brainwave-based models: Steady-state visual evoked potentials (SSVEPs), P300 visual evoked potentials (P300s), and mu/beta rhythms. Finally, this

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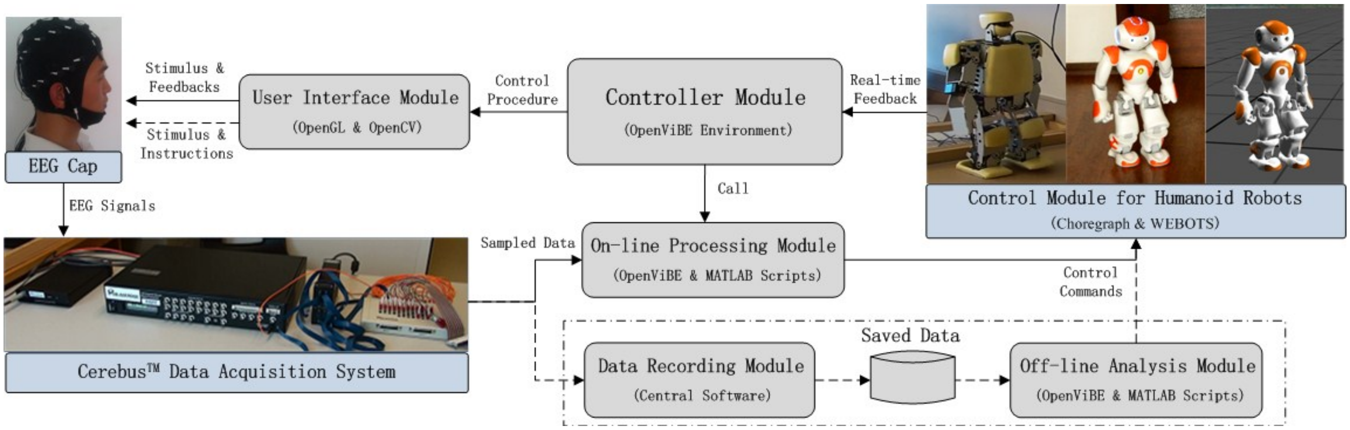


Fig. 1. The structure of the proposed brainwave control system: The neural signals acquired by Cerebus™ are processed for real time control using the On-line Processing Module, or are saved by the Data Recording Module and analyzed later using the Off-line Analysis Module as shown in the dotted line. The major software tools utilized in building the modules are listed between parentheses.

paper summarizes the experimental results of control of four robot walking behaviors: turning right, turning left, walking forward and walking backward via brainwaves acquired by the three models.

II. Cerebot Platform

Cerebot is a mind-controlled humanoid robot platform that is developed for investigating different brainwave-based models in humanoid robot control applications. It consists of a humanoid robot and a Cerebus™ Data Acquisition System that is an electroencephalograph up to 128 channels, as shown in Fig. 1.

The Cerebus™ Data Acquisition System works as the most important part of the platform for acquiring and recording brain signals. Cerebus™ is a professional multichannel system for recording, processing and displaying bio-potential signals from various types of electrodes including electroencephalography (EEG). It consists of a neural signal amplifier, an amplifier power supply and a neural signal processor, as shown in Figure 1. The system is capable of recording at most 128 signal channels simultaneously at a sampling rate of 30 kHz with 16-bits resolutions, and provides several on-line processing options for reducing signal noises such as adaptive line noise cancellation, fiber-based data transmission and custom-designed digital filter. In addition, the Cerebus™ system provides multiple analog and digital inputs and outputs and supplies easy-to-use Software Development Kids for both C++ and MATLAB, which makes it easier for flexible design and extension of the experimental procedure.

The system uses a NAO robot with 25 degrees of freedom (DoFs) or a KT-X PC humanoid robot with 20 DoFs as shown in Fig. 1. Both types of humanoid robots are equipped with speakers, a camera, 3 axis gyro/accelerometer chips, and wireless connection adaptors. The robots can be controlled in real-time or based on predefined behaviors in C++ and Python.

III. OpenViBE-based Control System

The brainwave control system for Cerebot platform is developed under OpenViBE programming environment. The control system integrates OpenGL, OpenCV, MATLAB, WEBOTS, Choregraph, Central software, and user-developed programs in C++ and Matlab. It enables users to establish a user-defined experimental procedure for both off-line and on-line brain-controlled humanoid robot experiments.

A. Introduction to OpenViBE

OpenViBE is a free open-source software platform for designing, testing, and implementing brain-computer interfaces. The platform consists of a set of software modules devoted to the acquisition, preprocessing, processing, and visualization of cerebral data, as well as to the interaction with virtual reality (VR) displays [12]. Users are able to easily add new software modules specifically tailored towards their needs. OpenViBE is a general-purpose software platform for BCI research in a graphical programming environment and provides users with flexibilities to design and alter the experimental procedures, and with powerful interfaces to applications and algorithms written in other languages. Its user-friendly graphical language even allows non-programmers to design a brain-computer interface (BCI) without need for writing a text-based script. Fig. 2 shows our implementation of the SSVEP model for control of a NAO humanoid robot using OpenViBE.

B. System Structure

In the Cerebot platform, the OpenViBE-based brainwave control system acquires neural signals from Cerebus™ Data Acquisition System, processes them by extracting signal features and classifying signal patterns, and sends corresponding control commands to the humanoid robot platform. The system structures for off-line analysis of acquired neural signals and for on-line control of a humanoid robot via brainwaves are shown in Fig. 1.

In an off-line analysis as shown with dotted line in Fig. 1, a subject is instructed to execute a specific mental task by the User Interface Module. Brain signals acquired in this process are amplified, sampled and preprocessed by the Cerebus^{TM} Data Acquisition System. The signals along with their relevant event markers are transmitted to the host PC through Ethernet UDP protocol and saved by the Data Recording Module. The Controller Module built under OpenViBE environment run the training procedure by instructing the subject via the User Interface and processes the acquired neural signals using the Off-line Analysis Module programmed in OpenViBE and MATLAB. This module loads the saved data files, extracts brain signal features and classifies the corresponding mental states. It also generates commands to control the relevant walking behaviors of humanoid robot.

For an on-line control application, the system processes brain signals acquired in real time to recognize the present mental state of the subject and sends a control command related to a desired robot behavior to the humanoid robot platform. In this case, the User Interface Module provides stimulus presentations in evoked-potential experiments such as P300 and SSVEP as well as real-time video feedbacks from the humanoid robot on its running state and its surroundings. The On-line Processing Module records the neural signals when the subject is conducting any one of the several specific mental activities at will, and processes and classifies them into different patterns according to the signal features. The Control Module for humanoid robots constructed based on WEBOTS and Choregraph controls the walking behaviors of both real and stimulated humanoid robots.

C. *Interactions between Different Modules*

The brainwave control system integrates a number of software, including OpenViBE, MATLAB, OpenGL, OpenCV, WEBOTS, Choregraph, and Central software. The interactions between these software platforms are shown in Fig. 3.

The Controller Module programmed in OpenViBE scripts works as the framework of the system that determines the experimental procedure and calls functional modules

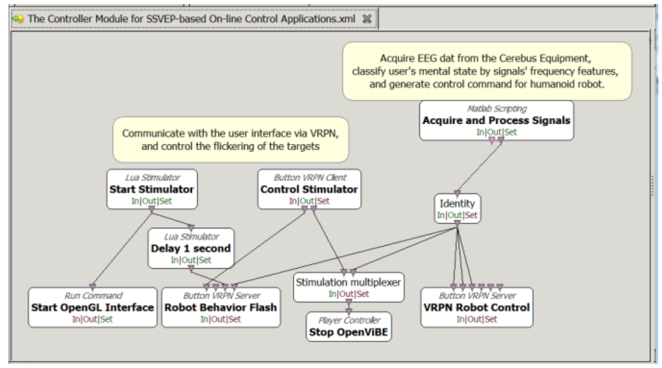


Fig. 2. OpenViBE script of the SSVEP-based Controller Module for on-line control applications

constructed with other software. The OpenViBE program of the Controller Module for SSVEP-based on-line control applications is shown in Fig. 2. The boxes in the graphical programming interface are modules of different functions, and the lines represent transmission paths of data flow. In the program, the Start Stimulator box runs the Start OpenGL Interface box to start up the User Interface Module. The User Interface Module is built by OpenGL and OpenCV in VC++ programming language, and communicates with the Controller Module through Virtual-Reality Peripheral Network (VRPN) interface. Fig. 5 shows the user interface for SSVEP-based on-line control applications. When the Robot Behavior Flash box receives the stimulation instruction, four images representing different robot behaviors start stably flashing but at different frequencies. Assigned keys for the user interface controls the flickering activities of the four images. The Control Stimulator box uses VRPN to manage the experimental procedure, i.e., to send corresponding commands to the Robot Behavior Flash box and the Stop OpenViBE box. The Acquire and Process Signals box read brain signals from Cerebus^{TM} and classifies them according to signal features (patterns). The Robot Control box through VRPN sends the classification results as the control commands of robot behaviors to the Control Module of Humanoid Robots.

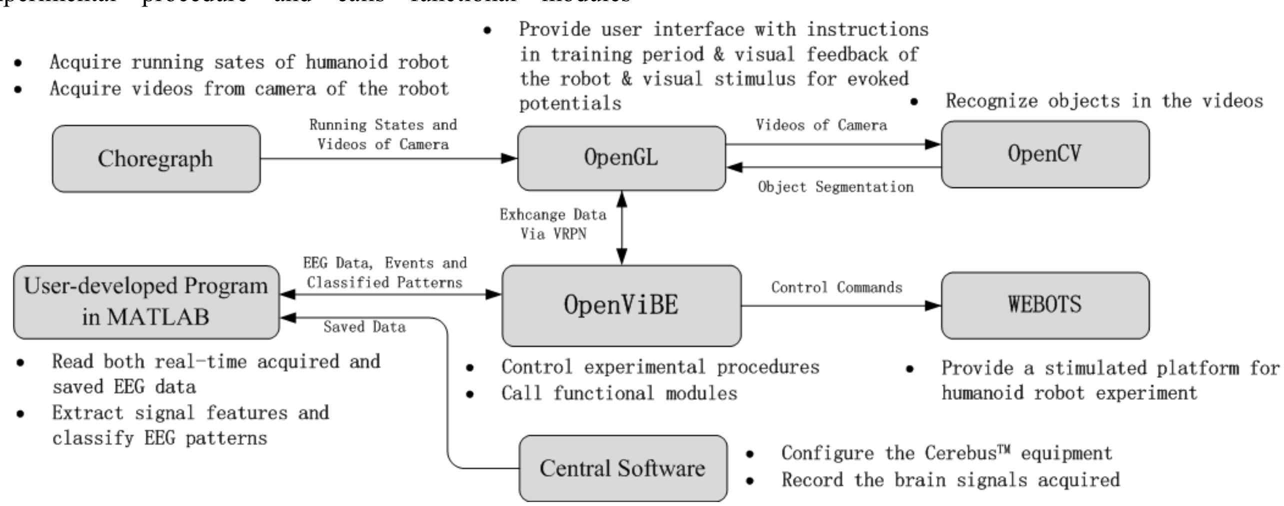


Fig. 3. Interactions between different programming platforms

IV. EXPERIMENTS

BCI provides a communication channel that allows an individual to send messages or commands to the external world by not passing through the brain's normal output pathways of peripheral nerves and muscles. Fig. 4 shows functional areas of cerebral cortex on a human brain. Three types of brainwave-based models, SSVEPs, P300s and mu/beta rhythms, have been implemented on our OpenViBE-based brainwave control system for evaluations. The first two are related to visual evoked potentials from particular brain regions by particular stimulus and the last one is related to reflecting oscillations in particular neuronal circuits from sensorimotor cortex [13].

A. Neural Brain Signal Features

1) SSVEPs: VEPs (Visual Evoked Potentials) elicited by stimulus are the electrophysiological responses of the brain's visual system and reflect certain properties of the stimulus [14]. In 1966, Regan [15] constructed an analogue Fourier series analyzer to record harmonics of the evoked potential to flickering (sinusoidally modulated) light. This allowed him to demonstrate that the brain attained a steady-state regime in which the amplitude and phase of the harmonics of the response were approximately constant over time. These brainwaves responded to a visual stimulus modulated at a constant frequency are termed as steady-state visual evoked potentials (SSVEPs). According to most studies, SSVEPs can be recorded from the scalp over the visual cortex, as shown in Fig. 4, with maximum amplitude at the occipital region [16]. It has also been shown by electrophysiological experiments that neurons in human visual cortex synchronize their firing to the frequency of flickering light, leading to SSVEPs which contain sinusoids at the fundamental and harmonic frequencies of the flickering stimulus [17].

2) P300s: Evoked potentials are electrical responses of the human nervous system to sudden changes in the input. Sutton et al. in 1965 first found a new kind of evoked potential which is related to the uncertainty of the event [18]. This potential is a large positive deflection for event after event being presented about 300ms, and its amplitude increases with the degree of event's uncertainty. In 1970, Smith et al. named this component as 'P300' based on its polarity and relative fixed latency [19]. P300 wave can be recorded in midline centroparietal regions, prominently channel Pz, Fz, and Cz, and its latency varies from 300ms to 800ms [20]. As its amplitude is about 5-15uV which may be drown in the other signals, people always get it by averaging the signal of a certain time length after target stimulus for several times. A P300 is usually elicited if four conditions are met. First, a random sequence of stimulus events must be presented. Second, a classification rule that separates the series of events into two categories must be applied. Third, the user's task must require using the rule. Fourth, one category of events must be presented infrequently [21].

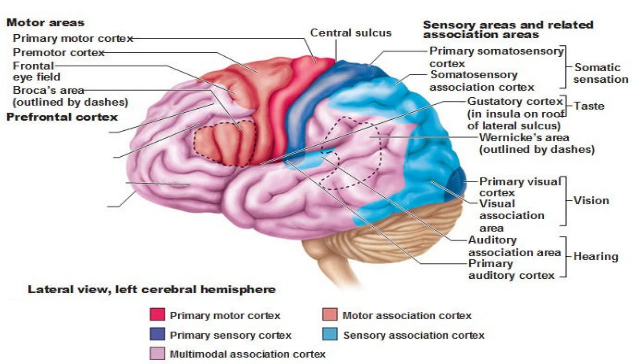
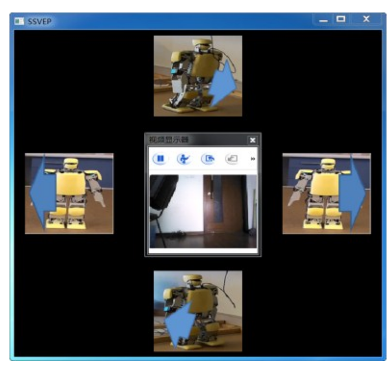


Fig. 4. Functional areas of cerebral cortex
(Available at http://antranik.org/functional-areas-of-the-cerebral-cortex/)

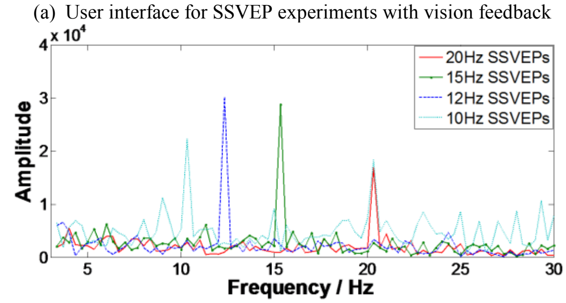
3) Mu/beta rhythms (also named motor imagery): Primary sensory or motor cortical areas of awake people, as shown in Fig. 4, often display 8–12 Hz EEG activity when they are not engaged in processing sensory input or producing motor output [13]. And it has also been demonstrated that the planning and execution of movement leads to predictable changes in the mu (8–12 Hz) and beta (13–28 Hz) frequency bands [22]. These rhythms that are produced by somatosensory or motor cortex and change with movement or imagination of movement are appropriate signal features for spontaneous brain-controlled humanoid robot applications.

B. Experiments and Results

The three types of brainwave-based models introduced above were utilized in our brainwave-controlled humanoid robot experiments both for off-line analysis of acquired neural signals and for on-line control of a humanoid robot. The



(a) User interface for SSVEP experiments with vision feedback



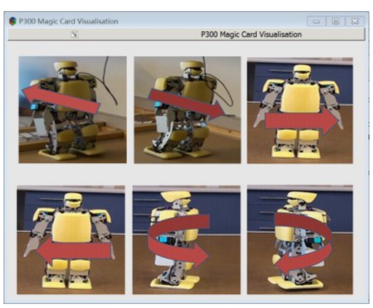
(b) Frequency spectrum of brainwaves from channel O2

Fig. 5. SSVEP interface and the acquired neural signals in frequency domain: (a) Four images representing different behaviors of humanoid robot are flickering at different frequencies. (b) When the subject stared at a specific image, the amplitude of his brainwave component at the flickering frequency and its harmonics are significantly prominent.

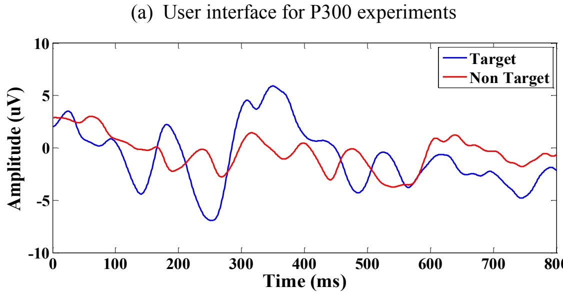
subjects try to control four behaviors of the humanoid robot (turning left, turning right, walking forward, and walking backward) through executing corresponding patterns of mental tasks. In off-line experiments, the subjects are instructed to execute a specific mental task, and the neural signals acquired during this period are recorded for later analysis. While in on-line experiments, the subjects are free to execute any one of the specific mental tasks spontaneously, and the neural signals acquired at real time is processed by the system to generate control commands for the desired robot behaviors. Figs. 5-7 show the user interfaces of the three models and their corresponding signal features acquired during our experiments.

For a SSVEP experiment, four images representing different robot behaviors flicker at steady but unique frequencies on the user interface, as shown in Fig. 5(a). When the subject selects a robot behavior to be executed by staring at its corresponding image, the system capitalizes on the magnification of amplitude at the same frequency and its harmonics, and determines the subject's direction of gaze relative to the flickering stimulus. The frequency spectrum of subject's brainwaves acquired when gazing on targets flickering at different frequencies is shown in Fig. 5(b). A video clip on the SSVEP model test can be found at http://v.youku.com/v_show/id_XNjA0MDUxMzYw.html.

For a P300 experiment, six images representing different robot behaviors flash successively but randomly at a rapid rate on the user interface, as shown in Fig. 6(a). The subject selects a robot behavior by focusing attention on its corresponding image and counting how many times it flashes. After averaging several evoked responses, the P300 component is

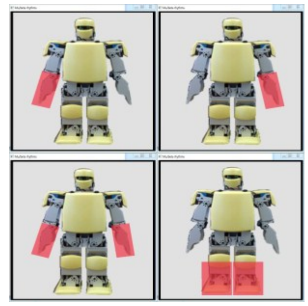


(a) User interface for P300 experiments

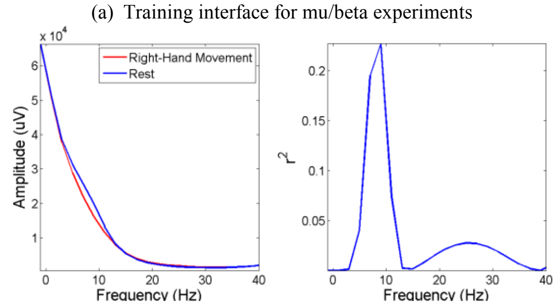


(b) P300 component recorded from the channel Pz

Fig. 6. P300 interface and the acquired neural signals in time domain: (a) Four images representing different behaviors of the humanoid robot are presented on the P300 interface randomly one at a time. (b) If the subject stared at a specific image, the brain signals recorded when this image is displayed (blue curve) have a larger positive deflection at about 300ms than signals recorded when the other images are displayed (red curve).



(a) Training interface for mu/beta experiments



(b) Signal features acquired from channel C3 under right-hand movement imagery conditions

Fig. 7. Training interface and the experimental results for Mu/beta model. (a)In the training period, one of the four images is displayed on the user interface. The subject is instructed to imagine the movement of left hand, right hand, both hands, or both feet corresponding to these images. (b) In the lower left window, power spectra of neural signals acquired from channel C3 are compared between resting (blue line) and imagining right-hand movement (right line). The lower figure is the corresponding r^2 spectrum for these two conditions where the difference in amplitude of mu and beta rhythms is clearly shown.

clearly extracted as in Fig. 6(b). The more detailed discussion on the P300 model is addressed in [23][24] and a video clip on the P300 model test can be found at http://v.youku.com/v_show/id_XNjAzNjE3Njc2.html.

For a mu/beta rhythms experiment, the subject is suggested to imagine the movement of a particular part of the body (left hand, right hand, both hands, feet) for control of the robot walking behaviors (turning left, turning right, walking forward, and walking backward correspondingly) during the training period. The designed images on the interface, as shown in Fig. 7(a), remind the subject to activate the corresponding mental activities. For the on-line tests, the subject is imagining any one of the above movements spontaneously to control the humanoid robot walking behavior. Fig. 7(b) shows the neural signals acquired during imagining right-hand movement for activating turning right behavior of the humanoid robot.

V. Conclusions and Future Works

This paper develops a brainwave-based control system for Cerebot. Under OpenViBE development environment, the control system integrates OpenGL, OpenCV, WEBOTS, Choregraph, Central software, and user-developed programs in C++ and Matlab. Cerebot is a powerful and flexible platform to investigate different brainwave-based models for control of the humanoid robot behavior. Compared with previous studies, our system has obvious advantages in scalability and control stability.

(a) Vision based feedback exploration and surveillance via brainwaves

(b) Vision based feedback control of NAO with obstacle avoidance in a cluster environment

Fig. 8. Walking behavior of NAO robot controlled via brainwaves

Three types of brainwave-based models: SSVEPs, P300s, and mu/beta rhythms, have been tested using this system for control of four robot walking behaviors. Fig. 8 shows the walking forward behavior of NAO robot controlled via brainwaves. The off-line analysis of acquired neural signals and the on-line control of humanoid robot demonstrate that the brainwave-based models developed in this paper work well. The video clips on navigating the NAO robot in a cluster environment and controlling the NAO robot exploration and surveillance via brainwaves can be found at http://v.youku.com/v_show/id_XNjA5ODI2MTk2.html and http://v.youku.com/v_show/id_XNjA5OTA5MDIw.html.

Our further research will report the evaluation results on the model based on imagination of robot behavior proposed in [10] under the OpenViBE development environment. In addition, the proposed control system will be considered to control rotorcraft or other physical devices.

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