https://doi.org/10.20965/jrm.2019.p0110

Paper:

Experimental Analysis of Acoustic Field Control-Based Robot Navigation

Yusuke Tsunoda, Yuichiro Sueoka, and Koichi Osuka

Osaka University
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan
E-mail: {y.tsunoda@dsc., sueoka@, osuka@}mech.eng.osaka-u.ac.jp
[Received February 28, 2018; accepted November 15, 2018]

This paper proposes novel robot navigation methods that utilize strong interaction between a designed field and a robot controller. In recent years, several studies have demonstrated the importance of interactions between different subject types (e.g., human-robot interaction, robot-environment interaction) instead of just that between a robot controller and an isolated subject. This study explores the *robot-field interaction* design to realize autonomous robot navigation, and verifies the proposed methods experimentally. We prepare acoustic navigation trails from the start to the goal; one is generated from multiple sounds with identical frequencies, while the other is generated from multiple sounds with different frequencies. For each field controller, both the dynamic acoustic trail and the static acoustic trail, two types of *static* robot controllers are designed based only on the *present* sensor data, *namely*, gradient-following controller and sound-habituation controller. The former is a microphone-array based controller for robots equipped with multiple microphones, while the latter is designed for robots with a single microphone. Throughout the real-world demonstration, we show the validity of our proposed methods.

Keywords: acoustic trail, sound-habituation, robot-field interaction, robot navigation

1. Introduction

Robot navigation is fundamental to the design of autonomous controllers for manipulating mobile robots to a pre-determined (i.e., given) goal zone [1, 2]. In recent years, some studies have suggested the importance of *field*, which is defined as the environment required for successful completion of navigation tasks, designed with the intention of assisting a designed robot controller [3–5]. Following this approach sometimes makes it easier to gain an intuitive understanding of a designed controller, meaning utilizing a desired potential field which a mobile robot follows as the field is perceived in the same way as physical phenomena [6, 7]. Moreover, this approach facilitates the categorization of navigational intelligence into the field design and the robot controller. This enables the developers to simplify the design of robot controllers, which would otherwise need to be much more sophisticated in order to process global information or a complicated network. Therefore, field-related control schemes are ideal for application to a systems comprised of several agents called multi-agents systems [8, 9].

Research studies, such as those conducted by Fink et al. [10], have successfully demonstrated the task of transporting objects cooperatively without any communication (e.g., exchanging positional information between robots). Okada et al. [11] treated the problem of navigating emergency exits as a flow vector problem, and attempted to control these by specifying the person who performs the task of controlling the flow of evacuees in group navigation tasks. In this paper, related works in this domain are briefly introduced; for example, the design of collective motions of groups based on the flow field [12], and effective navigation route searching with incorporating assumptions of pheromone trails that draw inspiration from the behavior of ants [13, 14].

In these works, however, the robots' controllers were designed after defining the gradient field, which was given as the mathematical equations necessary to achieve the robot's desired movement (e.g., obstacle avoidance) (**Fig. 1(a)**). In contrast, as shown in **Fig. 1(b)**, we propose a novel navigation system design: we treat the field as one of the navigation controllers, and build the robot controller and field controller simultaneously. The novelty of the proposed system lies in the design of an appropriate trail for navigation as well as in the use of interactions with the robot. Additionally, our approach facilitates a reduction in the computing the power necessary to equip each robot and simplifies control structure design.

This paper attempts to realize robot navigation based only on *present* sensor data of the sound field from two types of controllers and an acoustic field; in other words, the acoustic trail, from the start to the end position.

As shown in **Fig. 2(1)**, the first type is the gradient-following controller for a designed dynamic acoustic trail. First, the endpoint acoustic field is designed using multiple sounds with an identical frequency. Then, the robot's controller is designed to follow the gradient of the acoustic field.

The latter is, as shown in **Fig. 2(2)**, the sound-

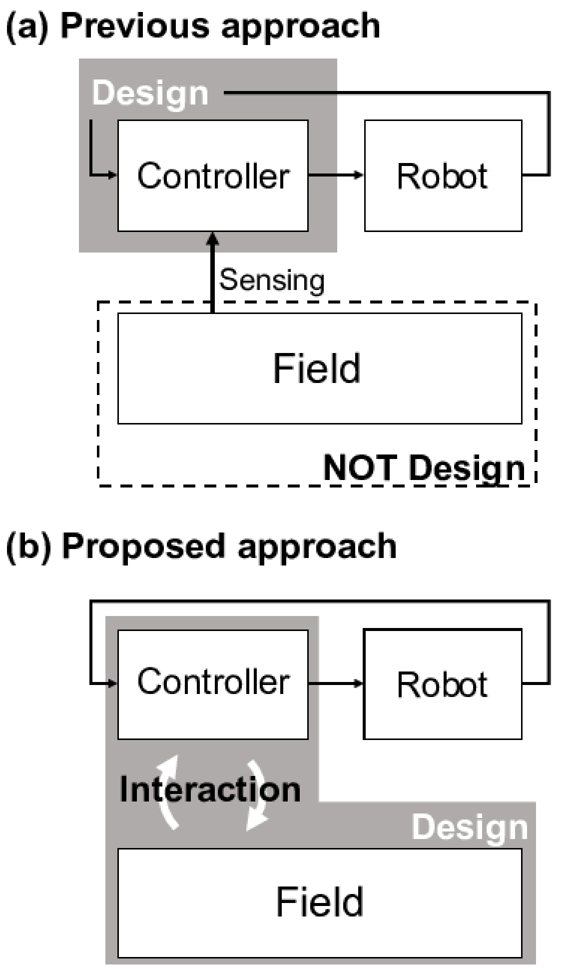

Fig. 1. Difference between previous and proposed approaches to designing the robot navigation system.

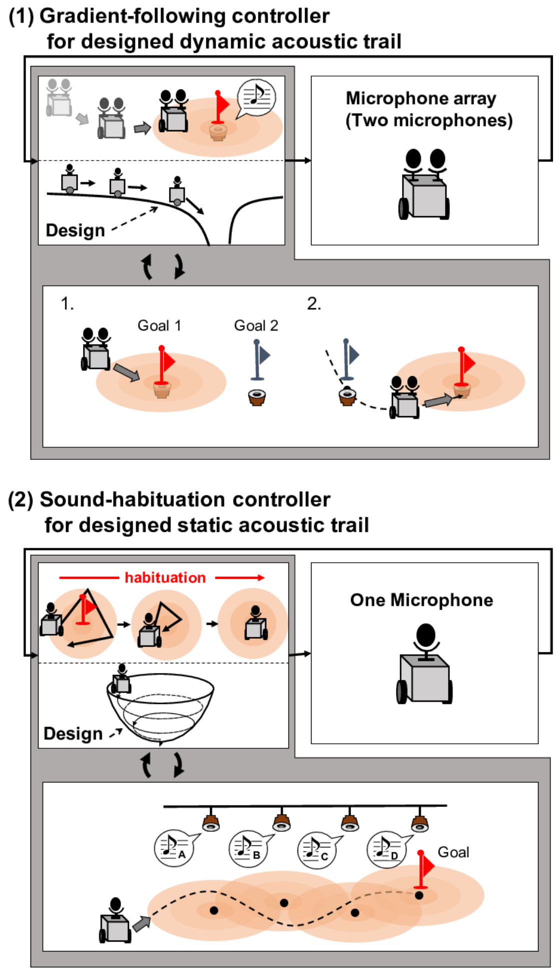

Fig. 2. Two proposed navigation methods: (1) gradient-following controller for designed dynamic acoustic trail: the robot is designed to follow the gradient of the acoustic field with two microphones, and is navigated by changing the field shape dynamically. (2) Sound-habituation controller for designed static acoustic trail: the robot, equipped with one microphone, is controlled toward the sound source by habituation of the acoustic sound, and is navigated using the static acoustic field.

habituation controller for a designed static acoustic trail. The acoustic trail is designed from the start to the goal position using multiple sounds with different frequencies. In addition, we propose a controller to guide the robot towards the center of the acoustic field by habituating the sound intensity.

After developing robots with both one and two microphones, we demonstrate robot navigation methods (1) and (2). In the navigation method (1), the robot is guided between several checkpoints using dynamic switching of acoustic trails. In the navigation method (2), the robot is navigated from the start to the pre-determined endpoint using static acoustic trails. In these experiments, we evaluate and compare the effectiveness of the designed navigation methods.

The remainder of this paper is organized as follows: Section 2 describes robot navigation method (1). Subsection 2.1 describes the robot developed to utilize microphone-array-based control, and Subsection 2.2 discusses the navigation performance. Section 3 describes the robot navigation method (2). In Subsection 3.1, the single microphone robot based on sound-habituation control is presented, and Subsection 3.2 discusses the navigation performance. In Section 4, we assess the validity of the proposed methods and discuss the effectiveness of the interactions between the robot controller and the acoustic trail. Section 5 presents the conclusions of the study and the scope for future work.

2. Robot Navigation Method (1): Gradient-Following Controller for Designed Dynamic Acoustic Trail

In this section, we describe the robot navigation method (1): a gradient-following controller for designed dynamic acoustic fields. In this method, the acoustic field is designed first at the endpoint, using a sound speaker. Then, we design a robot that navigates based on the intensity of the acoustic field using a dual-microphone setup.

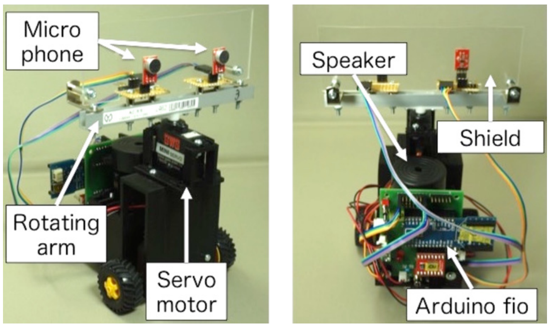

Fig. 3. The proposed sound-searching robot.

In addition, we conduct experiments on the robot's navigational performance, guiding the robot to several checkpoints by the switching acoustic fields.

2.1. Developed Robot: Gradient-Following Controller

In this paper, we estimate the direction of the sound source using a microphone array. When multiple sound waves are superimposed, they intensify when they are in phase. Conversely, the intensity of the superimposed soundwaves is weakened when they are out of phase. On the basis of the above phenomena, the robot senses the sound pressure signals received by the two microphones and determines the resultant amplitude of the composite wave. The robot then determines the direction of highest intensity of the resultant sound wave.

As illustrated in **Fig. 3**, the robot is equipped with the following:

1. Microcomputer (Arduino Fio)
2. Electret Microphone Breakout (BOB-12758, made by Sparkfun)
3. Piezoelectric Speaker (PB10-Z338R, made by SPL)
4. Dual Motor GearBox (ITEM 70097, made by TAMIYA)
5. Servo Motor (GWS MINI Mini Servo, made by GWS)

The robot is equipped with two microphones modules, which can be rotated by 180° using the servomotor. In addition, a screen set is positioned behind the microphone to prevent interference due to reflected sounds. The distance between the two microphones corresponds to half the wavelength of a sinusoidal sound that is received, because each waveform of the received sounds is in the opposite phase when the sound source and the two microphones are aligned. In this setting, the robot can sense the direction of the sound source accurately. Thus, the frequency of the speaker sound used in the experiment can be obtained as follows:

$$f = \frac{c}{\lambda} = \frac{c}{2L} \quad \cdots\cdots\cdots\cdots \quad (1)$$

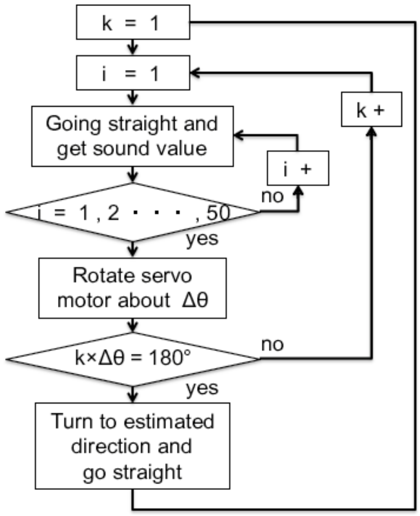

Fig. 4. Flowchart of the robot's movement based on the controller (1).

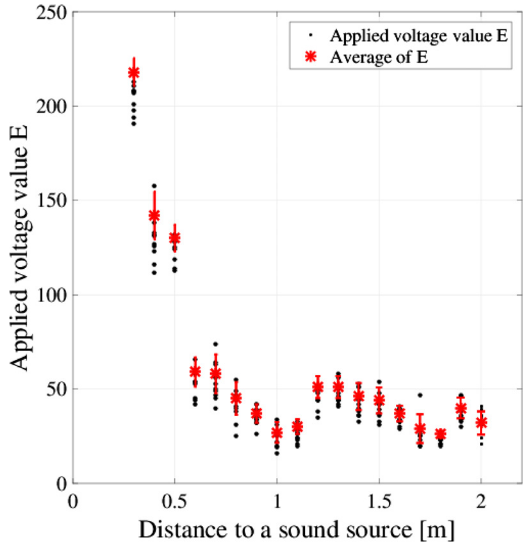

Fig. 5. Sound intensity of the acoustic field using navigation method (1): applied voltage value vs. distance between and the microphone and the sound source l [m].

Here, f [Hz] is the frequency of the sine wave, λ [m] is the wavelength of the sine wave, and the sound speed is $c = 340$ m/s, where $c = f\lambda$. From the above equation, the frequency used in the experiment is $f = 2850$ Hz and the distance L [m] between two microphones is $L = 0.06$ m. **Fig. 4** shows a flowchart of the robot's movement.

Next, we describe the navigation experiment using a single acoustic field. The experiments were conducted in an indoor area of 2×2 m. **Fig. 5** shows the gradient of the sound intensity of a 2850 Hz sound wave generated from the speaker. The horizontal axis indicates the distance from the sound source to the observation point, and the vertical axis indicates the value of E as calculated by the microcomputer. The dot indicates the measured value, the asterisk indicates the average value of 10 times mea-

Table 1. Results of the navigation method (1) experiment.

l_0 [m] / $\Delta\theta$ [deg]	1.0	1.5	2.0	2.5	3.0
30	(0.4,0.212)	(0.507,0.364)	(0.759,0.481)	(0.896,0.498)	(1.57,0.982)
60	(0.45,0.19)	(0.687,0.444)	(0.691,0.502)	(0.669,0.658)	(0.933,0.775)
90	(0.372,0.167)	(0.638,0.394)	(0.968,0.662)	(0.989,0.565)	(1.299,0.887)

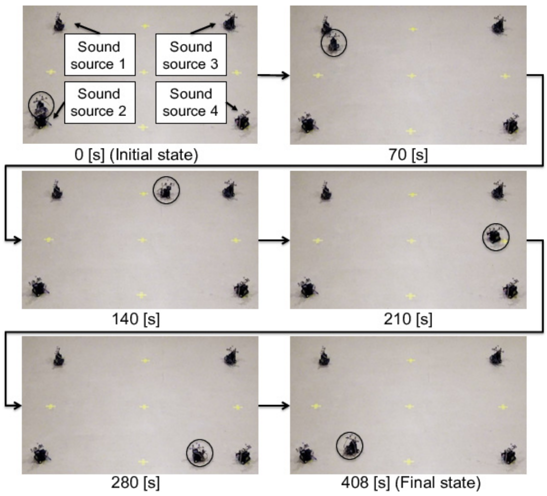

Fig. 6. Snapshots of the round trip experiment based on dynamic acoustic trail generated by four sound sources.

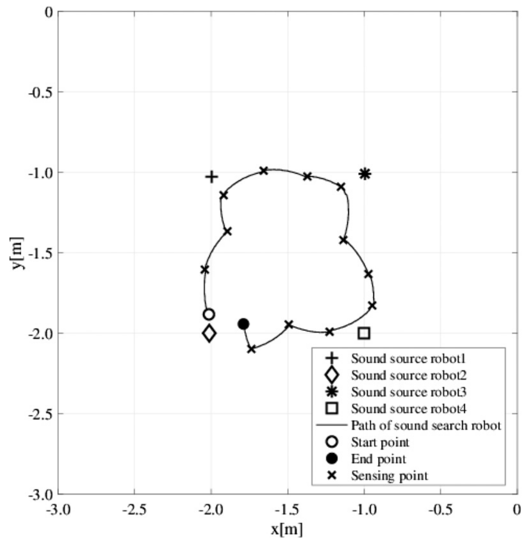

Fig. 7. Robot trajectories in the round trip experiment based on dynamic acoustic trail generated by four sound sources.

surement, and the error bar indicates the standard deviation.

Figure 5 indicates that it is possible to form a gradient field by using sound intensity in the real space within a 1-m-range of the sound source. We estimate that the undulations at points beyond 1 m are caused by superposition of reflections from the surrounding walls and floor of the indoor experiment area. Therefore, the navigation in this experiment is regarded as successful only when the robot is within 1 m.

The navigation experiment is described as follows: the robot is placed at distances of $l_0 = 1.0, 1.5, 2.0, 2.5, 3.0$ m away from the sound source, and the angle of the robot's direction estimate is set as $\Delta\theta = 30°, 60°, 90°$. **Table 1** shows the average and standard deviations of the minimum distances between the robot and the sound source for 20 experiments. It can be seen that the navigation performance is likely to decrease as l_0 [m] increases because the gradient of the acoustic field (**Fig. 5**) is smooth when the robot is within 1.0 m of the sound source.

2.2. Robot Navigation Experiment Using Dynamic Acoustic Trail

In this work, we attempt to navigate the robot between sound sources by dynamically switching several sound sources ON/OFF. As shown in **Fig. 6**, we set one guiding robot and four tone generator robots at the vertices of a square of side 1 m. First, the guidance robot is navigated to sound source 1, which generates the sound at the point. Next, if the robot satisfactorily approaches sound source 1, this source is switched OFF and sound source 3 is switched ON using the radio module. Likewise, sound sources 1–4 are switched ON/OFF. As shown **Fig. 7**, the guidance robot is successfully navigated between the checkpoints by dynamically changing the gradient of the sound field.

3. Robot Navigation Method (2): Sound-Habituation Controller for Designed Static Acoustic Trail

In this section, we describe the robot navigation (2): a sound-habituation controller for a designed static acoustic trail. Given that the robot has only one microphone, it is a simpler and has lower functionality than the robot set up in the navigation method (1). Given that the robot can obtain only the intensity of the sound, we propose a controller to guide the robot towards the peak of the acoustic field by increasing the sensitivity of the sound intensity. In addition, the navigation experiments are conducted wherein the robot is guided to the checkpoint by sensing the static sound field generated by four sound sources.

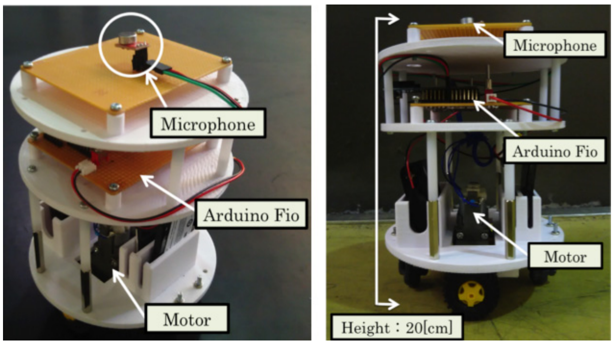

Fig. 8. Robot developed for the proposed navigation method (2).

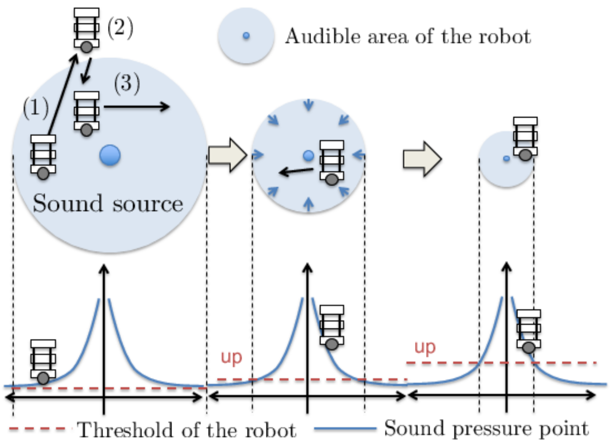

Fig. 9. Algorithm developed for the robot based on method (2).

3.1. Developed Robot: Sound-Habituation Controller

As shown in **Fig. 8**, the robot is equipped with the same microphone, gearbox, and microcomputer as the robot for method (1). The microphone is placed on the top of the robot such that it faces upwards, enabling it to sense the generated speaker sound more accurately. The robot detects the sound and acquires the frequency spectrum value of the received sound by performing fast Fourier transform (FFT). In addition, the robot sets a variable threshold for the sensed spectral value, and autonomously determines its corresponding behavior. The flow chart for the robot algorithm is as follows.

(1) As shown in **Fig. 9**, if the spectral value exceeds the threshold value, the robot traverses the circled area (in this work, this area is referred to as the audible area). In addition, the robot increases the threshold value by a fixed value as it moves along.

(2) If the acquired spectral value is below the threshold (i.e., it goes out of the audible range with **Fig. 9**), the spectrum value retreats until it exceeds the threshold value.

(3) When the spectral value returns to the point above the threshold, the robot immediately turns to the left by 90° and moves straight ahead for a fixed time period. The algorithm is repeated again. If the spectral value exceeds a certain value, the robot stops.

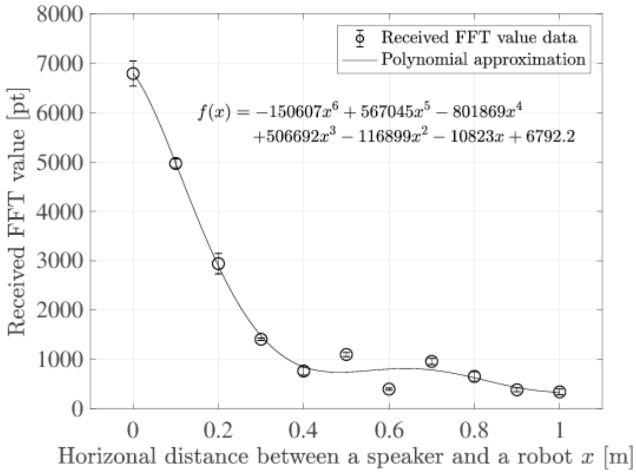

Fig. 10. Sound intensity of an acoustic field: received FFT value [pt] vs. horizonal distance between the speaker and the robot x [m].

We set the threshold value approximate datum (the spectrum value) at the distance from the sound source x, which is also referred to as the estimated audible circle radius. The robot incrementally decreases the threshold value, which is the approximate value at x [m]; in other words, it increases the sensitivity to the sound intensity. Using this algorithm, although the robot can be guided to the sound source through determination of the sound strength, the direction of the sound source cannot be estimated. Moreover, this method, wherein the robot compares the threshold value and the acquired value, is more robust and resilient to sensor-value noise when compared with the method based on the gradient of the sensor value.

Next, we describe the static acoustic field in the navigation experiment. **Fig. 10** shows the spectral data for 4500 Hz sine wave sound generated by the speaker, which is arranged pointing downward toward the floor at a height of 30 cm. The horizontal axis indicates the distance from the sound source in the horizontal direction, and the vertical axis shows the spectrum value [pt] sensed by the robot. Each point indicates the average value and standard deviation in the horizontal distance from the sound source with error bars. From this data, we can see that the distance from the sound source is a smooth gradient within about 30 cm. Therefore, we set the robot's action range in this experiment to 30 cm.

First, we confirm whether the robot can be navigated to a static single sound source using on the proposed controller. **Fig. 11** presents the snapshots of the navigation experiment. The initial position of the robot is set at a point 30 cm away from the sound source, and the radius of the initial audible area for the robot is set as 0.7 m. Moreover, the moving speed of the robot is set to 100 mm/s, and the decay rate of the radius of the audible area is set

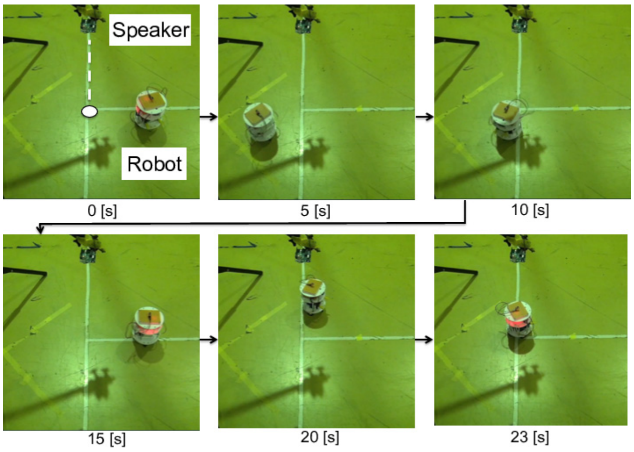

Fig. 11. Snapshots of the robot's movement around the source.

to 33.3 mm/s. The robot's threshold value is an exponential function, as shown in **Fig. 10**. The robot moves along a straight line when the obtained spectral value is above the threshold, and moves backward and rotates to the left 90° if the value falls below the threshold. As shown in **Fig. 10**, the robot is guided to under the sound source and stops when the distance from the sound source is estimated to be 0.1 m. To evaluate the inductive performance, we performed 24 experiments. The results showed that the navigation was successful 22 times out of 24, which implies a success rate of approximately 92%. In the two experiments that failed, the gradient of the acoustic field could not be sensed as it was too far away from the sound source.

3.2. Robot Navigation Experiment Using the Static Acoustic Trail

Next, we describe an experiment wherein the robot is guided using the acoustic trail generated by several acoustic fields. The static acoustic field is formed by affixing, in the experiment, several sound sources that differ in frequency. Moreover, the robot is provided with the approximate data of each of the sound sources. First, the robot is navigated toward a sound source with a specific frequency by decreasing the threshold of the sound source. When the robot determines that it has approached the sound source, it is guided toward the next sound source through automatic switching of the threshold. The robot repeats this behavior until it arrives at the endpoint. **Fig. 12** illustrates the navigation experiment. As shown in **Fig. 13**, we arranged four sound sources with different frequencies between the robot and the goal point, with the frequencies set to 4500, 4000, 4750, and 4250 Hz. The four speakers were arrayed from left to right at the same height, and the robot was placed in the acoustic field. The distance between each sound source was 20 cm, and the distance between the origin and the end point was 60 cm. As shown in **Fig. 12**, the robot was guided successfully with only one microphone.

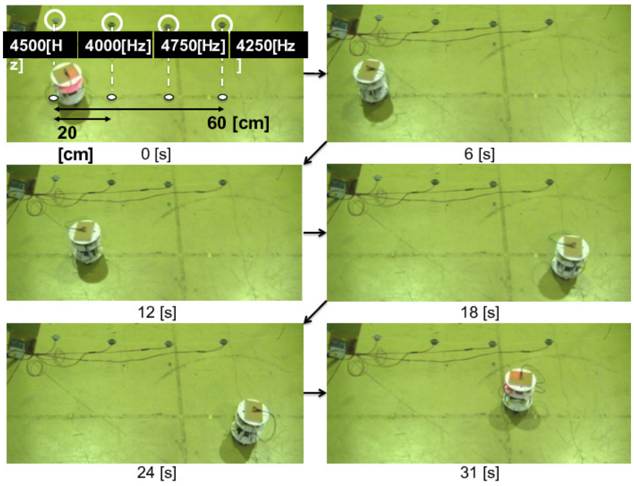

Fig. 12. Snapshots of the robot's movement when navigating to the sound source by using static acoustic trails generated by four sound sources.

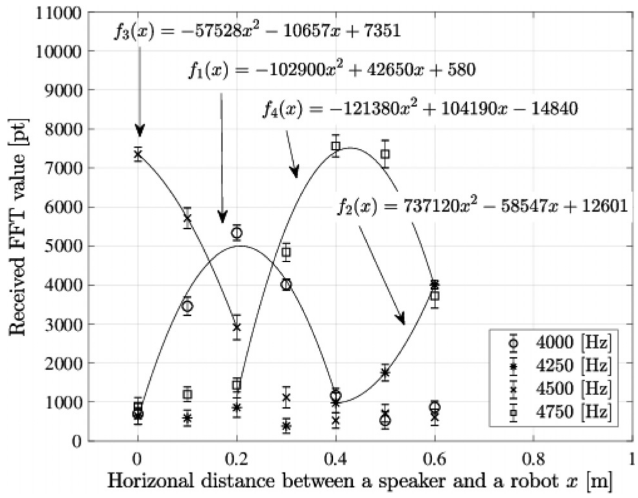

Fig. 13. Sound intensities of acoustic trails using navigation (2): received FFT value [pt] vs. horizontal distance between the speaker and the robot x [m].

4. Discussion

In this section, we discuss the performance of the two types of controller. The gradient-following controller for the designed dynamic acoustic fields demonstrated desirable navigational performance, traversing several checkpoints. We found that the controller allowed for the accurate detection of the gradient of the acoustic fields by using two microphones when the robot was placed far from the source (the strongest point) of the acoustic field. Second, the sound-habituation controller for the designed static acoustic trail was based on minimal sets, with an angle microphone, and simple action settings. The controller realized successful navigation; however, the navigation zone was relatively limited. The results of this examination of the two controllers allow a user to select the ideal controller for use in application in multi-agent systems.

5. Conclusion and Future Work

In this work, we proposed two types of navigation methods that utilize the interaction between the designed acoustic trail and the robot controller that is based on the sensing of present states of the acoustic field.

In the navigation method (1), we developed a robot with two microphones and designed a gradient-following controller. Furthermore, we demonstrated the navigation experiments based on the dynamic acoustic trail and showed that the robot can be navigated by merely following the gradient of the acoustic trail. In the navigation method (2), we designed a robot with only one microphone to be navigated toward the sound source by habituating the sound intensity. In addition, we conducted the navigation such that the robot was guided to a goal position based on a static acoustic trail.

The two types of navigation experiments conducted in this work support our idea that it is important for the robot's navigation design to include the field's controller, as well as to incorporate interaction between the field and the robot's controller. In addition, we would like to emphasize that using interaction with two controllers makes it easier to realize a robot navigation system. In our proposed system, the robot can be navigated using only a simple controller; as such, these controllers hold potential for application to group agent navigation.

In future work, we will attempt to realize acoustic-field-based robot navigation by utilizing sound diffraction. Moreover, we intend to extend the scheme to use illumination or olfactory devices.

Acknowledgements

This research was partially supported by CREST, JST, and JSPS KAKENHI Grant Number 15H06360 and 18K13776. The authors express their sincere gratitude for the support provided.

References:

[1] J. J. Leonard and H. F. Durrant-Whyte, "Directed sonar sensing for mobile robot navigation," Vol.175, Springer Science & Business Media, 2012.

[2] E. Rimon and D. E. Koditschek, "Exact robot navigation using artificial potential functions," IEEE Trans. on Robotics and Automation, Vol.8, No.5, pp. 501-518, 1992.

[3] O. Khatib, "Real-time obstacle avoidance for manipulators and mobile robots," I. J. Cox and G. T. Wilfong (Eds.), "Autonomous robot vehicles," pp. 396-404, Springer, 1990.

[4] J.-O. Kim and P. K. Khosla, "Real-time obstacle avoidance using harmonic potential functions," IEEE Trans. on Robotics and Automation, Vol.8, No.3, pp. 338-349, 1992.

[5] Y. Koren and J. Borenstein, "Potential field methods and their inherent limitations for mobile robot navigation," Proc. 1991 IEEE Int. Conf. on Robotics and Automation, pp. 1398-1404, 1991.

[6] A. H. Purnamadjaja and R. A. Russell, "Guiding robots' behaviors using pheromone communication," Autonomous Robots, Vol.23, No.2, pp. 113-130, 2007.

[7] R. A. Russell, "Heat trails as short-lived navigational markers for mobile robots," Proc. 1997 IEEE Int. Conf. on Robotics and Automation, Vol.4, pp. 3534-3539, 1997.

[8] J. Ferber, "Multi-agent systems: an introduction to distributed artificial intelligence," Vol.1, Addison-Wesley Reading, 1999.

[9] R. Olfati-Saber, J. A. Fax, and R. M. Murray, "Consensus and cooperation in networked multi-agent systems," Proc. of the IEEE, Vol.95, No.1, pp. 215-233, 2007.

[10] J. Fink, M. A. Hsieh, and V. Kumar, "Multi-robot manipulation via caging in environments with obstacles," IEEE Int. Conf. on Robotics and Automation 2008 (ICRA 2008), pp. 1471-1476, 2008.

[11] M. Okada and T. Ando, "Optimization of personal distribution for evacuation guidance based on vector field," J. of the Robotics Society of Japan, Vol.29, No.4, pp. 395-401, 2011.

[12] L. C. A. Pimenta, N. Michael, R. C. Mesquita, G. A. S. Pereira, and V. Kumar, "Control of swarms based on hydrodynamic models," IEEE Int. Conf. on Robotics and Automation 2008 (ICRA 2008), pp. 1948-1953, 2008.

[13] R. Fujisawa, H. Imamura, T. Hashimoto, and F. Matsuno, "Communication using pheromone field for multiple robots," IEEE/RSJ Int. Conf. on Intelligent Robots and Systems 2008 (IROS 2008), pp. 1391-1396, 2008.

[14] A. H. Purnamadjaja and R. A. Russell, "Pheromone communication in a robot swarm: necrophoric bee behaviour and its replication," Robotica, Vol.23, No.6, pp. 731-742, 2005.

Name:
Yusuke Tsunoda

Affiliation:
Master's Course Student, Department of Mechanical Engineering, Osaka University

Address:
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

Brief Biographical History:
2016- Master's Course Student, Osaka University

Main Works:
• Y. Tsunoda, Y. Sueoka, and K. Osuka, "On statistical analysis for shepherd guidance system," IEEE Int. Conf. on Robotics and Biomimetics (ROBIO2017), 2017.

Membership in Academic Societies:
• The Japan Society of Mechanical Engineers (JSME)

Name:
Yuichiro Sueoka

Affiliation:
Assistant Professor, Department of Mechanical Engineering, Osaka University

Address:
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

Brief Biographical History:
2013- Research Fellow in Japan Society for the Promotion of Science (DC2)
2015- Assistant Professor, Department of Mechanical Engineering, Osaka University

Main Works:
- Y. Sueoka, T. Kita, M. Ishikawa, and K. Osuka, "Harnessing control of sheepdog agents by on-line clustering," Int. Symp. on Nonlinear Theory and its Applications, pp. 49-52, September 2013.
- Y. Sueoka, T. Kita, M. Ishikawa, Y. Sugimoto, and K. Osuka, "Distributed control of the number of clusters in obstacle collecting by swarm agents," J. of Nonlinear Theory and Its Applications, Vol.5, No.4, pp. 476-486, 2014.

Membership in Academic Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Institute of Systems Control and Information Engineers (ISCIE)
- The Robotics Society of Japan (RSJ)

Name:
Koichi Osuka

Affiliation:
Professor, Department of Mechanical Engineering, Osaka University
Japan Science and Technology Agency (CREST)

Address:
2-1 Yamadaoka, Suita, Osaka 565-0871, Japan

Brief Biographical History:
1986- Research Associate and Assistant Professor, Osaka Prefecture University
1998- Assistant Professor, Kyoto University
2003- Professor, Kobe University
2009- Professor, Osaka University

Main Works:
- Y. Sueoka, T. Kita, M. Ishikawa, Y. Sugimoto, and K. Osuka, "Distributed control of the number of clusters in obstacle collecting by swarm agents," Nonlinear Theory and its Applications, Vol.5, No.4, pp. 476-486, 2014.
- T. Kinugasa, T. Akagi, T. Haji, K. Yoshida, H. Amano, R. Hayashi, M. Iribe, K. Tokuda, and K. Osuka, "Measurement System for Flexed Shape of Flexibly Articulated Mobile Track," J. of Intelligent and Robotic Systems, Vol.75, No.1, pp. 87-100, 2014.
- Y. Sueoka, T. Tahara, M. Ishikawa, and K. Osuka, "On Statistical Analysis of Object Pattern Formation by Autonomous Transporting Agents," 2014 Int. Symp. on Nonlinear Theory and its Applications (NOLTA2014), pp. 854-857, 2014.

Membership in Academic Societies:
- The Philosophical Association of Japan (PAJ)
- The Institute of Electrical and Electronics Engineers (IEEE)
- The Japan Society of Mechanical Engineers (JSME)
- The Robotics Society of Japan (RSJ)