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Description	

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Fusion of Direction Sensing RFID and Sonar for Mobile Robot Docking

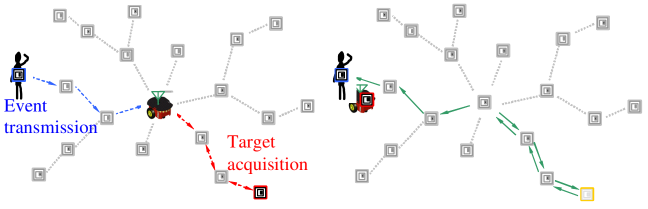
Myungsik Kim, Nak Young Chong, and Wonpil Yu

***Abstract*— Finding and moving to a target is a key element toward enhancing functionality and autonomy of mobile robots in a variety of applications. For the purpose, the location sensing radio frequency identification (RFID) system has been proposed by the authors. Real time tracking of the target transponder became available by employing the dual-directional antenna. However, since the system depended on the accuracy of the estimation for direction of arrival (DOA) of transponder signals, the system's performance may deteriorate in electromagnetically noisy or cluttered environments. In this paper, the features of the system are improved to accommodate such situations. The error correction algorithm is incorporated to provide a robust estimation of DOA, and sonar data are fused to characterize the environment. To verify the validity of the proposed system, we perform simulations and experiments of mobile robot docking in a real environment populated with stationary and movable obstacles.**

I. INTRODUCTION

Robots should understand as much as possible about the environmental situations and react appropriately to any event that may happen in the course of our everyday lives. Recent advance in RFID systems and networking technologies enables to construct an easy-to-understand environment that can support robots to easily identify and understand about the environment [1], [2]. As shown in Fig. 1, RFID transponders can be attached to such objects as people, animals, furniture, and somehow construct an *ad hoc* network, whereby the robot equipped with the RFID reader can characterize the situation of the environment. If any of the transponders transmits its event, the robot needs to move to a certain target, for instance, by following the data transmission path in the network. However, since most RFID systems do not support localization, it is quite difficult for robots to find and move to a specific target. For the purpose, several approaches have been reported [3], but most of them require multiple reference stations [4]–[6], which is not well suited to complex environments.

As a stand-alone solution to automating the process of mobile robot docking, the first RFID-based guidance system was developed in our previous work [7], [8]. By employing the dual-directional antenna, real time target transponder tracking became available. The experiment results showed that a mobile robot could find and dock to the target transponder successfully. However, the system possesses several problems which might appear significant in electromagnetically noisy or cluttered environments. For instance, if there exist obstacles near from the transponder and reader, multipath signal propagation causes significant errors in DOA estimation. Also, even though obstacles block the signal transmitting path, the signal can pass through them, causing the robot to collide with those obstacles. To cope with the above-mentioned problems, the direction sensing RFID system is improved in the following ways. First, the DOA estimation error correction algorithm is incorporated based on the Kalman filtering technique. Secondly, additional sonar data is fused to characterize the environmental conditions. Employing the sonar data, the vector field histogram is created to enable the robot to avoid collisions with obstacles.



(a) target acquisition problem (b) path finding problem

Fig. 1. Environment populated with RFID transponders

To verify the proposed system, we performed experimental tests using an in-house simulator and a commercial mobile robot in a cluttered environment. The results show that the robot can dock to the target transponder while avoiding collisions without requiring a map of the environment or the coordinates of the target spot. In Section II, the developed RFID system is explained with the fundamentals of electromagnetic theory underlying the measurement of the DOA. The error correction and collision avoidance algorithm are described in Section III. Simulation and experimental results are summarized in Sections IV and V, respectively. Finally, conclusions are drawn in Section VI.

II. SYSTEM OVERVIEW

Fig. 2 shows a commercial mobile robot the authors customized to suit direction-finding needs. The dual-directional antenna is a pair of identical loop antennas positioned perpendicular to each other. The received signal strength (RSS) of each loop antenna has a sine wave pattern according to the bearing between the antenna face angle and the line of signal transmission [10]–[13]. Since there exists a 90° phase difference between the RSS of each antenna, the DOA of the

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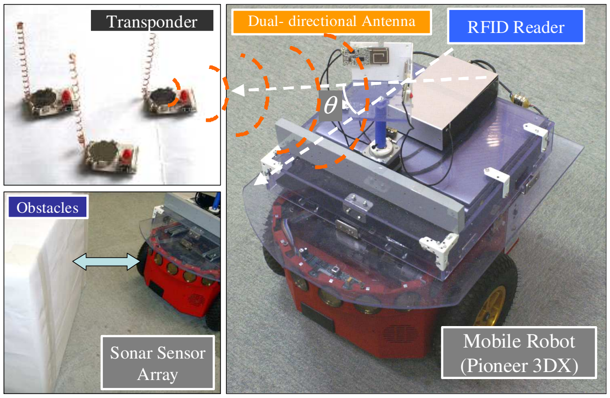


Fig. 2. Overview of the developed system

transmitted RF signal can be estimated by their ratio given by

$$\nu_{12} = \frac{V_1}{V_2} = |tan(\theta)| \rightarrow \theta = \tan^{-1}(\pm\nu_{12}) \tag{1}$$

Therefore, the robot can move toward a specific target position along the estimated direction. The accuracy of the DOA estimation using a directional antenna was about ±4° in a free space [9]. However, since RF signals are easily reflected, refracted, and scattered by neighboring obstacles, multiple signals will be propagated as shown in Fig. 3 [14], [15]. Thus, the total field received at the antenna is the superposition of all those various RF waves given by

$$\Phi_{total} = \Phi_{direct} + \sum_{i=1}^{n} \Phi^{i}_{non-direct}, \tag{2}$$

where Φ is the magnetic flux that pass through the antenna. This field changes in amplitude and phase according to the conditions of the propagated waves as

$$A\sin(\theta + \eta), \tag{3}$$

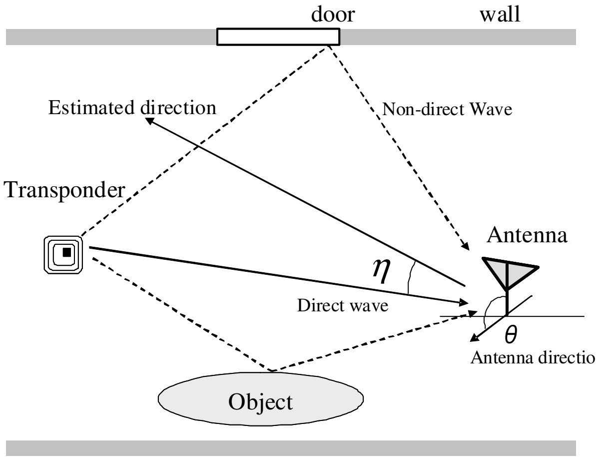


Fig. 3. Multi-path propagation of RF signals in ray-tracing model

where A is the constant reflecting the amplitude changes and η is the phase shift in the superposed waves comparing with the direct wave, which appears as an error in the estimated DOA.

III. ROBOT DOCKING IN CLUTTERED ENVIRONMENTS

A. Error correction algorithm

To find out the exact DOA of the signal, a robust yet efficient filtering algorithm is needed. The amount of the error depends on the geometrical relations among the obstacle, the target transponder, and the antenna, as well as the physical properties of the obstacle. It can be verified that the error oscillates if the position of the antenna or transponder changes. Now the Kalman filter is applied to the estimated DOA to help the robot find the direction of the signal more accurately [16]. The direction at the current time step can be considered to be the summation of the direction at the previous estimation and a differential given by

$$\theta^{*}_{n} = \theta^{*}_{n-1} + g(\theta_n - \theta^{*}_{n-1}), \tag{4}$$

where θ^{*}_{n} is the filtered DOA, θ_n is the originally estimated DOA, and g is the gain updated using the variance of filtered and estimated directions.

$$g = \frac{VAR(\theta^{*})}{VAR(\theta)}. \tag{5}$$

If the number of measurement points are large enough, the gain becomes more suitable for each measurement point. However, up to several dozen measurement points in ordinary sized spaces, the proposed filtering depends heavily on the initial value g_0. Fig. 4 shows a typical example of how

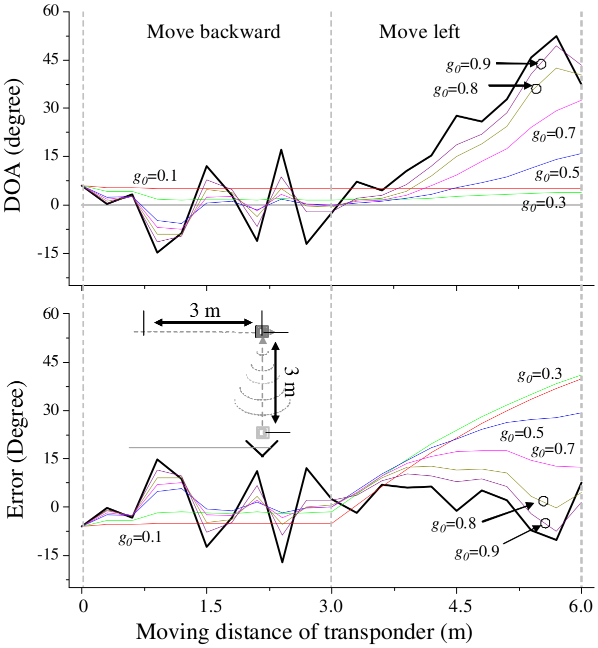


Fig. 4. (top) filtered ratios according to the initial value of the gain, (bottom) errors in DOA estimation

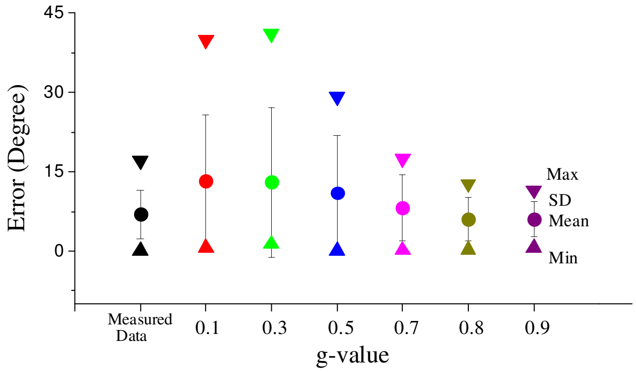


Fig. 5. Error statistics according to the initial value of the gain

the initial value of the gain affects the filtered value. We tested the change of the filtered value of the DOA obtained when a transponder moves $3m$ backward, leaving the direction unchanged, and subsequently $3m$ left in our hallway environment. The top graph shows the relation between g_0 and DOA estimations, and the bottom graph is the error in DOA estimations. The thick solid line shows the non-filtered DOA. The mean and the standard deviation of the error are also shown in Fig. 5. As shown in the figure, a low gain may worsen the accuracy of the estimation. We empirically evaluate the accuracy of each gain and select the initial value between 0.8 and 0.9 in this work.

B. Collision avoidance based on vector field histogram

The DOA of RF signals does not always allow the robot to move toward the target. There exist many obstacles in our daily environment through which RF signals can pass. The permeability of RF signals is useful in object identification, but this may not be advantageous in mobile robot navigation, since the signal path is not quite the same as the feasible path to the transponder. Thus, additional sensors to detect obstacles are required. Specifically, we add the distance measuring sensor to the current direction finding RFID system whereby the collision avoidance algorithm is developed using the vector field histogram technique. In this work, our goal is to develop the indoor mobile robot system navigating through the environment toward the goal position without using any *a priori* map of the environment. Under such conditions, it is required that the robot should autonomously find the collision free area. Specifically, the vector field histogram technique enables the robot to react to the changes in the environmental condition rapidly using one-dimensional histogram within the sensing range of sensors. Thus, when the robot is faced with an obstacle in the estimated direction, the robot can find a bypass route toward the goal without any collisions. Since the DOA estimation can give the goal direction continuously, the local collision avoidance technique is really effective for our system.

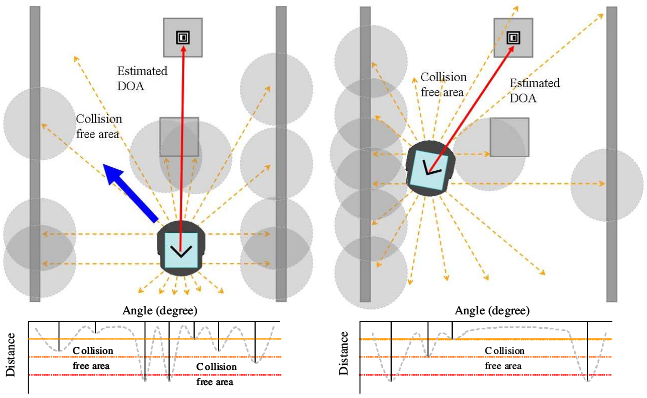


Fig. 6. Collision-free path planning using vector field histogram

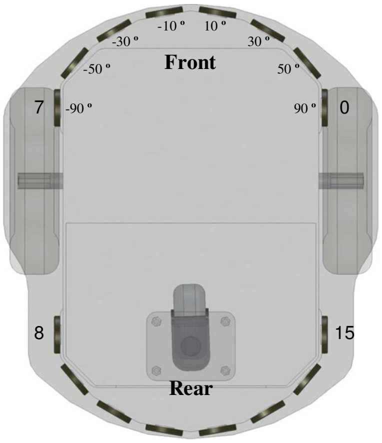
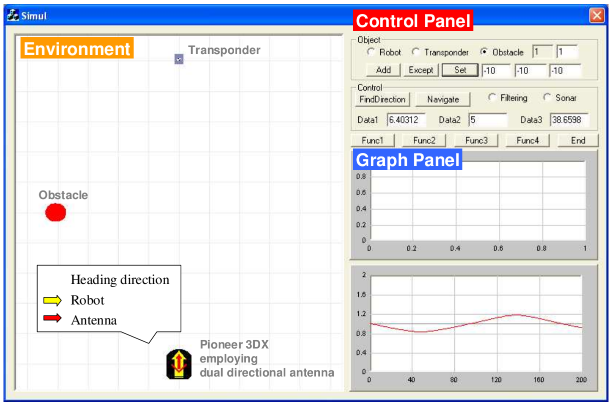


Fig. 7. Alignment of sonar sensors in Pioneer 3-DX

Fig. 6 shows the basic concept of the collision avoidance. The top figures show the geometrical relations between the robot, the target transponder, walls, and obstacles, and the bottom graphs show the vector field histogram created using the measured distance from the array of distance sensors. The robot checks the distance to the obstacles, and finds the collision free direction. Advantageously, the robot can move in the nearest collision free direction from the estimated DOA of target signals. However, the accuracy of the histogram is determined by the number and property of the sensors. In this work, we use a Pioneer 3-DX whose sonar sensor alignment is illustrated in Fig. 7. A total of 16 front and rear array sensors are installed with non-uniform intervals. A sensor can sense the distance up to $5m$ within the cone angle (or angle of coverage) about $\pm 12^\circ$, which was determined empirically.

IV. SIMULATION RESULTS

To test the proposed method of mobile robot docking, we have built a simulator as shown in Fig. 8 consisting of three interactive panels. On the left is the virtual environment showing the positions of the robot, transponders, and obstacles. The robot is controlled by the control panel on the top right, and the RSS ratio and the vector field histogram of the sensed obstacles are shown in the graph panel on the bottom right. The multi-path propagation effects of the RF signal is calculated using the ray tracing model shown in Fig. 3. It is assumed that the robot moves with a uniform velocity



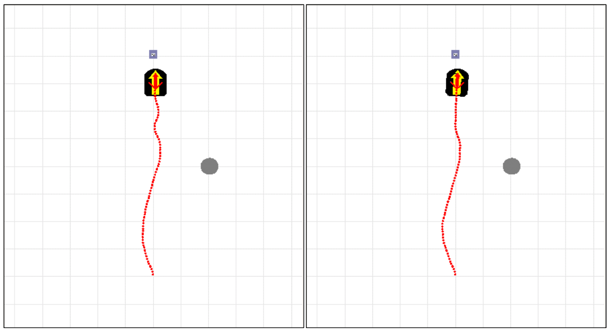
○ Robot ○ Transponder ● Obstacle 1 1

-10 -10 -10

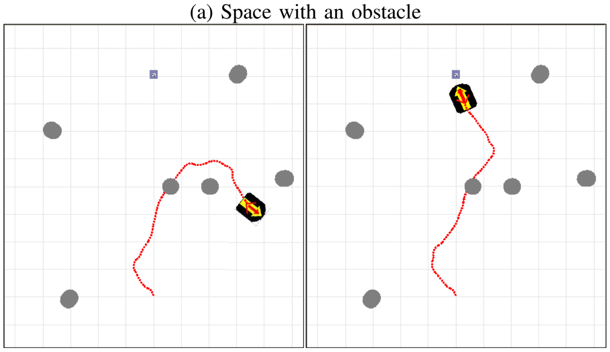
○ Filtering ○ Sonar

Data1 6.40312 Data2 5 Data3 38.6598

Fig. 8. Layout of the simulator



(a) Space with an obstacle



(b) Space occupied by randomly positioned obstacles

Fig. 9. Simulation results of RFID direction finding

and no odometric errors exist. The simulation conditions are summarized as follows:

- The environment is an open, $5.5m \times 6m$ square space.
- The environment is perfectly shielded, thus the transmitting signal is not affected by other and unspecified conditions except for obstacles.
- All obstacles are cylindrical in shape with the same physical properties.
- The distance estimation error is not included.
- Intrinsic sensing error of $\pm 4^\circ$ with the Gaussian distribution is included in DOA estimates.

The robot moves according to the current step DOA estimate, thus the odometric error can be ignored when finding the goal direction. On the other hand, the odometric error may affect the estimation of distance to the obstacle updated by transforming the measurements of previous steps, thus the accuracy of distance estimates from the sonar sensors may deteriorate. To cope with this, the robot uses the information of the latest measurement. Under such conditions, the robot navigates according to the following steps:

1) The robot scans the transmitting signal from -90° to 90° and estimates the DOA from the ratio pattern.
2) The robot moves a uniform distance in the estimated DOA.
3) The robot heading is adjusted by controlling the velocities of a pair of wheels.
4) The robot stops when it enters the target area, which is determined by the signal strength measurement.

Fig. 9 shows the simulation results obtained under various conditions. On the left is the case that the robot followed the originally estimated DOA, while on the right is the case that the robot followed the filtered DOA. Fig. 9-(a) shows the results when there was only one obstacle in the environment. The deflection of the path was caused by the distortion of the transmitting signal. In both cases, the robot could arrive at the target position, but the proposed filtering scheme gave a smoothened path. In Fig. 9-(b), where the robot navigated through randomly positioned obstacles, the robot could not reach the transponder position when the robot just followed the originally estimated DOA. The DOA estimation error will be affected by the number of obstacles and their position and physical properties. However, the robot could arrive at the target position when the proposed filtering algorithm was employed. The error still remained in the filtered DOA, but the error decreased significantly by the proposed algorithm.

The previous results show that the robot can dock to the target position even though multi-path propagation causes significant errors in DOA estimation. However, when the robot moves toward the target position, the robot may pass through the obstacle position as shown in Fig. 9-(b). Thus, additionally we use an array of ultrasonic distance sensors whose data is fused with the DOA estimation. The left-hand side of Fig. 10 shows the vector field histogram created using the distance sensor. The robot can obtain the distance to obstacles according to its heading, and determine the possible directions of movement. If the estimated DOA points to the

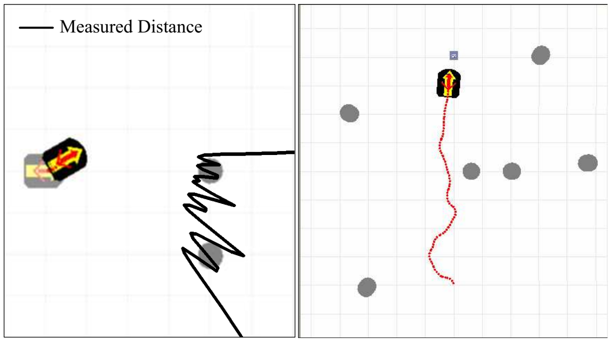


Fig. 10. Simulation results of RFID-sonar fusion (left) vector field histogram using sonar data (right) collision-free robot docking

area of possible collision, the robot can select, for instance, the nearest collision free direction from the estimated DOA. Based on the above method, we perform experiments of robot docking under the same condition as shown in Fig. 9-(b), where the robot collided with an obstacle. The right-hand side of Fig. 10 shows the path that the robot took using the estimated DOA and the vector field histogram. The robot could arrive at the target position without any collision by finding the shortest collision-free path.

V. EXPERIMENTAL RESULTS

Experiments are performed under various conditions using a real robot Pioneer 3-DX. Fig. 11 shows a snapshot of the experimental scene and its graphic representation. The experimental space includes one person, four large desks, two small desks, three metallic chairs, and other tiny objects. In order to simulate some complex situation, several corrugated boxes block the robot path, but they almost never affect the RF signal. The chair and person are included to test the signal scattering and absorption situation. The environment is not electromagnetically shielded, thus the RF signal can be affected even though there are no obstacles near from the robot and the transponder.

Fig. 12 shows the results obtained under two different conditions. The target transponder is located at the position of $(0, 3.5)m$ in a Cartesian coordinate system whose origin is at the initial position of the robot. After the robot finds the direction to the transponder, the robot moves to the transponder guided by the RFID system. The robot stops approaching the transponder when the transponder is around the range of $50cm$ from the robot. The distance is estimated from the signal strength. In the figure, the gray squares indicate the initial position of the robot and the transponder. The black and red dashed lines are the paths that the robot navigated and the black and red circles are final position of the robots. The left-hand side of the figure shows the results of docking where no obstacles are positioned. The robot could arrive at the transponder position in both cases. Note that the error in the DOA estimation varies according to the numbers, positions, and material properties of the obstacles. If the obstacles are located at the position that affects the transmission of the signals, the error increases. On the right are the results where two metallic objects and one person are positioned. Since the error increases by the obstacles, the robot could not arrive at the target position. The robot lost the direction to the target and finally collided with the desk. However, by using the proposed filtering algorithm, the error was reduced and the robot could arrive at the target position successfully.

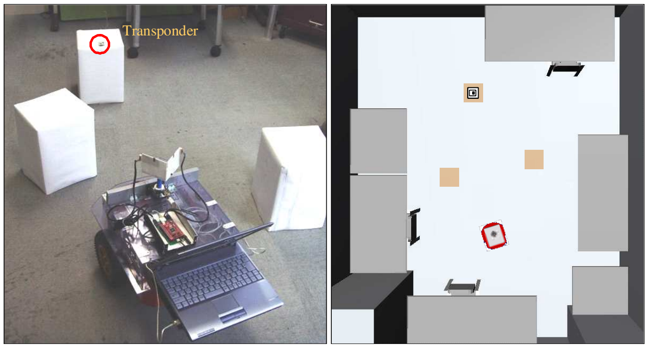


Fig. 11. (left) snapshot of the experiment (right) virtual environment showing experimental results

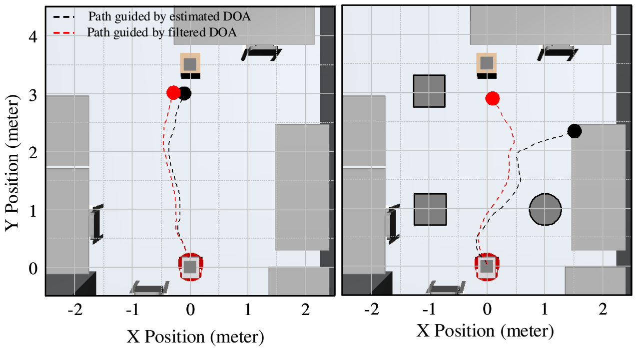


Fig. 12. Experimental results of RFID direction finding (left) with no obstacles (right) with metallic obstacles and person

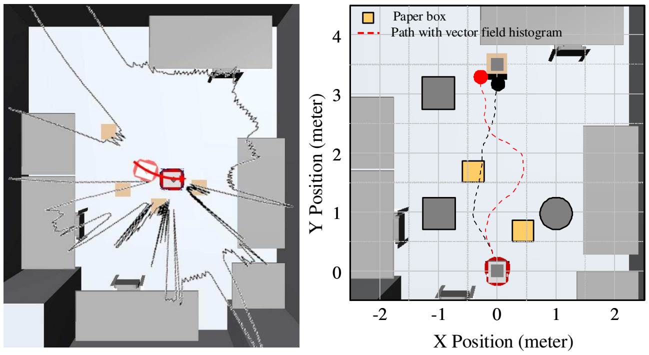


Fig. 13. Experimental results of RFID-sonar fusion (left) vector field histogram (right) collision-free robot docking

It is evident from the previous results that the robot can arrive at the target position employing the proposed RFID system. However, the problem of collision still remains. Thus, the collision avoidance algorithm is applied based on the vector field histogram. The left-hand side of Fig. 13 shows the vector field histogram using real sonar sensor data drawn in polar coordinates. Four obstacles of corrugated boxes are positioned nearby the robot. As shown in the figure, the obstacles are successfully detected, then the robot finds the way to the target transponder without collisions. The right-hand side of the figure shows the experimental results. Corrugated boxes block the possible path of the robot. When the robot follows the originally estimated DOA, the robot collides with the boxes. In contrast, by using the collision avoidance algorithm, the robot can effectively avoid the boxes and arrive at the target position. Note that the box on which the transponder is positioned is also detected as the obstacle on the vector field histogram. Thus, the robot tries to avoid the transponder, showing that the path is deflected in the vicinity of the transponder position.

VI. CONCLUSIONS

We proposed a fusion of direction sensing RFID reader and sonars for collision-free mobile robot docking in cluttered indoor environments. The DOA estimation error correction and collision avoidance algorithms were incorporated into the proposed system. Our major contribution is to design an automated docking guidance system of mobile robots without *a priori* maps and target positions. Simulation and experimental results showed that the robot could arrive at the target location successfully by finding the most feasible path in an unknown environment populated by stationary and movable obstacles. Our future effort will be devoted to the realization of robot docking to the remote target beyond the sensing range using the data transmission path in the *ad hoc* network of RFID transponders.

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