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Ph. D. Dissertation

자발적 본능행동 제어를 통한 거북과 잉어 원격 유도 시스템 개발

Remote guidance system for turtle and carp by controlling voluntary instinctive behavior

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School of Mechanical and Aerospace Engineering

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by

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A thesis submitted to the faculty of KAIST in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Mechanical Engineering. The study was conducted in accordance with Code of Research Ethics[1]

November 16, 2015
Approved by
Professor Phill-Seung Lee

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[1]Declaration of Ethical Conduct in Research: I, as a graduate student of KAIST, hereby declare that I have not committed any acts that may damage the credibility of my research. These include, but are not limited to: falsification, thesis written by someone else, distortion of research findings or plagiarism. I affirm that my thesis contains honest conclusions based on my own careful research under the guidance of my thesis advisor.

Remote guidance system for turtle and carp by controlling voluntary instinctive behavior

Cheol-Hu Kim

The present dissertation has been approved by the dissertation committee as a Ph. D. dissertation at KAIST

November 16, 2015

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ABSTRACT

Recently, several studies have been carried out on the direct control of behavior in insects and other lower animals in order to apply these behaviors to the performance of specialized tasks in an attempt to find more efficient means of carrying out these tasks than artificial intelligence agents. In this dissertation, we selected turtle and carp as the animal platform, and examined obstacle avoidance and escape behavior, which are one of the typical reactive behaviors, to control their moving path. Furthermore, we suggest novel remote guidance system that based on our research findings and also check operability and applicability of this suggested system through various tests. In the future, we expect that our technology will become an innovative framework for human-animal control systems.

Keywords: Remote guidance system; Behavioral biology; Turtle (*Trachemys scripta elegans*); Carp (*Cyprinus carpio)*; Instinctive behavior

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Chapter 1. Introduction

Recently, several studies have been carried out on the direct control of behavior in insects and other lower animals in order to apply these behaviors to the performance of specialized tasks in an attempt to find more efficient means of carrying out these tasks than artificial intelligence agents.

While most of the current methods cause involuntary behavior in animals by electronically stimulating the corresponding brain area or muscle. However, these methods are not suitable for long-term or long-range operations because they cause involuntary behavior by direct stimulation of the corresponding musculature or brain by an implanted controller which is very complicated, and damage the controlled animals.

So through this study, we show that, in turtles and carp, it is also possible to control certain types of behavior (such as movement trajectory) by evoking an appropriate voluntary instinctive behavior. Among the voluntary instinctive behaviors, a reactive behavior is one of the essential behaviors of organisms to protect their body. Such behavior must occur fast, but also be mediated, planned, and directed by a stimulus. As a result, if any animal does not exhibit learned behavior from the stimulus, we potentially could control an animal behavior by causing this planned reaction.

In this dissertation, we selected turtle and carp as the animal platform, and examined obstacle avoidance and escape behavior, they are one of the typical reactive behaviors, to control their moving path. Further, we suggest novel remote control system that based on our research findings and also check operability and applicability of this suggested system through various tests.

This paper is structured as follows:

In chapter 1, the research background is presented. We introduced research purpose and key idea of this dissertation.

In chapter 2, we have found that causing a particular behavior, such as obstacle avoidance, by providing a specific visual stimulus results in effective control of the turtle's (*Trachemys scripta elegans*) movement. Also, by applying the experimental results, we were able to successfully control the turtle's walking paths.

In chapter 3, we would show our animal control scheme is still vailed in outdoor condition and, as an application aspect, we introduce our novel attempt to remotely control an animal's behavior by human thought alone. The turtle was also selected as the target animal and, in this study, is referred to as a "Human brain-actuated cyborg turtle." Using a brain-computer interface, head-mounted display, wireless communication, and a specially designed stimulation device which could evoke turtle's instinctive escape behavior for guiding the turtle's orientation, turtles were remotely controlled in both indoor and outdoor environments successfully.

In chapter 4, we expanded our target animal area, choose carp (*Cyprinus carpio*) and implement primary experiments for developing a remote control system for carp. We examined the specific role of the vision sense in obstacle avoidance behavior of carps. Through two kind of basic experiments, we show that the visual and vibration stimulation could be used to guide fish along specified moving paths.

Lastly, in chapter 5, we discuss about present conclusions.

Chapter 2. Remote guidance of untrained turtles by controlling voluntary instinct behavior

2.1 Introduction

Several artificial intelligent agents, such as micro- and nano-aerial vehicles (MAVs/NAVs), have been developed for the performance of tasks which humans cannot easily handle. However, these agents have not performed as well as expected due to the limitations of size/weight, battery capability/charging, range of operation, and so on. A major lesson, thus far, is that we are still far from artificially reproducing a level of intelligence even of insects. Thus, interest in alternative approaches based on biologically inspired or biomimetic methods has increased.

Recent work on the direct control of lower animal behavior has focused on the measurement of operating range and speed, versus payload and maneuverability, and on studies of animal social behavior [1]. Several mechanical control systems have been reported, such as the insect flight control system proposed by Sato et al., which electronically stimulates the insect's brain and muscles in charge of its flight [2]; the wireless communication device of Britt et al., which provides commands to a well-trained dog [3]; the remote flight control system of Tsang et al., which uses micro-fabricated flexible neuroprosthetic probes integrated with carbon nanotube-gold nano-composites in a moth [4]; and the 2.5-mW wireless insect flight controller designed by Daly et al., which utilizes a non-coherent pulsed ultra-wideband receiver system-on-chip (3-5 GHz) [5]. In studies of differential brain stimulation, Talwar et al. have shown that rats are easily guided by specific stimulation of either the somatosensory cortical (SI) or medial forebrain bundle (MFB) as a cue or reward, respectively [6]. Most proposed behavior control systems require a well-trained animal or cause involuntary behavior by direct stimulation of the corresponding musculature by an implanted controller. In insects, implantation is carried out at the adult or pupal stage.

Our study has addressed the problem of control in two fundamentally different aspects: whether we can control an untrained animal in a non-invasive and remote manner, and if this may be done via control of voluntary behavior. Our results indicate this is indeed the case. All animals, including humans, usually act by reaction to stimuli. In particular, a reactive behavior connected with bodily protection is essential and must occur quickly, and it must be evoked, mediated, and directed in a consistent manner by a stimulus [7, 8].

From these studies in turtles, we have observed a consistent pattern of control of an animal's movement trajectory utilizing the innate instinctive behavior of obstacle avoidance, and we propose this as a novel behavior control scheme. Using this non-invasive scheme, our system of animal behavior control can be more stable and adoptable. The system is suitable for application in tasks traditionally carried out by mobile robots, such as surveillance and reconnaissance, exploration and navigation, as well as other missions dangerous for humans.

We first conducted experiments to investigate in detail the turtle's obstacle avoidance behavior, in which we took advantage of earlier work on the turtle's vision wavelength discrimination [9] and the observation that hatchling sea turtles recognize a white light source as an open space and so move toward it [10, 11].

2.2 Material and Methods

2.2.1 Turtles

We decided to do our experiment with turtles because it is easy to detect their movement, and they are capable of living in various types of habitats on land and in water. The turtles used in this study were red-eared sliders (*Trachemys scripta elegans*). Four turtles were grown indoors in laboratories at the Korea Advanced Institute of Science and Technology (KAIST). The turtles were housed together in a large, water-filled glass tub (91x61x20cm). The tank was fitted with a water filter and a dry platform for basking, and the turtles were sunbathed 6~7 hours under a UV lamp. They were fed commercial pellets four times a week. After at least 6 hours without feeding in the tank, they were moved to the floor of the laboratory or the experimental table for experiments as shown in Figure 2-1.

As each experiment was repeated, the turtles became sluggish from fatigue; therefore, different turtles were used for our experiments every 10 minutes. Thus, we carried out the experiments using all four turtles (Figure 2-1). Also, turtles (*Trachemys scripta elegans*) were manipulated under the following animal permits from the Korea Advanced Institute of Science and Technology according to the KAIST Animal Experiment Ethical Law RR0303, last changed on 10/6/2009. Our animal experiment qualification certifications are Cheol-Hu Kim (2010-OE01), Serin Lee (2011-CE01) and Dae-Gun Kim (2011-OE01).

2.2.2 Method

As mentioned in the Introduction, this study aimed to control turtle's behavior by providing visual stimuli. We therefore examined how turtles respond to various visual stimuli. The experiments were performed in arenas on the experiment table (90x20cm) (Figure 2-1B) and the floor (223.8x166cm) (Figure 2-1C). The turtles' responses, that is, their navigational paths, were continuously recorded by a simple color-based tracker. Except for our target stimulation, other factors (olfactory stimuli, auditory stimuli, room temperature, brightness distribution, etc.) were controlled during the experiments.

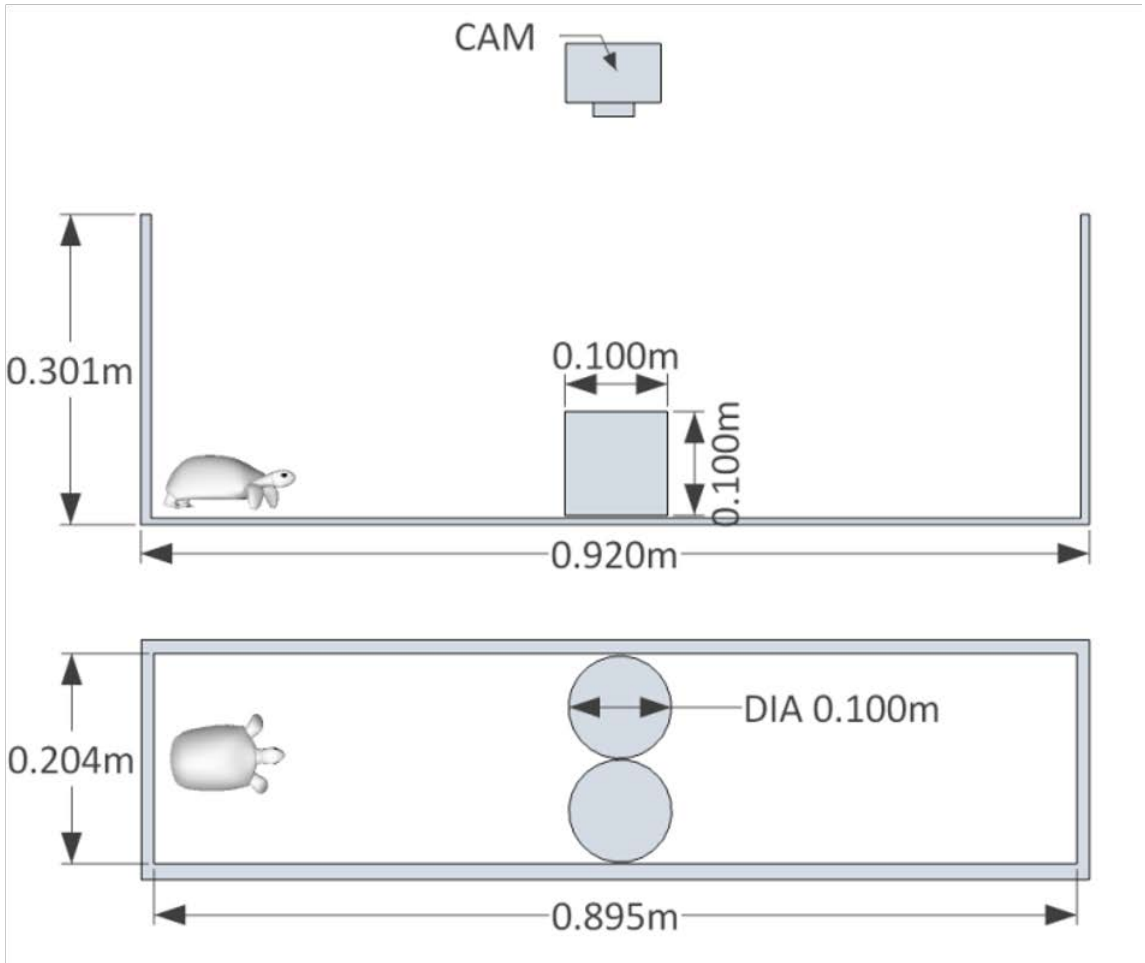
Each turtle's path was tracked by a 20Hz digital camera (VLUU NV4, SAMSUNG, KOREA) with 800x592 pixel resolution. The center of a circular color patch (radius=3cm) attached to the center of the turtle's upper shell was tracked by a color-based tracker that used a MATLAB (The Mathworks Inc., USA) image processing program developed by Matpic (See http://www.matpic.com). The average distance between the center of the patch and the end of the turtle's head was 6cm.

The raw data from the color-based tracker was post-processed by projective transformation mapping of the oblique view to the top view, and a Kalman filter with linear models was used for both the dynamics of the system and the observation process. Like other Bayesian-based tracking algorithms [12], the parameters of the filter were carefully chosen by an iterated trial-and-error procedure comparing the filtered and real trajectories by eye, and we found that we could obtain good results under the covariances of Q= 10^{-3} and R=0.1. The whole system is described in Figure 2-1.

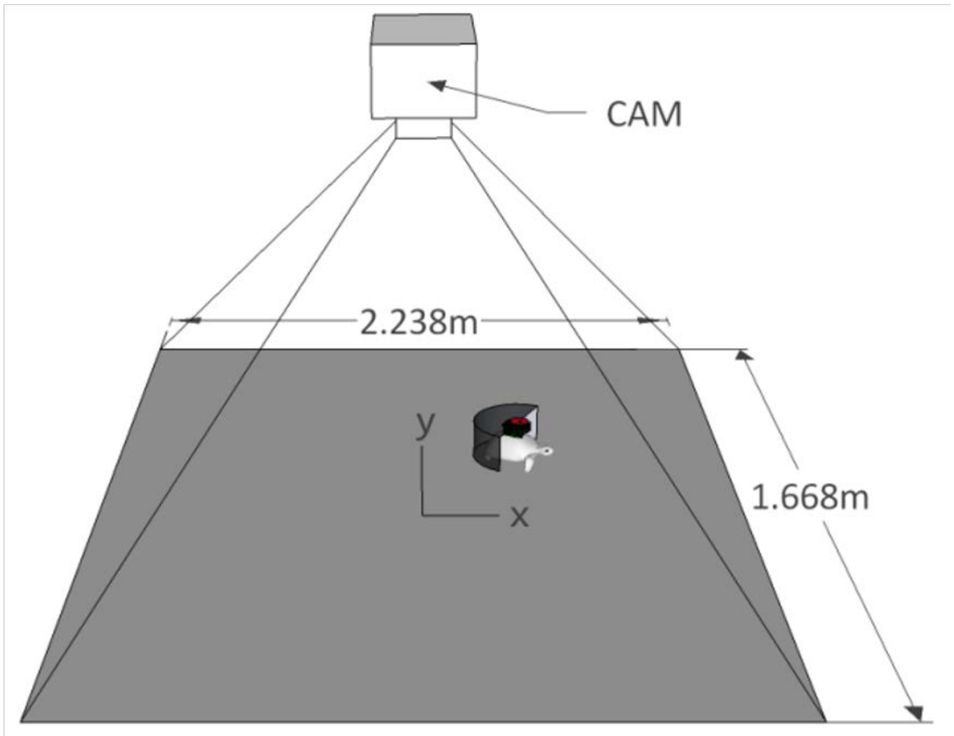
2.2.3 Apparatus

To provide the turtle with stimulus causing obstacle avoidance, a simple control device was designed to locate a semi-cylinder at any given angle with respect to the anteroposterior axis of the turtle. An embedded control module (5.3x7.5x4.8cm, 133.5g) was mounted on the turtle's upper shell with the circular color patch for tracking, and a black semi-cylinder was used to block the turtle's view. A micro controller unit (ARM Cortex-M3, STM32F101V8T6) received an angular value to control the servo motor (Maximum output angle: 2,160 degrees, Resolution: 4.9 degrees, Motorbank, KOREA), which could rotate the black semi-cylinder within ±180 degrees with respect to its body axis, from a PC control software written in C# via Bluetooth communication (Baud rate: 19,200bps, Firmtech, KOREA).

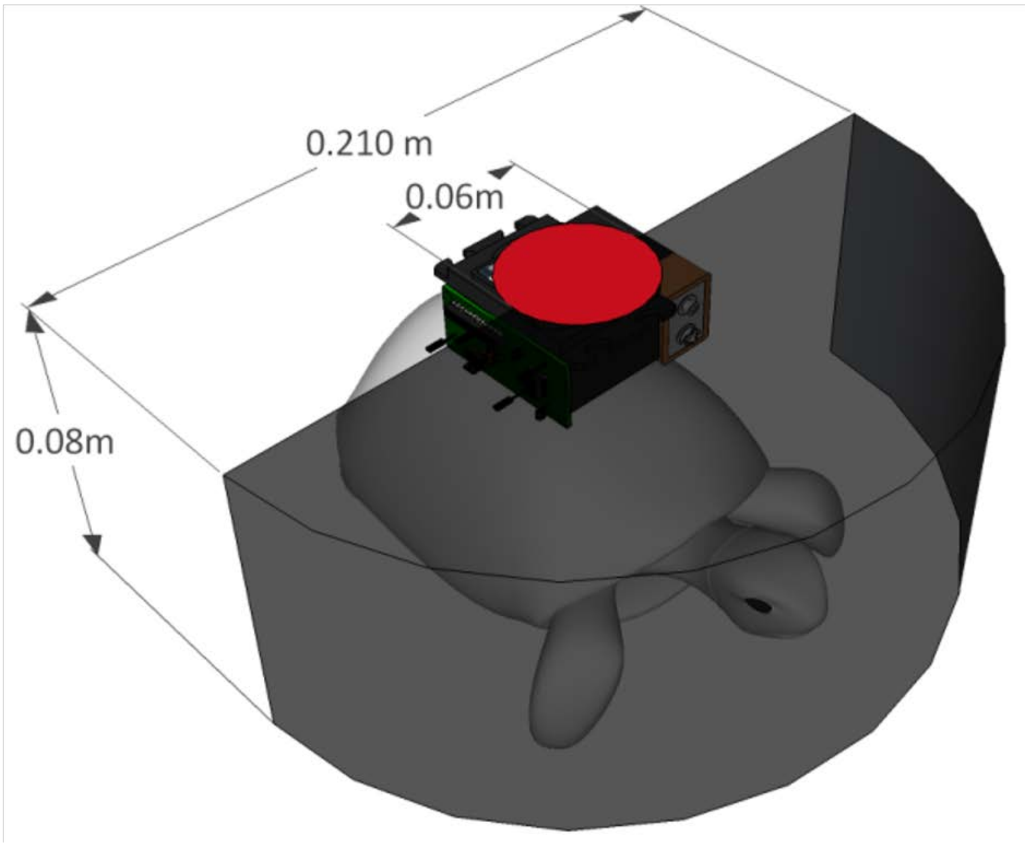
A



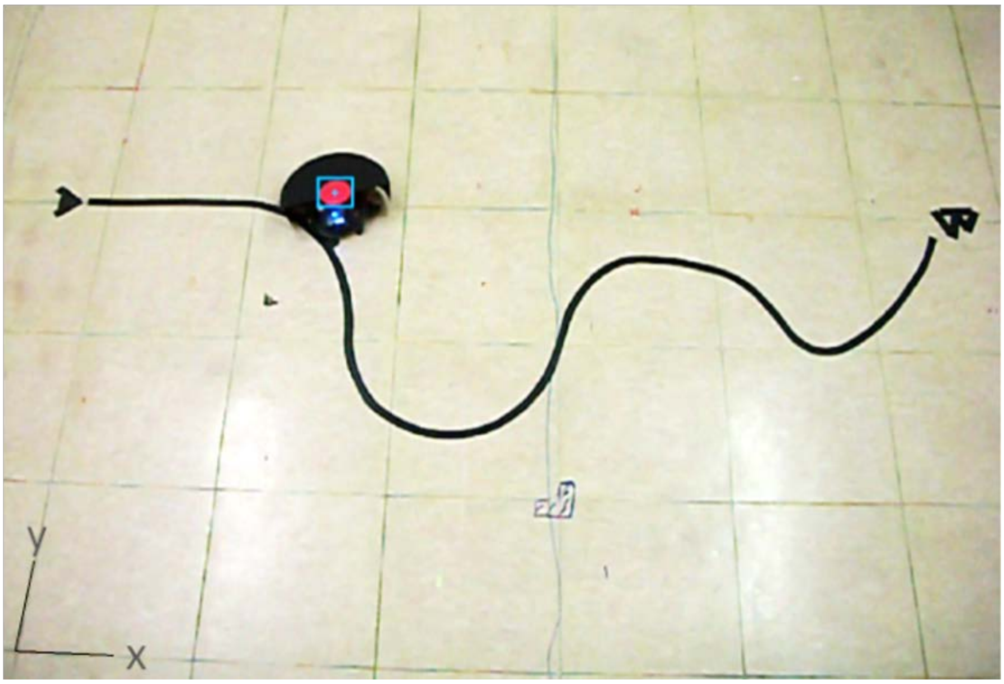
B



C



D


y
x

E

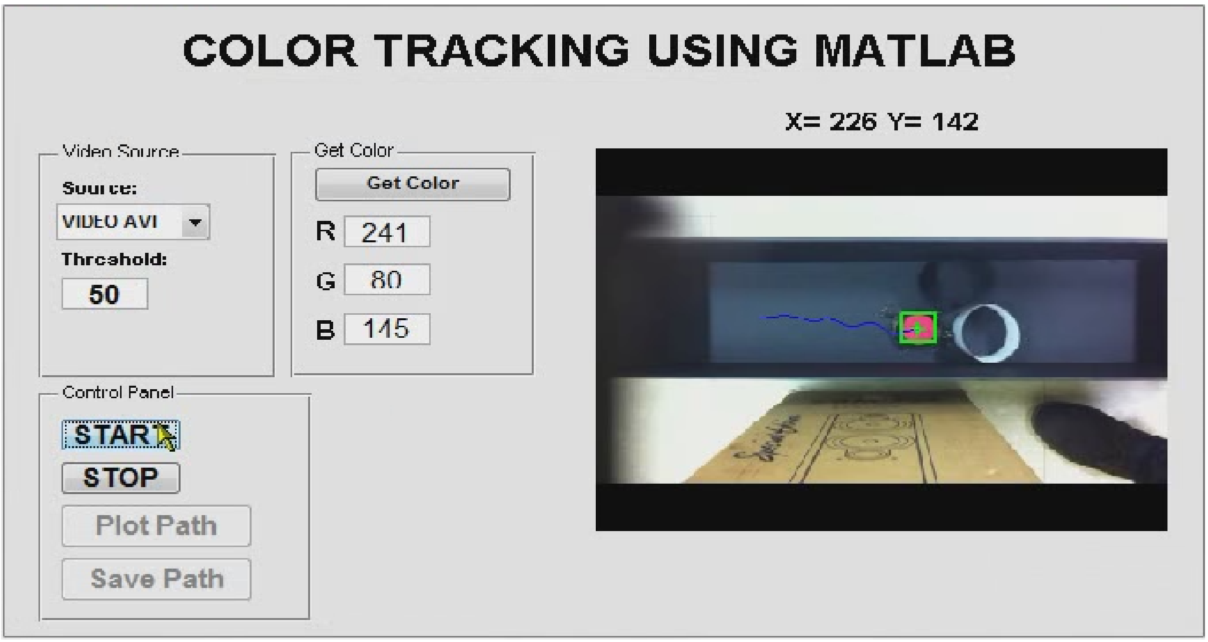

COLOR TRACKING USING MATLAB
X= 226 Y= 142
Video Source
Source:
VIDEO AVI
Threshold:
50
Get Color
Get Color
R 241
G 80
B 145
Control Panel
START
STOP
Plot Path
Save Path

Figure 2-1. Depiction of experimental remote-controlled visual stimulus delivery and tracking systems.

(A) To examine the turtle’s visual obstacle recognition, an experimental arena was equipped with a camera and two movable cylinders as obstacles (shown from the side view and from above). The dimensions of the arena, surrounding walls, and obstacles are indicated.

(B) Experiments performed on the laboratory floor area (with the dimensions indicated) are shown in the drawing. The placements of the turtle, obstacle, and tracking system are shown.

(C) The embedded control system to block the turtle’s view is shown in the drawing. The servo motor controls the positioning of the semi-cylinder obstacle (in the image, it is positioned directly in front of the turtle). The red circle on the controller tracked by the simple tracking algorithm was regarded as the location of the turtle.

(D) The turtle was remotely controlled to follow the desired path by alternating the visual angle of the obstacle between ±180 (no stimulus) and ±90 degrees.

(E) The interface of color-based tracker program that used a MATLAB image processing program.

2.3 Results

2.3.1 Visual Recognition of Obstacles

There have been several studies on turtle's vision [9], but no research has addressed what kinds of objects the turtles recognize as obstacles. Therefore, by examining the turtle's movement trajectories when a black and a white cylinder (radius=5cm, height=10cm) were initially placed 30cm in front of it, we found that the turtle recognized the black cylinder as an obstacle, rather than the white cylinder (Figure 2-2A and B for example). Figure 2-3A shows the experimental results. The color of the wall surrounding the arena varied: black, white, or a natural scene. In Figure 2-2A, avoidance tendency, described by a turtle's location when it was less than 7.5 cm from an obstacle (pink-shaded region), is shown in histograms. The turtles were placed in an arena with black side walls facing toward a white obstacle, or with white side walls. With white side walls (recognized as an open space), most turtles moved through the narrow passageway between a wall and the cylinder (n=14-27).

2.3.2 Obstacle Recognition Distance

To examine the obstacle recognition distance, a black wall was placed 55 cm in front of a turtle in an arena with 10 cm-high white side walls (Figure 2-2C for example). Black walls of various heights (2, 5, 10, and 15 cm) were used to test if obstacle recognition distance also depends on the obstacle’s apparent size. The turtle’s walking trajectories were recorded by the color-based tracker as described in Figure 2-1. The experimental results are shown in Figure 2-3B. In this figure, the histograms indicate the approach distance to the obstacle wall as cumulative frequency. Trajectories were aimed in the direction of white side walls. In more than 90% of the trials (dotted line in the histogram), the turtles did not come closer than 15 cm from the obstacle, regardless of its height (apparent size) (n=10-25).

A

B

C

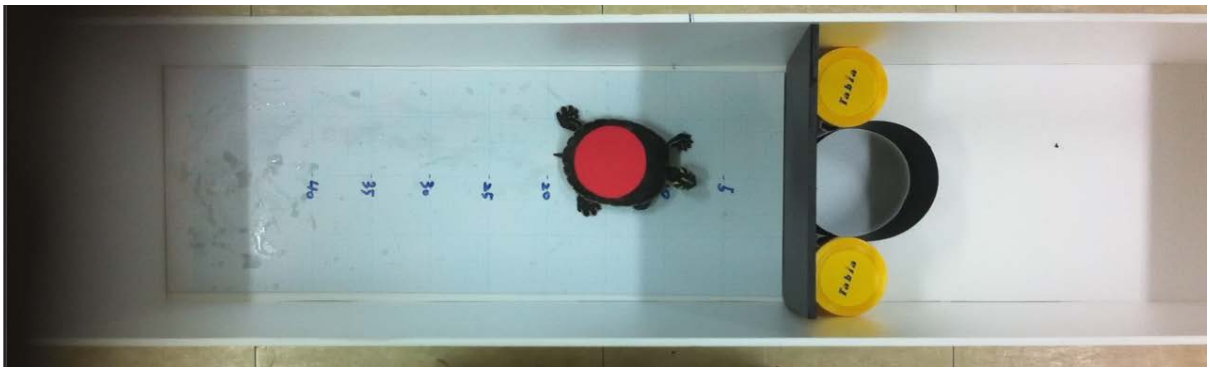
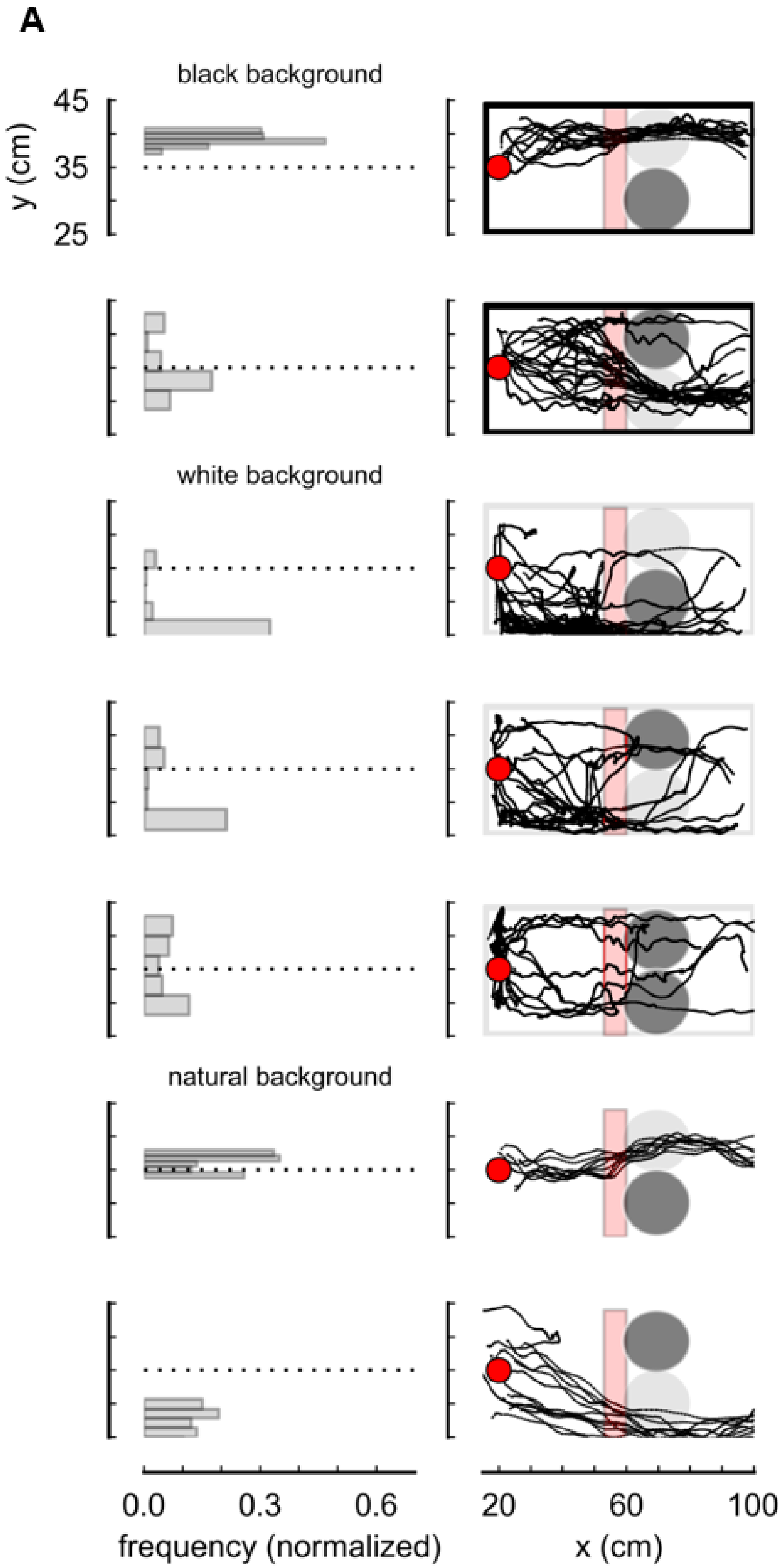


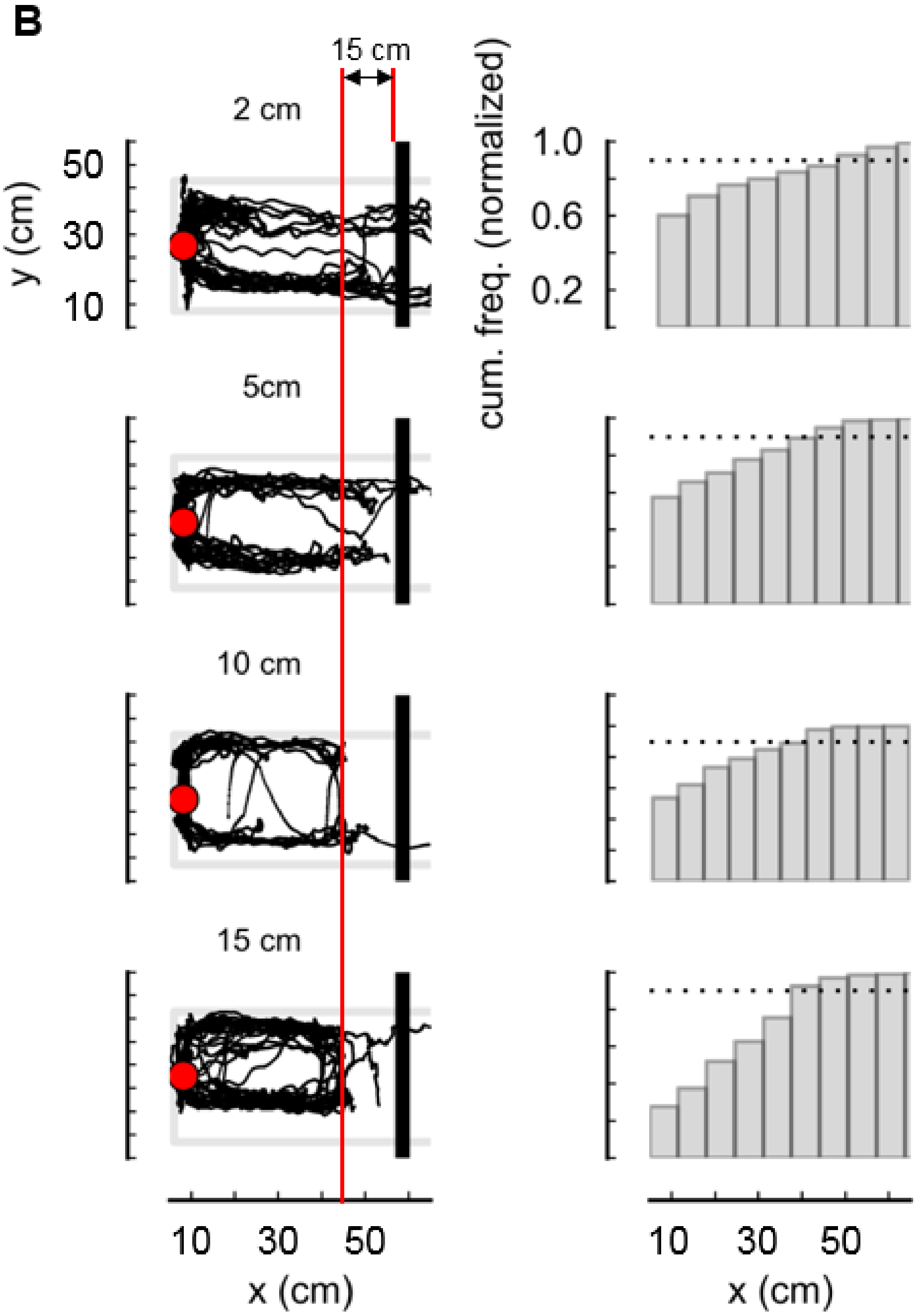
Figure 2-2. Depiction of example cases for basic experiments.

(A) Experiments on visual recognition of obstacles. In this figure, turtle crashed its way through the white cylinder, because it recognized the black cylinder as an obstacle rather than white one.

(B) When the turtle was surrounded white arena, it moved closely attaches itself to the white wall.

(C) Experiments on obstacle recognition distance. It did not come closer than 15 cm from the wall type obstacle.


A
black background
white background
natural background
y (cm)
45
35
25
0.0
0.3
0.6
frequency (normalized)
20
60
100
x (cm)



B
15 cm
2 cm
5cm
10 cm
15 cm
y (cm)
50
30
10
cum. freq. (normalized)
1.0
0.6
0.2
10
30
50
x (cm)
10
30
50
x (cm)

Figure 2-3. Control of obstacle avoidance behavior.

(A) The movement trajectories were tracked after turtles (red circles) were initially placed 50cm in front of obstacles. Obstacles were movable black or white cylinders (radius=5cm, height=10cm), and the turtles could push them to go past.

(B) Turtles were initially located 55cm (marked by red circles at mid-carapace) in front of a movable black obstacle wall in an arena with white side walls.

2.3.3 Visually Planned Obstacle Avoidance

To test how turtles respond to obstacles in more detail, we provided stimulus by utilizing a device mounted on the turtle’s carapace (Figure 2-1D). Since the turtles recognized the black object closer than 15cm as an obstacle as shown in the previous experiments, a simple device, which could stimulate obstacle avoidance behavior, was designed to locate a black semi-cylinder (radius=10.5cm, height=8cm) at any specific angle in front of it. Since this can give a constant stimulus to the turtle, this could be considered as a device for an open-loop experiment that can amplify behavioral responses by removing a turtle’s visual feedback [13].

When the black semi-cylinder only blocked the turtle’s view horizontally, no meaningful results were obtained. We then found it necessary to simultaneously block horizontal and vertical views by placing a top cover on the device. We also believe that the controlling factor is the location of the black/white edge relative to the front of the eye, but for convenience, we used the center of the circumference of the semi-cylinder instead. The location of the center of its circumference can be thus varied from +180 to -180 degrees in a clockwise direction with respect to the anteroposterior axis of the turtle. Since a turtle shows little response to a light emitted from ±180 degrees [10], we assumed that a semi-cylinder located at ±180 degrees could be regarded as providing no stimulus.

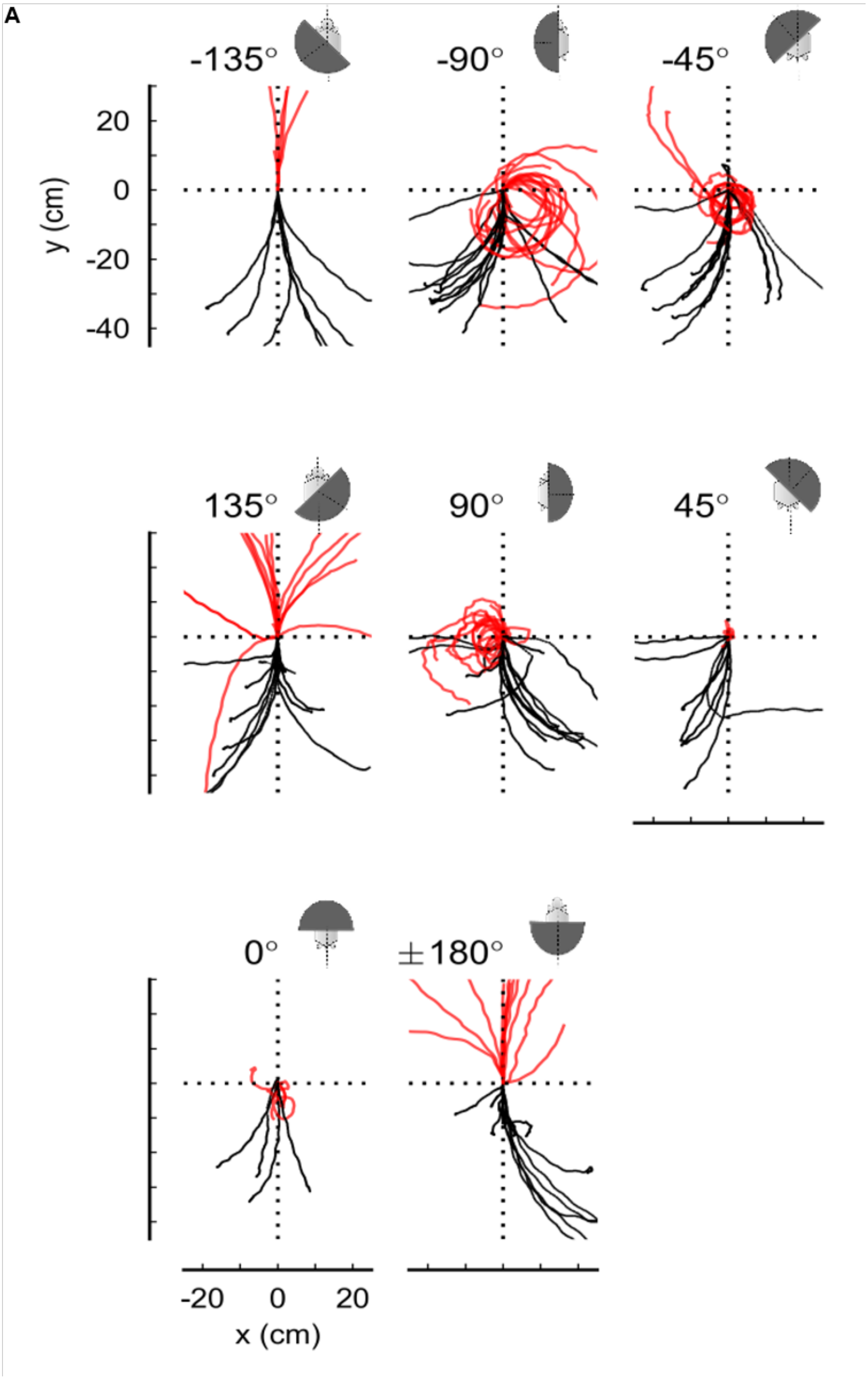
After the turtle walked for 5.0 sec with no stimulus, the black semi-cylinder was positioned in front of it at a specific angle within ±180 degrees and kept in this position for 30 sec (Figure 2-4A). We then tracked the turtle's walking path under this condition. Throughout this experiment, the turtles continued to move around in a circle when they were exposed to constant visual stimuli, until they got tired.

For such experiments, we introduced the concept of average turning velocity (ATV) to measure the amount of displacement or shift from the turtle's previous heading per unit of time. After the turning distance (TD) is derived by dividing the entire path into n-segmental vectors by sampling each second, the ATV under the condition $\theta \leq 90$ degrees can be defined by

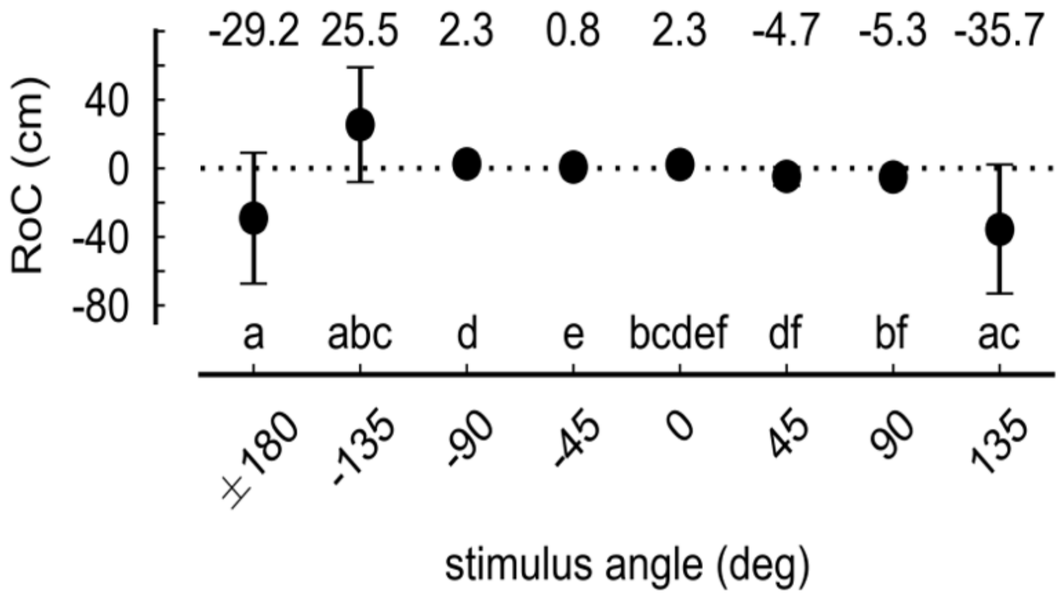
$$\mathrm{ATV} = \frac{\mathrm{TD}}{(\text{total travel time})} \quad \text{with} \quad \mathrm{TD} = \sum_{i=1}^{n} \left|\overrightarrow{a_i}\right| \sin \theta_i$$

as shown in Figure 2-4D. In this experiment, the more a turtle's view was blocked by an obstacle, the sharper it turned away from the stimulus (Figure 2-4A). The radius of curvature (RoC) is then described as shown in Figure 2-4B. In this figure, the two-tailed Mann-Whitney U test ($p<0.05$) and Bonferroni correction was performed for statistical comparisons of the data sets. The results shown in lower case are shown as statistically homogeneous groups [14]. For example, the groups 'a' and 'b' are significantly different; but 'a' is not significantly different from 'ab', which shares membership with group 'a'.

Although the conventional curvature only considers the change of angle, the ATV takes both the change of angle and distance traveled into consideration. In the case of ±135 degrees, the ATV was small since the change of angle was small; on the other hand, the ATV for ±45 degrees was small because the distance traveled was short. The maximum absolute ATV values were obtained when the black semi-cylinder was located at ±90 degrees (Figure 2-4C).

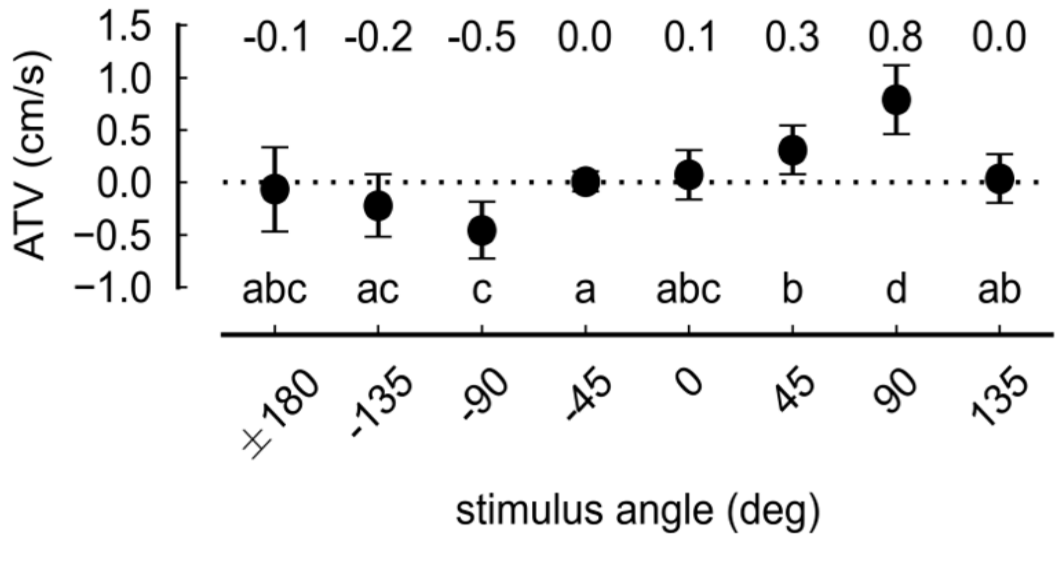

A
-135°
-90°
-45°
135°
90°
45°
0°
±180°
y (cm)
20
0
-20
-40
-20
0
20
x (cm)

B



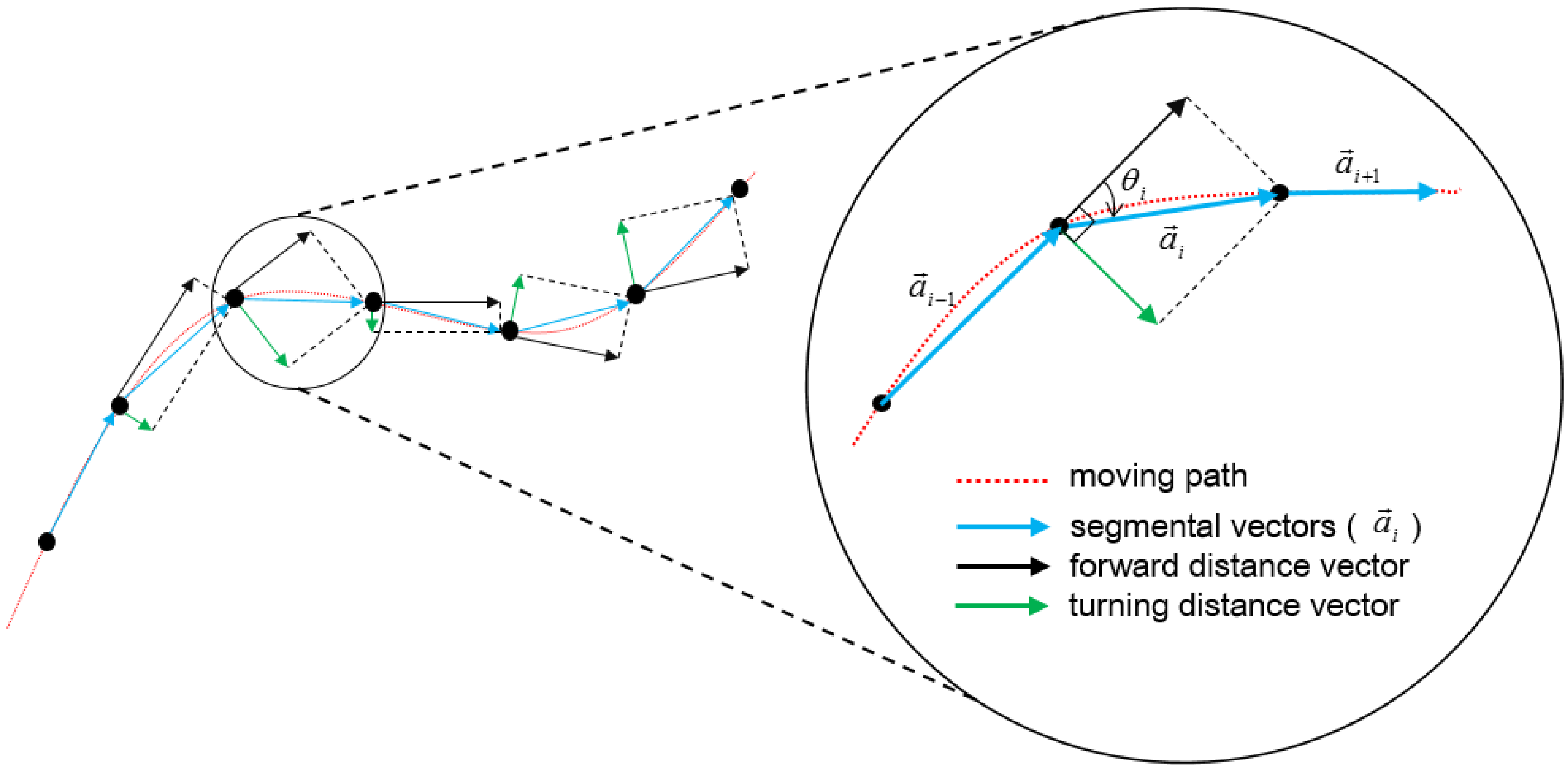
-29.2
25.5
2.3
0.8
2.3
-4.7
-5.3
-35.7
RoC (cm)
40
0
-40
-80
a
abc
d
e
bcdef
df
bf
ac
±180
-135
-90
-45
0
45
90
135
stimulus angle (deg)

C



-0.1
-0.2
-0.5
0.0
0.1
0.3
0.8
0.0
ATV (cm/s)
1.5
1.0
0.5
0.0
−0.5
−1.0
abc
ac
c
a
abc
b
d
ab
±180
-135
-90
-45
0
45
90
135
stimulus angle (deg)

D



$\vec{a}_{i-1}$
θ_i
$\vec{a}_i$
$\vec{a}_{i+1}$
moving path
segmental vectors ($\vec{a}_i$)
forward distance vector
turning distance vector

Figure 2-4. Relationship between a turtle's movements and visual angle to the obstacle.

(A) Each movement trajectory was translated to place the location at which the stimulus was given at the origin, and then rotated so that its tangential line at that location coincides with the y-axis. The red lines represent the trajectories after the visual stimuli were provided. The black lines describe the trajectories before the stimuli. The angle of the obstacle is indicated numerically and by the image of the semi-cylinder. Two black dotted lines show orientation and comparison (n=10-21).

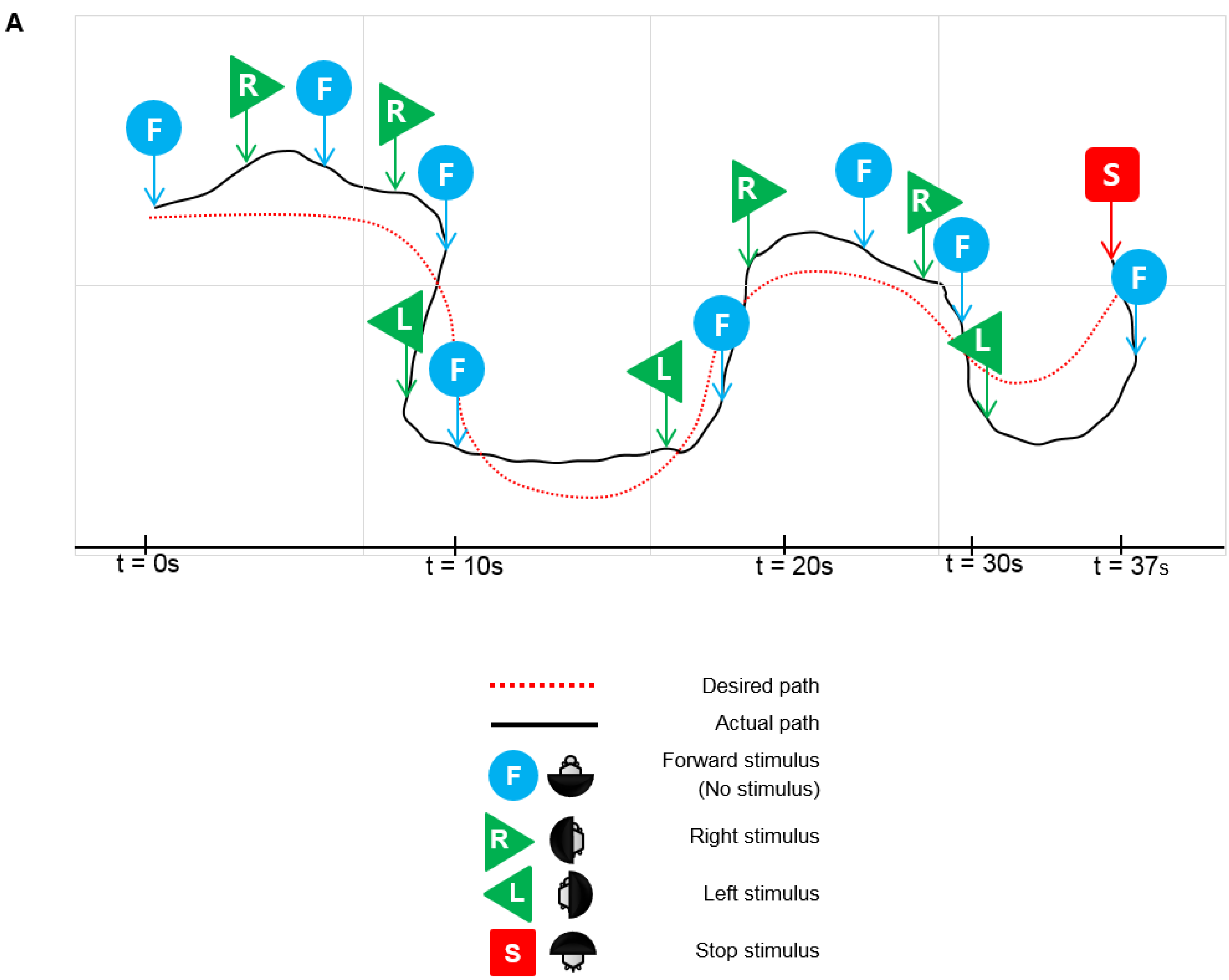
(B) The radii of curvature (RoC) of the red trajectories in (A) are plotted by mean and standard deviation, although they were not always normally distributed.

(C) The average turning velocities (ATV) of the trajectories are plotted and analyzed as described for the RoC in (B).

(D) To measure the turning behavior, a turning distance vector was defined as shown in this figure (see text for details).

2.3.4 Controlling Turtle's Walking Path

In most trials, when a turtle's view was largely blocked, it became immobile. On the other hand, a small degree of blockage did not affect a turtle's path. We therefore attempted to remotely cause a change in the path of a moving turtle by alternating between no stimulus (±180 degrees) and that of ±90 degrees (Figure 2-5). During these experiments, we also discovered that immobile turtles (occasionally induced by a moderate stimulus) could be prompted to begin moving again by remotely waving the cover of the obstacle.


A
F
R
L
S
t = 0s
t = 10s
t = 20s
t = 30s
t = 37s
Desired path
Actual path
Forward stimulus
(No stimulus)
Right stimulus
Left stimulus
Stop stimulus

B

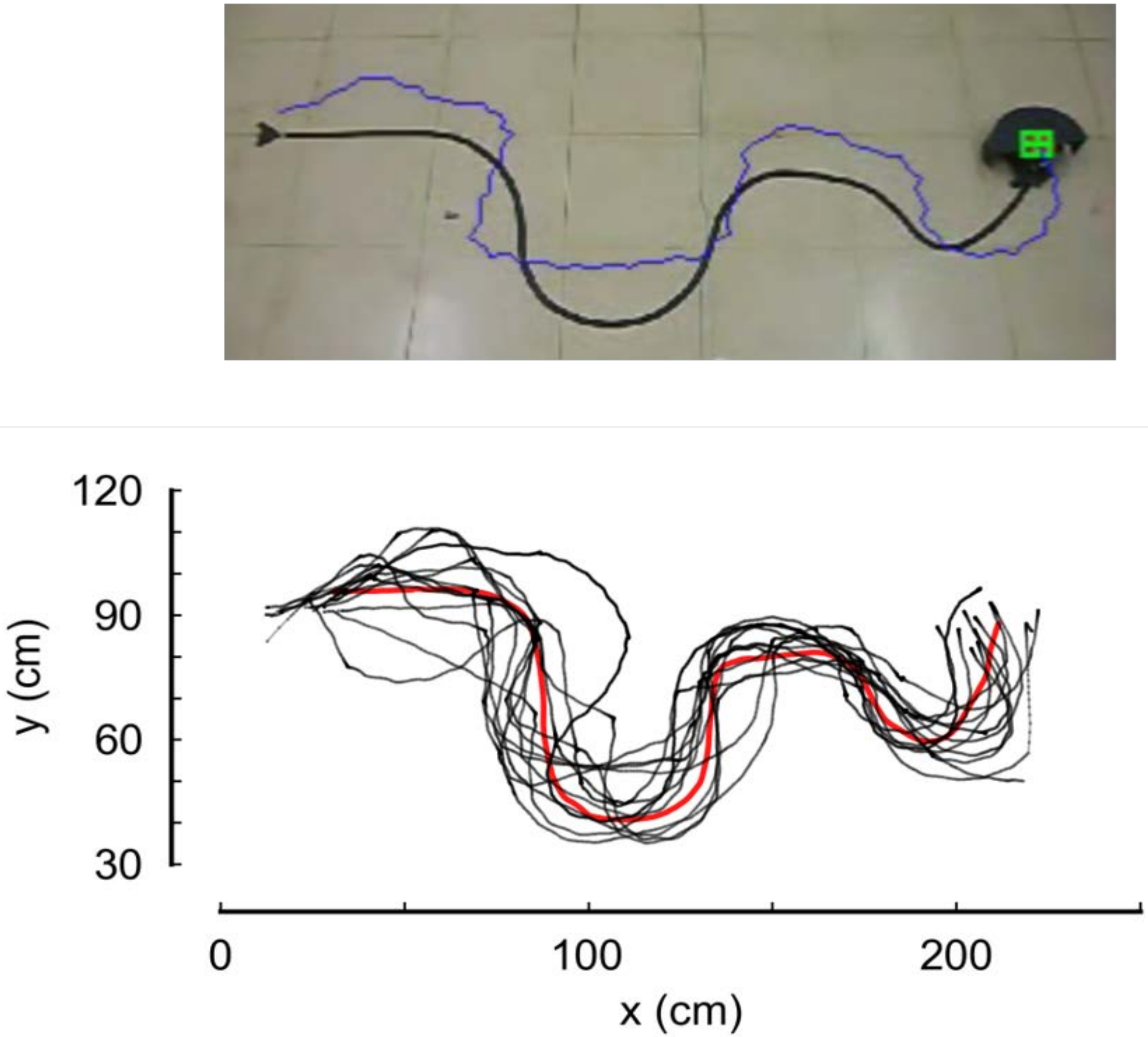


Figure 2-5. Controlling turtle's walking path.

(A) Examples of guided turtle navigation using the embedded control system to block the turtle's view. Each arrow indicates positions at which forward (F), stop (S), right (R) and left (L) directional stimuli were issued.

(B) Turtle movement was controlled by alternately providing forward, right, left and stop stimuli causing obstacle avoidance (see text). The desired (red) and actual (black) paths of the turtles are plotted

2.4 Closure

In this chapter, we examined one of the essential responses for an organism's survival: obstacle avoidance. By providing a visual stimulus that causes the behavior, we remotely controlled a turtle's walking behavior. We first examined the turtle's visual recognition of obstacles under various conditions. We found that the turtles, recognizing the white object as open space, headed for it regardless of other conditions. Second, we tried to find out the turtle's obstacle recognition distance. We discovered that no matter what the obstacle's height (apparent size), the turtle did not come closer to it than 15cm. Third, we then designed a simple device to examine the turtle's visually planned obstacle avoidance behavior. We found that the more the turtle's view was blocked by the obstacle, the sharper it turned away from it. Lastly, by applying the above results, we were able to successfully control the turtle's walking paths.

These experiments demonstrate that animal behavior can effectively be guided by evoking instinctive behavior essential for survival. Unlike the involuntary behavior control schemes that have been previously proposed, which compel a response by stimulating the corresponding neural circuit (or musculature) regardless of the animal's intention, our approach is to guide the animal by elaborately inducing its voluntary instinctive behavior. In addition, while most involuntary controllers may require additional sensors to adjust responses to an abrupt or unexpected situation (e.g., when an insect meets an uncontrolled obstacle in its otherwise controlled or planned path), voluntarily controlled animals are expected to adapt themselves to the situation by combining the directed and adaptive behaviors.

We therefore believe that an innate behavior caused by a visual stimulus can easily and effectively be employed to control an animal's movement, and will not impose a heavy strain on the animal. Although it is necessary to overcome the technical difficulties of designing a new device in order to apply the specific stimulus causing the innate behavior to other animals in other environments, this approach may provide a clue to a general framework for behavior control.

Chapter 3. Navigation of untrained turtle using escape behavior with human brain-computer interface

3.1 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 James Cameron's 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 [15-19]. Rao et al. demonstrated the possibility of sending information extracted from one brain directly to another brain through direct brain-to-brain communication [20]. 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) [21].

On the other hand, in previous chapter, we also succeeded in controlling an untrained turtle's walking paths by inducing obstacle avoidance behavior. Also, 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 from the locomotion and energy efficiency aspects. For this reason, some researchers have tried to control animal movement by applying a direct control method. Daly et al. designed a wireless flight control system for moths that consisted of a 3- to 5-GHz non-coherent pulsed ultra-wideband receiver system-on-chip [22]. Sato et al. proposed a beetle flight control system which provided electrical stimuli to the beetle's wing muscles [2]. Tsang et al. suggested the possibility of the remote flight control of a moth by using micro-fabricated flexible neuroprosthetic probes (FNPs) [4]. There have also been studies of animal movement control by stimulating instinctive behaviors. Holzer et al. proposed a bio-robot system for controlling a cockroach with electrical stimuli [23]. Butler et al. suggested a virtual fence system for containing cattle that used sound stimuli [24]. Britt et al. were able to navigate a well-trained dog using commands provided through wireless devices [3].

Using the technologies mentioned above, our animal guidance scheme and BCIs technologies, it is possible to develop a system to control an animal using human thought alone. To realize this, however, the system architecture and interfacing techniques require further development. In this chapter, we propose a conceptual system that is capable of remotely guiding an animal by inducing 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 [9, 10], and has a hard shell on which devices can be mounted. We call this concept system the "human brain-actuated cyborg turtle."

Also, our objective is 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 [8, 25-27]. 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.

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 animal. 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 control the turtle's trajectory.

In order 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 our cyborg system. Additional tests were performed outdoors to check the availability and applicability of the system under real-world conditions. Especially, the field test carry an important meaning that our animal guiding scheme is still valid in outdoor condition where a lot variables exist. 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.

This chapter is structured as follows: First, we describe the overall architecture of the proposed system and its components. Second, we introduce the design of the user interface and wearable control devices and establish the experimental conditions. We then present the implemented tests and analysis results. Finally, we discuss the results of the tests.

3.2 Methods

3.2.1 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.

Figure 3-1 illustrates the architecture of our proposed system. The overall system consists of two main subsystems: the pilot and cyborg turtle. The pilot part consists of a BCI device, a head-mounted display (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 turtle were fitted with their respective devices (BCI device, HMD, and stimulation device). Then, through the HMD, the human viewed 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 path by inducing its instinctive behavior (e.g. 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 animal brains or nerves (e.g. BBI), our animal control system relies on the animal's instincts, namely, its escape response. 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.

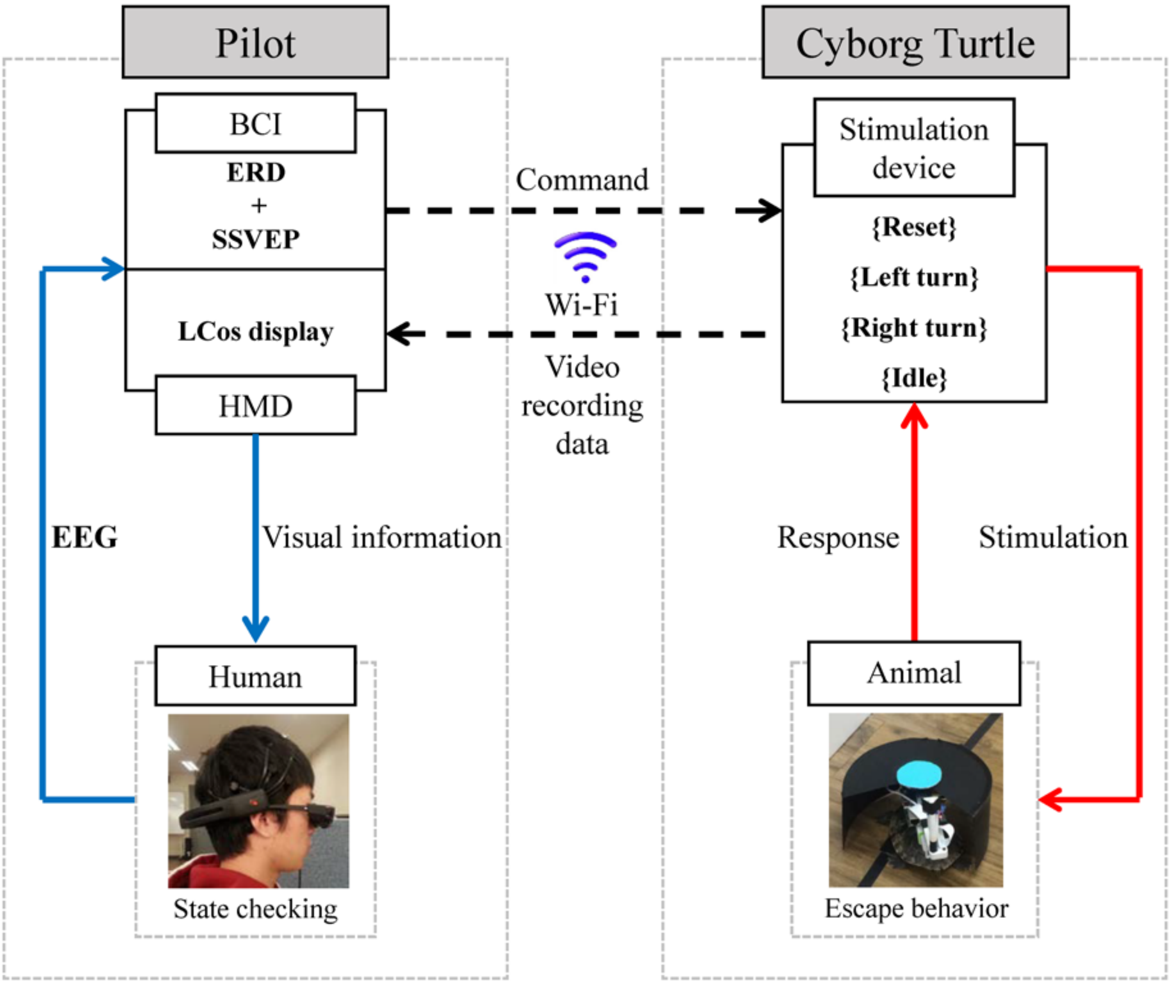


Figure 3-1. Architecture of the human brain-actuated cyborg turtle system.

3.2.2 Introduction of BCI System

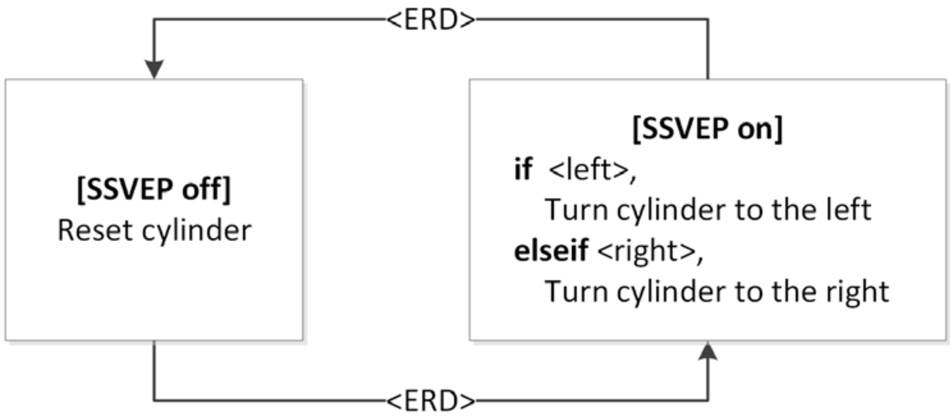
In a previous study [17], our research group proposed the use of the hybrid event related de-synchronization (ERD) and steady-state visually evoked potential (SSVEP) BCI protocols to navigate a humanoid robot. We also adopt this asynchronous BCI system to guide the path of the turtle. It can provide three commands; <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 cyborg 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 (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 °.

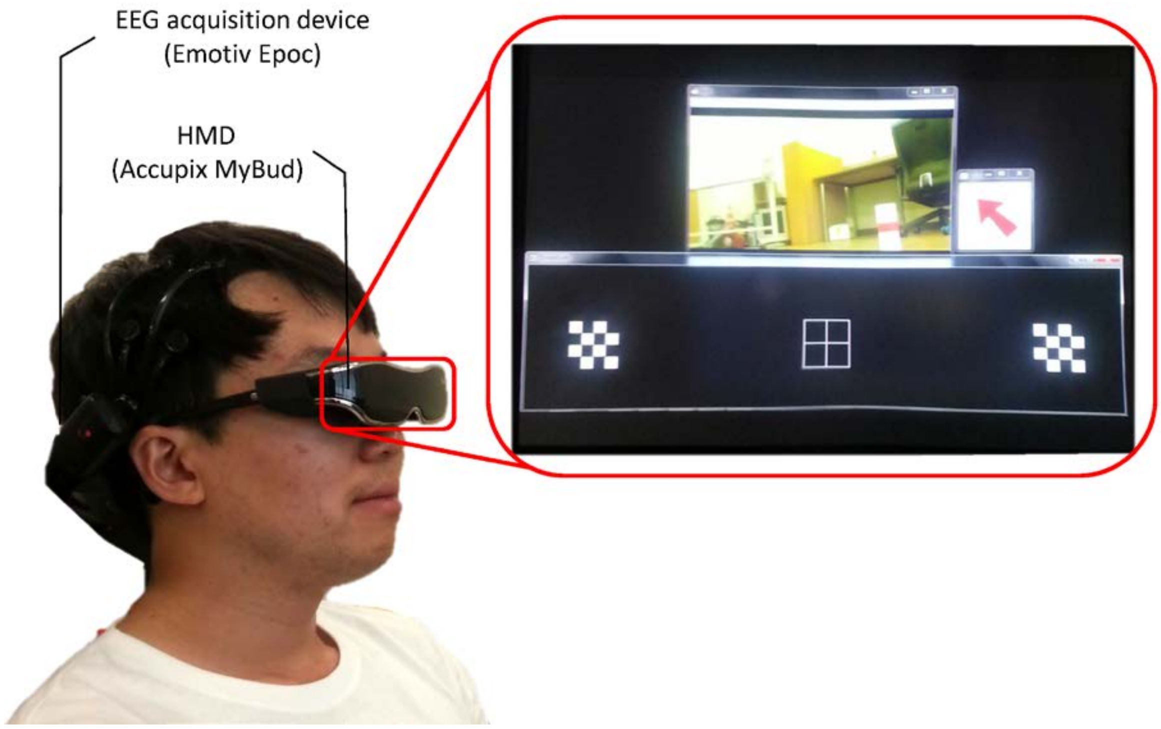
Because our approach relies on the animal's instincts (escape response), the human subjects did not need to command to the turtle continuously during the navigation. The stimulation device on the turtle induces its instinct behavior consistently until another command is received. In other words, the human subjects did not need to provide ongoing BCI commands which would be annoying and fatiguing for the users [27]. Therefore, we needed a means of activating the visual stimuli only when the users needed it. To solve this problem, we introduced the state transition paradigm illustrated in Figure 3-2A. In this case, <ERD> serves as a state transition 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 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 subject.

The subject sat comfortably and wore the HMD and EEG acquisition device. The subject obtained visual feedback from the environment surrounding the 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 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. Figure 3-2B illustrates how the subject remotely controls the cyborg turtle through the BCI system described above.

A


<ERD>
[SSVEP off]
Reset cylinder
[SSVEP on]
if <left>,
Turn cylinder to the left
elseif <right>,
Turn cylinder to the right
<ERD>

B


EEG acquisition device
(Emotiv Epoc)
HMD
(Accupix MyBud)

C

Figure 3-2. Depiction of 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.

(C) Detailed image of wearable devices for human (BCI device and HMD).

3.2.3 Subjects

3.2.3.1 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 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).

3.2.3.2 Animal subjects

The turtles used in this study were red-eared sliders (*Trachemys scripta elegans*). Four turtles were grown indoors in the laboratory at KAIST to a size of 15 to 20 cm. They were housed in a glass tank (91 cm x 61 cm x 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 to 7 hours 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 suffering.

3.2.4 Apparatus

3.2.4.1 Human

EEGs were recorded using a wearable EEG acquisition device (Epoc neuroheadset, Emotiv Inc., USA) [29]. 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 [17], 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) [30]. It consists of an 852 x 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. Figure 3-2B shows the interface devices used by human subjects during the experiment. The subjects communicate with the turtle through an EEG acquisition device and the HMD.

3.2.4.2 Turtle

We designed a simple stimulation device to induce the turtle's escape behavior. The stimulation device and embedded control module (8.6 cm x 5.4 cm x 5.5 cm, 171.5 g) was mounted on the turtle's upper shell. It consisted of a servo-motor and black semi-cylinder with a slit to restrict the turtle's view (Figure 3-3A).

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 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 through ± 36° with respect to its 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 x 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.

3.2.5 Experimental setup

3.2.5.1 Indoor test

This test was implemented on the floor of the laboratory (Figure 3-3B). We placed four waypoints (white, red, yellow, and black) at each corner of the test area. The turtles’ responses, that is, their navigational paths were continuously recorded by a simple color-based tracker. To ensure that the turtles would only be affected by our stimulation, other possible stimuli (olfactory and auditory stimuli, room temperature, brightness, etc.) were all controlled during the tests.

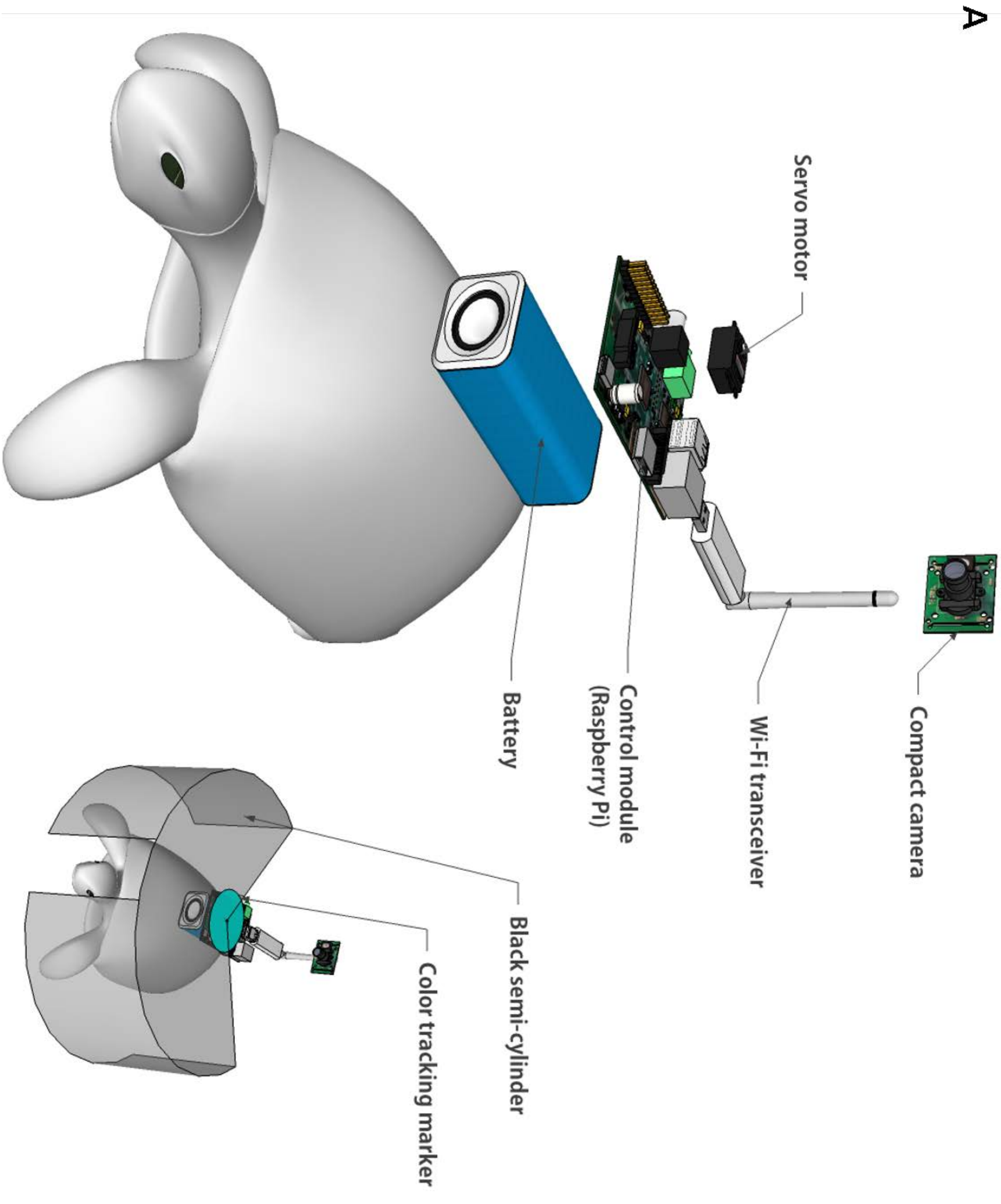
Each turtle's path was tracked by a web camera and a color-based tracker based on a MATLAB (The Mathworks Inc., USA) image processing program developed by Matpic. During the experiments, a Kalman filter with linear models was used to describe the turtle's trajectory.

3.2.5.2 Outdoor test

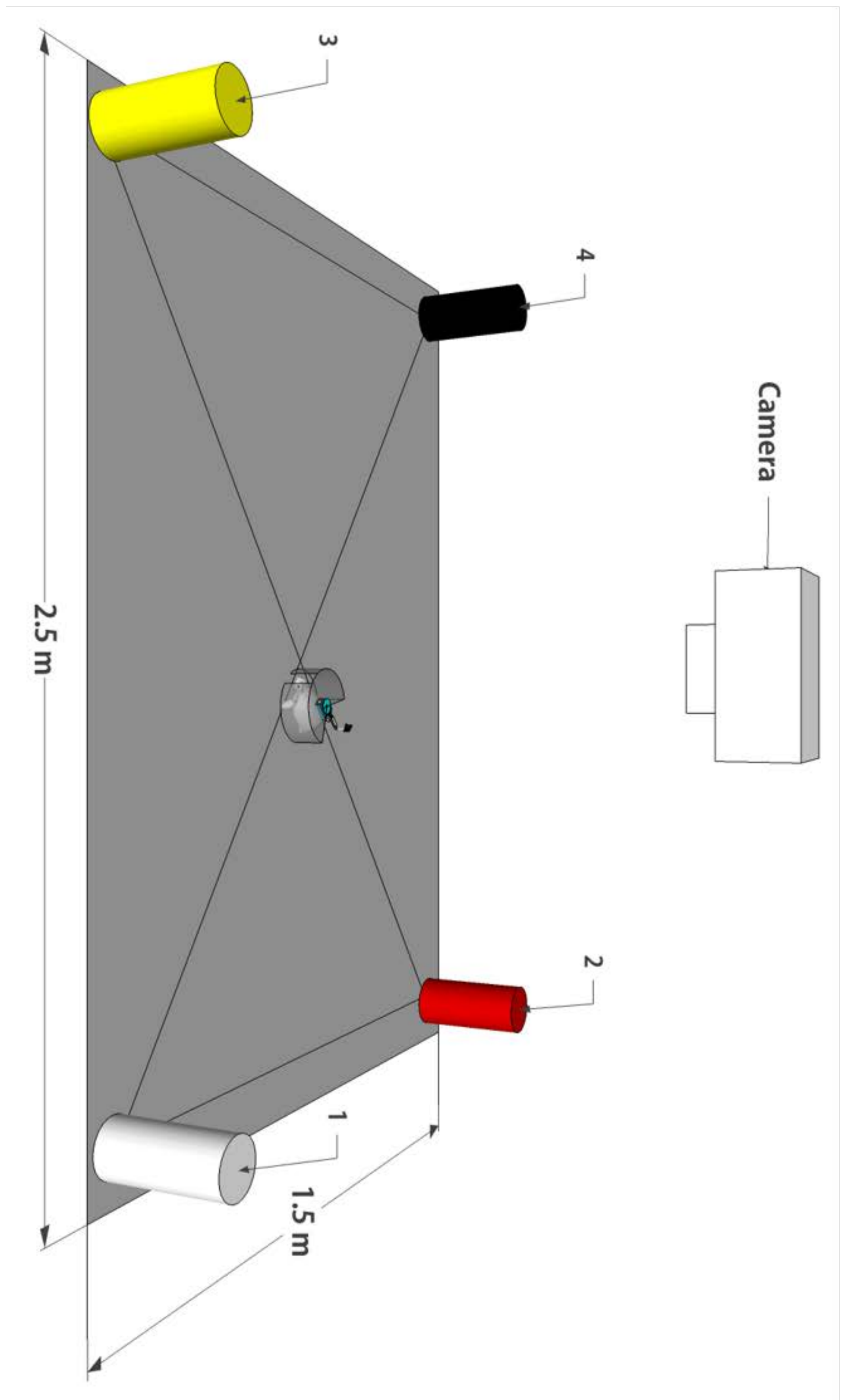
This test was performed in a natural environment that was 5 km distant from the human pilot. Because this test was done outdoors, it was not possible to control the stimuli factors described for the indoor trial during the test. As shown in Figure 3-3C, the start/end position and artificial obstacles were set on an uneven lawn. Again, the tests were recorded using the color-based tracker.

3.2.5.3 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 outdoor 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.


A
Servo motor
Compact camera
Wi-Fi transceiver
Control module
(Raspberry Pi)
Battery
Black semi-cylinder
Color tracking marker

B



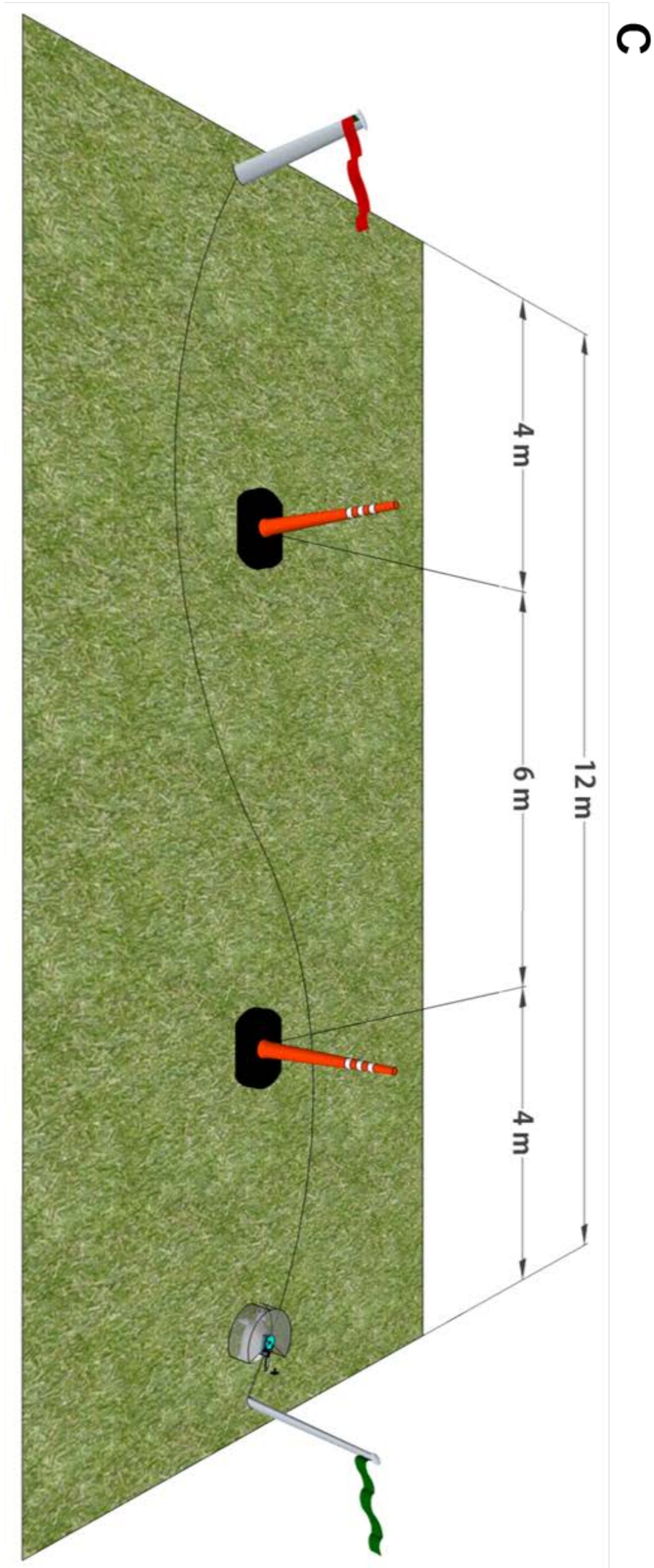

C
4 m
6 m
4 m
12 m

Figure 3-3. Experimental setups.

(A) 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.

(B) The 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.

(C) 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.

3.3 Results

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 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 3-1 summarizes the cross-validation accuracy results and the information transfer rates (ITR) for each protocol.

The ERD- and SSVEP-based BCI protocols achieved an overall accuracy of 91.2% and 89.9%, respectively. The ITRs of the ERD- and SSVEP-based BCI protocols were 17.5 and 16.3 bits min-1, 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 [17]. 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%.

Table 3-1. 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 min-1)	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 min-1)	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	

3.3.2 Indoor test

In this test, we verified how the turtles responded to our stimulation device and checked the operability in greater detail. Figure 3-3A illustrates the overall design of our 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 center 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° [10], it moves towards the slit.

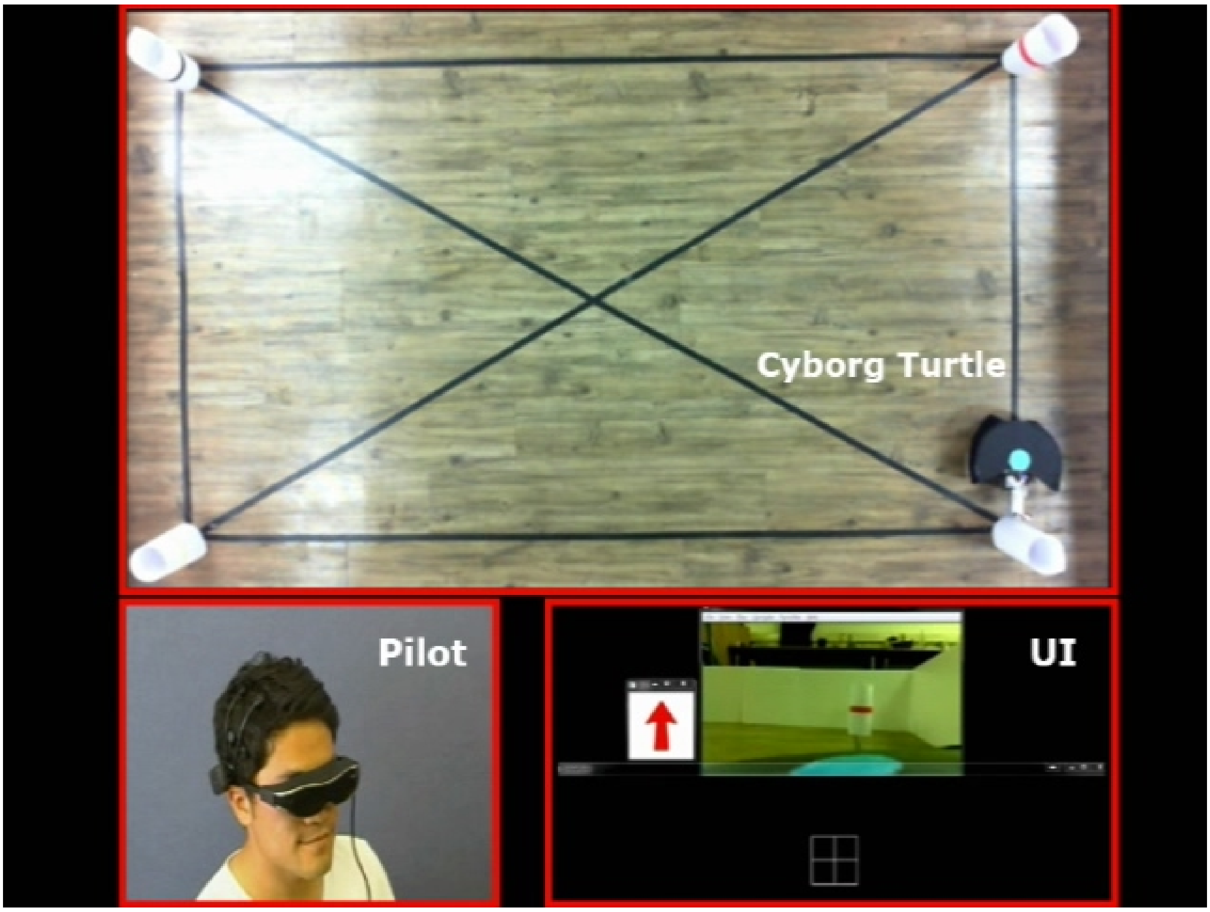
In Figure 3-3B, the cyborg turtle moved within a 2.5 m x 1.5 m area in which there were four waypoints and an 8.83 m optimal path which is a straight line between the waypoints. The turtle passed through the four waypoints in order and then came back to the first waypoint. The pilot was able to guide 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. The turtle's trajectories were recorded by the color-based tracker as shown in Figure 3-3A.

As shown in Figure 3-4, 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 3-2).

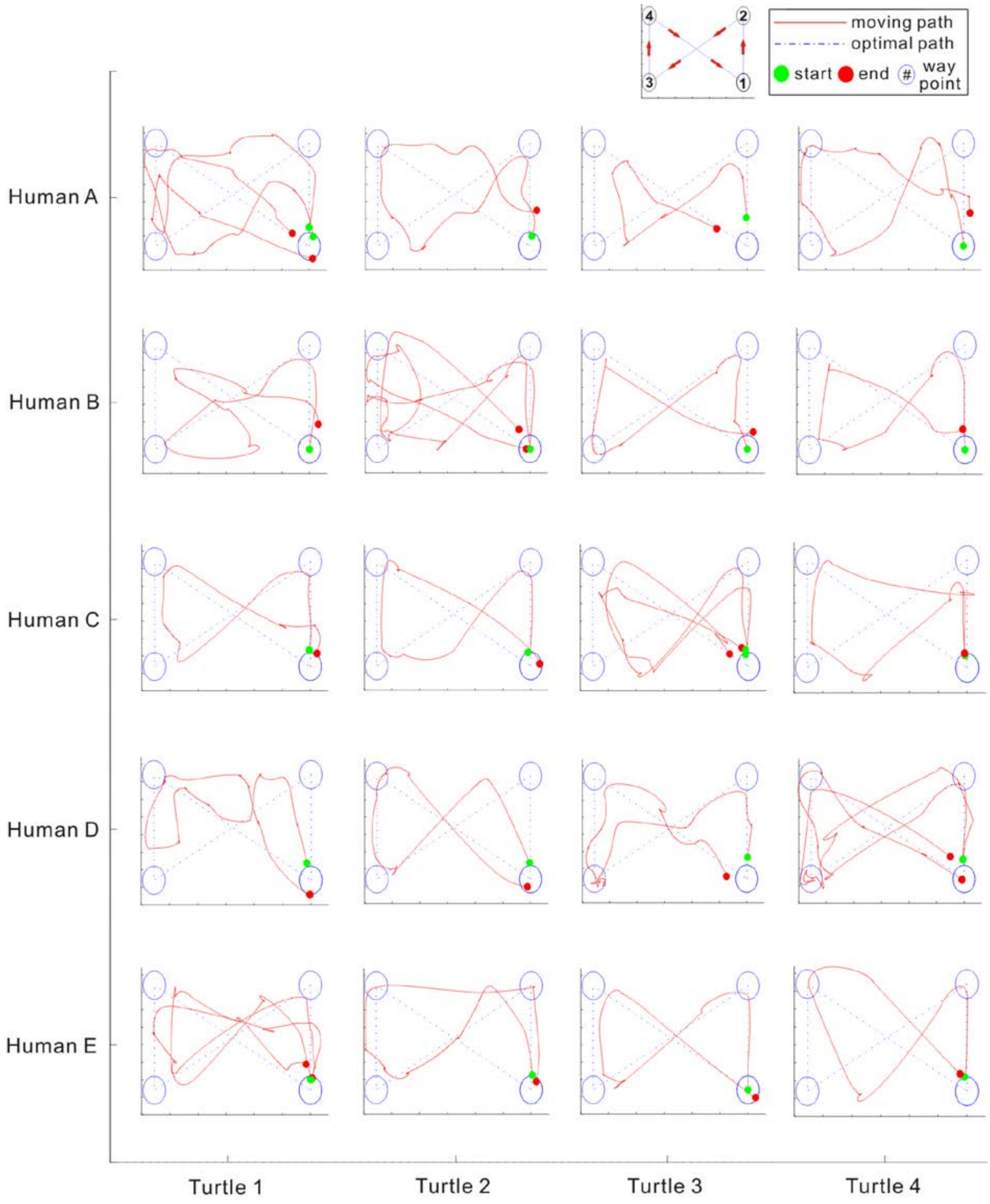
The average travel time and distance were found to be 538.4 s and 907.5 cm, respectively. The average speed of the cyborg turtle was 1.84 cm s-1. The average CTE over the five subjects was 24.45 cm. This value means that an average error of 24 cm was incurred between the cyborg turtle and the optimal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

A



B



4
2
3
1
moving path
optimal path
start
end
#
way point
Human A
Human B
Human C
Human D
Human E
Turtle 1
Turtle 2
Turtle 3
Turtle 4

Figure 3-4. Controlled trajectories of cyborg turtles with each human pilot.

(A) Description of implementation of the indoor test.

(B) The cyborg turtle was 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 closely resembles the blue path.

Table 3-2. Results of the indoor test.

Subject	A	B	C	D	E	**Total**
Avg. 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)**
Avg. 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)**
Avg. speed (cm 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)**
Avg. 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 Avg. speed of comparison group (unstimulated turtle) = 2.53 (± 0.42) cm s-1						

3.3.3 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. Figure 3-3C illustrates the outdoor test area. The straight line distance between the start and end positions was 12 m. In Figure 3-5, our 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).

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

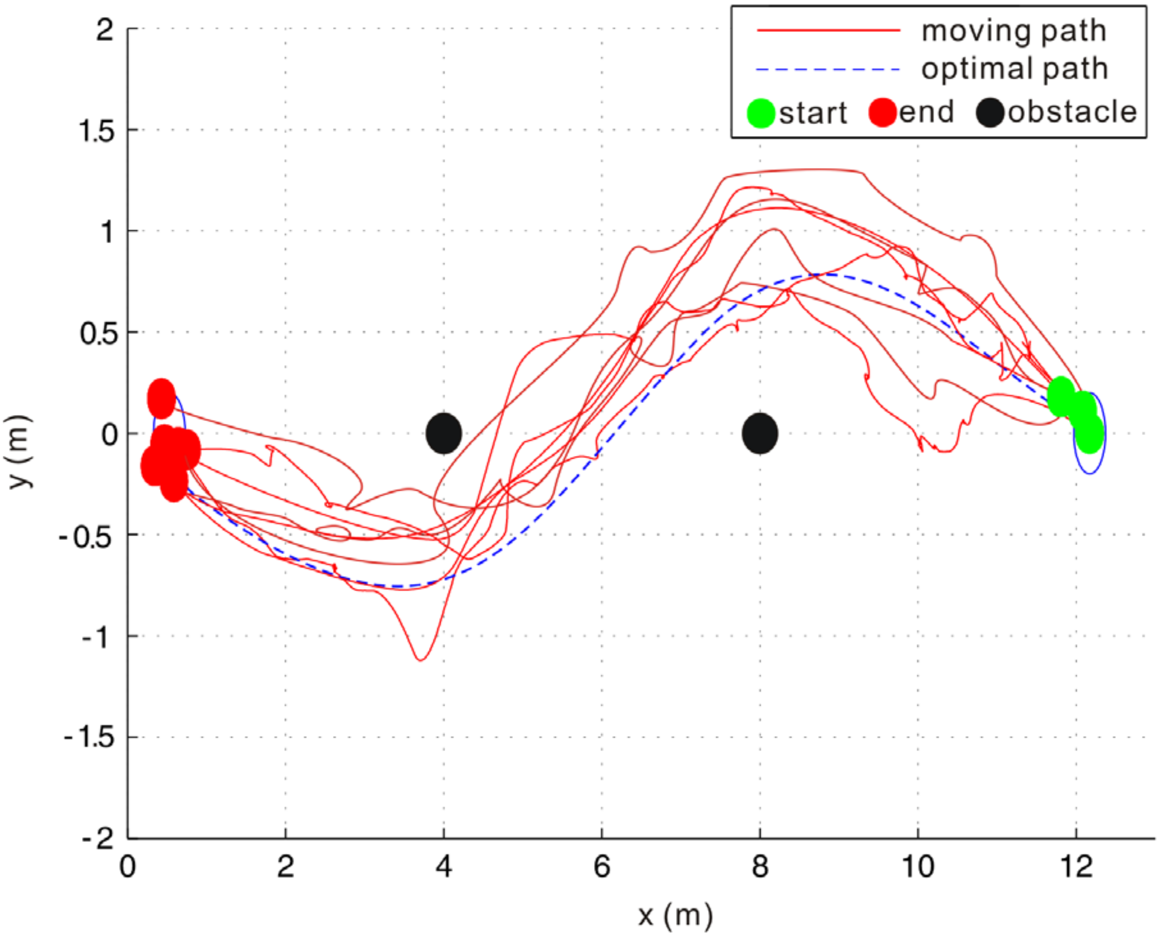


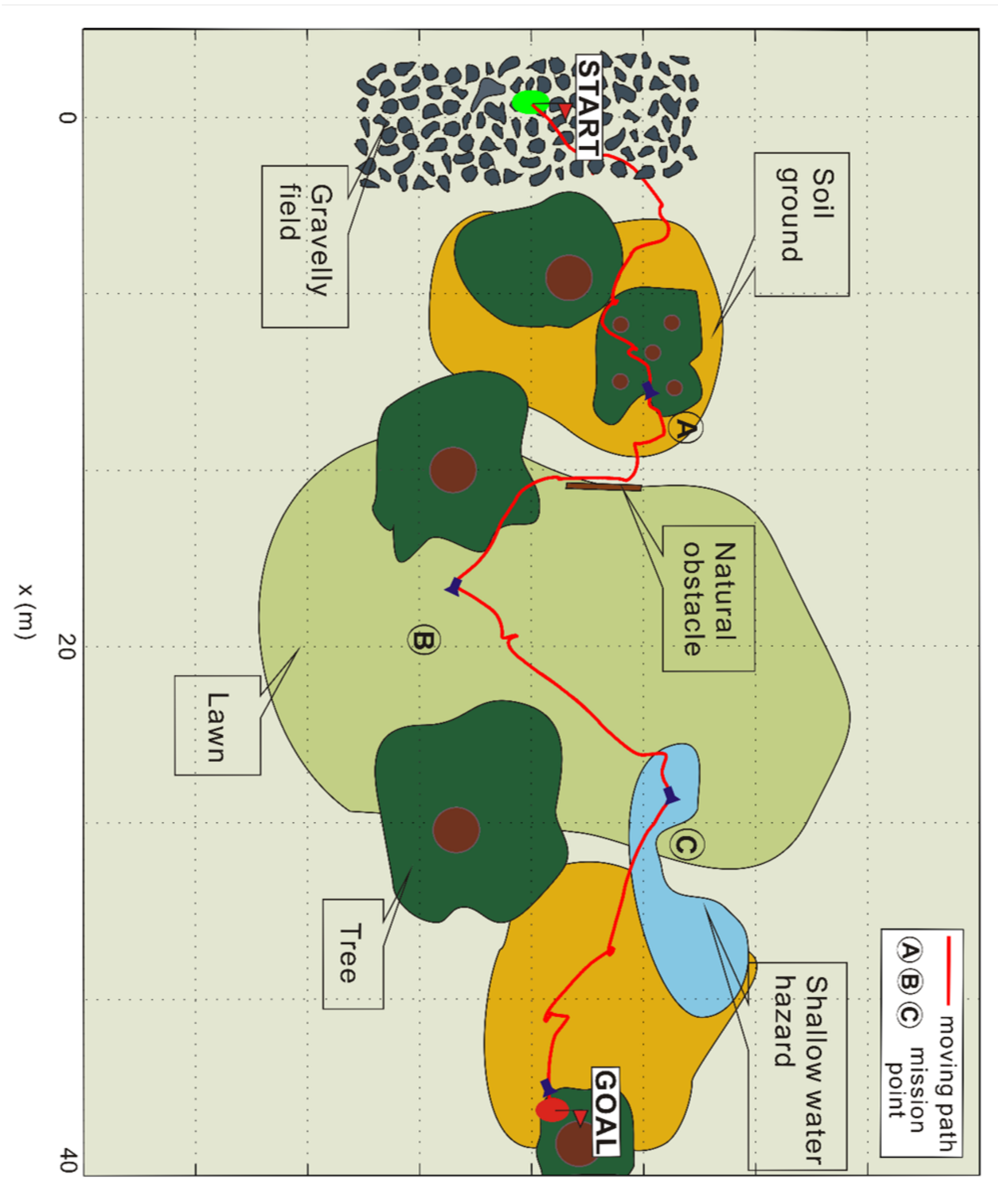
Figure 3-5. Results of outdoor test.

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.

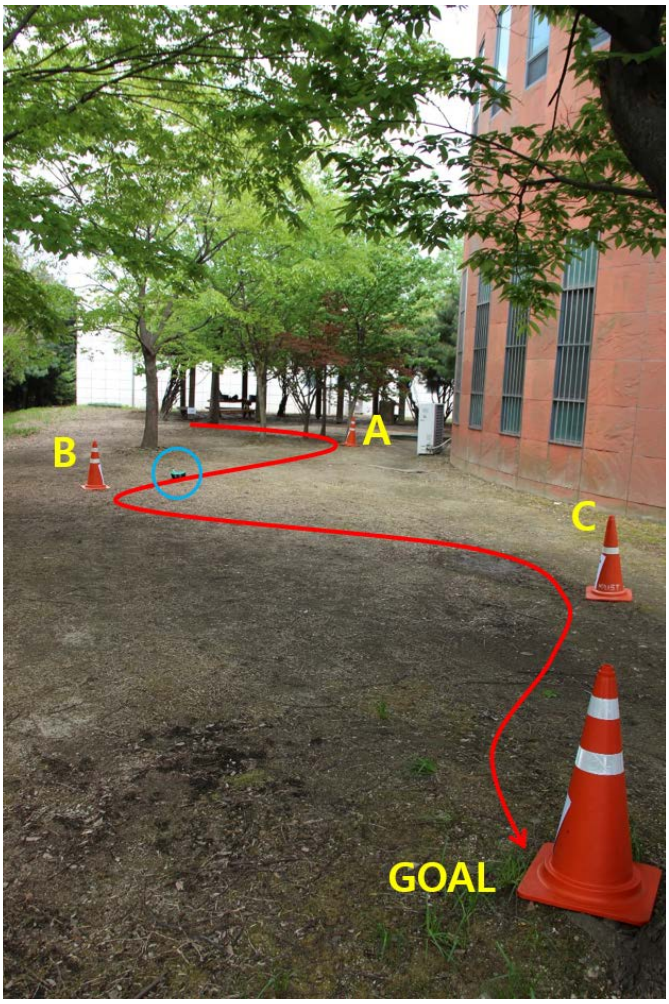
3.3.4 Field test

To examine the applicability of our system, we operated it in an actual field. Figure 3-6A 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 Figure 3-6B, despite the relatively rugged geomorphological conditions, our cyborg turtle was able to carry out the assigned mission and successfully capture 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 (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.

A


moving path
Ⓐ Ⓑ Ⓒ mission point
START
GOAL
Soil ground
Gravelly field
Natural obstacle
Lawn
Tree
Shallow water hazard
A
B
C
0
20
40
x (m)

B



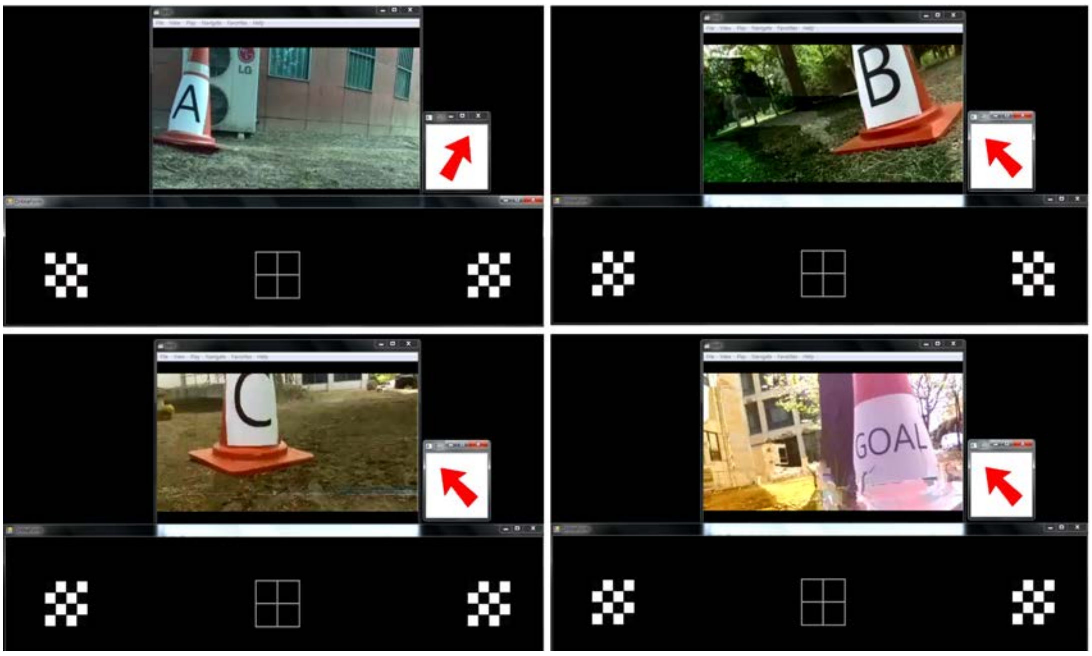


Figure 3-6. Results of field test

(A) Cyborg turtles’ 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 turtles’ cameras 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 pilots’ visual cortex are synchronized with the left and right SSVEP flickering stimuli, respectively, provided by these checker boards.

3.4 Closure

Through this study, we would show our animal control scheme is still vailed in outdoor condition and, as an application viewpoint, we introduce our novel attempt to remotely control an animal's behavior by human thought alone. So, we constructed a "human brain actuated cyborg turtle," and conducted various tests not only indoor but outdoor conditions.

We designed the architecture of our concept system, user interface, and each of the devices to be worn by the human and the turtle. Especially, the design of the overall architecture and user interface was salient to our concept system. All of the devices were designed to be non-invasive and wearable systems by considering of the system characteristics. We then performed three kinds of tests to verify our concept system. An indoor test was done to check the operability of our system (Figure 3-4 and Table 3-2) and two outdoor tests were implemented to check the applicability under more complicated natural environment conditions (Figure 3-5 and 3-6). The results of these three tests showed that our cyborg turtle system can be operated successfully under a wide range of environmental conditions. Notably, the result of field test carry an important meaning that our animal guiding scheme is still valid in outdoor condition where a lot variables exist. Generally, from lower to higher animals, escape behavior is essential instinctive behavior for their survival. So, this reactive behavior must occur quickly, and be evoked, mediated, and directed in a consistent manner by a stimulus. For this reason, we surmise our animal guiding scheme could be valid in outdoor environments.

Our proposed system constitutes an innovative approach to constructing a human-animal control 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. First, by inducing instinctive behavior, our system can control the movement of a living animal and perform a particular mission while minimizing the danger to the animal. Secondly, this research widens the range of application of BCI through the success of controlling animal behaviors using human BCI techniques. Thirdly, our wearable devices are more accessible than existing BCIs or animal control devices. Finally, we evaluated the applicability of our system not only in indoor but also in outdoor conditions.

Chapter 4. Directing the turning behavior of carp using virtual stimulation

4.1 Introduction

Recently, outstanding progress in electronics, mechanics, and biological sciences has facilitated research on the use of animals as mobile platforms, similar to that of drones and micro robots. Animal platforms have the merit of locomotion and energy efficiency, because their bodies have evolved through natural selection over millions of years. Thus, there have been several trials to control the movement of insects and other lower animals by applying direct control methods or by stimulating instinctive behaviors [2, 3, 5, 6, 53, 70].

In our previous study, chapter 2, we showed that it is possible to control the behavior of animal by evoking instinctive behaviors through virtual stimulation. Using a special device that provides visual stimulation, obstacle avoidance behavior in freshwater turtles (*Trachemys scripta elegans*) was evoked, allowing us to control their movement trajectories. This result led us to question whether similar virtual stimulation could be employed to control other animals, such as fish.

For the purpose of fishery and aquaculture, research on fish behavior has focused on certain aspects, such as the structure of the sense organs, locomotion, and social behavior. Various methods of eliciting fish movement have been explored, including the use of sound, light, electrical/chemical stimuli, and water flow [41, 44, 45, 48, 53, 54, 62, 63]. Fish's innate sense, Mechanosensory hair cells on the lateral line sensory organs allow fish to detect hydrodynamic pressure differences created by flow velocity gradients and encode hydrodynamic information is critical for many fundamental behaviors [35-39, 50, 56, 57, 61]. Also, like most animals, vision is the dominant sense for many fishes. In particular, fish rely on vision to initiate and modulate locomotion [40, 43, 47, 65]. Vision and the lateral line sensory organs are highly important for fish behavior, including searching for prey, evading predators, and school formation [34, 60, 67], and its locomotion [39, 49, 58, 60].

The common carp (*Cyprinus carpio*) was chosen to examine the visual obstacle avoidance behavior. To control the carp's moving path using its obstacle avoidance behavior, we should comprehend its behavior mechanism and reactions to stimulation for visual sense. So in this chapter, we implemented two experimental tests: (1) the obstacle cognition test and (2) the turning behavior test. The obstacle cognition test was performed in a flow chamber to determine how carp reacted to cognitive obstacle objects. We then attached a stimulation device to carp to evoke the obstacle avoidance instinct of carp through the virtual visual and vibration stimulation. The turning behavior test was performed in a water tank to analyze the movement trajectories of carp. Based on our results, we discuss the potential to control fish behavior using innate sensory stimuli, without any form of training. Finally, we discuss about our experimental result to develop a remote control system for carp.

4.2 Material and Methods

4.2.1 Fishes

Carp (*C. carpio*) were chosen because: (1) they move actively, (2) are easy to obtain, and (3) are easy to maintain in the laboratory. Fifteen carp (length = 30~40 cm, weight = 550~730 g) were housed indoors in laboratories at Korea Advanced Institute of Science and Technology (KAIST). The carp were housed together in water-filled glass tubs (1.5 x 3 x 1 m). The tank was fitted with a water filter and maintained at 18 °C. The carp were fed commercial pellets three times a week. After at least 12 hours without any feed in the tank, the fish were moved to the flow chamber and experimental water tank for the experiments (Figures. 4-1 and 4-2)

4.2.2 Experimental protocol and Apparatus

When running the experiments, each carp was only used within bounds that they did not experience fatigue during the experimental session. Fifteen carp were selected at random for each set of tests. In each test, their behavior was video recorded for 10~30 s (obstacle cognition test) and 300 s (turning behavior test) using an experimental camera (Firefly FMVU-13S2C, Pointgrey, Canada).

The obstacle cognition test was implemented in a flow chamber with semi-laminar flow at 1.0–1.5 cm/s. The flow chamber was 1.5 m long and 0.75 m wide, with a water depth of 0.6 m. This chamber had opaque white sides, and three different wall type obstacles. The wall type obstacles were made of transparent, black/transparent, and transparent/black acryl, and were of 60-cm height (Figure 4-1).

For the turning behavior test, a simple stimulator (Figure 4-2A) was designed to provide the carp with a stimulus causing obstacle avoidance. This device looks like a full face helmet and consists of a vision stimulator (blinder), a vibration stimulator (vibration motor [Φ10, 9000 ± 2000 rpm]), and a 1.5 V button cell (LR44, Toshiba, Japan). The stimulator weighed 24 g (with the pair of vibration motors weighing 2 g and the batteries, 4 g), representing 3.3–4.5% of the carp's weight. For the test, we allowed the carp to acclimate this device first, and then the carp were allowed to swim in a square water tank (1.5 m × 1.5 m, water depth 0.6 m) without flow (Figure 4-2B).

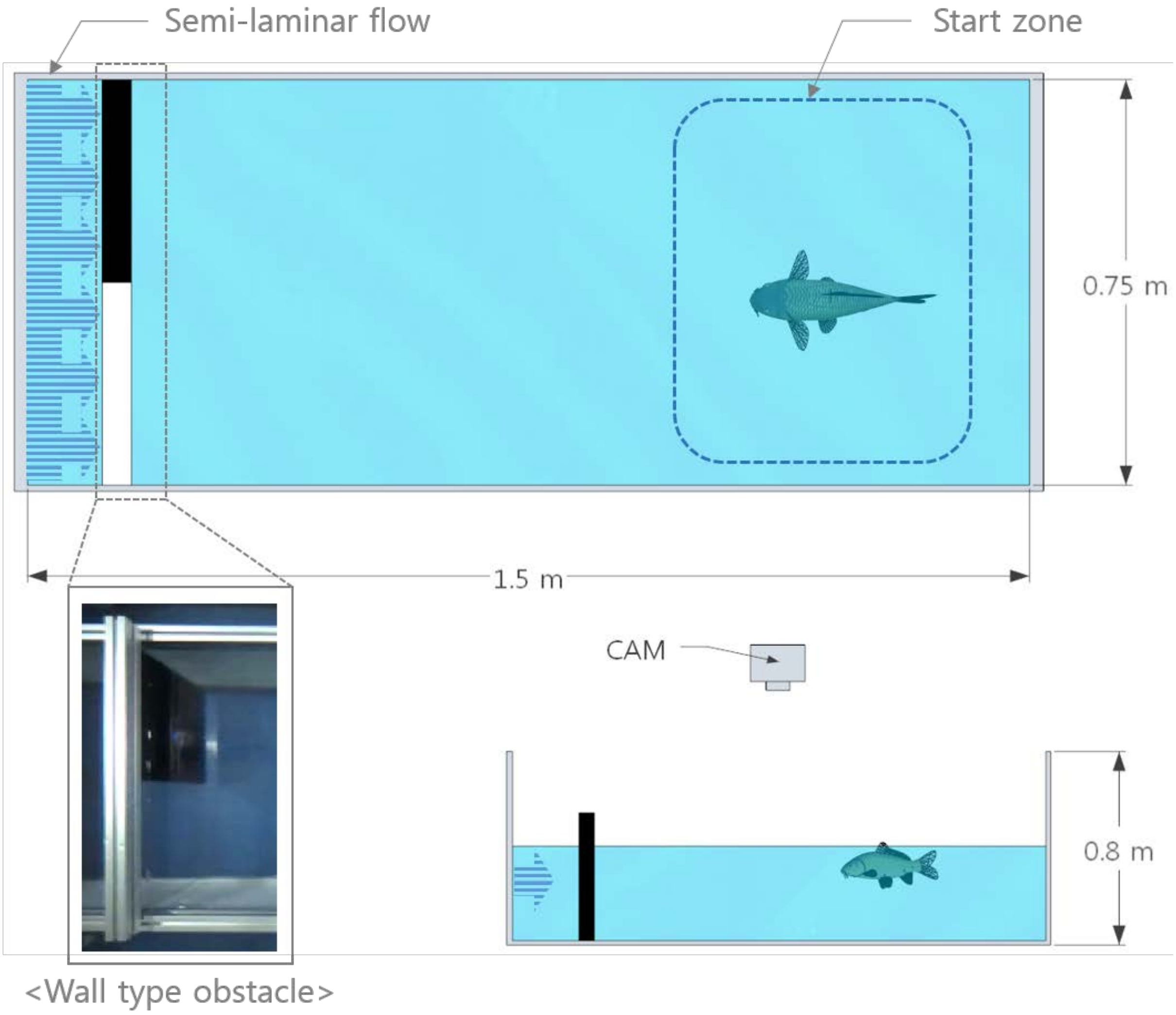


Figure 4-1. Experimental setup for the obstacle cognition test. In the flow chamber, there was a semi-laminar flow of 1.0–1.5 cm/s from the opposite end to the point where carp would start swimming. Then, the carp (*C. carpio*) swam against the current (showing positive rheotaxis).

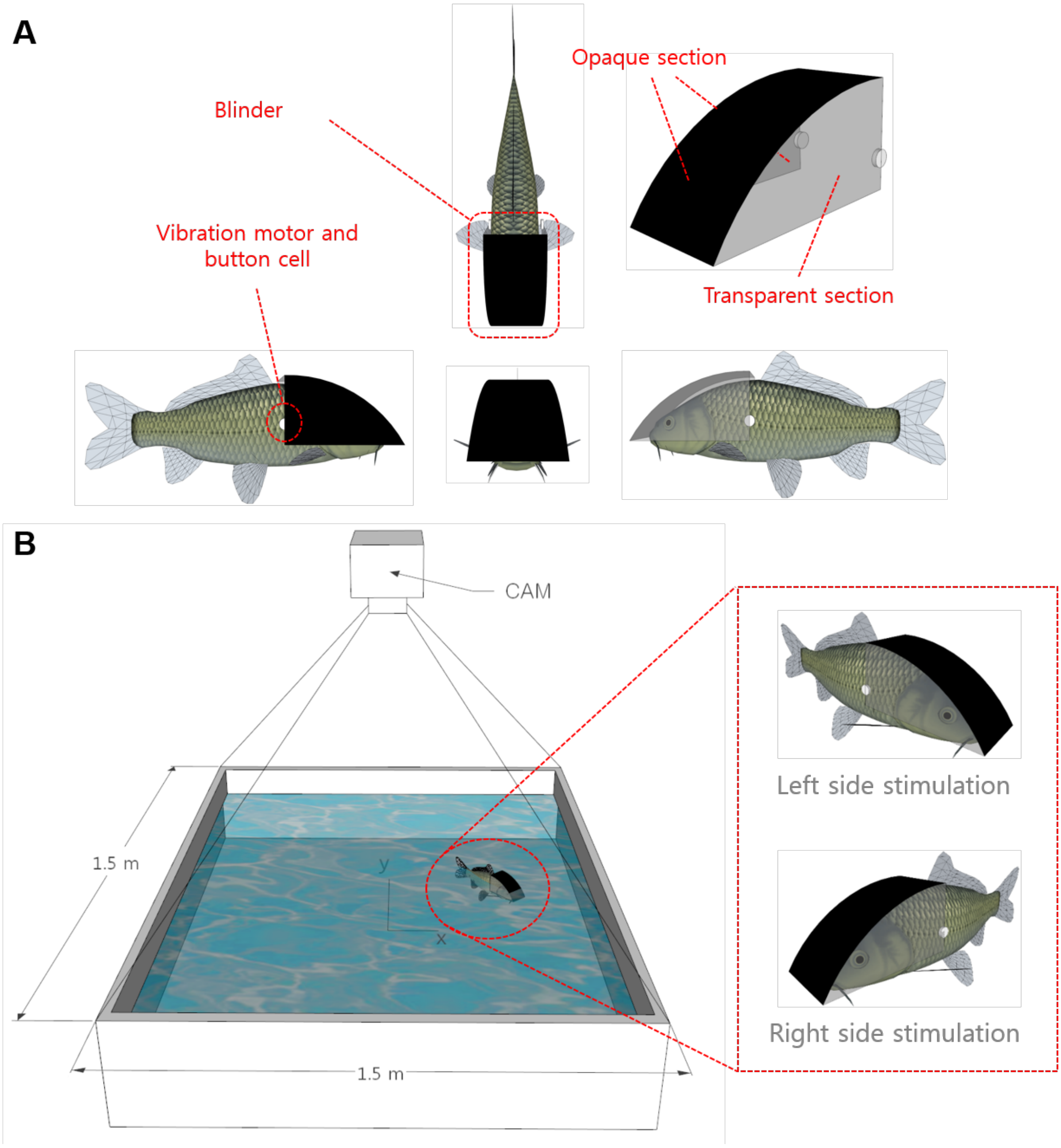


Figure 4-2. Schematic of the experimental device and settings for the turning behavior test.

(A) The stimulation device used to induce carp (*C. carpio*) obstacle avoidance behavior. The device consists of a blinder, vibration motor, and button cell.

(B) Experimental setup for the turning behavior test. The water depth was 0.6 m.

4.2.3 Data analysis

Throughout all of the tests, the path used by the carp was tracked by a camera using a color-based tracker based on a MATLAB (The Mathworks Inc., USA) image processing program developed by Matpic. During the tests, a Kalman filter with linear models was used to describe the trajectory of the carp.

In the obstacle cognition test, fish behavior was recorded for 30 s, and each session was repeated 20 times. We also calculated the “avoidance rate” (defined as the percentage of number of times that the fish avoided visual obstacles throughout the trials) from the trajectory of the carp. Then, in the turning behavior test, the behavior of each individual was recorded for 300 s, and each session was repeated 50 times. This information was used to calculate “the amount of turning” in each experiment; specifically, “turning distance (TD)” and “average turning velocity (ATV).” These parameters are defined by the following equation in chapter 2:

$$\mathrm{ATV} = \frac{\mathrm{TD}}{(\text{total travel time})} \quad \text{with} \quad \mathrm{TD} = \sum_{i=1}^{n} \left|\vec{a_i}\right| \sin\theta_i$$

The TD is derived by dividing the entire path into n-segmental vectors by sampling each second, after which, the ATV under the condition $\theta \leq 90°$ is defined by this equation (see Figure 4-3 for example). These measures quantify the amount of displacement from the carp’s previous heading per unit of time. Using these measures, we could calculated the amount that each carp turned during its movement trajectory. (see Figure 4-5)

We used various statistical tests to analyze our data (Figure 4-6), depending on the assumptions of the tests met by the data. We used a Mann-Whitney U test (M-W U test), with $p < 0.05$. In all cases where data were compared multiple times, we used a Bonferroni correction for multiple comparisons of each trial after stimuli presentation. Lower case letters represent statistically homogeneous groups (Robie et al., 2010). For example, in Figure 4-6, groups “a” and “b” are significantly different, whereas “a” is not significantly different to “ab,” which shares membership with group “a.” All statistical analyses were performed using Minitab (Minitab Inc., USA).

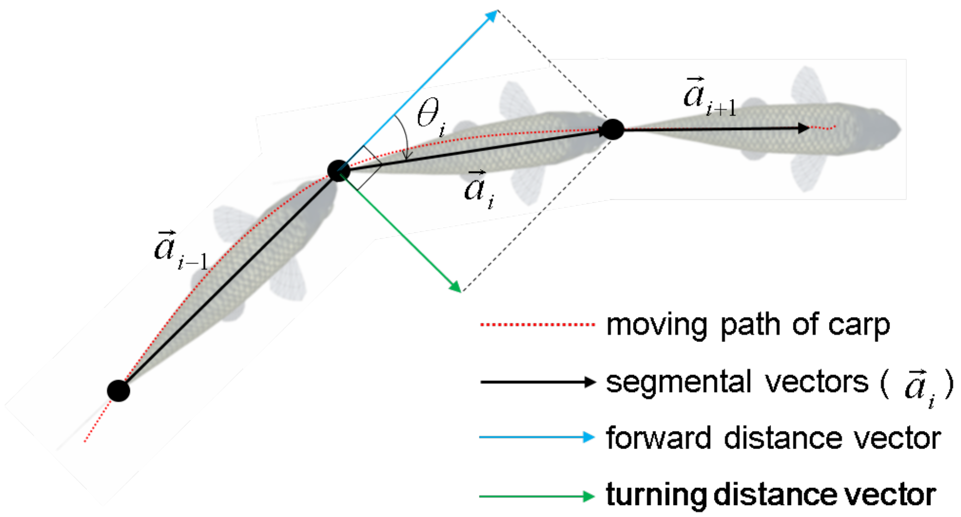


Figure 4-3. Schematic of the turning distance (TD) vector. To measure the carp’s (*C. carpio*) turning behavior, a TD vector was defined (see the methods section for details).

4.2.4 Ethical Note

The animal experiments were approved by KAIST (Korea Advanced Institute of Science and Technology) Institutional Animal Care & Use Committee Board (Permit Number: KA2014-27). The personal certification numbers were as follows: Cheol-Hu Kim (2010-OE01), Dae-Gun Kim (2011-OE01), Daesoo Kim (2008-BS7), and Phill-Seung Lee (2014-OS01). Our target animals (common carp: *C. carpio*) were manipulated in strict accordance with KAIST Animal Experiment Ethical Law RR0303 (revised 24/07/2013), and all efforts were made to minimize suffering.

4.3 Results

4.3.1 Obstacle cognition test

This test was performed to identify the type of objects that carp recognize as obstacles, and how they react to recognized obstacles along their moving route. We first examined carp movement trajectories when wall type obstacles (width = 75 cm, height = 60 cm) were initially placed 100 cm in front of each individual. We found that carp recognized the black wall as an obstacle, but not the transparent wall. The carp faced toward the transparent side, but avoided the black side (Figure 4-4). The avoidance rate calculated from each experiment generated a score of more than 90% (N = 20), regardless of the position of black wall obstacle.

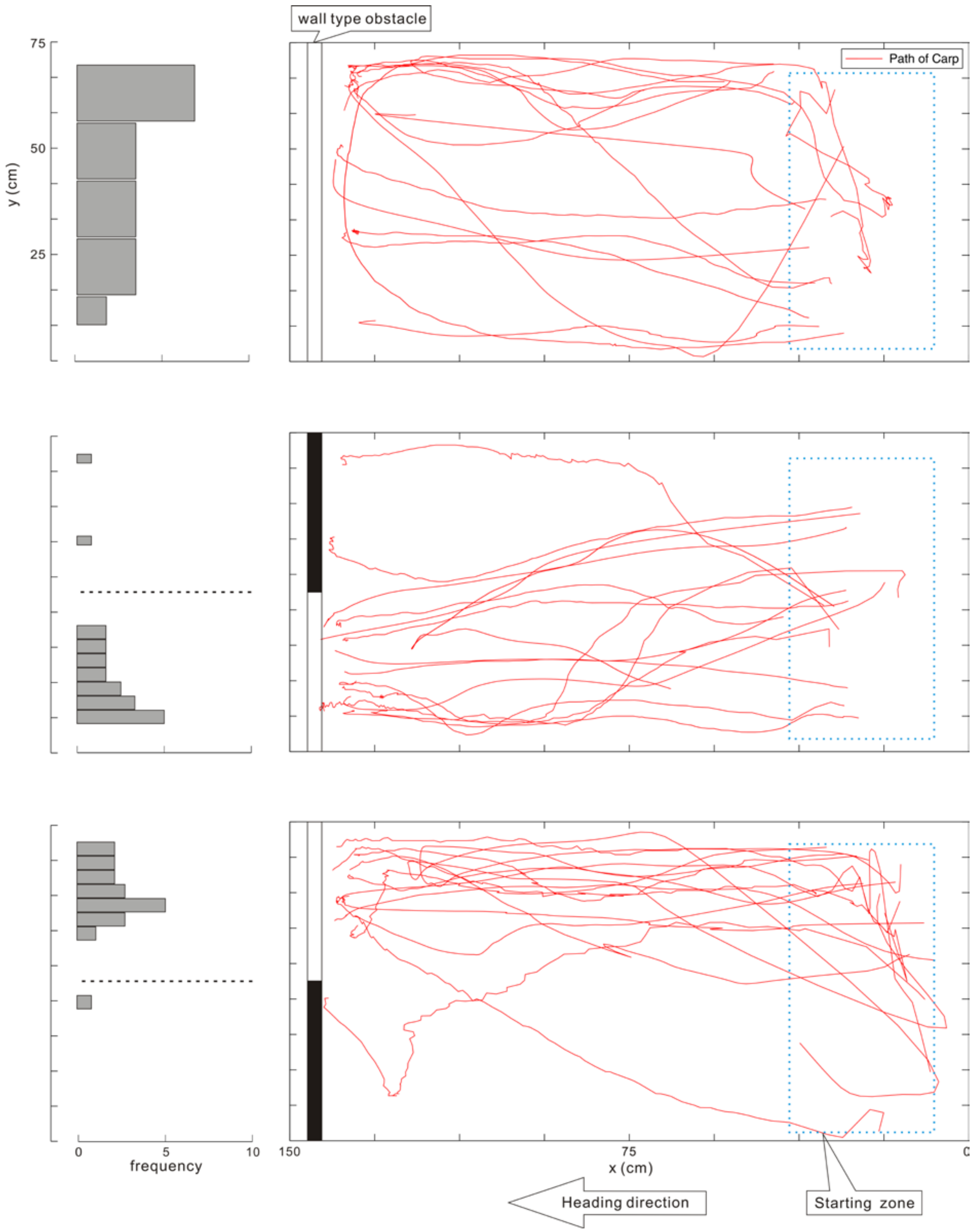


Figure 4-4. Movement trajectories of carp (*C. carpio*) in the obstacle cognition test. Three types of obstacles (transparent, black/transparent, and transparent/black) were used in this test.

4.3.2 Turning behavior test

In this test, we examined the movement trajectories of carp when their vision and lateral line senses were stimulated by our device (see Figures 4-5 and 4-6). The preceding test showed that carp avoid black wall obstacles, moving toward the transparent side. Based on these results, we designed a simple stimulator (Figure 4-2A), and performed four experiments. Each experiment was conducted 50 times, and each session was recorded for 300 s, with 15 carp being used at random. We analyzed the results of each experiment using ATV and the M-W U test.

4.3.2.1 Free Swimming

First, we examined the free swimming condition of carp without any stimulation. This test was implemented 50 times by replacing 15 carp each time. Under these conditions, the ATV value was almost zero (+0.0194 cm/s) for free swimming ("+" and "-" signs indicate left and right turning directions, respectively; left turning was dominant in this moving trajectory). Thus, carp movement was inconsistent under free conditions. These data were used as a baseline for comparison with the subsequent experiments (Figure 4-6A).

4.3.2.2 Vibration stimulation

Carp movement trajectories were examined when vibration stimulating on each side of the body. The pair of vibration motors vibrated at 150 Hz, changing the flow of water near each lateral line. When we stimulated the right side, the ATV value was +0.2573 cm/s. When we stimulated the left side, the ATV value was -0.1103 cm/s. The M-W U test results were similar for the right (W = 2534, N = 50, P = 0.9533) and left (W = 2499, N = 50, P = 0.8605) sides. Therefore, these stimulations were not significant under our experiment condition.

4.3.2.3 Visual stimulation

In this test, we blocked the vision (right and left) of carp using our visual stimulation device (blinder), and analyzed their moving paths. Throughout the obstacle cognition test, we found that carp tend to move to the transparent side. As a result, using our device, the overall moving path of carp tended to rotate in the direction that was not blocked. When we blocked the right vision, the ATV value was +0.9788 cm/s, and when we blocked the left vision, the ATV value was -0.6244 cm/s. However, the absolute ATV value was higher than when we stimulated the lateral line of the carp. The M-W U test showed that the control group (free swimming; N = 50) was not significantly different to the right (W = 2408, N = 50, P = 0.4219) and left (W = 2639, N = 50, P = 0.4340) blocked vision stimulation groups.

4.3.2.4 Simultaneous stimulation: vision and vibration

In this test, we stimulated carp's vision and give vibration stimuli simultaneously. When an obstacle was presented virtually through simultaneous stimulation, the carp efficiently turned to move in the opposite direction. Following simultaneous stimulation, the ATV value on the right side was +1.3208 cm/s, while it was -1.1832 cm/s on the left side. These values were considerably higher than those obtained in the previous experiment. The M-W U test showed that the control group (free swimming; N = 50) was significantly different to the right side (W = 2092, N = 50, P = 0.0029) and left side (W = 2837, N = 50, P = 0.0318) stimulation groups.

Table 4-1. Results of the turning behavior test

Types of stimulation	None (Free state)	Vibration		Vision		Simultaneity	
		Right	Left	Right	Left	Right	Left
ATV (cm/s)	+0.0194	+0.2573	-0.1103	+0.9788	-0.6244	+1.3208	-1.1832
P value	·	0.9533	0.8605	0.4219	0.4340	**0.0029**	**0.0318**

"+" and "-" signs indicate left and right turning directions, respectively.
The Mann-Whitney U test (M-W U test) with p < 0.05 was been used.

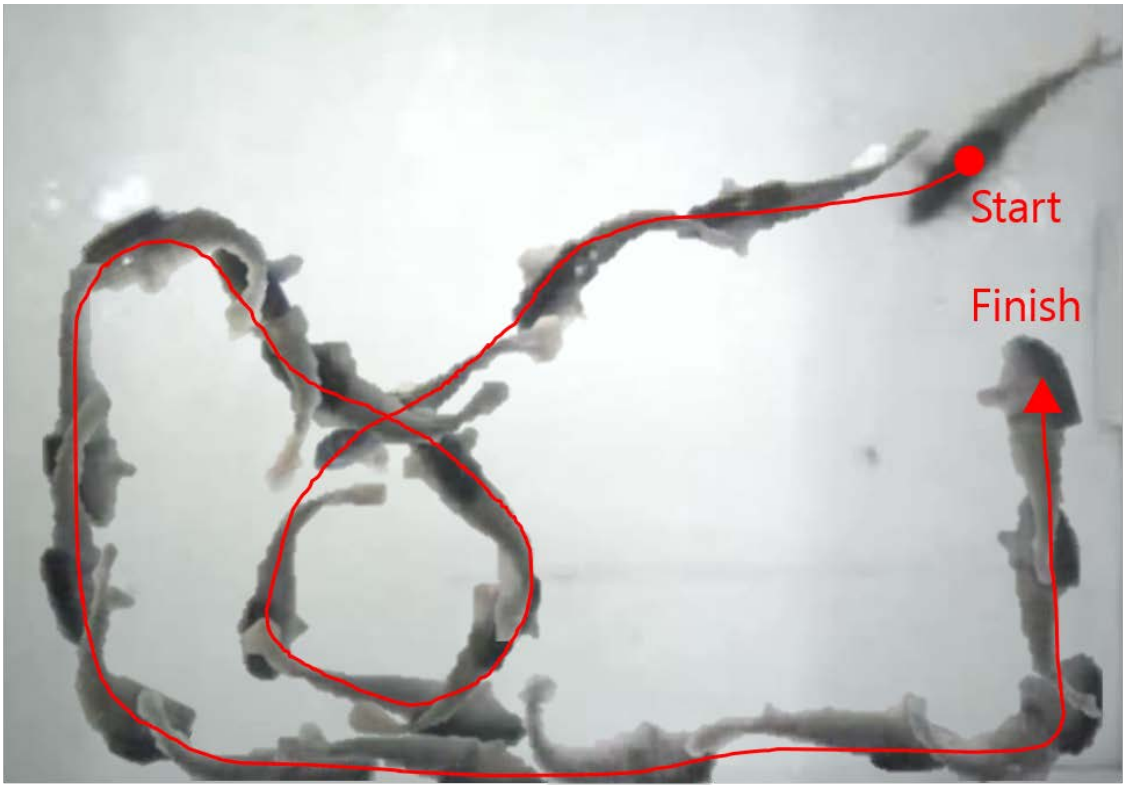


Figure 4-5. Movement trajectory during the simultaneous stimulation of the right side (right vision was blocked and the right side vibration motor was operated). Carp (*C. carpio*) consistently turned to the left, as if avoiding a virtual obstacle.

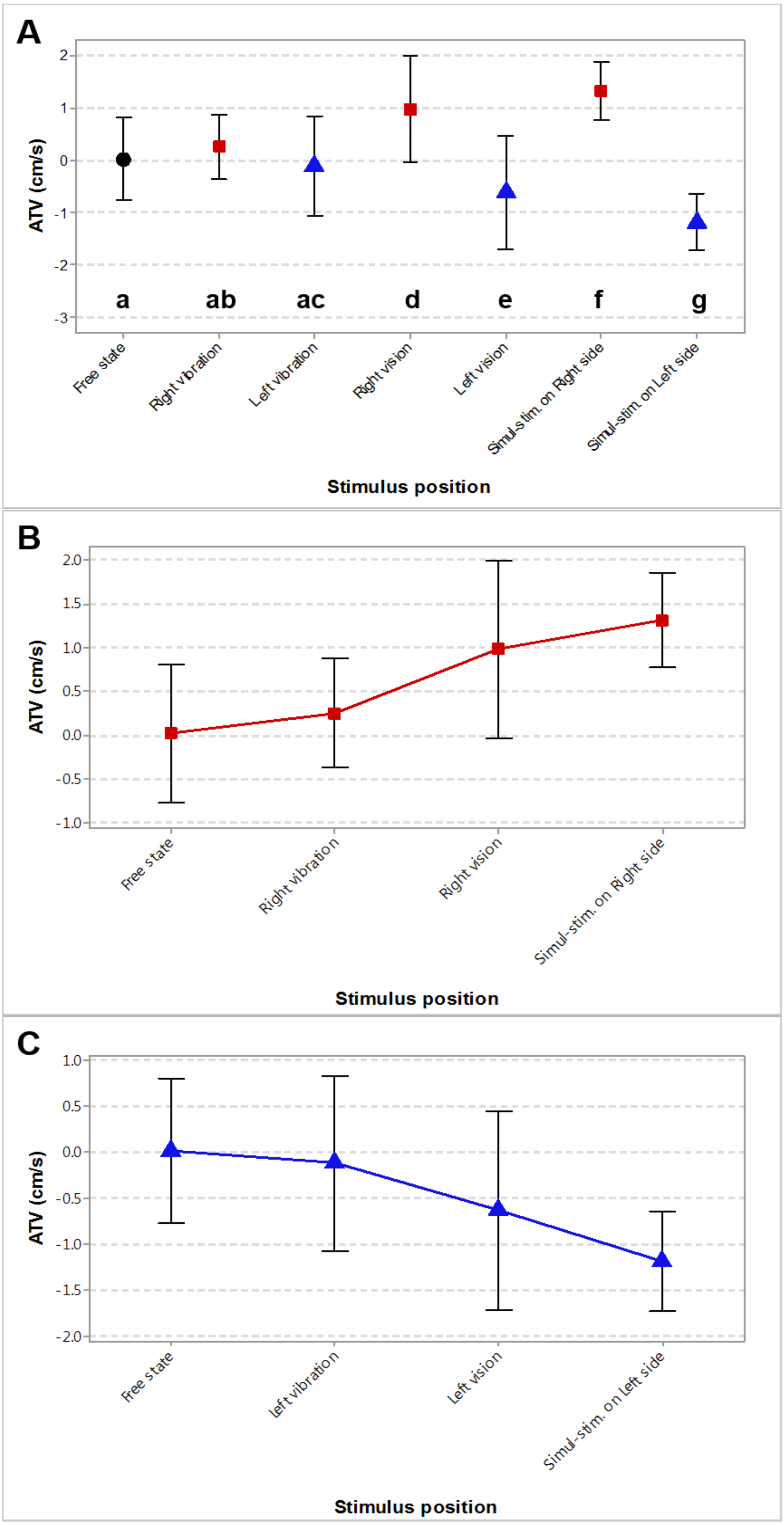

A
ATV (cm/s)
a
ab
ac
d
e
f
g
Free state
Right vibration
Left vibration
Right vision
Left vision
Simul-stim. on Right side
Simul-stim. on Left side
Stimulus position
B
ATV (cm/s)
Free state
Right vibration
Right vision
Simul-stim. on Right side
Stimulus position
C
ATV (cm/s)
Free state
Left vibration
Left vision
Simul-stim. on Left side
Stimulus position

Figure 4-6. Relationship between carp (*C. carpio*) movement and the different types of stimulation. (A) The average turning velocities (ATV) of the tracked trajectories in the turning behavior tests (e.g. Figure 4-5) were plotted from the mean and standard deviation, even though they were not always normally distributed. The positive ATV value meant that left turning was dominant in the moving path, while the negative ATV meant that right turning was dominant. The Bonferroni correction for multiple comparisons (lower-case letters) showed that the “right vibration” and “left vibration” groups were not significantly different from the “free state” group (comparison group). In contrast, the “right vision,” “left vision,” “simul-stim. on the right side,” and “simul-stim. on the left side” were significantly different from the “free state” group and the other groups.

(B) and (C) Comparison of the ATV for stimulations on the same side. The absolute ATV value increased with different stimulation types (vibration < vision < simultaneous stimulation of both the vision and vibration).

4.4 Closure

This study was designed using the simple concept that fish movement patterns may be controlled by virtually stimulating their avoidance instinct. Through two basic experiments, we demonstrated that the visual and vibration stimulation could be used to guide fish along specified moving paths or towards goal positions. These results confirm the potential utility of fish as mobile living platforms, similar to robots and drones.

In our experiment, the results indicate that carps avoid visual obstacle stimulation more effectively than vibration stimulation. Theoretically, most moving animals show obstacles avoidance behavior in their surroundings, and, in general, fast moving animals use vision as the sensory basis for this behavior [42, 46, 64, 66]. Slow moving animals often employ other senses, such as touch [55]. This generalized concept fits well with our observations of obstacle avoidance in carp being visually guided, since these animals are nimble swimmers [68].

Also, we observed interesting facts that carps are able to decide their moving path more effectively when it receive the simultaneous stimulation; vision and vibration stimuli together. Therefore, the turning direction of carp is more effectively guided when both virtual stimulations are given in combination.

Further, from a different standpoint, we surmised that our vibration stimulation amplified the carp’s turning motion. We could present several hypothesis for these results such as our stimuli caused the direct muscle stimulations which is associated with carp’s turning movement or evoked another instinct behavior. Also, we think that more studies are necessary to investigate which sense of organ is stimulated by our vibration stimuli and interrelation of visual and vibration stimulation clearly.

The current study examined obstacle avoidance, which is one of the essential responses for an organism’s survival. By providing a visual and vibration stimulus that induces obstacle avoidance behavior, we controlled carp turning movement. Our experiments demonstrate that fish behavior could be effectively guided by evoking instinctive behavior, with our results providing the first evidence about the modulation of fish behavior through the simple combination of innate sensory stimuli, without any form of training.

Previous studies have trailed controlling fish movement by using electrical brain stimulation [51, 52]. However, these techniques were invasive, requiring surgical intervention. To overcome these limitations, we developed devices and platform technologies to modulate fish innate behavior by stimulating external senses. Our devices were designed to be non-invasive, which would be suited for submersible control systems.

Our findings are expected to contribute information to control fishes with a stimulation/control device attached to the fish body in the future. To develop effective stimulation/control devices and achieve the desired level of control, further research is required on the reciprocal actions of fish sense organs. A number of challenges remain, including telecommunication, navigation, miniaturization, and waterproofing. However, ultimately, this technology could be used in deep-sea exploration, and could replace our dependence on robotic probes. This technology could also be used to observe fish movement from an ethological perspective and to understand their complicated interactive behavior with conspecifics.

Chapter 5. Conclusion

Through these researches, we examined one of the essential responses for an organism's survival: obstacle avoidance and escape behavior. By providing an external stimulus that causes the behavior, we remotely controlled our target animal's moving behavior.

We first examined the turtle's visual recognition of obstacles under various conditions. We found that the turtles, recognizing the white object as open space, headed for it regardless of other conditions. Second, we tried to find out the turtle's obstacle recognition distance. We discovered that no matter what the obstacle's height (apparent size), the turtle did not come closer to it than 15cm. Third, we then designed a simple device to examine the turtle's visually planned obstacle avoidance behavior. We found that the more the turtle's view was blocked by the obstacle, the sharper it turned away from it. Lastly, by applying the above results, we were able to successfully control the turtle's walking paths.

Further, as an application viewpoint, using BCIs technology, we attained success in remotely controlling the path of an animal in real field condition through human thought alone. This concept grew out of the popular science-fiction concept of a person being able to exist in another human body or being able to control an animal by a remotely connected mind. We constructed a “human brain actuated cyborg turtle,” which is a remote guidance system for a turtle, controlled by a human BCI.

Our proposed system constitutes an innovative approach to constructing a human-animal control 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. First, by inducing instinctive behavior, our system can control the movement of a living animal and perform a particular mission while minimizing the danger to the animal. Secondly, this research widens the range of application of BCI through the success of controlling animal behaviors using human BCI techniques. Thirdly, our wearable devices are more accessible than existing BCIs or animal control devices. Fourthly, we evaluated the applicability of our system not only in indoor but also in outdoor conditions. Especially, the result of field test carry an important meaning that our animal guiding scheme is still valid in outdoor condition where a lot variables exist.

Lastly, we expanded our target animal area, choose fish and implement primary experiments for developing a remote control system. Fishes detect various sensory stimuli, which may be used to direct their behavior. Through this research, we examined the specific role of obstacle avoidance behavior on carp’s movement. When a visual obstacle was presented, the carp efficiently turned and swam away in the opposite direction. In contrast, vibration stimulation could not induce strong turning behavior. The vibrator only regulated the direction of turning when presented in combination with the visual obstacle. Our results provide first evidence on the innate capacity that dynamically coordinates visual and vibration signals in fish and give insights on the novel modulation method of fish behavior without training.

Through these studies, we could know that animals (especially turtle and carp) behavior can effectively be guided by evoking instinctive behavior essential for survival. Unlike the involuntary behavior control schemes that have been previously proposed, which compel a response by stimulating the corresponding neural circuit (or musculature) regardless of the animal's intention, our approach is to guide the animal by elaborately inducing its voluntary instinctive behavior. In addition, while most involuntary controllers may require additional sensors to adjust responses to an abrupt or unexpected situation (e.g., when an insect meets an uncontrolled obstacle in its otherwise controlled or planned path), voluntarily controlled animals are expected to adapt themselves to the situation by combining the directed and adaptive behaviors.

We therefore believe that an innate behavior caused by an external stimulus can easily and effectively be employed to control an animal's movement, and will not impose a heavy strain on the animal. Although it is necessary to overcome the technical difficulties of designing a new device in order to apply the specific stimulus causing the innate behavior to other animals in other environments, this approach may provide a clue to a general framework for behavior control.

In future works, we will study controlled behavior in more detail and also apply this framework to other animals. We consider pigeons and rats are good candidates for system. They are also big and strong enough to carry larger devices. Also, with the development of BCI technology or an enhanced HMD system, our system could be further improved in terms of its adaptability and usability. Then our system allowed us to attain a wider range of experience and information from different species of controlled animals.

To achieve this goal, we will face a lot of challenges related to miniaturization, waterproofing, telecommunication, and navigation at the least. We expect the most useful behavior controller will incorporate nonlinear control methods with a positioning system (like indoor GPS) and IMU (Inertial Measurement Unit) to direct animal behavior without any human intervention. This technology could be used exploration or navigation applications like robotic probes. We could also take such opportunities to observe their movement from an ethological perspective to understand their complicated social behavior. 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. We expect that our technology will become an innovative framework for human-animal control systems.

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요 약 문

자발적 본능행동 제어를 통한 거북과 잉어 원격 유도 시스템 개발

최근, 기계 및 전자 그리고 생명공학 기술이 발달함에 따라, 동물을 로봇과 같이 활용하고자 하는 동물-사이보그 시스템 개발 연구들이 시도되고 있다. 현재, 기존 일부 선행연구에서는 곤충, 어류 및 설치류의 행동유도를 이끌어 내는 데에 성공하였으나, 대부분의 동물 조종방법은 뇌 또는 근육에 침습적인 방법을 이용하여 전기자극을 부여함으로써 동물의 움직임을 강제적으로 제어하는 방식으로 이루어 진다. 하지만, 이러한 방법은 지속적인 조종이 힘들뿐만 아니라 조종되는 동물의 생명에 극심한 피해를 입히는 한계점을 가진다.

본 논문에서는 동물의 필수적인 행동요소인 장애물회피 및 탈출본능을 자극하여 동물의 자발적인 행동을 유도하는 비 침습적인 방법을 활용하여 동물의 이동경로를 제어할 수 있는 새로운 시스템을 개발하고자 한다. 본 조종 시스템은 안정성 및 지속성, 나아가 생명윤리적인 측면에서도 기존의 침습적 동물 조종방법과 비교하여 이점을 가진다.

먼저, 거북을 첫 번째 동물플랫폼으로 선택하여 다양한 행동생물학적 실험을 통한 행동패턴분석 실험을 실시하였다. 다양한 환경 및 조건에서 거북의 장애물 회피 본능을 자극하여 행동을 분석한 결과, 조종자가 원하는 방향으로의 거북의 이동경로를 제어할 수 있다는 결과를 얻을 수 있었다. 또한 수집된 실험데이터를 바탕으로 동물의 이동경로를 원격 제어할 수 있는 행동유발 자극장치를 설계하여, 실제로 조종자가 원하는 경로를 따라 거북을 원격에서 조종하는데 성공하였다. 또한, 한정된 실내실험 공간에서뿐만 아니라 다양한 외부변수가 존재하는 실외환경에서도 본 동물조종방법을 적용한 조종시스템이 적절히 작동됨을 실험을 통해 확인하였다.

나아가 시스템의 활용적 측면에서, 뇌-컴퓨터 인터페이스 (BCIs) 기술을 본 조종시스템에 적용하여 조종자가 자신의 생각만으로 조종플랫폼인 거북을 원격에서 조종할 수 있는 신개념 원격조종 플랫폼을 개발하였다. 본 개발된 새로운 시스템은 “인간 뇌파 작동 사이보그-거북(Human Brain Actuated Cyborg-turtle)” 이라고 부르며, 해당 시스템은 크게 조종자의 머리에 착용되는 뇌파 센서, 거북에 부착되는 원격 이동제어 장치, 그리고 거북의 현재 시야를 실시간으로 인간이 그대로 볼 수 있는 HMD 로 이루어 지며, 다양한 실험을 통해 실제 야외환경에서도 정상적으로 운용이 가능함을 확인하였다. 추가적인 연구를 통해본

시스템을 더욱 개발한다면, 이를 활용하여 거북을 인간의 아바타와 같이 조종하여 재난 탐색 및 정찰과 같은 특정임무를 수행할 수 있을 것으로 기대되며, 이외에도 교육 및 레저활동 등 다양한 분야로의 활용이 가능할 것으로 기대된다.

마지막으로 본 조종시스템의 사용범위를 확장하여, 두 번째 동물플랫폼으로서 잉어를 선택하여 행동생물학적 실험을 실시하였다. 먼저, 잉어의 다양한 감각기관 중 이동경로를 선택하는데 주요한 역할을 하는 감각기관을 찾아내는 연구를 통해 시각감각이 가장 결정적인 역할을 한다는 것을 발견하였다. 본 감각을 통해 잉어의 장애물 회피 본능을 자극하는 실험을 실시하고, 추가적으로 진동자극을 부여하여 각 자극에 대한 잉어의 이동패턴을 분석하였다. 통계적 분석 결과, 시각과 진동자극을 같은 방향으로 자극하였을 때, 잉어의 회전이동이 크게 활성화 된다는 사실을 알 수 있었다. 대조적으로, 진동으로만 자극하였을 때는 명확한 행동패턴을 얻기 힘들었다. 따라서 잉어의 경우, 시각이 동시에 진동을 통한 주변의 수류변화가 동시에 이루어질 때 자신의 이동방향을 명확히 결정할 수 있다는 결론을 얻을 수 있었다. 본 연구결과를 활용하여 거북 원격조종시스템과 같은 잉어 조종시스템 또한 구축할 수 있을 것이라 기대된다.

향후 추가적인 연구를 통해, 거북과 잉어뿐만 아니라 다른 환경에서 서식하는 동물들 (비둘기, 쥐 등)로 조종 동물플랫폼을 확장할 계획이다. 또한, 다양한 행동생물학 실험을 통하여, 보다 정밀하고 신뢰성 있는 조종시스템을 구축하기 위한 연구를 진행할 계획이다. 그리고 BCIs 기술과의 접목과 같이, 다른 기술과의 융복합 연구를 통해 이전에 없던 새로운 원격 조종 플랫폼 개발을 시도할 계획이다. 이러한 연구를 통해 인간들은 다양한 종의 동물플랫폼들을 활용하여 다양한 경험과 정보들을 얻을 수 있을 것으로 기대된다.

이런 수준의 기술에 도달하기 위해선, 우리는 아직 많은 문제들을 해결하여야 한다. 행동생물학적 실험을 토대로 설계되는 하드웨어를 바탕으로 본 장치의 통신, 방수, 소형화 그리고 항법장치 등 다양한 방면의 난관들을 해결하여야 하며, 이를 위해선 기계공학, 전자전기공학 그리고 생물학의 융복합적 연구가 필수적이다. 본 연구가 실제 상용화 된다면, 우리의 생활은 많을 변화가 생길 것 이다. 먼저 인간과 반려동물 간의 능동적인 교감을 통해 전에 없던 새로운 동물교감 시스템을 구축할 수 있을 것이다. 나아가 인간이 접근하기 힘든 환경 (심해, 창공, 사막 등등)에 서식하는 동물에 본 시스템을 적용하여 다양하고 흥미로운 정보들을 습득할 수 있을 것 이다. 특히 본 시스템을 국방 및 정찰 시스템에 도입한다면, 기존의 군사용 드론 및 로봇 시스템과의 협업을 통해, 탐사 및 정찰 시스템의 획기적인 발전을 이룰 수 있을 것이다. 본 연구를 통해 우리는 혁신적인 인간-동물 상호작용 시스템을 구축하는데 일조 할 수 있을 것이라고 생각한다.

Keywords: 원격조종; 행동생물학; 거북; 잉어; 본능행동