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Description	

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RFID-enabled Target Tracking and Following with a Mobile Robot Using Direction Finding Antennas

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Abstract— **A stand-alone direction finding RFID reader is developed for mobile robot applications employing a dual-directional antenna. By adding search and localization capabilities to the current state of RFID technology, robots will be able to acquire and dock to a static target in a real environment without requiring a map or landmarks. Furthermore, we demonstrate RFID-enabled tracking and following of a target moving unpredictably with a mobile robot. The RFID reader keeps the robot aware of the direction of arrival (DOA) of the signal of interest toward which the dual-directional antenna faces the target transponder. The simulation results show that the proposed RFID system can track in real time the movement of the target transponder. To verify the effectiveness of the system in a real environment, we perform a variety of experiments in a hallway including target tracking and following with a commercial mobile robot.**

I. INTRODUCTION

To enable a robot to perform a variety of tasks in a real environment, an important challenge is localizing the objects in the environment as well as the robot itself. Replacing expensive hardware and additional processing power of the robot with the knowledge acquisition or pointing interface such as RFID, an environment can be properly structured so that it can be easily recognized by robots [1], [2]. In such an environment, the robot equipped with RFID readers can identify the objects using the RF signal transmitted from the object, but RFID does not usually support localization. To solve the problem of object localization, the direction finding RFID reader has been developed using the directionality of the antennas [3], [4]. It was demonstrated that the developed system enabled the robot to acquire and dock to the static target transponder. In many typical situations, our environment may contain some moving objects. Thus, to extend the capabilities of RFID-based mobile robot applications, we investigate some particular techniques for target tracking and following with a mobile robot in this paper.

In order to deal with the aforementioned localization problems, vision-based schemes have appeared to be successful to some extent [5]–[7]. However, the optical line of sight to the target is required and the performances are often significantly affected by the environmental conditions. Other approaches use sets of RF beacons installed in the ceiling by which the target position can be trilaterated [8]. These approaches can give the absolute position of the target, but suffer from relatively large errors, since the distance estimated from the received signal will not be as accurate as measurement. In contrast, the time difference of arrival based approaches ensure a high level of accuracy [9], [10], but it suffers from multi-path effects of the ultrasonic signal and requires the optical line of sight.

In this paper, we propose a new target tracking and following system using the direction finding RFID reader featuring our dual-directional antenna. The dual-directional antenna finds the DOA of transmitted RF signals based on the ratio of the received signal strengths at two adjacent spiral antennas. The reader can estimate the direction of the target from the level of the ratio, keeping the robot aware of the direction of the target in real time. In practice, the ratio could change due to the unknown effects of the environment and this uncertainty may cause the robot to change its heading frequently and unpredictably. Thus, the proposed RFID system rotates the antenna independently of the robot's orientation to find the direction of the target transponder by keeping the ratio within a certain boundary. With estimated DOA values obtained from the RFID reader, the robot becomes able to keep track of the transponder and moreover follow it that moves unpredictably.

This paper is organized as follows. In Section II, we introduce the developed system and briefly describe the fundamentals of electromagnetic theory underlying the measurement of the DOA. Section III shows the simulation and experiment results about the changes in the strength ratio as the target transponder moves under a variety of conditions. In Section IV, the direction finding based scheme for target docking and following is experimentally verified in a real world hallway environment. Finally, conclusions are drawn in Section V.

II. SYSTEM DESCRIPTION: DUAL-DIRECTIONAL ANTENNA

For DOA estimation, it is possible to compute the strength of an RF signal via classical electromagnetic theory [11]. When a signal wave is transmitted from a transponder, a voltage is induced at the antenna with directional characteristics as

$$V \propto \left| \frac{CS_0B}{r} sin(\theta) \right|, \tag{1}$$

where S_0 is the surface area of the antenna, B is the magnetic flux density of the wave passing through the antenna, C

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accounts for the environmental conditions and system properties, and r is the distance from the transponder, respectively. The area through which the wave passes will vary according to the incident angle θ between the antenna plane and the transmitted wave plane. Therefore the transponder direction can be estimated by monitoring the changes in the induced voltage while the antenna rotates.

In this work, a dual-directional antenna is employed to facilitate real-time estimation that consists of two identical spiral antennas perpendicularly positioned with each other. Fig. 1 shows the developed direction finding RFID reader mounted on top of the mobile robot Pioneer-3DX. The RFID system is developed using commercial active sensor nodes of Ymatic Limited [12] that operates on the 303.2 MHz frequency using a 3.0 V battery supply. A set of two nodes read simultaneously the identification and strength of the signals received from two adjacent antennas. The size of each antenna is 20 mm × 20 mm that exhibits a gain of -6.5 dBi and a wide beam width of 90°. An AVR microcontroller analyzes data transmitted from the nodes through the RS-232C interface. The signal pattern of both antenna has a 90 degree phase difference caused from the positioned bearing difference. Then we can calculate the ratio ν between the strength of both antennas given by

$$\nu_{12} = \frac{V_1}{V_2} = |tan(\theta)|. \tag{2}$$

As is shown in the above equation, ν is the absolute tangent of the DOA of the target signal. However, the erroneous offset voltage caused by the white noise and the conditions of the system will probably be included in the signal strength (see for instance Fig. 2-(a)). The maximum and minimum level of the ratio therefore will change according to the actual working condition of the system as shown in Fig. 2-(b). This makes it difficult to precisely estimate the DOA directly from the ratio. However, even though the ratio changes by the variation of the offset level, there always exists a stationary point on the ratio curve. Note that the ratio curve intersects the axis of the ratio 1.0 when the transponder is located on the center line between both antennas. At this crossover point, the ratio remains 1.0 regardless of the offset voltage. Since the ratio increases beyond 1.0 or decreases below 1.0 as the transponder moves left or right, respectively, the transponder can be tracked in real time by monitoring the changes in the value of the ratio.

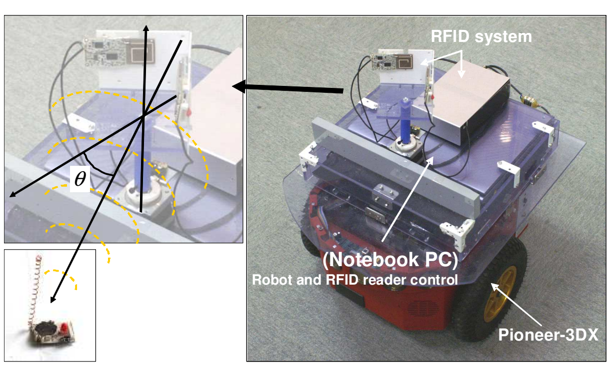
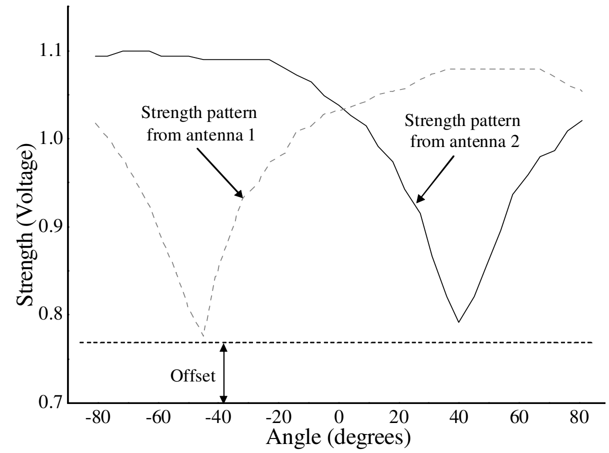
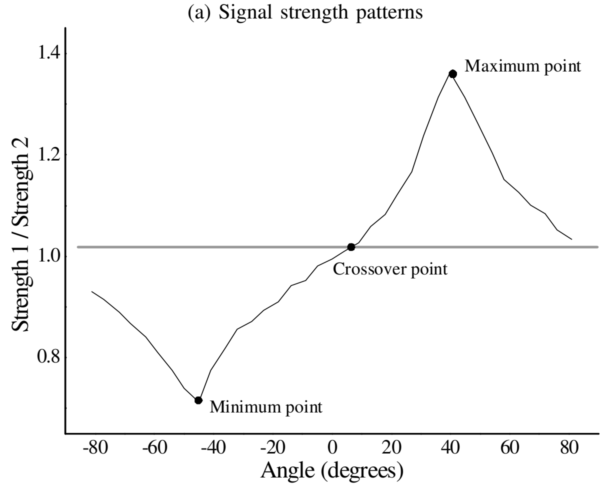


Fig. 1. Direction finding RFID reader with a mobile robot



(a) Signal strength patterns



(b) Signal strength ratio

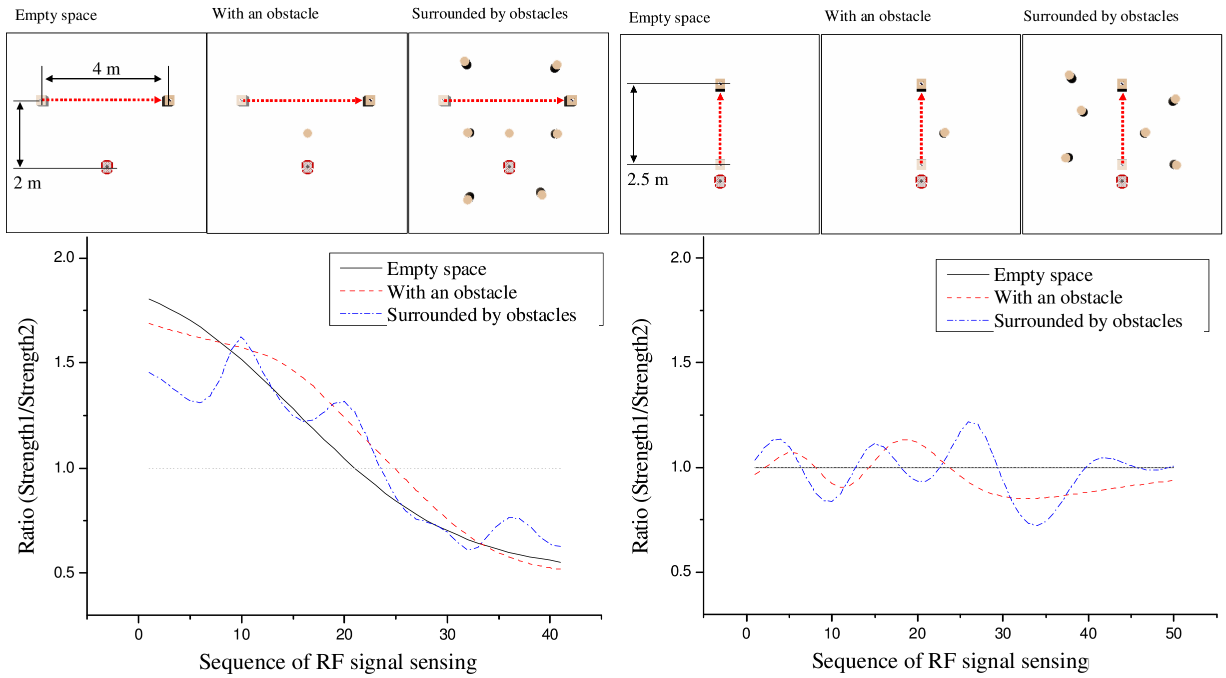
Fig. 2. Patterns and ratio of the signal strength

III. Target Tracking Using Dual-Directional Antenna

A. simulation results

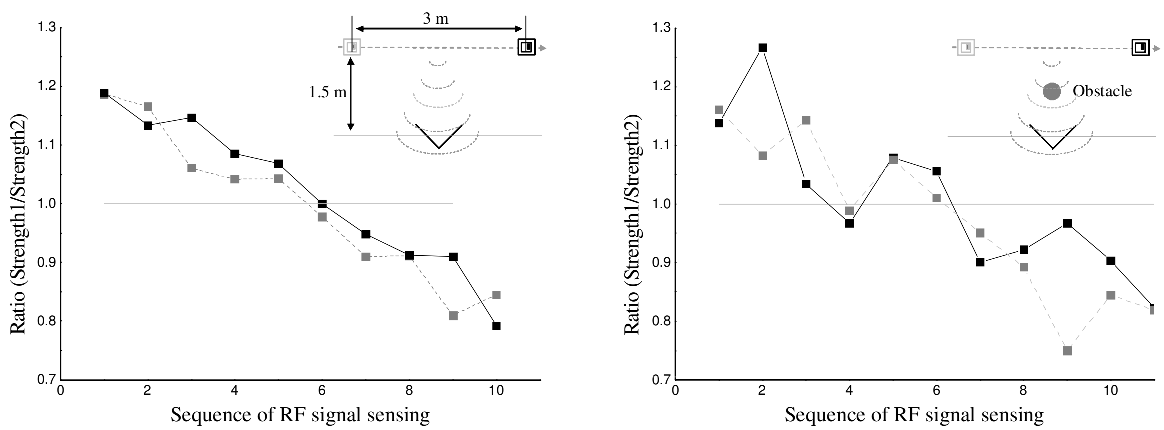
As mentioned in the previous section, the strength ratio will vary according to the DOA of the signal. When an RF transponder moves ± 45 degrees from the center line of the dual-directional antenna, the ratio increases or decreases according to the moving direction of the transponder. In order to validate the capability of the real-time target tracking of the antenna, we perform a series of simulations.

Fig. 3 is the simulation results showing the changes in the ratio when a transponder moves in a certain direction under three different environmental conditions illustrated in the upper figures. The signal distortion by the environmental effect is calculated using the multi-path propagation of RF signals in the ray tracing model [4], [13]–[15], where the obstacle is considered as a point that can scatter the signals. The ratio variation for each case is shown in the lower

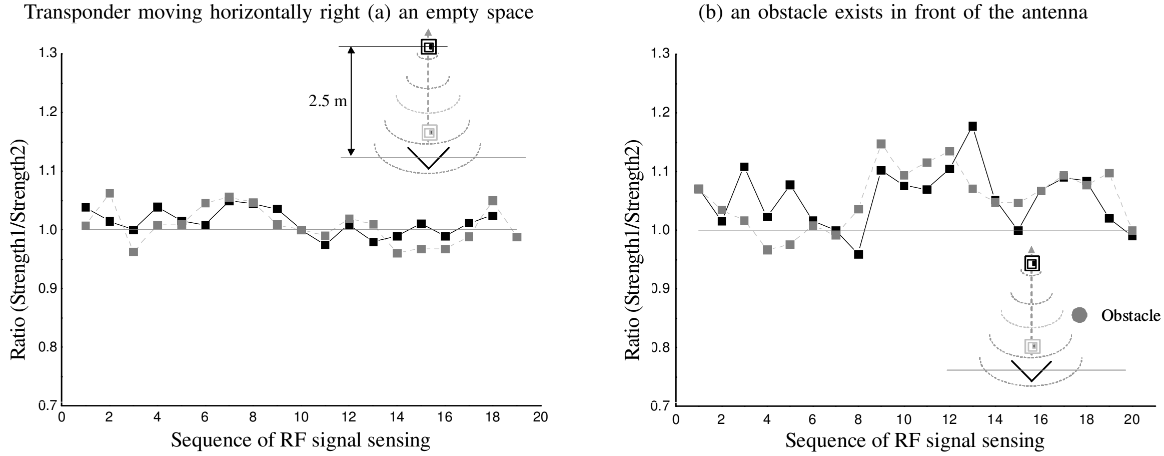


(a) transponder moving horizontally right (b) transponder moving vertically upward

Fig. 3. Simulation results of tracking transponder



Transponder moving horizontally right (a) an empty space (b) an obstacle exists in front of the antenna



Transponder moving vertically upward (c) an empty space (d) an obstacle exists in front of the antenna

Fig. 4. Experimental results of tracking transponder

figures. Fig. 3-(a) shows the results about the transponder moving horizontally to the right. The transponder at (-2, 2) m in a Cartesian coordinate system whose origin is at the antenna position moves to (2, 2) m. Therefore, the direction to the transponder is changed from left 45 to right 45 degrees. As known from the figure, the ratio is higher than 1.0 when the transponder is at the left 45 degrees, and decreases as the transponder moves to the right. Because the obstacles affect the transmission of RF signals, the decreasing curve is shown deflected in shape, which is determined by the number, physical property, and position of the obstacles. Fig. 3-(b) shows the results about the transponder moving 2.5 m vertically upward away from the initial position (0, 0.5) m. Even though the transponder moves, the direction to the transponder and the ratio remain unchanged in an empty space. It can be observed that the error increases and the curve oscillates when obstacles are included in the space.

B. Experiment results

We repeated the previous test with the real hardware under the same conditions as the simulation. Fig. 4 shows the changes in the ratio of the received signal strengths at the dual-directional antenna. The transponder motion is also shown in each of the figures. The transponder is located at the same elevation as the antenna. We measured the pattern of the ratio twice and depicted as the black solid and gray dashed lines.

Fig. 4-(a) and (b) show the ratio when the transponder moves horizontally from (-1.5, 1.5) m to (1.5, 1.5) m in a 5 $\times$ 6 m hallway. Fig. 4-(a) shows the results of the environment considered empty, but the effects of the walls were included. It can be observed that the obtain pattern is almost monotonically decreasing as expected. Fig. 4-(b) shows the ratio pattern when an obstacle exists between the antenna and the transponder. The error increases and oscillates in this case. Fig. 4-(c) and (d) show the result with the transponder moving vertically upward. Even though the transponder moves away, the direction is unchanged, thus the ratio also remains the same around the axis of 1.0 as shown in Fig. 4-(c). However, the error increases and oscillates when an obstacle exists nearby the antenna as shown in Fig. 4-(d).

It is evident that the movement of the target can be tracked in real time from the changes in the strength ratio. The proposed system has several advantages over other approaches. The system tracks a desired target without expensive sensors or reference points and moreover it does not require the line of sight. As shown in Fig. 4-(b), the system can track the movement even though the target is behind the obstacle. This will be very practical in the real environment where many obstacles exist and prevent from observing the target.

IV. Target Docking and Following

A. Target tracking dual-directional antenna

Based on the directionality of the dual-directional antenna, the target tracking RFID reader is designed. However, since the ratio pattern is easily deteriorated by the environment effect such as obstacles, the ratio pattern may not give the accurate direction. It was observed in the previous section that the ratio oscillated and changed very rapidly when there existed obstacles in the environment. This will cause the robot to change its heading frequently. In order to practically apply the proposed direction finding RFID reader to target tracking and following in a real environment densely populated with obstacles, the DOA estimation should be performed independently of the robot's orientation. Therefore, we use an additional positioning motor with the mount for rotating the antenna as shown in Fig. 1. The motor is also controlled by the AVR micro-controller of the RFID reader, allowing the antenna to face the direction to keep the ratio at the crossover point. The angle of antenna rotation φ_i at the time instant i can be determined from the ratio as

$$\varphi_i = A_i(1 - \nu_{12}^i), \tag{3}$$

where A_i is the value representing the relation between the rotation angle and the strength ratio. As mentioned before, since the magnitude of the ratio will vary due to the environment and system conditions, A_i should be determined by monitoring the ratio variation according to the antenna rotation at the previous time instant given by

$$A_i = \frac{\varphi_{i-1}}{\nu_{12}^i - \nu_{12}^{i-1}}. \tag{4}$$

In practice, by averaging A_i over several time instants, the fluctuations in the magnitude of the ratio will be strongly

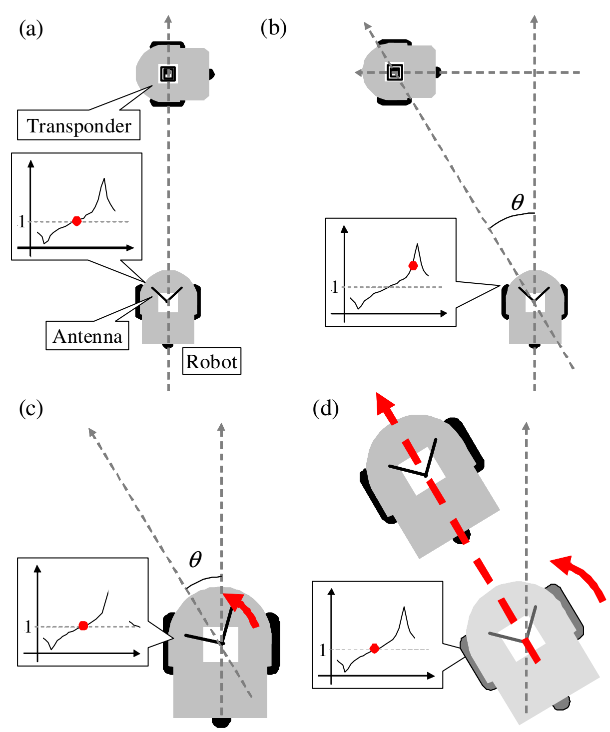


Fig. 5. Robot following a moving target (a) target in front of the antenna, (b) ratio changes while the target moves, (c) direction finding by rotating the antenna, (d) robot turns and follows the target.

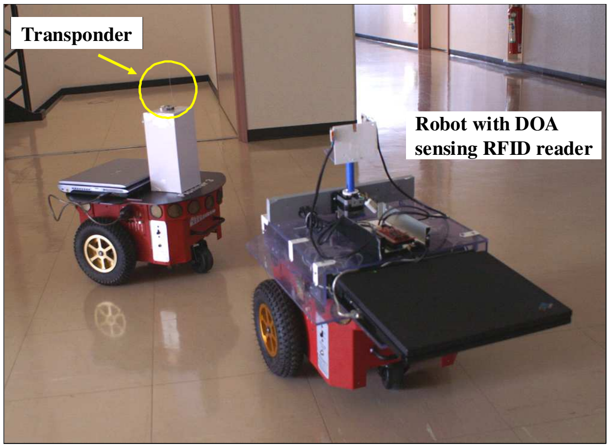


Fig. 6. A robot follows another robot guided by RF signals

attenuated. If the ratio changes rapidly while the antenna rotates, a temporally averaged value of A_i will force the antenna to rotate slowly and smoothly.

Fig. 5 shows how the follower robot tracks a target transponder. When the target is in front of the antenna, the ratio is at 1.0 as shown in Fig. 5-(a). As the follower robot approaches, the target moves to the left, then the ratio increases as shown in Fig. 5-(b). Then the antenna rotates toward the target direction and allows the follower robot to turn toward the antenna direction and approach to the target as shown in Figs. 5-(c) and (d).

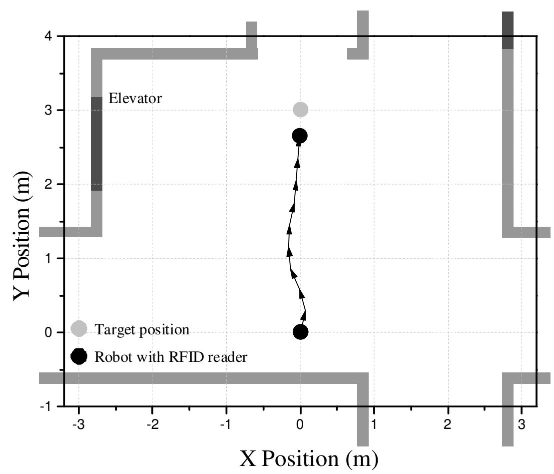
B. Experiment result

Based on the developed system introduced in the previous section, we perform experiments on target docking and following with real robots. Fig. 6 shows the snapshot of the experiment that a robot follows another robot guided by RF signals. A robot equipped with the developed direction finding RFID reader senses the direction to a target transponder mounted on another robot. Both robots are controlled by the client PC through wireless communication. The microcontroller of the RFID reader outputs signals to rotate the antenna that monitors the changes in the target direction, whereby the follower robot adjusts its heading accordingly.

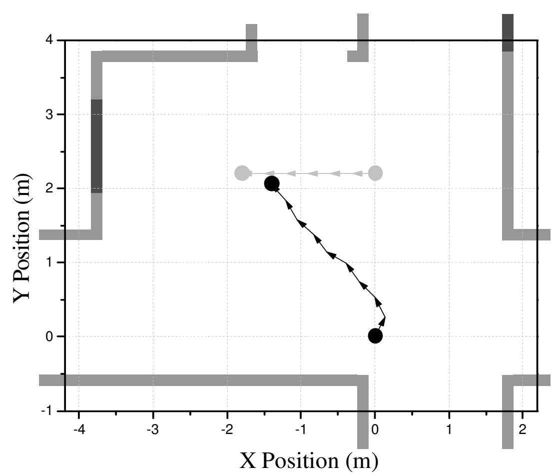
The experiment results are shown in Figs. 7 and 8. The black circles show the initial and final positions of the follower robot and the black arrows are its movement path, and the gray circles and the arrows are the path of the transponder mounted on the target robot. The gray thick lines are the walls of the hallway, and the black thick lines are the metallic object such as an elevator and a steel door that can significantly affect the path of signal transmission. Fig. 7-(a) shows the case when the robot docks to a stationary transponder successfully in an almost empty space. Fig. 7-(b) shows the result of the same experiment with a moving target. The transponder moves to the left while the robot approaches the transponder. Even though the target position is changed, the robot does not lose its direction and can finally dock to the target.

Fig. 8 shows that the follower robot approaches the target robot in the hallway condition. The target robot moves vertically upward and turns to the left and moves horizontally along the hallway. The initial distance between the transponder and the antenna is 30 cm. The follower robot tracks the direction of the target robot and follows it, maintaining a distance of approximately 1 m. Sometimes the follower robot's path is deflected by the environmental effect. For instance, the fire extinguisher is a metallic object that attracts the robot, but the robot can adjust its path to the target. Note that there is no regularity in the environmental effect. In this experiment, the robot moves close to to the obstacle due to the effects of scattered waves. However, the obstacle will not always attract the robot. It will also repel the robot, whereby the path of the follower robot may oscillate. Finally, the robot can arrive at the position that the target robot stops.

The proposed RFID system has several advantages and potentials. First, the reader can not lose its target while the target is located within the effective sensing range. Even though there is no line of sight to the target, and the target



(a) Stationary target



(b) Target moving horizontally left

Fig. 7. Experiment result of target docking

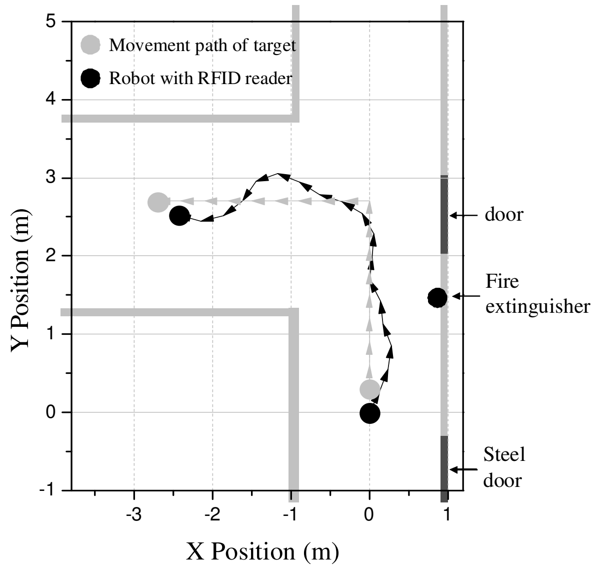


Fig. 8. Experimental result of target following

condition changes, the robot can track and follow the target. In this work, the collision avoidance problem for moving obstacles that rush into the path has not been included. This problem can be coped with in various way, for instance by fusing heterogeneous sensor data. Secondly, the system can be used for the multiple robot navigation problem. Since multiple RF readers can detect a single RF transponder simultaneously, a group of multiple robots equipped with the proposed system can estimate the direction to a common target and navigate in formation.

V. Conclusion

We proposed an effective approach to target tracking and docking with a mobile robot using the developed direction finding RFID reader. The reader was able to track any target moving unpredictably by rotating the dual-directional antenna to keep the ratio of the received signal strengths at the crossover point. Therefore, robots could easily determine the direction of heading by following the estimated DOA of the signals received from the target. Our major contributions can be summarized as: 1) The proposed system enables mobile robots to track and follow arbitrary moving targets using only the received signal strength. 2) The system can acquire a hidden target without any additional efforts and sensors, which is very effective in deploying robots into a real world, changing environment densely populated with unknown obstacles. However, since the proposed system just gives the path of signal transmission, robots will not be aware of the geographical location of various entities in the environment. Thus, our future effort will be devoted to enhancing the robot navigation by fusing heterogeneous sensor data and constructing the map of the environment. Also, a new method on target following by a group of multiple robots will be included.

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