Development of the Shortest Path Display System Using Swarm LED Indicators Based on Signal Strength of Wireless Communication

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***Abstract*— Our research group has proposed swarm robotics network which searches a target cooperatively. Once a robot detects a target, robots immediately communicate with a base station via intermediate relay robots due to the multihop transmission of wireless communication. In this study, we developed the shortest path display system between the target and the base station based on the received signal strength of wireless communication. We conduct a series of both indoor and outdoor experiments in order to investigate the validity of the developed system.**

I. INTRODUCTION

Swarm Robotics (SR) [1], [2] have attracted much research interest in recent years. Generally, the tasks in SR are difficult or inefficient for a single robot to cope with. Thus, you find overlap between SR and multi-robot systems. Şahin [3] enumerated several criteria[1] for distinguishing swarm robotics as follows:

- autonomy: Each robot should be physically embodied and situated.
- redundancy: Group sizes accepted as swarms is 10 to 20.
- scalability: SR system should be able to operate under a wide range of group sizes.
- simplicity: Each robot should employ cheap design, that is, the structure of a robot would be simple and also the cost of it would be cheap.
- homogeneity: SR system should be composed of homogeneous individuals. This enhances the above 2nd and 3rd criterion.

According to the last criterion, homogeneous controllers for individuals are desirable for SR systems. Additionally, this approach does not assume the existence of an explicit leader in swarm robots due to the above criteria. This results in that a collective behavior emerges from the local interactions among robots and between the robots and the environment. Therefore, it is required for SR systems that individuals in swarm show various behaviors through interactions although the individuals are homogeneous.

The typical control tasks in SR are navigation, aggregation, formation and transport requiring distributed collective strategies [2]. In the previous paper, our research group copes with a target detection problem, which is one of navigation problems. In this control task, several robots can communicate with each other via wireless communication networks (WCN) [4], [5] due to the multi-hop transmission to achieve collective exploration. As soon as a robot detects a target, the information is sent from the robot to the base station via intermediate relay robots. Therefore, all robots should be "connected" to the base station via WCN.

This system would be applicable to victim search, seabed resources exploration and planetary exploration. In these scenarios, it would be desirable that the shortest path connected from a base station to the target is visible for system users after the system finds the target. We assume that our swarm robots system is operated on the ground in this paper.

In this paper, we developed the shortest path display system using swarm LED indicators based on the received signal strength of wireless communication. The paper is organized as follows. The next section shows the wireless module employed in this study. Section III defines the shortest path problem in this study and briefly introduces an algorithm for shortest path search. Section IV describes the details of the shortest path display system developed in this study. Section V and VI show the setting and results in indoor and outdoor experiments, respectively. Conclusions are given in the last section.

II. WIRELESS MODULE

In this study, wireless devices, XBee[6], were employed (Fig.1). XBees, based on ZigBee wireless standard, can compose wireless ad hoc networks, where nodes can communicate with each other via multi-hop path. An XBee on each robot is set as a router of the network. The wireless base station is a laptop equipped with the same XBee as those on the swarm robots. The XBee equipped on the base station is set as a coordinator. The API of the above wireless devices[2] can display the structure of wireless communication network (WCN) with link quality indication (LQI)[3] values among all the nodes (Fig.2). In addition to this, this can export the data on the WCN including the LQI values among all the nodes (Fig.3).

III. DIJKSTRA'S ALGORITHM

The XBee API provides the structure of WCN with LQI values as mentioned in the previous section. Such a structure of WCN is described as a directed graph with non-negative weights, where a node corresponds to a wireless module and a weight value corresponds to the distance information

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[1]Şahin [3] claimed that these criteria should be used as a measure of the degree of SR in a particular study.

[2]Digi International Inc. provides a software, *Next Generation XCTU*[6]

[3]The LQI is calculated from the value of the received signal strength in the API.

Fig. 1. Wireless module: XBee

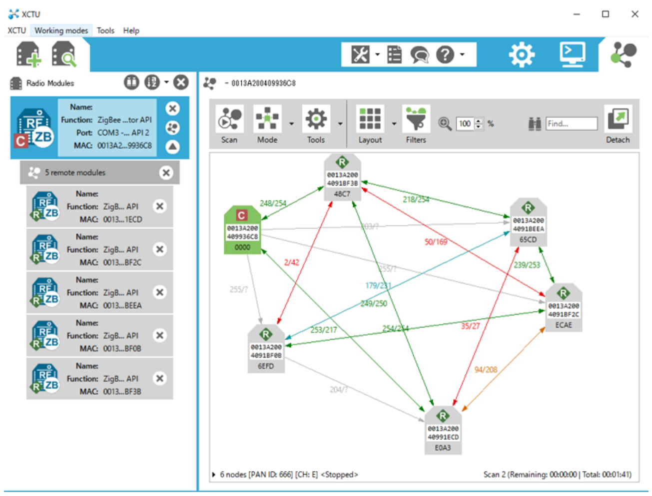

Fig. 2. API of XBee

between wireless modules. For searching the shortest paths between arbitrary nodes in the graph, the Dijkstra's algorithm [7] can be applied. In order to apply the Dijkstra's algorithm, the weight values of the edge between nodes in a graph are required. According to this, the LQI value should be converted into distance information. The LQI value in the XBee API is expressed over the range $[0, 255]$. Therefore, a weight value is calculated as follows:

$$w_{ij} = \begin{cases} 256 - LQI_{ij} & (LQI_{ij} \neq 0) \\ 10000 & (LQI_{ij} = 0) \\ 0 & (i = j) \end{cases} \tag{1}$$

where $i, j \in \{1, \cdots, N\}$, N is the number of nodes and LQI_{ij} is the LQI between the i-th node and the j-th node. When $LQI_{ij} = 0$, we set w_{ij} at a relatively big value because the distance between the nodes would be effectively infinite. The LQI value downward and upward between wireless modules are different (For example, see XX/YY in Fig.2). This results in that the adjacency matrix, w_{ij}, is asymmetry. The Dijkstra's algorithm employs a smaller weight value of the edge between nodes when those weight values are different. However, this does not reflect the actual condition observed in the preliminary experiment. Thus, we redefine the adjacency matrix such as to employ a bigger weight value between nodes (Eq.(2)).

$$w_{ij} = w_{ji} \quad (w_{ij} < w_{ji}, i \neq j) \tag{2}$$

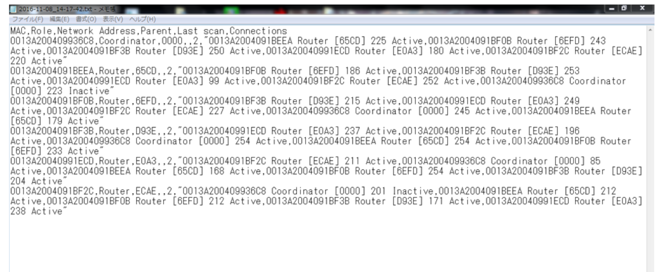
MAC,Role,Network Address,Parent,Last scan,Connections
0013A20040993 6C8,Coordinator,0000,,2,"0013A2004091BEEA Router [65CD] 225 Active,0013A2004091BF0B Router [6EFD] 243 Active,0013A2004091BF3B Router [D93E] 250 Active,0013A20040991ECD Router [E0A3] 180 Active,0013A2004091BF2C Router [ECAE] 220 Active"
0013A2004091BEEA,Router,65CD,,2,"0013A2004091BF0B Router [6EFD] 186 Active,0013A2004091BF3B Router [D93E] 253 Active,0013A20040991ECD Router [E0A3] 99 Active,0013A2004091BF2C Router [ECAE] 252 Active,0013A200409936C8 Coordinator [0000] 223 Inactive"
0013A2004091BF0B,Router,6EFD,,2,"0013A2004091BF3B Router [D93E] 215 Active,0013A20040991ECD Router [E0A3] 249 Active,0013A2004091BF2C Router [ECAE] 227 Active,0013A200409936C8 Coordinator [0000] 245 Active,0013A2004091BEEA Router [65CD] 179 Active"
0013A2004091BF3B,Router,D93E,,2,"0013A20040991ECD Router [E0A3] 237 Active,0013A2004091BF2C Router [ECAE] 196 Active,0013A200409936C8 Coordinator [0000] 254 Active,0013A2004091BEEA Router [65CD] 254 Active,0013A2004091BF0B Router [6EFD] 233 Active"
0013A20040991ECD,Router,E0A3,,2,"0013A2004091BF2C Router [ECAE] 211 Active,0013A200409936C8 Coordinator [0000] 85 Active,0013A2004091BEEA Router [65CD] 168 Active,0013A2004091BF0B Router [6EFD] 254 Active,0013A2004091BF3B Router [D93E] 204 Active"
0013A2004091BF2C,Router,ECAE,,2,"0013A200409936C8 Coordinator [0000] 201 Inactive,0013A2004091BEEA Router [65CD] 212 Active,0013A2004091BF0B Router [6EFD] 212 Active,0013A2004091BF3B Router [D93E] 171 Active,0013A20040991ECD Router [E0A3] 238 Active"

Fig. 3. Data exported from the API of XBee

TABLE I

EXAMPLE OF ADJACENCY MATRIX

node No.	1	2	3	4	5	6
1	0	33	13	6	171	55
2	33	0	77	3	157	44
3	13	77	0	41	7	44
4	6	3	41	0	52	85
5	171	157	7	52	0	45
6	55	44	44	85	45	0

After these steps, this adjacency matrix is symmetry (Table I).

Including the above steps, the Dijkstra's algorithm is implemented in Microsoft Excel/VBA (Fig.4). After a robot detects a target and sends the information to the base station via intermediate relay robots, the system user runs the VBA program as follows; First, a node list is composed of all the XBee used in an experiment ((1) in Fig.4). In the node list, the XBee equipped on the base station is designated as a source node while the XBee equipped on the robot finding a target is designated as a destination node ((2) in Fig.4). Then, the nodes included in the shortest path are displayed after the Dijkstra's algorithm is executed ((3)(4) in Fig.4). Finally, the XML files which shows the nodes in the shortest path are output ((5) in Fig.4).

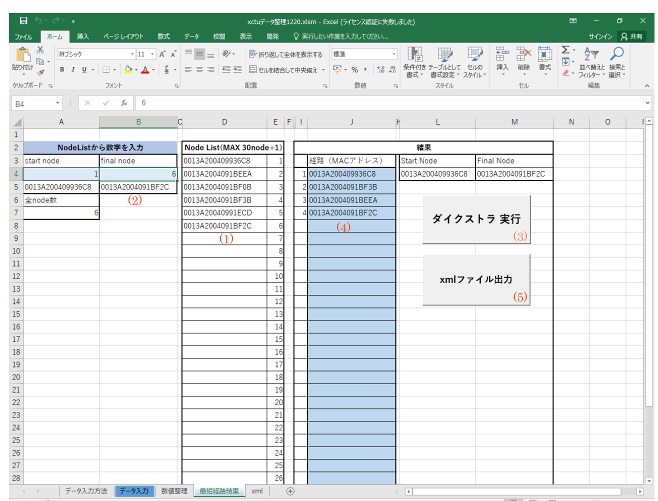

Fig. 4. Dijkstra's algorithm in Excel/VBA: the algorithm finds the shortest path between a source node and a destination node.

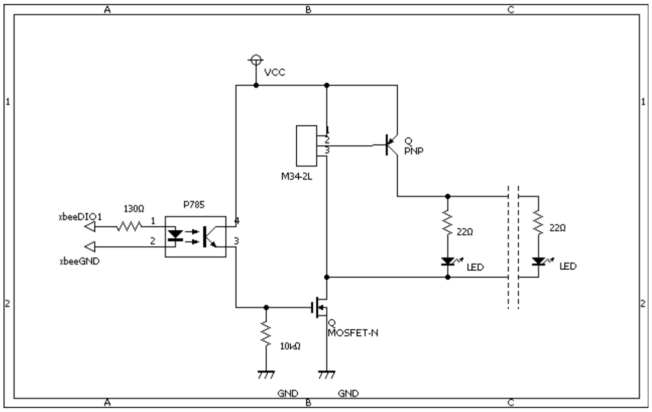

Fig. 5. Circuit for a LED indicator

IV. Display system of the the shortest path

Display system of the the shortest path in this study is composed of wireless modules and LED indicators. The details are described as follows.

A. Communication between wireless modules

For communication between XBee wireless modules, a format called API frame is used in the XML files. The wireless base station sends a message to the module to be displayed according to the XML files obtained at final step in the previous section. The MAC address of the wireless device and the pin number of the XBee to be turned on are written in the message. These files are sent one by one from the base station to the WCN.

B. Circuit for a LED indicator

This study assumes that people trace a path to a target. Thus, visible light is employed in order to display a path. Considering the indoor and outdoor environment in a series of real experiments in this work, a functional specification is required as follows;

- visibility at a distance of 80 m indoor in the daytime,
- visibility from any direction in a two-dimensional plane,
- an electrical source other than the battery of a robot.

Fig.5 shows an electrical circuit designed according to the above specification. The current supplied to LEDs is set at a value larger than the rated current as well as the light sources are blinked so as to increase the visibility of a light emission. Red LEDs with a diameter of 0.01 m were employed. 8 LEDs were arranged radially (Fig.6).

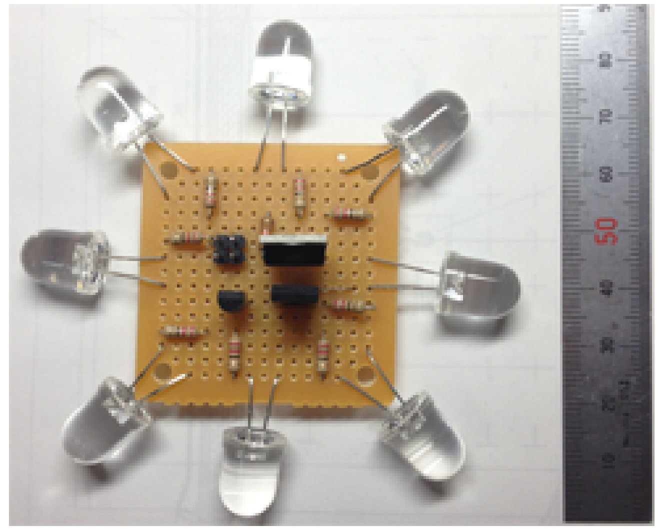

Fig. 6. LED indicator composed of eight LEDs

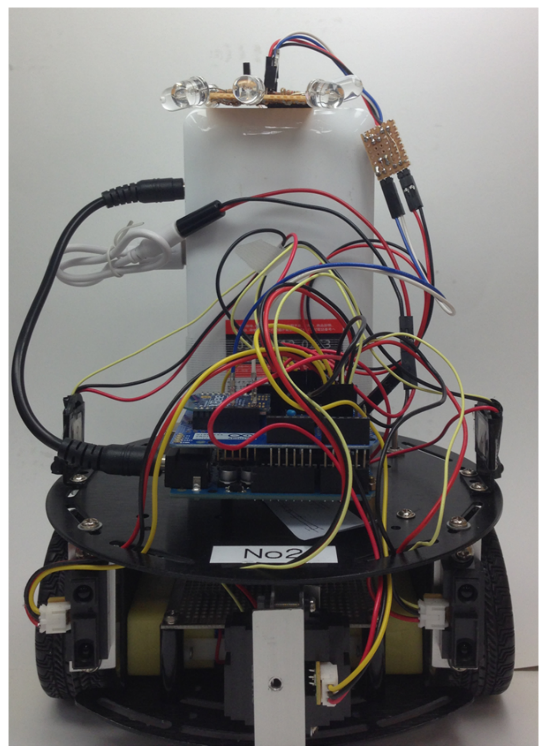

Fig. 7. Setup for mobile robots: front view

V. Indoor Experiment

A. Setup for Swarm Mobile Robots

Differential wheeled robots (Figs.7, 8) were used in this experiment. The robot's diameter and height are approximately 0.17 m and 0.075 m, respectively. The robot is equipped with four infrared distance sensors located at the front of the body for measuring the distance to other robots and walls, and two infrared sensors located at both ends of the body for detecting a target. The maximum detection ranges of the former infrared sensor and the latter infrared sensor are 0.3 m and 0.2 m, respectively. The robot's processor is the Arduino microcontroller, which gets sensory inputs and outputs signals to control two wheels through motor drivers. The robot is equipped with an XBee. As a target, an infrared-emitting ball is employed to make handling easy, which is the official ball for RoboCup Junior [8]. Its infrared rays are distinguishable from those emitted by the distance sensors described above due to the different wavelength. An indicator lamp as mentioned in the previous section is mounted on the robot (Figs.7, 8).

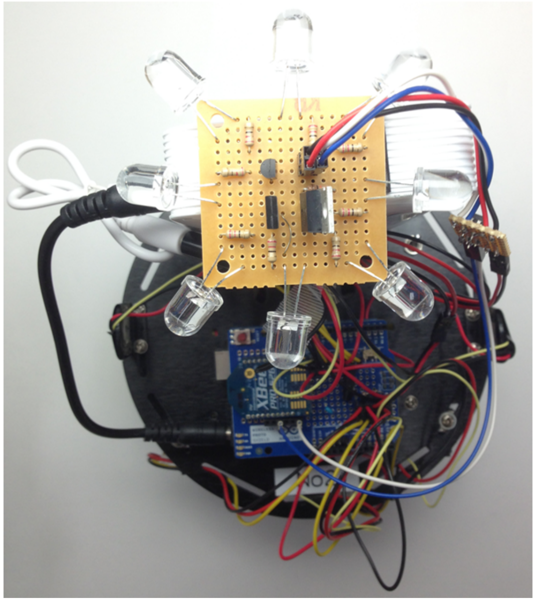

Fig. 8. Setup for mobile robots: top view

B. Experimental Environment

We conducted a real experiment in the corridor of the building at Setsunan University in Neyagawa (the yellow part in Fig. 9). There are some class rooms adjacent to this corridor. Thus, the experimental environment is surrounded by walls. A target (an infrared-emitting ball) was placed at the lower left corner in Fig. 9. At the upper right corner, a wireless base station was placed. The base station is a laptop equipped with the same XBee as those on the swarm robots as mentioned before. At the beginning of each trial, swarm robots were always placed at the same initial position, the lower right corner, next to the base station at random orientations (Fig. 9).

C. Setting of the Experiments

In this control task, swarm robots explore the above environment, detect a target located so far (around 80 m) from the base station as not in line-of-sight communication and send a message to the base station via intermediate relay robots. Therefore, all robots should be "connected" to the base station via swarm robotic network mentioned in Section I. Thus, we conducted a real experiment by setting the number of robots 16 [10]. One trial ends either when the base station receives the message from the robot detecting a target or when 1800 sec (30 min.) are performed without receiving the message. For details, readers may refer to [9].

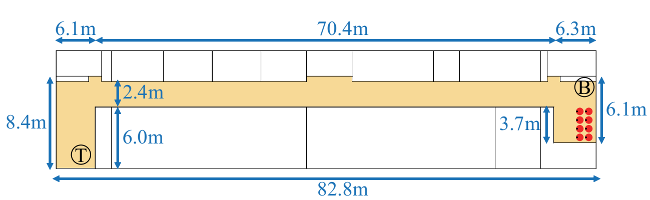

Fig. 9. Experimental setup for target detection problem (B: base station, T: target)

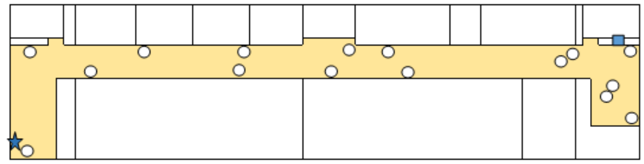

Fig. 10. Distribution of the robots just when a robot found a target

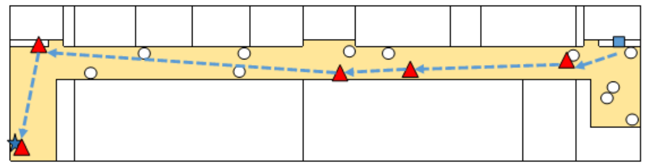

Fig. 11. Shortest path given by Dijkstra's algorithm

D. Experimental result

Fig.10 shows a sketch map of the environment with the location of the robots just when a robot found a target and sent a message to the base station. Fig.11 shows the shortest path given by the Dijkstra's algorithm. Figs.12-15 show the snapshot of the path displayed by blinking LEDs. We confirmed that the lights were visible from the vicinity of the base station. We also confirmed that we can walk along the path to the target.

VI. Outdoor Experiment

A. Setup for LED indicators and wireless modules

In this section, we report the results of the outdoor experiment. The mobile robots employed in the previous section are designed only for indoor. Therefore, only the LED indicators and wireless modules described in Section IV were used for the outdoor experiment to demonstrate the path display system (Fig.16). The details of the goal in this experiment are described in the next subsection.

B. Experimental Environment

It's doubtful whether the path obtained in the previous experiment is shortest because the environment was narrow. In this experiment, the validity of the system was investigated in the open, that is, the environment unsurrounded by walls. We conducted the experiment in the artificial lawn ground at Setsunan University. Fig.17 shows a sketch map of the ground.

C. Setting of the Experiments

In this experiment, the mobile robots were not used. Thus, the positions of a LED indicator with a wireless module were fixed in advance. The LED indicators were arranged so that the shortest path between the target and the base station is apparent. Fig.17 shows the positions of the LED indicators, where the rectangle shows a base station, the circle shows a LED indicator and the star shows a virtual target. The dashed line shows the theoretical shortest path. The number of LED

Fig. 12. Blinking LEDs near the target

Fig. 13. Blinking LEDs in the middle of the corridor (1)

Fig. 14. Blinking LEDs in the middle of the corridor (2)

Fig. 15. Blinking LEDs in the middle of the corridor (3)

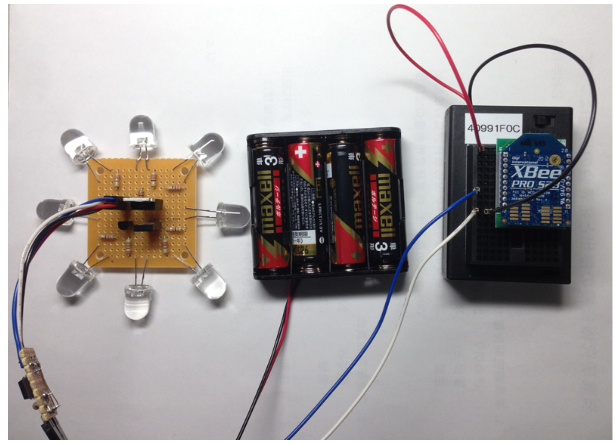

Fig. 16. Setup for an LED indicator and a wireless module

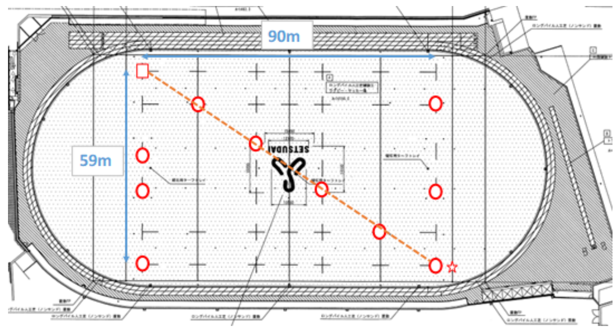

Fig. 17. Positions of the indicator lamps in the artificial lawn ground

indicators with wireless modules was 11. We conducted the experiment four times in the nighttime.

D. Experimental result

Figs.18-21 show the path given by the Dijkstra's algorithm for each trial, where the dashed line shows the given path and the triangles show the LED indicators blinking in the path. In all the runs, we can walk along the path to the target. The blinking lights were visible in the nighttime. However, these paths were not shortest. The distances of the path obtained in this experiment are about 1.6 times longer than the one of the theoretical shortest path.

When we measured the LQI values, those values among the wireless modules located inside were lower than those among the wireless modules located outside. This is because a few LED indicators located outside were included in the obtained path. We did not investigate this reason yet.

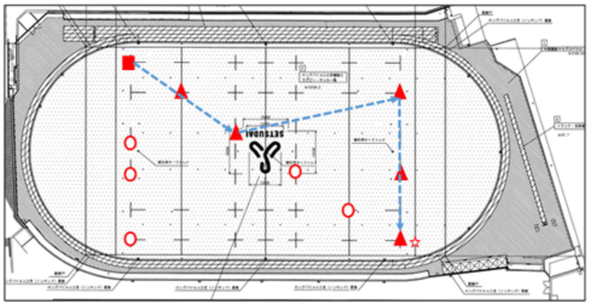

Fig. 18. Path given by the Dijkstra's algorithm in the 1st trial

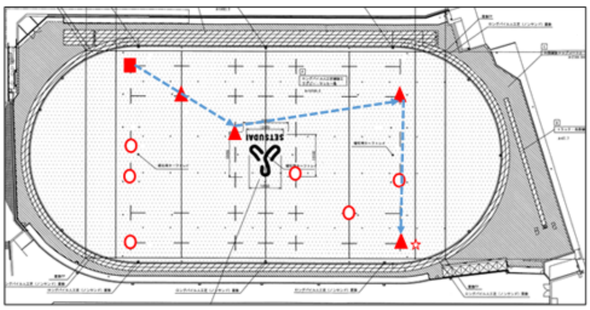

Fig. 19. Path given by the Dijkstra's algorithm in the 2nd trial

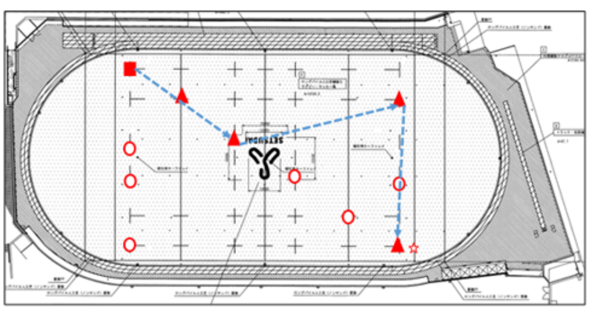

Fig. 20. Path given by the Dijkstra's algorithm in the 3rd trial

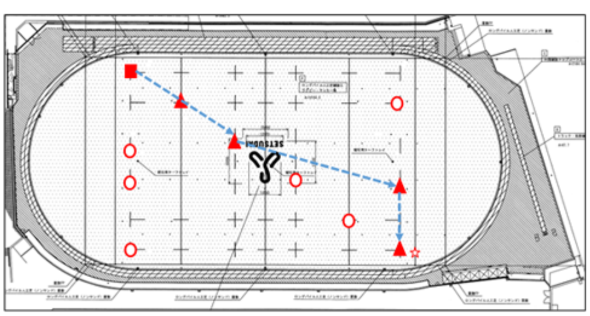

Fig. 21. Path given by the Dijkstra's algorithm in the 4th trial

VII. CONCLUSIONS

In this paper, we developed the shortest path display system between a base station and a target using swarm LED indicators based on the received signal strength of wireless communication. We employed a shortest path search algorithm and implemented it in our system. We confirmed that we can trace the path obtained in the indoor and outdoor experiments to a target. This system would be affected by noise, e.g., interference, diffusion, diffraction and reflection from the environment of electric wave. In future work, we will improve our system in order to decrease the effects.

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