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Remote Navigation of Turtle by Controlling Instinct Behavior *via* Human Brain-computer Interface

Cheol-Hu Kim[1], Bongjae Choi[2], Dae-Gun Kim[1], Serin Lee[3], Sungho Jo[2], Phill-Seung Lee[1]

1. *Department of Mechanical Engineering*, *Korea Advanced Institute of Science and Technology* (*KAIST*), 373-1 *Guseong-dong*, *Yuseong-gu*, *Daejeon* 34141, *Republic of Korea*
2. *School of Computing Science*, *Korea Advanced Institute of Science and Technology* (*KAIST*), 373-1 *Guseong-dong*, *Yuseong-gu*, *Daejeon* 34141, *Republic of Korea*
3. *Institute for Infocomm Research*, 1 *Fusionopolis Way*, #21-01 *Connexis* (*South Tower*) 138632, *Singapore*

Abstract

Brain-Computer Interface (BCI) techniques have advanced to a level where it is now eliminating the need for hand-based activation. This paper presents a novel attempt to remotely control an animal's behavior by human BCI using a hybrid of Event Related Desynchronization (ERD) and Steady-State Visually Evoked Potential (SSVEP) BCI protocols. The turtle was chosen as the target animal, and we developed a head-mounted display, wireless communication, and a specially designed stimulation device for the turtle. These devices could evoke the turtle's instinctive escape behavior to guide its moving path, and turtles were remotely controlled in both indoor and outdoor environments. The system architecture and design were presented. To demonstrate the feasibility of the system, experimental tests were performed under various conditions. Our system could act as a framework for future human-animal interaction systems.

Keywords: brain-computer interface, turtle (*Trachemys scripta elegans*), remote navigation, instinct behaviour, escape behavior

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1 Introduction

A repeated theme in fiction involves people imagining themselves in the body of another human or that of an animal. For example, the premise of the movie "Avatar" was that a human can exist in another body, with that body controlled by a remotely connected mind. Of course, we cannot expect to realize the technology described in the movie in the near future. However, recent advances in electronics and computer technology have allowed researchers to approach this appealing topic. A novel technique for interfacing between humans and machines, based on human thought or neural responses, has been developed. This development is called a "Brain-Computer Interface" (BCI). Using this technique, it is possible to read human thought and use that ability to control machines. Previous BCI studies have successfully controlled a humanoid robot[1–5]. Rao *et al.* demonstrated the possibility of sending information extracted from one brain directly to another brain through direct brain-to-brain communication[6]. Yoo *et al.* created a "Brain-to-Brain Interface" (BBI) system that combines a BCI with a "Computer-to-Brain Interface" (CBI) that could be used to establish a functional link between the brains of different species (*i.e.* humans and Sprague-Dawley rats)[7].

On the other hand, there have been several attempts to control animals by stimulation in order to draw on their high levels of locomotion and energy efficiency. In general, animals exhibit superior locomotion and survival abilities as a result of their adapting to the environment over millions of years. Therefore, their bodies are optimized in terms of locomotion and energy efficiency.

Some researchers have tried to control animal movement by applying invasive control methods. Daly

Corresponding author: Sungho Jo, Phill-Seung Lee
E-mail: shjo@kaist.ac.kr, phillseung@kaist.edu
Cheol-Hu Kim and Bongjae Choi contributed equally to the work

et al. designed a wireless flight control system for moths that consisted of a 3 GHz to 5 GHz non-coherent pulsed ultra-wideband receiver system-on-chip[8]. Sato and Mahabiz proposed a beetle flight control system which provided electrical stimuli to the beetle's wing muscles[9]. Tsang *et al*. suggested the possibility of the remote flight control of a moth by using micro-fabricated Flexible Neuroprosthetic Probes (FNPs)[10]. Sun *et al*. proposed the automatic navigation of rat-robots using the General Regression Neural Network (GRNN) method[11]. Sanchez *et al*. designed hybrid cockroach robots which applied electrical stimuli to the prothoracic ganglia *via* a remotely operated backpack system and implanted electrodes[12].

There have also been studies for controlling an animal's movement through non-invasive control methods. Holzer and Shimoyama proposed a bio-robot system for controlling an insect (*Periplaneta Americana*) with electrical stimuli[13]. Butler *et al*. suggested a virtual fence system for containing cattle that used sound stimuli[14]. Britt *et al*. were able to navigate a well-trained dog using commands provided through wireless devices[15]. Lee *et al*. succeeded in controlling an untrained turtle's walking paths by inducing obstacle-avoidance behavior[16]. Pi *et al*. proposed a non-invasive remote control system for rat-robot *via* ultrasonic, epidermal and LED photic stimulators[17].

Using the technologies mentioned above, it is possible to develop a system to control an animal's behavior using human BCI technology. To realize this, however, the system architecture and interfacing techniques require further development. In this paper, we propose a conceptual system that is capable of remotely guiding an animal's moving path by controlling its instinctive behavior (*e.g*. escape behavior) using a simple stimulation device controlled by a human's brain signals. As the target animal, the turtle was chosen because it has good cognitive abilities, is capable of distinguishing the wavelength of visible light[18]. It is known that turtles recognize a white light source as an open space and so move toward it[19,20]. Also, turtles show specific avoidance behavior patterns by external visual obstruction[16]. Further, it has a hard shell on which devices can be mounted. Also, our objective was to invoke instinctive behavior, specifically, the escape behavior that induces the operant responses that cause the animal to move away from an ongoing punishing or obstructing stimulus. In particular, this reactive behavior is connected to those instincts which protect the body and which must be evoked and directed in a consistent manner by a stimulus[21–23]. In our previous research, this instinctive behavior was utilized to control the turtle's path. As a result, coherent patterns in the turtle's trajectory were observed[16].

In our concept system, a Head-Mounted Display (HMD) is adopted as the user interface. The combination of the wearable BCI and HMD enables users to become more immersed in the control of the turtle. The human operator wears the integrated BCI-HMD system, while the turtle is equipped with devices for stimulation, wireless communication, and imaging. Based on the images acquired from the cyborg turtle, the human uses thought to command the turtle. These thought commands are recognized by the wearable BCI system. Using Wi-Fi, these commands are transmitted to a stimulation device attached to the turtle's upper shell. Then, the turtle is induced to move by the stimulation device that invokes the turtle's instinctive behavior. Finally, the human acquires updated visual feedback from the camera mounted on the turtle's upper shell. In this way, the human can remotely navigate the turtle's trajectory.

To check our system's operability and applicability, three tests were conducted in both indoor and outdoor environments. An indoor test was performed to confirm the responsiveness of the stimulation device and to check the basic operability of the cyborg system. Outdoor tests were also performed to check the availability and applicability of the system under real-field conditions. All of the tests were successfully implemented and the results were found to point to the usefulness of the concept system for extended applications in a real environment.

2 System

2.1 System architecture

The principal objective of the proposed system is to provide a control feedback loop for remotely guiding a turtle by means of human thought alone. To close the loop, the human operator is provided with visual information (such as a real-time video stream) from the cyborg turtle that he or she is controlling.

Fig. 1 illustrates the architecture of our proposed system. The overall system consists of two main

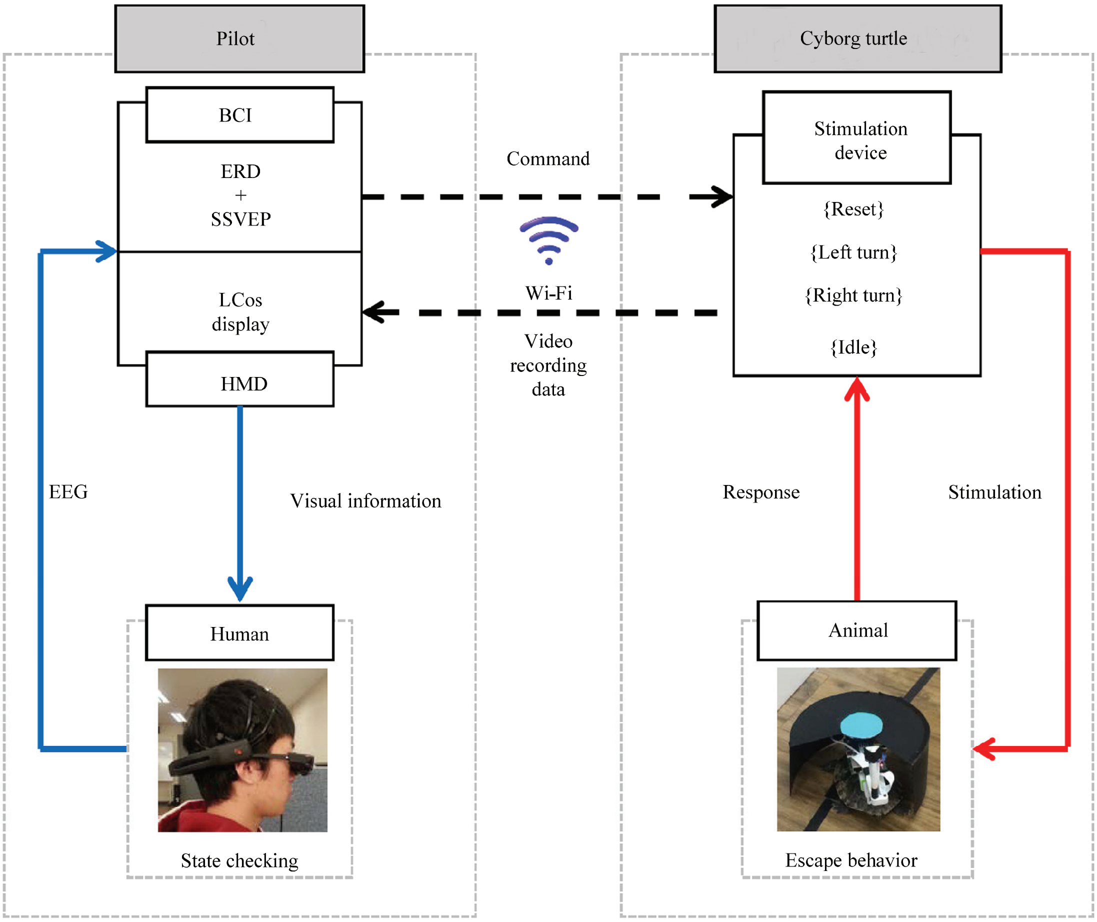

Fig. 1 Architecture of the remote navigation system for turtle with human BCI.

subsystems: the pilot and cyborg turtle. The pilot part consists of a BCI device, a HMD, and a human subject. The cyborg turtle part consists of a stimulation device with telecommunication services, a video recording system, and the animal subject (turtle).

The overall procedure was as follows. In the first instance, the human and the turtle are fitted with their respective devices (BCI device, HMD, and stimulation device). Then, through the HMD, the human views the image being captured by the camera attached to the cyborg turtle. Based on this visual information, the human provides electroencephalography (EEG) signal orders to the BCI system. Using Wi-Fi communication, the BCI system passes the commands to the stimulation device to control the turtle's moving path by inducing its escape behavior in response to the human EEG signals. As the turtle is responding to the stimulation device, the attached camera records the turtle's field of view and sends the captured images back to the human's HMD in real-time. By viewing this visual feedback, the human operator understands the progress of the turtle's motion and then issues BCI commands again. This procedure is repeated until the turtle arrives at the desired position or completes the assignment.

In particular, instead of a direct connection between the human and the animal brains or nerves (*e.g.* BBI), our animal control system relies on the animal's instincts, namely, its escape behavior. Through the use of this scheme, our system offers advantages in terms of adaptability and usability in comparison with a direct connection due to its simple and non-invasive devices.

2.2 BCI System

An EEG-based BCI system was used for the guidance of the turtle by human thought. EEG signals have been studied because they have several practical advantages over other brain signal modalities[24,25]. Preconditions for the practical usage of BCI system are inexpensiveness, compactness and usability of the acquisition devices. Invasive brain signals and several non-invasive brain signals, such as magnetoencephalography (MEG) and functional magnetic resonance imaging (fMRI), do not satisfy these conditions. Compared with functional near-infrared spectroscopy (fNIRS), which offers an inexpensive, portable and practical alternative to fMRI, an EEG has a much better temporal resolution, but the spatial resolution is poor. EEG signals are generally more suitable for controlling tasks using BCI due to higher temporal resolution and rapid electrical response to neuronal activity.

We adopt the hybrid Event Related Desynchronization (ERD) and Steady-State Visually Evoked Potential (SSVEP) based BCI system which successfully demonstrated the humanoid robot navigation using human though[3]. It can discriminate three mental states; <left>, <right>, and <ERD> with an idle state. The BCI system determines a command every 250 ms. We introduced a control algorithm to guide the path of the turtle using these three commands.

The reactive SSVEP-based BCI is based on brain responses to visual stimulation at specific frequencies. The <left> and <right> commands indicate that the brainwaves acquired from the visual cortex are synchronized with the left and right SSVEP flickering stimuli, respectively. The <left> and <right> commands are used to turn the black semi-cylinder with a slit (the turtle stimulation device) on the turtle in the selected direction by 12 degrees per decision. The maximum range through which the semi-cylinder can be moved is ±36˚.

Since our approach relies on the animal's instinct behavior, the human subjects do not need to command to the turtle continuously during navigation. The stimulation device on the turtle induces its instinct behavior consistently until another command is received. In other words, the human subjects do not need to provide ongoing BCI commands, which would be annoying and fatiguing for the users[26]. Therefore, we needed a means of activating the visual stimuli only when users needed it. To solve this problem, we introduced the brain switch approach of a hybrid BCI system. The hybrid BCI utilizes a combination of two or more BCIs to take advantage of the benefits of each protocol. A typical hybrid BCI system is used to improve the accuracy of classification and distinguish more mental states[27]. Another approach to hybridization, called brain switching, is to turn off a BCI when the user does not intent to communicate[26]. It reduces the false positive rate of the BCI system and minimizes the fatigue of the user from the stimuli of reactive BCI.

In this study, an ERD-based BCI was used to control the stimuli of an SSVEP-based BCI. The state transition diagram of the ERD-based brain switch to turn on/off the SSVEP BCI is shown in Fig. 2a. In this case,

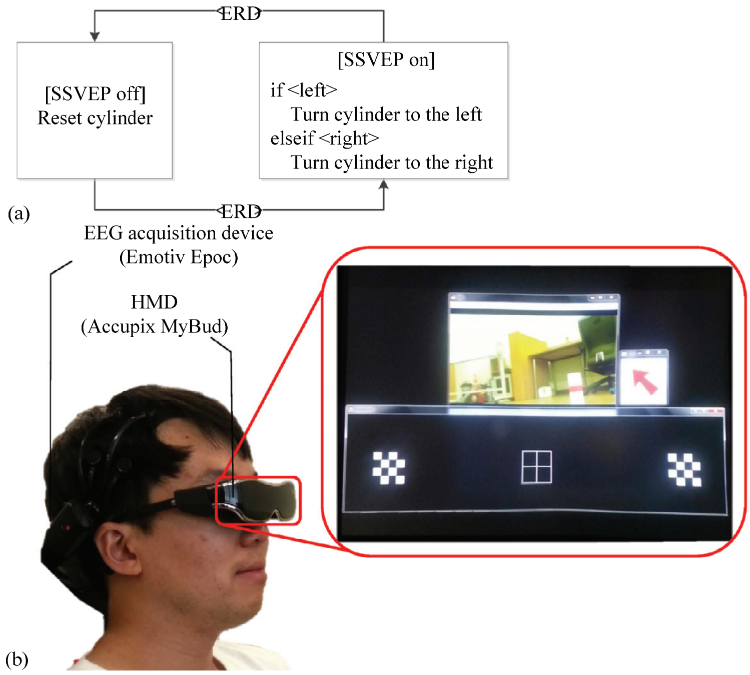

Fig. 2 Depiction of the BCI system. (a) Proposed control algorithm for controlling the cyborg turtle; (b) the human pilot remotely controls the cyborg turtle through the BCI and HMD. The user interface is displayed on the HMD and consists of a flickering checker board, direction arrow, and video player.

<ERD> serves as a brain switch. The <ERD> command is issued when the BCI system detects specific motor imagery from the subject. Whenever the ERD-based BCI translates the <ERD> commands, the state of the BCI system is changed. If the visual stimuli are flickering, the system turns them off and then resets the angle of the slit of semi-cylinder. Otherwise, the system turns on the visual stimuli for SSVEP-based BCI. The SSVEP flickering stimuli are initially turned off. This state transition paradigm allows the subject to take his or her attention off the system. As such, it can increase the usability of the system and minimize the fatigue of the human subject.

In our experiment, the subject sat comfortably and wore the HMD and EEG acquisition device. The subject obtained visual feedback from the environment surrounding the cyborg turtle. The real-time video stream from the camera attached to the turtle was displayed in the HMD at 15 fps. The video stream used the Real-Time Streaming Protocol (RTSP) and thus incurred a very slight delay of 0.5 s to 1.0 s, depending on the quality of the Wi-Fi signal. To provide visual feedback, the commands translated by the BCI system, as well as the current angle of the semi-cylinder, were also displayed. Fig. 2b illustrates how the subject remotely controlled the cyborg turtle through the BCI system described above.

3 Materials and methods

3.1 Subjects

3.1.1 BCI subjects

Five healthy male subjects (age 29 ± 3 years) voluntarily participated in our experiment. All of the subjects were of the same gender (male), were of the same laterality (right-handed), and were free of neurological diseases. They provided their written informed consent.

The BCI experiments were approved by the Korea Advanced Institute of Science and Technology (KAIST) Institutional Review Board (Permit Number: KH2014-08) and our personal experiment qualification certifications are: Bongjae Choi (K-2014-12526414), and Sungho Jo (K-2012-9135188).

3.1.2 Animal subjects

The turtles used in this study were red-eared slider (*Trachemys scripta elegans*). Four turtles were grown indoors in the laboratory at KAIST to a size of 15 cm to 20 cm. They were housed in a glass tank (91 cm × 61 cm × 20 cm) with oxygenated freshwater with a recycling system and a dry platform for basking. The water temperature was maintained at 20˚ to 25˚ Celsius. The turtles were provided with UV light for basking for 6 h to 7 h per day, and fed commercial pellets four times a week.

The animal experiments were approved by the KAIST Institutional Animal Care & Use Committee Board (Permit Number: KA2014-26) and the personal certification numbers are: Cheol-Hu Kim (2010-OE01), Dae-Gun Kim (2011-OE01), Bongjae Choi (2014-CS03), Sungho Jo (2014-CS01) and Phill-Seung Lee (2014-OS01). Our target animals (turtle: *Trachemys scripta elegans*) were manipulated in strict accordance with the KAIST Animal Experiment Ethical Law RR0303 (revised 24/07/2013) and all efforts were made to minimize the suffering.

3.2 Apparatus

3.2.1 Human

EEGs were recorded using a wearable EEG acquisition device (Epoc neuroheadset, Emotiv Inc., USA)[28]. This is a consumer-level EEG acquisition wireless headset which can acquire brain signals at a sampling frequency of 128 Hz through 14 channels, namely, AF3, AF4, F3, F4, F7, F8, FC5, FC6, P7, P8, T7, T8, O1 and O2, which are designated according to the 10-20 system. The headset's ease of use, portability, and simplicity of operation made it very attractive for application to this study. In a previous study[3], we proposed a successful SSVEP/ERD hybrid BCI system with which we navigated a humanoid robot using this device.

We also adopted an HMD system (MyBud, Accupix Co., Ltd., Korea)[29]. It consists of an 852 × 480 (WVGA) liquid crystal on silicon (LCoS) display in front of each eye. It has a refresh rate of 60 Hz, a separation distance of 20 to 30 mm, and weighs 78 g. The Field Of View (FOV) is 35 degrees diagonally. The HMD display was thus perceived as a 100 inch screen at a distance of 4 m from the subject. This was used to provide the subject with a more realistic view of the environment during navigation. Faller *et al.*[30,31] reported that SSVEP-based BCI can be successfully implemented in a virtual environment when combined with an HMD. Fig. 2b shows the interface devices used by human subjects during the experiment. The subjects communicated with the turtle through the EEG acquisition device and the HMD.

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

3.2.2 Turtle

We designed a simple stimulation device to induce the turtle's escape behavior. It is well known that animals move away from an external obstruction by instinctive escape behavior[22,23]. Through our previous research, we observed the turtle's specific behavior pattern, namely, that it recognizes a black object as an obstacle and turns toward open space[16]. Based on these findings, we designed a stimulation device for the turtle. The stimulation device and embedded control module (8.6 cm × 5.4 cm × 5.5 cm, 171.5 g) was mounted on the turtle's upper shell. It consisted of a servo-motor and a black semi-cylinder with a slit to restrict the turtle's view (Fig. 3). By adjusting the orientation of the slit, we could guide the turtle's moving path.

The embedded control module was based on the Raspberry Pi single-board computer with a Broadcom BCM2835 system on a chip (SoC), a Video Core IV GPU, 512 MB of RAM, and a 16 GB SD card. This

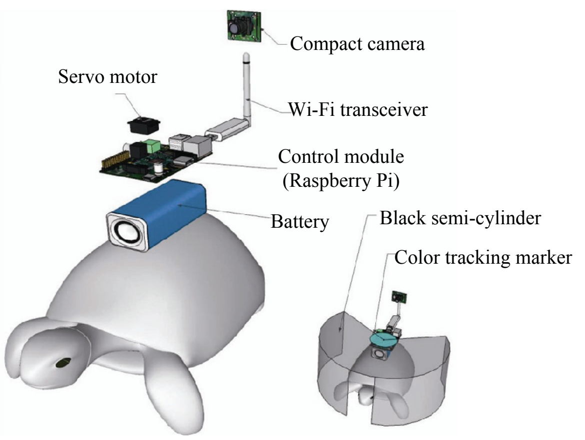

Fig. 3 Depiction of cyborg system. The embedded control system used to induce the turtle's escape behavior is shown in the drawing. The device consists of a main computer (Raspberry Pi), servo motor, battery, Wi-Fi transceiver, compact color camera, and semi-cylinder with a slit. The servo motor controls the positioning of the slit in the semi-cylinder (in the image, it is positioned directly in front of the turtle). The blue circle on the controller was tracked by a simple tracking algorithm and was regarded as indicating the location of the turtle.

embedded module was connected to a servo motor which moved the stimulation semi-cylinder, as well as a 2600 mAh Li-Po battery. Altogether, the device weighed 171.5 g, with the embedded control module weighing 85 g and the battery 86.5 g.

The controller unit received an angular value to control the servo motor, thus rotating the black semi-cylinder with the slit through ± 36˚ with respect to the turtle's body axis, from the PC control software *via* a Wi-Fi connection. The user sent <left>, <right> and <ERD> commands remotely through the BCI sensor on the human BCI headset. The embedded control module on the turtle's upper shell demodulated the signal and then passed it to the servo motor. The turtle's field of view was recorded using a compact color camera (2592 × 1944 pixels) mounted on the turtle's upper shell. The captured video stream data was returned to the human's HMD, again through the Wi-Fi connection. All of the devices attached to the turtle were waterproofed to allow their application to the outdoor field tests.

3.3 Experimental setup

3.3.1 EEG BCI training

To translate the human subject's thoughts to commands, the following procedures were performed to build a training dataset for the SSVEP/ERD hybrid BCI system.

First, we set two flickering stimulus frequencies, each corresponding to either the left or right commands for the SSVEP-based BCI protocol. The stimulus frequencies were selected from 6.67 Hz, 7.5 Hz, 8.57 Hz, 10 Hz, 12 Hz, 15 Hz, or 20 Hz because of the characteristics of the acquisition device and the LCD display. These frequencies were determined by empirical pre-tests for each subject. In this study, checkerboard visual stimuli were used to evoke the SSVEP. The subjects were asked to look at each visual stimulus for 5 s. These trials were repeated a total of 10 times. Then, a dataset for each 2 s time window with 250 ms increments was obtained. SSVEP features based on Canonical Correlation Analysis (CCA)[32] were used to train a linear Support Vector Machine (SVM) classifier.

For the ERD-based BCI protocol, EEG signals were recorded while each subject remained at rest for 5 s and imagined a specific motor imagery for 5 s. Each subject selected their own motor imagery. Each subject repeated this 10 times. Then, again, a sliding window of

Table 1 Cross-validation accuracy results and the Information Transfer Rates (ITR) for each protocol

Subject	A	B	C	D	E	Overall (± Std)
ERD cross-validation accuracy (%)	93.3	94.2	85.0	95.4	88.3	91.2 (± 4.4)
ERD ITR (bits per min)	19.3	20.4	11.7	21.9	14.4	17.5 (± 4.3)
SSVEP cross-validation accuracy (%)	90.4	80.8	94.2	91.2	92.7	89.9 (± 5.3)
SSVEP ITR (bits per min)	16.3	8.8	20.5	17.1	18.7	16.3 (± 4.5)
Flickering stimuli frequencies (Left, Right) (Hz)	10, 12	10, 12	15, 20	12,15	10, 12	

2 s with 250 ms increments was obtained. The Common Spatial Pattern (CSP) algorithm[33] was used to extract the features needed to train a linear SVM classifier.

A tenfold cross-validation was assessed to evaluate the classification performance. Table 1 summarizes the cross-validation accuracy results and the Information Transfer Rates (ITR) for each protocol.

The ERD-based and SSVEP-based BCI protocols achieved an overall accuracy of 91.2% and 89.9%, respectively. The ITRs of the ERD-based and SSVEP-based BCI protocols were 17.5 and 16.3 bits per min, respectively. The worst performer in terms of the ERD cross-validation accuracy was subject C who achieved 85.0%. With SSVEP, subject B produced the worst result of 80.8%. After confirming the classifiers for the SSVEP- and ERD-based protocols, the hybrid classifier for the SSVEP- and ERD-based protocols was built as described in Ref. [3]. The average accuracy for the five subjects was 77.1 (± 3.2) %. The worst performer was subject A, whose accuracy was 75.2%, while subject D achieved the highest accuracy of 82.3%.

3.3.2 Indoor test

This test was implemented on the floor of the laboratory (Fig. 4a). We placed four waypoints (white, red, yellow, and black) at each corner of the test area. The turtle's responses, that is, its navigational paths were continuously recorded by a simple color-based tracker. To ensure that the turtles would only be affected by our stimulus, other possible stimuli (olfactory and auditory stimuli, room temperature, brightness, *etc*.) were all controlled during the tests.

Each turtle's path was tracked by an experimental camera and a color-based tracker based on a MATLAB (The Mathworks Inc., USA) image processing program developed by Matpic. During the experiments, a Kalan filter with linear models was used to describe the turtle's trajectory.

3.3.3 Outdoor test

This test was performed in a natural environment that was 5 km distant from the human pilot. Because this test was done outdoors, it was not possible to control the stimuli factors described for the indoor trial during the test. As shown in Fig. 4b, the start/end position and artificial obstacles were set on an uneven lawn. Again, the tests were recorded using the color-based tracker.

3.3.4 Field test

This test was implemented in a natural field with a range of geomorphological conditions. In this test, we assigned the cyborg turtle a mission in more demanding

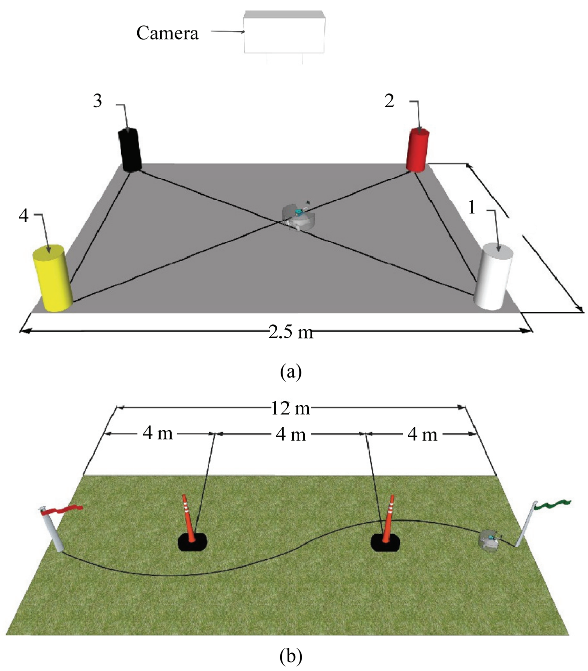

Fig. 4 Experimental setups. (a) An indoor test was performed on the laboratory floor (of the dimensions indicated), as shown in the drawing. The placement of the cyborg turtle, waypoints 1 to 4, and the tracking system (camera) are shown; (b) an outdoor test was performed on a lawn (of the dimensions indicated), as shown in the drawing. The placements of the cyborg turtle, start/end position, and artificial obstacles are shown. Note particularly that this area was 5 km distant from the pilot, to test the teleoperation performance.

outdoor real-field conditions. Three mission points were set between the start and end positions. We placed a mission card at each mission point, in alphabetical order. The intention was for the cyborg turtle to capture an image of the printed letter at each mission point using the compact color camera mounted on its upper shell. During the test, we also recorded the turtle's path using color tracking.

4 Results

4.1 Indoor test

In this test, we verified how the turtles respond to stimulation device and checked the operability in greater detail. Fig. 3 illustrates the overall design of the cyborg turtle. The simple device was designed to position the black semi-cylinder (radius = 22 cm, height = 10 cm) at any specific angle in the turtle's line of sight. The slit at the centre of the circumference can thus be varied from +36˚ to −36˚ in the clockwise direction, relative to the anteroposterior axis of the turtle. Since the turtle shows little response to light emanating from ±180˚[18], it moves towards the slit.

In Fig. 4a, the cyborg turtle moved within a 2.5 m × 1.5 m area in which there were four waypoints and an 8.83 m optimal path which is a straight line between the waypoints. The turtle passed through the four waypoints in order and then came back to the first waypoint. The pilot was able to guide the turtle to approach each waypoint with an accuracy of about 15 cm, based on the visual feedback information. Each experiment was performed for 5 to 10 minutes and then repeated five times per person.

As shown in Fig. 5, all of the subjects attained successful navigation trajectories, passing through all of the waypoints without any omissions. During the experiment, there were several cases where the turtle would not move from the start point due to fatigue. These cases were excluded from consideration, and we allowed the subject turtle to rest, replacing it with another. Also, for such experiments, we calculated the average travel time, travel distance, speed, and Cross-Track Error (CTE, the minimum distance between the optimal path and the actual position) of the turtle from each trajectory to check the operability (Table 2).

The average travel time and distance were found to be 538.4 s and 907.5 cm, respectively. The average speed of the cyborg turtle was 1.84 cm·s^{-1}. The average CTE over the five subjects was 24.45 cm. This value means that an average error of 24 cm was incurred between the cyborg turtle and the optimal track position.

The worst performer was subject B whose CTE was 28.37 cm while subject D (who achieved the highest accuracy in the EEG BCI training) achieved the lowest CTE of 18.41 cm. The difference between the two was 9.96 cm (relative error: 35.1%). Also, a comparison between the speed of an unstimulated turtle (2.53 cm·s^{-1}) and our average speed (1.84 cm·s^{-1}), revealed a difference of only 0.69 cm·s^{-1} (relative error: 27.3%) between them.

4.2 Outdoor test

This test was designed to check the availability of our system when faced with outdoor conditions. In addition, to test the teleoperation performance, the test area was set up 5 km away from the pilot. Fig. 4b illustrates the outdoor test area. The straight line distance between the start and end positions was 12 m. In Fig. 6, the cyborg turtles successfully reached the desired location by following an S-shaped curve in spite of the changing environment and telecommunication condition. The average travel time and speed of the turtles were measured and found to be 430.4 s and 1.80 cm·s^{-1}, respectively. These figures were very similar to those attained in the indoor test (1.84 cm·s^{-1}).

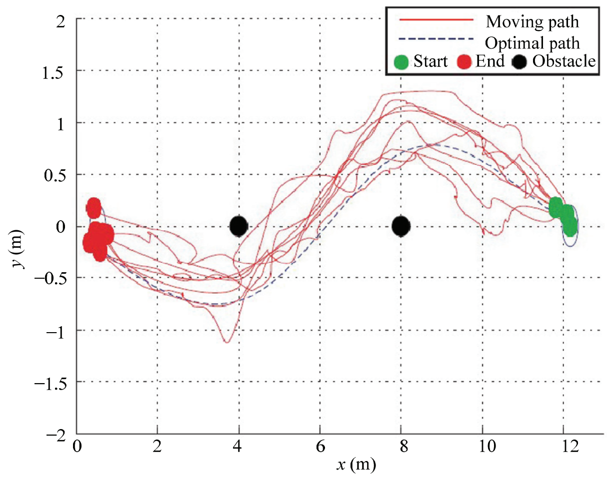

Fig. 5 Controlled trajectories of the cyborg turtles with each human pilot. The cyborg turtles were remotely controlled to move between waypoints through the alternate provision of stimuli that invoked the escape behavior (see text). The optimal (blue) and actual (red) paths of the turtles are plotted. Each test was repeated five times per person, although the turtle subjects were changed. Despite the changes in the human and turtle subjects, each red path passes through all of the waypoints without any omission.

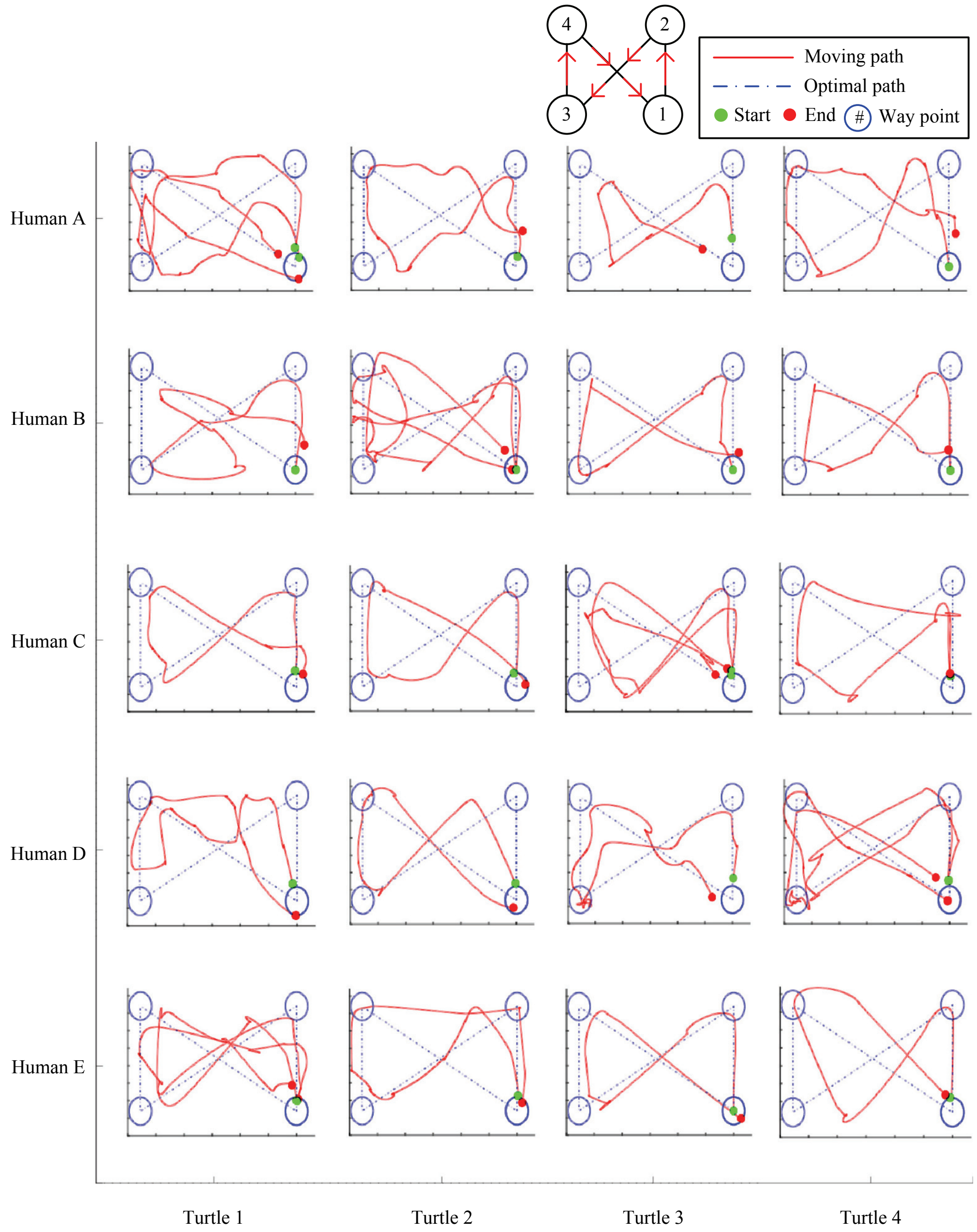

Fig. 6 Results of the outdoor test. Trajectories of the cyborg turtles in outdoor test. The experiment was performed on an uneven lawn. The paths followed that of the pilot's intention.

Table 2 Results of the indoor test

Subject	A	B	C	D	E	Total
Average travel time (s) (± Std)	497.2 (± 189.2)	758.6 (± 141.3)	531.6 (± 69.2)	425.2 (± 64.5)	479.4 (± 83.3)	538.4 (± 166.2)
Average travel distance (cm) (± Std)	911.1 (± 3.0)	911.5 (± 14.5)	908.4 (± 10.4)	901.5 (± 10.4)	905.3 (± 9.6)	907.5 (± 10.9)
Average speed ($cm{\cdot}s^{-1}$) (± Std)	2.07 (± 0.63)	1.27 (± 0.34)	1.74 (± 0.26)	2.17 (± 0.35)	1.95 (± 0.38)	1.84 (± 0.52)
Average CTE (cm) (± Std)	27.99 (± 3.00)	28.37 (± 14.52)	25.32 (± 10.36)	18.41 (± 10.35)	22.17 (± 9.59)	24.45 (± 10.92)

Optimal travel distance = 883.10 cm
Average speed of comparison group (unstimulated turtle) = 2.53 (± 0.42) $cm{\cdot}s^{-1}$

During the tests, we sometimes remotely waved the black semi-cylinder to encourage an immobile turtle to move. Also, during early trials with the system, there were several cases where the equipment failed. These failures were typically caused by a Wi-Fi communications problem or the battery becoming dislodged. If the equipment failure interfered with the turtle, that trial was excluded from consideration.

4.3 Field test

To examine the applicability of the proposed system, we operated it in an actual field. Fig. 7a shows the conditions presented by the experimental field and the path followed by the turtle. The turtle covered a 40 m route that presented various geomorphological conditions (gravelly field, soil, lawn-like surfaces, shallow-water hazards, *etc.*) and natural obstacles. As shown in Fig. 7b, despite the relatively rugged geomorphological conditions, the cyborg turtle was able to carry out the assigned mission and successfully captured images at three mission points. The total travel time was 2436 s and the average speed was 1.64 cm·s^{-1}. There was a 0.16 cm·s^{-1} (relative error: 8.89%) drop in speed relative to that attained in outdoor test (1.80 cm·s^{-1}) and 0.2 cm·s^{-1} (relative error: 10.9%) relative to the indoor test (1.84 cm·s^{-1}). If we look at the zonal speeds, the turtle achieved 1.34 cm·s^{-1} in the gravelly field, 1.42 cm·s^{-1} over soil, 1.81 cm·s^{-1} on the lawn, and 1.49 cm·s^{-1} in the shallow water hazard.

5 Discussion

We performed three kinds of test to verify the remote navigation system for a turtle with a human BCI controller. An indoor test was done to check the operability of our system (Fig. 5 and Table 2). In particular, the calculated CTE of navigation paths was only 2.77%

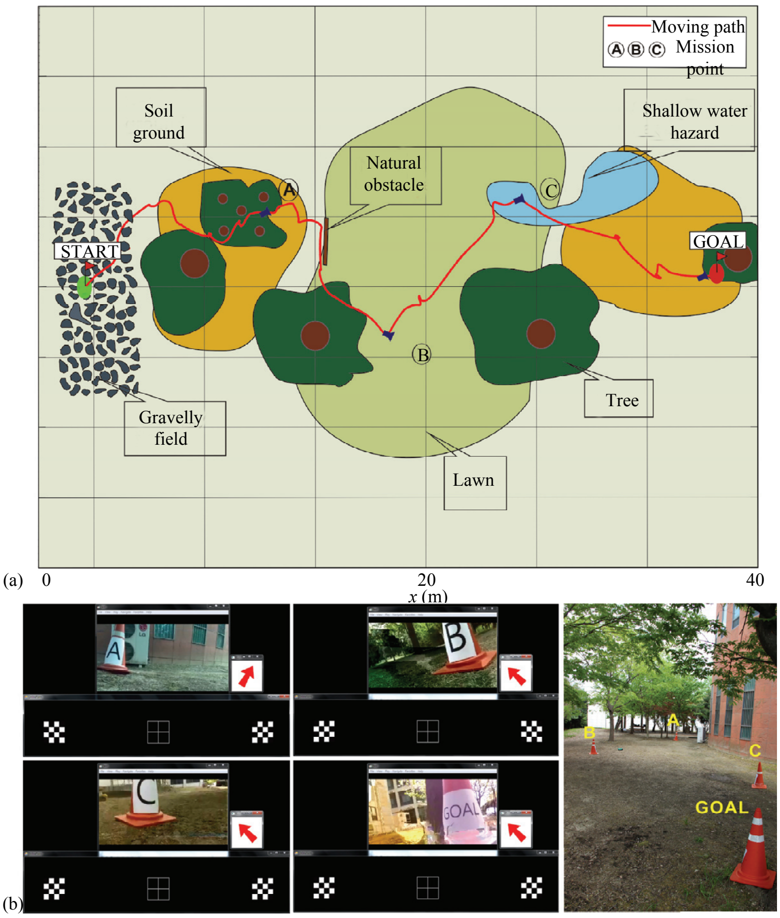

Fig. 7 Results of the field test. (a) The cyborg turtle's trajectories when traversing a range of geomorphological conditions (gravelly field, soil/dirt field, lawn, treed and shallow water hazard) and natural obstacles; (b) the letters were recorded by the cyborg turtle's camera at each mission point. Also, the flickering checker board for the SSVEP-based BCIs is located at the bottom of the screen. The <left> and <right> commands indicate that the brainwaves acquired from the pilot's visual cortex are synchronized with the left and right SSVEP flickering stimuli, respectively, provided by these checker boards.

in the 8.83 m track. Then, two outdoor tests were implemented to show the applicability under more complicated natural environment conditions and performed through long-distance (5 km) wireless real-time remote control (Figs. 6 and 7). The results of these three tests showed that our turtle navigation system can be operated successfully under a wide range of environmental conditions. In particular, the field test showed that our animal guiding scheme is still valid in outdoor conditions, and it demonstrated the feasibility of navigation applications, such as mobile robots.

To obtain higher operability of the proposed system, further experiments for augmenting the accuracy of the guidance systems can be performed. The major trajectory errors come both from fatigue and external stimuli of the turtles, and the misclassification of the BCI system. In order to investigate these errors, additional cross-check methodologies might be necessary to distinguish which factors are more influential in the operability. For an example, the guidance through manual controls, such as keyboard inputs, might be able to resolve the false-positives from the BCI controller. Also, it is possible to perform the experiment with a mobile robot, removing unexpected behaviors by turtles' instincts. Such cross-check methods are able to determine the source of the error in the current system.

Our proposed system constitutes an innovative approach to constructing a human-animal interaction system. Through a combination of simple BCI protocols, we provide orders to control the subject turtle by means of human thought alone. In BCI research as well as the animal control research field, this is a very meaningful result. Firstly, by inducing instinctive escape behavior, our system can control the movement of a living animal and perform a particular mission while minimizing the danger to the animal. That is, a non-invasive method was used. A disadvantage is that relatively large devices are required compared to small implanted devices used in invasive methods[8–12]. Secondly, this research widens the range of application of BCI through the success of controlling animal behavior using human BCI techniques. Thirdly, our wearable devices are more accessible than existing BCIs or animal control devices. Finally, unlike previous attempts including our previous study[8–17], we evaluated the applicability of our system not only in an indoor but also in outdoor conditions.

In the future, with the development of BCI technology and an enhanced HMD system, our system can be further improved in terms of its adaptability and usability. Moreover, we expect that more effective animal control systems will integrate a positioning system and improved Augmented Reality (AR)/Virtual Reality (VR) techniques. Therefore, we could apply this animal control framework to other animals (such as rats, pigeons, *etc*.) with more research into their behavior. Our system allowed us to attain a wider range of experience and information from different species of controlled animals. In future work, we plan to study the behavior of other animals in more detail and then apply our framework to them.

Meanwhile, from an application viewpoint, this system could be used in exploration or navigation applications like robotic probes. Through a connection with animals which live in various environments (*e.g*. underwater or in hazardous areas), a user could acquire valuable visual information by using controlled animals. Also, this concept system could have military applications such as reconnaissance and surveillance. In the BCI area, this system could be used in unconventional applications such as immersive virtual reality systems that give the user a sense of oneness with the controlled animal, as if it were their surrogate agent.

6 Conclusion

In this paper, we proposed an animal remote navigation system using a human BCI. We selected the turtle as the first target animal and developed the human-turtle interaction system. Using the turtle's escape behavior pattern and an ERD-/SSVEP-based BCI system, we could guide the turtle's moving path according to the human brain signal. To demonstrate the feasibility of the proposed system, three kinds of experiments (indoor, outdoor and field tests) were implemented. The results showed that the proposed system could be operated well in real-time conditions, and the animal guiding scheme can be used in outdoor applications. This study was the first attempt to remotely guide the moving path of animals through a human BCI controller. In the future, our system could be developed with a positioning system, AR/VR techniques, and enhanced BCI technologies. We expect that our technology will inspire the development of an innovative framework for human-animal interaction systems.

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