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Parasitic Robot System for Waypoint Navigation of Turtle

Dae-Gun Kim[1], Serin Lee[2], Cheol-Hu Kim[1], Sungho Jo[3], 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. *Institute for Infocomm Research*, 1 *Fusionopolis Way*, #21-01 *Connexis*, *Singapore*
3. *Department of Computer Science*, *Korea Advanced Institute of Science and Technology*, (*KAIST*) 373-1 *Guseong-dong*, *Yuseong-gu*, *Daejeon* 34141, *Republic of Korea*

Abstract

In research on small mobile robots and biomimetic robots, locomotion ability remains a major issue despite many advances in technology. However, evolution has led to there being many real animals capable of excellent locomotion. This paper presents a "parasitic robot system" whereby locomotion abilities of an animal are applied to a robot task. We chose a turtle as our first host animal and designed a parasitic robot that can perform "operant conditioning". The parasitic robot, which is attached to the turtle, can induce object-tracking behavior of the turtle toward a Light Emitting Diode (LED) and positively reinforce the behavior through repeated stimulus-response interaction. After training sessions over five weeks, the robot could successfully control the direction of movement of the trained turtles in the waypoint navigation task. This hybrid animal-robot interaction system could provide an alternative solution to some of the limitations of conventional mobile robot systems in various fields, and could also act as a useful interaction system for the behavioral sciences.

Keywords: parasitic robot, operant conditioning, waypoint navigation, red-eared slider, trachemys scripta elegans

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1 Introduction

Remarkable progress has been made in the development of robot technology. Many variations of robot products and machine systems are now used in numerous industries. Moreover, the need for robots has extended to almost every segment of society. Notably, in the defense sector and certain industries, demands exist for small mobile robots that can explore hazardous areas and dangerous environments, such as the scenes of accidents or disasters. However, small robots that can operate in inhospitable environments can only do so for a limited time and within a given range owing to battery limitations. The actuators and sensors of the robot can also be easily damaged or destroyed in harsh and humid conditions.

Therefore, researchers have strived to develop a means of controlling animals to make use of their locomotive abilities to perform particular tasks. Many animals have extraordinary means of locomotion that have evolved through natural selection over millions of years. Thus, their bodies are ideal for designing small mobile locomotion platforms. In this study, we examined the prospect of a hybrid animal-robot system.

Meanwhile, in recent years, there has been considerable interest in virtual reality and augmented reality through wearable computing. The commercialization of products from several companies has become imminent because of rapid technological advancements in the fields of sensors, displays, and computing. Nevertheless, with the technology available to date, it is difficult to completely deceive human senses. Humans are very intelligent and have highly attuned sense organs, making it nearly impossible to deceive all human senses with existing technology. On the other hand, lower-level animals are more dependent on virtual stimuli than humans. These lower-level animals react to virtual reality and assume it to be their reality, despite the existence of limited stimuli.

Several studies have shown that certain animals can effectively interact with virtual stimuli; accordingly, the application of an animal control system has been pro-

Corresponding author: Phill-Seung Lee
E-mail: phillseung@kaist.edu

posed. In some of these studies, the feasibility of a biorobot was demonstrated. In 1997, Holzer and Shimoyama connected the antennae of a roach, which are used to detect adjacent obstacles, to the output pin of an 8-bit μ-controller board. Thus, the roach movement was induced[1]. In addition, rats have been guided through the application of electric stimuli to the brain as cues and rewards[2–5]. For agricultural applications, a virtual fence system of sound stimuli used for restricting cattle movement was proposed[6]. Moreover, Harvey *et al.* recorded the behavior of mice on a virtual linear track. They showed that the mice could interact with a virtual reality device[7–9]. Furthermore, it was demonstrated that trained dogs could be guided by remote audio commands through wearable GPS unit control[10]. Lee *et al.* controlled the movement of a turtle by leveraging the characteristic obstacle avoidance capability of creature[11,12]. Meanwhile, Cai *et al.* modulated motor behaviors of pigeons by electric stimulation of specific neurons[13].

Studies have also been conducted for controlling rat movement through automation control. Zhang *et al.* developed an automatic control system for "rat-bot" navigation[14]. Gao *et al.* developed a rat-bot automatic navigation system based on a distance measurement in unknown environments[15]. Furthermore, Sun *et al.* applied the General Regression Neural Network (GRNN) algorithm for automated navigation of rat-bots by enabling automatic decision control[16].

As mentioned above, a training system can be developed to automatically control animal behavior using a particular virtual reality system. In this paper, we propose a "parasitic robot system" that mimics the behaviors of natural parasites. It is known that some parasites that live in the bodies of host animals can influence the host behavior to fulfill the specific objectives of parasite. Similarly, the proposed parasitic robot is attached to a target animal and invokes specific behavior through virtual stimulation.

We selected the turtle as the host animal because it can effectively sense visible light[17]. In addition, it is relatively intelligent and has long-term memory, which enables it to be trained to develop certain behaviors[18]. Furthermore, the turtle moves sufficiently slow to be easily controlled and observed. Moreover, its hard shell is an ideal surface for attaching the robot device.

We developed a parasitic robot for the turtle to achieve a waypoint navigation task in a water tank. We observed the parasitic robot and turtle interaction and recorded the extent to which the waypoint navigation performance of the parasitic robot is improved.

To this end, a heads-up display for the turtle was adopted as the virtual stimulator for navigation. The parasitic robot used a heads-up display (cue) and feeder (reward) to train the turtles to move in a certain direction of the heads-up display. The robot obtained the turtle pose information and waypoint position from an indoor monitoring system using wireless communication. All of the experimental tests were conducted in a water tank. The results validated the usefulness of the proposed concept system.

The remainder of this paper is organized as follows. Section **2** describes the concept of the parasitic robot and the experimental setup. In addition, details of the parasitic robot and turtle are presented. In section **3**, the experimental results are provided. In section **4**, we discuss the results and future work is described. In section **5**, conclusions of the study are presented and the contributions of this research are summarized.

2 Material and methods

We tested an example of the parasitic robot concept. In this study, the turtle was selected as the host animal and a parasitic robot was designed to induce the turtle to navigate between waypoints.

2.1 Parasitic robot system concept

Parasitism is a life form relationship between two organisms: one is a parasite, and the other is the host. A parasite lives inside or on the body of a host, either temporarily or permanently. It benefits from the host, such as by removing nutrients from the host to sustain itself and reproduce. Certain kinds of parasites can manipulate the behavior of the host to increase the probability of its own reproduction. For example, a three-spined stickleback (*Gasterosteus aculeatus*) infected with a bird tapeworm (*Schistocephalus solidus*) behaves in a way that increases its exposure to piscivorous (carnivorous) birds. This behavior enables the tapeworm to lay its eggs in the stomach of bird. The eggs are then widely spread through the feces of the bird[19]. Likewise, some parasites can change the behaviors of their hosts through special interactions.

Similarly, in the proposed concept of a "parasitic robot," a specific behavior is induced by the robot in its host to benefit the robot. The robot attaches to its host in a way similar to an actual parasite, and it interacts with the host through particular devices and algorithms. This concept and the relationship between the parasitic robot and the host animal are shown in Fig. 1. The parasitic robot can achieve a task assigned by the human operator by using the locomotion abilities of the host. This is because the parasitic robot can induce the behavior of the host through stimulus-response training. We believe that this proposed architecture based on parasitic relationships often observed in nature can be applied to various animals, robots, and algorithms.

In this study, we employ the "operant conditioning" method that was first described by Skinner to induce the animal behavior by the parasitic robot[20]. Operant conditioning is a type of training that reinforces a certain behavior toward a particular stimulus through reward or punishment. Skinner demonstrated this notion with a cage (Skinner box) that provides specific stimuli and corresponding rewards or punishments. Likewise, the parasitic robot can be regarded as a portable Skinner box that is used to control the behavior of an animal. The target animal is trained to exhibit the desired behavior through its interaction with the parasitic robot. The parasitic robot continues to provide stimuli and feedback to prevent a decrease in its maneuverability. Many advanced animals possess a degree of cognitive ability and intelligence that make them receptive to operant conditioning and thus, well suited to the proposed parasitic robot system.

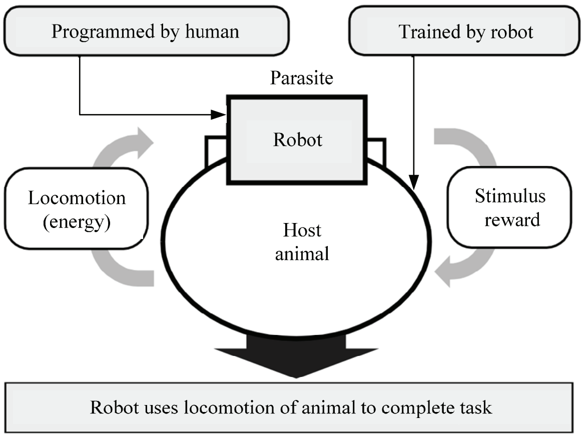

Fig. 1 Overview of interaction between parasitic robot and host. The parasitic robot borrows the locomotion ability of the host by various interactions.

2.2 Parasitic robot design for the turtle

We first developed a parasitic robot that can train and reinforce the behavior that a turtle typically relies on to seek and obtain food. The parasitic robot presents a virtual food source to the turtle and thereby induces the turtle behavior described below.

2.2.1 Turtle as host animal

We chose the turtle as our host animal because it offers several advantages over other animals to test our concept. Turtles can effectively sense visible light, and they have sufficient intelligence and long-term memory to be trained in a certain behavior through operant conditioning. Furthermore, they are deemed suitable for our experiment because they move slowly and can thus be easily observed. In addition, they have a hard shell onto which the robot could be easily mounted. The parasitic robot was mounted on the upper shell of a turtle, as shown in Fig. 2.

The turtles used in this study were red-eared sliders (*Trachemys scripta elegans*). Five turtles were housed in a water-filled glass tub (91 cm × 66 cm × 16 cm) during the laboratory experiments. The glass tub had a water temperature controller, filter, dry platform for basking, and an ultraviolet (UV) sunlamp. Turtles tend to sunbathe for six or seven hours each day. The turtles were typically fed three times a week during the experimental period. After at least 24 h without feeding in the tub, the turtles were moved to the main water tank for the experiments.

2.2.2 Robot as parasite

The parasitic robot consisted of three parts: a

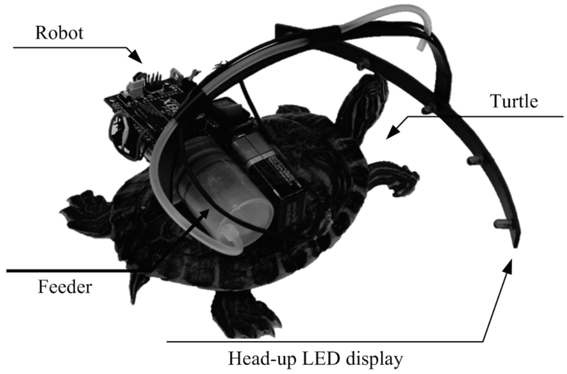

Fig. 2 The parasitic robot is mounted on the carapace of the turtle. It induces the turtle to move to the waypoint by using a head-up Light Emitting Diode (LED) display as well as rewarding the turtle with food when it performs well.

stimulation module, reward module, and control module. Fig. 3 illustrates the interaction between the parasitic robot and turtle. To lead the turtle to the waypoints, the parasitic robot monitored the current position and head angle through a comparison with the given waypoints. It thus provided an appropriate stimulus and reward to the turtle. For operant conditioning, it continued to train and control the turtle while completing a navigation task.

The stimulation module guided the turtle to a desired location by providing appropriate stimuli. The turtle relies on its good vision for its movement decisions. Thus, we used visual stimulation by means of red Light Emitting Diodes (LEDs) with a wavelength of 635 nm, which is within the range of the visual discrimination of turtle. Our parasitic robot was designed to accomplish the waypoint navigation task by providing visual cues to the host. We devised a heads-up LED display consisting of a round carbon-fiber frame with five LEDs to provide the visual cues. The LEDs were installed in the frame at 30˚ intervals to cover a 120˚ range of movement. It was mounted on the turtle, allowing it to easily view the LEDs in front of its eyes.

The reward module reinforced the behavior of the turtle in response to the visual stimulation. Specifically, when the turtle effectively responded to the LED stimulation, the module ejected a gel-type food from a syringe using a linear servo motor (PLS-5030, PoteNit). Thus, the behavior of following the LEDs was trained by operant conditioning. As the training progressed, the parasitic robot caused the host turtle to follow the LEDs through the positive reinforcement of the operant conditioning.

The control module consisted of a microcontroller board (ATMEGA8_Xbee Board, TESOL) and a ZigBee radio modem (XBP24-AWI-001, DIGI) to transmit the position, head angle, and waypoint information. The control module operated the stimulation module and reward module through the application of a navigation training algorithm for operant conditioning. The entire parasitic robot (19.36 cm × 10.84 cm, 133.5 g) was waterproof to enable its operation in water, and it was firmly attached to the turtle shell with an epoxy resin adhesive.

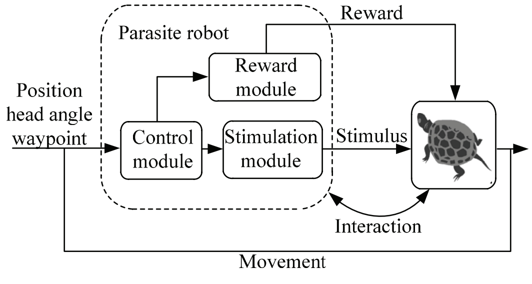

Fig. 3 Schematic diagram of parasitic robot system and turtle. The parasitic robot uses LEDs as a visual cue to train the turtle to follow an object through operant conditioning with rewards.

2.2.3 Training method

As mentioned above, the operant conditioning training method was used through the parasitic robot to induce the desired behavior in the turtle. In the initial trials, none of the turtles recognized the information conveyed by the virtual stimulation (the illuminated LED was a signal for food). Therefore, all five turtles were guided to connect the reward (food) with the stimulus (illuminated LED) before interacting with the parasitic robot. This "shaping process" is a teaching method that is often used when the host animal can not recognize the stimulus before the start of operant conditioning[21]. For 10 min at each meal time over two weeks, a red LED was arbitrarily lit, and food was provided only at the location of the lit LED. The turtles began to recognize the stimulus and eventually followed it. As a result, after two weeks, each turtle showed the same behavior; they all recognized the lit LED to obtain food.

After the shaping stage, we conducted training experiments to test our parasitic robot system with the five turtles. Before the training session began, we attached the parasitic robot to the turtle and positioned the turtle at a certain starting position in the water tank. In each training session, three stages were involved in a waypoint route:

Stage 1: Recognize: The turtles were trained to recognize the lit LED controlled by the stimulation module of the parasitic robot.

Stage 2: Follow: The turtles were trained to walk in the direction of the illuminated LED. The parasitic robot then guided the turtle to each waypoint by controlling the stimulation module.

Stage 3: Reward: The turtles were rewarded for walking toward the waypoints. Once the turtle reached the acceptance area for each waypoint, the parasitic robot provided food as a reward to further reinforce the following behavior.

These three stages were repeated by the parasitic robot from start to end points through five waypoints.

The navigation training was automatically performed using the parasitic robot. If the turtle failed to complete the task within 5 min, the session was deemed complete. The experiment with each turtle was comprised of five sessions; each session was performed at a one-week interval.

2.3 Robot algorithm

As a result of the operant conditioning, the turtle could follow an LED representing a virtual target on the way to a waypoint. Thus, if the LEDs of the stimulation module were continuously controlled to guide the turtle toward the waypoint, the turtle could reach the target waypoint.

Fig. 4 illustrates the algorithm used to control the visual cue (LED) that induced the following behavior. Here, we applied the Line-of-Sight (LOS) guidance algorithm[22] to guide the turtle $p(x, y)$ to the nth waypoint $w_n(x_{\text{los}}, y_{\text{los}})$ by controlling the stimulation module. As shown in the figure, the head angle of the turtle θ indicates the angle between the horizontal line and the forward direction of turtle. The LOS angle φ_{los} is defined by $\varphi_{\text{los}} = \tan^{-1}((y_{\text{los}} - y)/(x_{\text{los}} - x))$. The direction of the LED was selected by the control angle δ_{control}, which is

$$\delta_{\text{control}} = \theta - \varphi_{\text{los}}. \tag{1}$$

Then, the parasitic robot illuminates the appropriate LED on the route to the waypoint using the control angle, δ_{control}. As shown in Fig. 4, five LEDs are installed in the view frame of turtle at 30° intervals to cover a 120° range. Each LED has a specific angle (num1 = −60°, num2 = −30°, num3 = 0°, num4 = 30°, num5 = 60°). Depending on the calculated δ_{control}, the robot illuminates the LED with the closest angle to δ_{control}.

Accordingly, the robot selects a virtual target point closest to the line between the position and waypoint n of the turtle. As expected, the turtle moves toward the illuminated LED. While approaching the waypoint, the parasitic robot continues to switch on the illuminated LED to guide the turtle to the target waypoint. If the position of turtle $p(x, y)$ satisfies

$$L \le R \text{ with } L = \sqrt{(y_{\text{los}} - y)^2 + (x_{\text{los}} - x)^2}, \tag{2}$$

then, the $(n+1)$ *th* waypoint is selected. Hence, the parasitic robot ejects food to the turtle as part of the operant conditioning. Here, R denotes the acceptance distance for the waypoint. The position, head angle, and waypoint data of turtle are continually provided to the parasitic robot. The parasitic robot was operated in the water tank as shown in Fig. 5. The robot task flow is described in Table 1.

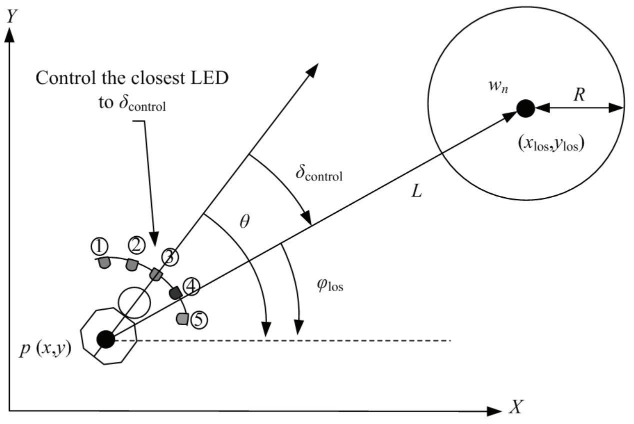

Fig. 4 Guidance algorithm for the parasitic robot from the $(n-1)$ th to nth waypoints. The parasitic robot gets data on the position of the turtle and waypoint, and controls the lit LED (virtual target point) with a line of sight guidance algorithm.

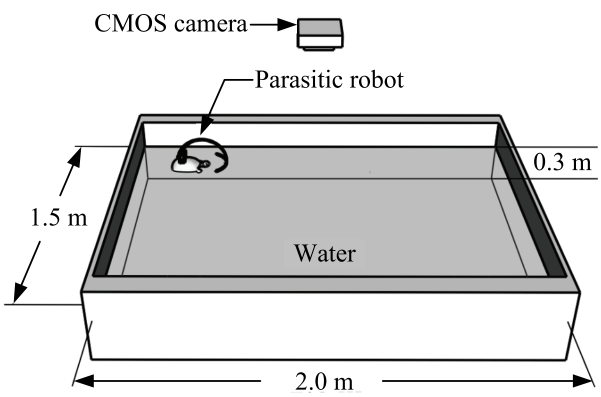

Fig. 5 Overview of the experimental setup for navigation. The parasitic robot induces the turtle to move to the waypoint in the water tank.

Table 1 Navigation algorithm for turtle

1.	$n \leftarrow 1$
2.	**while** navigating **do**
3.	Get the waypoint $w_n(x_{\text{los}}, y_{\text{los}})$ and robot pose $p(x,y)$, θ
4.	$\varphi_{\text{los}} \leftarrow \tan^{-1}(y_{\text{los}} - y)/(x_{\text{los}} - x)$
5.	$\delta_{\text{control}} \leftarrow \theta - \varphi_{\text{los}}$
6.	Turn on the LED which is the closest to δ_{control}
7.	**if** $L \le R$ **then**
8.	Activate the feeder and give the reward
9.	$n \leftarrow n+1$
10.	**end if**
11.	**end while**

3 Results

3.1 Evaluation metric

In this study, the parasitic robot trained the turtle in following behavior through repeated operant conditioning. We designed a “reaction speed” metric to evaluate the training level of turtle during each experimental session. By using this metric, we checked how quickly and accurately the turtle moved toward the LED to evaluate the performance of the parasitic robot. As shown in Fig. 6, the parasitic robot provides an LED stimulus at position p_t and induces the reaction of turtle during time step Δt. We measured the displacement of turtle $\vec{U}$ at each Δt and calculated the metric given by

$$V_{\mathrm{LED}} = \left|\vec{U}\right| \cos(\theta_{\mathrm{LED}}) / \Delta t \quad \text{for } -90^\circ < \theta_{\mathrm{LED}} < 90^\circ, \quad (3)$$

where V_{LED} is the speed of reaction toward the LED stimulation, that is, the velocity of movement toward the LED stimulation source. If the metric is negative, it is set to zero for a data comparison. We evaluated the navigation performance of the parasitic robot by using the above metric.

3.2 Training results

As shown in Fig. 7, the parasitic robot trained the turtle to move through a 5 m optimal path, which was a straight line between the five waypoints in the water tank (1.5 m × 2.0 m). The parasitic robot guided the turtle to approach each waypoint with the stimulation module and reward module based on the training algorithm. The turtle sequentially passed through five waypoints. All of

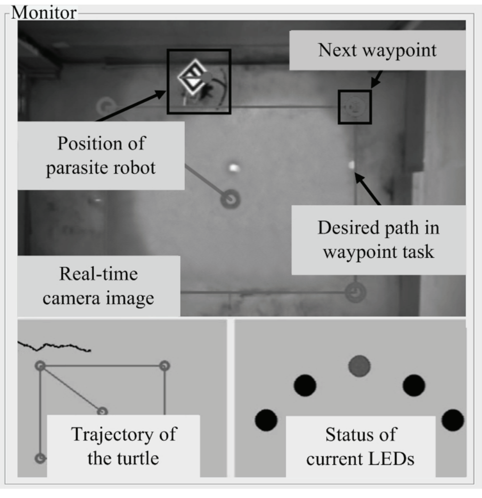

Fig. 6 Graphic User Interface (GUI) of monitoring system.

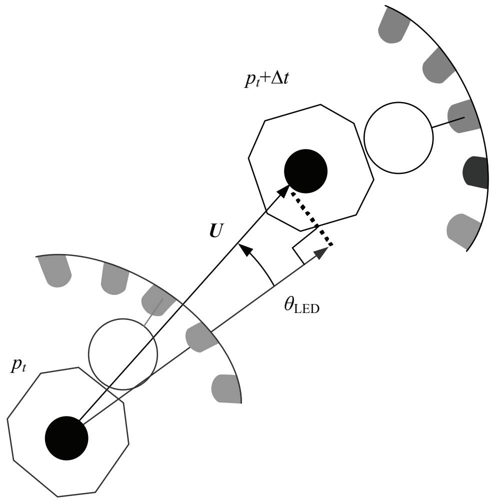

Fig. 7 Illustration of reaction speed of turtle toward the LED stimulation given by the parasitic robot.

the turtles were successfully trained to navigate the specific trajectories by passing through all the waypoints.

To evaluate how well the turtles followed the stimulus as the session proceeded, we determined the average reaction speed toward the LED (V_{LED}) on the path of each turtle. This describes the turtle training level. Fig. 8 shows the learning curve for average V_{LED} derived in each session. The repeated analysis of variance (ANOVA) measure[23] showed that the average V_{LED} of each turtle between the first and fifth sessions was significantly different ($F_{0.05,4,16}$=20.183, p<0.001). All five turtles followed the LED of the parasitic robot from the first day (average V_{LED} = 2.36 mm·s^{-1}). During the experiments, the strength of the following behavior of the turtles was gradually reinforced by the parasitic robot. The average strength, V_{LED}, was dramatically increased in 2.36 mm·s^{-1}, 3.03 mm·s^{-1}, 5.63 mm·s^{-1}, 9.52 mm·s^{-1}, 10.24 mm·s^{-1}, and 48.03 mm·s^{-1}, respectively. The average performance score of the following behavior showed an increasing curve with a rate of 333.41% between the first and fifth weeks. In particular, Turtle 3 showed the highest increasing curve with a rate of 504.07%, while the performance of Turtle 5 improved most slowly at 67.46%. Although each turtle did not initially exhibit the following behavior, the reaction speed of the turtles gradually improved as the parasitic robot continued to reward the turtles when they followed the illuminated LED. Differences also existed in the learning among individual turtles.

Fig. 9 shows the travelled trajectories of the five turtles that were recorded in the fifth session. The dotted lines indicate the traveled pathways. The circles represent the waypoints, and the desired pathway is denoted by the solid line. In the fifth session, each turtle succeeded in navigating all of the waypoints as a result of the stimulation provided by the parasitic robot after operant conditioning.

Table 2 summarizes the characteristic values of the travelled trajectories shown in Fig. 9. The average travel distance and elapsed time were 7.18 m and 75.07 s, respectively. The average cross-track error for the five turtles was 18.83 cm. The cross-track error is defined as the shortest distance between the desired path line and current position of the turtle. The average cross-track error indicates how accurately the turtle moves toward the desired path during the waypoint navigate mission. The data represent the mean ± the Standard Error of Mean (SEM). As shown in the table, the values representing the length of the travelled trajectory, elapsed time, and average cross-track error of Turtle 5 are much greater than those of the other turtles. In other words, the well-trained turtles with a higher V_{LED} were more accurately and rapidly guided toward the waypoints.

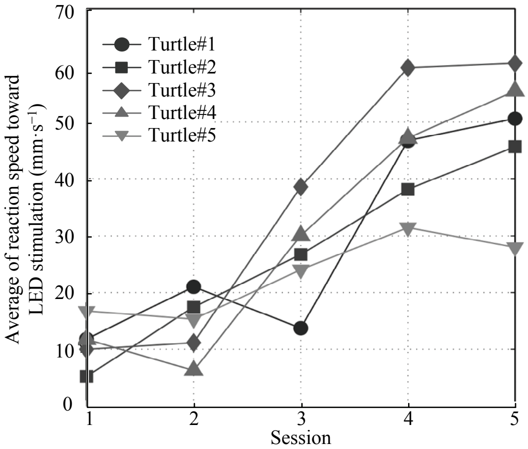

Fig. 8 Learning curves for average reaction speed toward the LED.

Table 2 Navigation path characteristics in the 5th session

	Total length (m)	Elapsed time (s)	Average cross-track error (mm)	Average V_{LED} ($\mathrm{mm \cdot s^{-1}}$)
Turtle 1	6.16	57.02	170.98 ± 2.57	51 ± 0.99
Turtle 2	8.51	88.62	134.21 ± 1.32	46 ± 0.60
Turtle 3	5.87	45.02	169.32 ± 3.32	60 ± 1.16
Turtle 4	5.89	52.93	162.91 ± 2.79	55 ± 1.14
Turtle 5	9.45	131.78	244.11 ± 1.57	27 ± 0.67

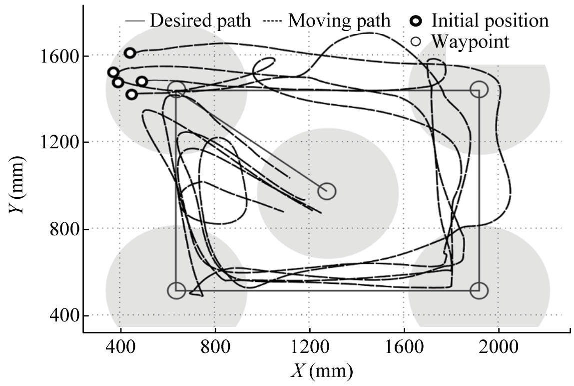

Fig. 9 Travelled trajectories of turtles in the 5th session. A movie of this figure is available at: https://youtu.be/LrL1K5-GpsA.

4 Discussion

We performed the training experiments with the turtles to demonstrate the validity of our concept system. The training test using the parasitic robot was successfully implemented, and the virtual stimulus (heads-up display) of the parasitic robot guided the turtles to move through predetermined routes. The performance of the following behavior of the turtles, which were trained by the parasitic robot, was enhanced at the rate of a 333.41% increasing curve (Fig. 8). On the last day of the experiment, the average cross-track error of the waypoint navigation paths was only 3.76% in the 5 m predetermined routes (Table 2). The results of these tests showed that our parasitic robot can be successfully operated with an animal-robot interaction. In particular, the test validated the possible use of our concept system in which a robot can assume the role of a parasite on a host animal.

Our proposed system presents the idea of a hybrid animal-robot interaction. Through a combination of simple robotic technology and traditional learning theory, our system mimics parasitic relationships in nature. The parasitic robot induces a specific behavior in its host to benefit the robot. In this study, we selected the turtle as the host animal and demonstrated the validity of our system through the simple animal-robot interaction. As an interaction example, we chose the "operant conditioning" training method[20]. Operant conditioning is a type of training method that reinforces a certain behavior using a particular stimulus and reward. Likewise, the parasitic robot trains and reinforces the following behavior of the turtle with the stimulus module (heads-up display) and reward module (feeder). As mentioned, lower-level animals effectively react to virtual reality or artificial environments. Therefore, we developed the parasitic robot to provide a virtual visual stimulus for the turtle.

This study was our first attempt to test this idea. In this research we focused on concept design with simple training method and robot algorithm. However, further studies are required to apply the various algorithms and increase the intelligence of the robot for real application task. The results showed that the parasitic robot seems to well guide the turtles. However, to date, this concept system remains unsuitable for real applications. In the real environment, turtles are affected by external stimuli, such as obstacles, light, and vibration. This presents a problem in terms of the stability and accuracy of the system.

To apply this idea in real application tasks, future work should increase the reliability of the system. To this end, our system can be a fully portable virtual reality environment with the development of virtual reality technology and an enhanced sensor system. This system would eliminate the external stimulus, and the robot could obtain the information of obstacles and pathways through sensors and a planning algorithm. The host animal would experience only virtual visual information from the parasitic robot without the external stimuli of the real environment.

Additionally, we can combine energy-harvesting technologies with the parasitic robot system. Thus, the parasitic robot could charge itself through the movement of its host animal. This idea can increase the operational time of the system. Moreover, the robot intelligence can be developed by applying various robotics technologies, such as infrared sensors and path planning algorithms. After these technological enhancements, it is expected that fully automatic animal control through the animal-robot interaction would be enabled in various task applications. Unlike a robot, the animals can obtain their own food and recover their stamina from the natural environment. Thus, they are capable of long-range and long-term missions, even in harsh environments such as dense forest and desert.

5 Conclusion

In this paper, we proposed a concept for a hybrid animal-robot interaction, which we call a "parasitic robot". The robot can take the role of a parasite on the turtles (host) and induce the following behavior through "operant conditioning." The robot reinforces the behavior of turtle using a virtual cue (LED) as a stimulus and gelatin food is given as a reward. We demonstrated its validity through a training test, whereby the turtles performed a waypoint navigation task. The experiment results showed that the proposed system could be effectively operated in behavior reinforcement and can thus effectively and automatically control movement toward the waypoints. We expect that our research can be used as an innovative framework for robot-animal interaction systems. In the future, our system could be used in real applications of long-range and long-term missions with the development of a fully virtual stimulus frame and various robot algorithms.

Ethical approval

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. Also, all applicable international and institutional guidelines for the care and use of animals were followed. All procedures performed in studies involving animals were in accordance with the ethical standards of the institution or practice at which the studies were conducted.

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