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Enhancing RFID Location Sensing Using a Dual Directional Antenna

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Abstract

A location sensing radio frequency identification (RFID) system has been developed employing a single directional antenna. This system enabled a mobile robot to identify, locate, and approach a stationary transponder. However, since the system determined the bearing of the transponder by scanning the environment about the azimuth axis, it faced difficulties if the transponder was not stationary. Also, even though the accuracy was within a reasonable range, it may deteriorate in the case of occlusions and cluttered environments. In this paper, we propose a dual directional antenna system to enhance RFID location sensing in dynamically changing environments. The dual directional antenna is a set of two identical directional antennas perpendicularly positioned to each other having a phase difference. A mobile robot system equipped with the proposed antenna can determine the bearing of the transponder using the ratio of the signal strength between two antennas. The proposed system, not requiring rotation of the antenna, is available to track the heading of a moving transponder and can minimize the environmental effects causing signal distortions. To verify the robustness of the proposed system to any reflective or signal blocking obstacles and moving transponders, we perform experiments under various conditions with applications to mobile robot navigation.

1 Introduction

To build an informatively structured environment enabling a robot to easily understand the context of the environment, a suitable interface should be needed that provides the robot with necessary information in real time [1], [2]. This interface should be small, cheap, and simple to implement in order to maximize the applicability. RFID has been considered as the viable candidate, since the radio frequency signal can eliminate the need for an optical line of sight, transmits a relatively large amount of information, and can be used for the bi-directional information flow [3], [4]. But the current RFID systems employing omni-directional antennas do not allow us to identify the spatial information of a target object. To date, several RF-based location sensing techniques have been proposed in indoor environments. A well-tried approach includes some form of triangulation based on the distance estimation from signal strength [5], [6]. However, this approach, requiring multiple reference stations, is presumably intended for providing coarse-grained location information and suffers from unpredictably varying signal strength due to uncertain environmental effects

For a stand-alone RFID-based location sensing system that can be installed into a mobile robot, the directionality of a loop antenna has been exploited. The system measures the direction of the transponder and triangulates its position using the measured directions and the distance between the measurements [7]. However, to find the direction of the transponder that remains stationary, the system needs to scan the environment by rotating the antenna at a measurement point. Also, the error is likely to increase significantly if the signal is highly distorted by multi-path propagation. Thus, much effort should be devoted to the study of reconstruction algorithms for distorted signals.

In this paper, we propose a dual directional antenna system to localize a stationary transponder in the presence of obstacles and track a moving transponder in real time. The dual antenna is an antenna set consisting of two identical directional antennas perpendicularly positioned to each other. Since the phases of the signal induced at each antenna are 90 degree different, the direction can be found by the ratio of the signal strength of two antennas without rotating them. Moreover, the system can sense the heading direction of a moving transponder in real time. In practice, since the two antennas are under the same conditions of electromagnetic signal, the strength ratio of the dual antenna will be robust to any reflective and signal blocking obstacles causing signal distortions.

To verify the validities of the proposed system, we develop a prototype system installed in a mobile robot and perform experiments with a stationary and a moving transponder under various conditions with applications to mobile robot navigation. In this paper, we will briefly describe the fundamental electromagnetic theories underlying the measurement of the angle of arrival bearings of RFID transponders. Details will also be provided regarding the development and evaluation of the prototype system. Experimental results will show that the proposed system can provide finer-grained location information in our daily environment even when clear signal path is not secured.

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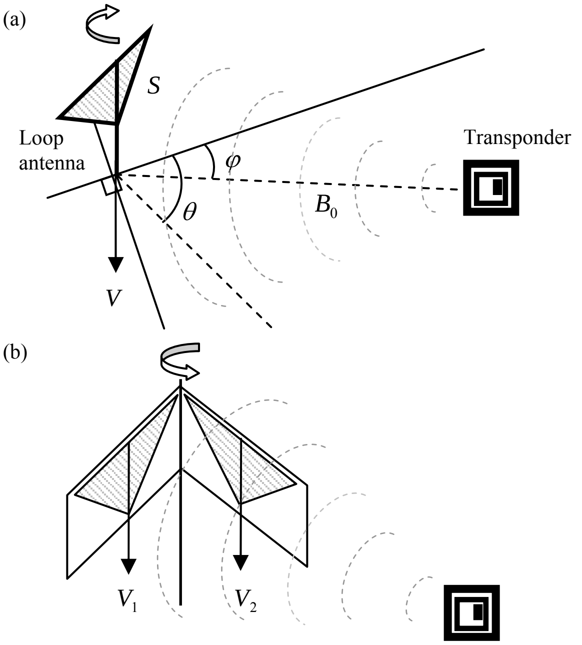


Fig. 1 Azimuth angle of the direction of arrival (a) Single antenna (b) Dual antenna

2 Direction Finding Antenna System

The location sensing in this work uses the triangulation principle with the bearing measurements. This can be achieved by loop antennas exploiting their directionality. In this section, we provide a description of fundamental principles governing the direction of arrival estimation with directional antennas.

A. Single Antenna System

When an electromagnetic signal is transmitted to a loop antenna as shown in Fig. 1-(a), a voltage is induced as

$$V \propto CSB_0 \left|\sin(\theta-\varphi)\right|, \qquad (1)$$

where S is the surface area of the antenna, B_0 the magnetic flux density of the wave passing through the antenna, θ the rotation angle of the antenna, φ the bearing of the transponder we need to determine, and C accounts for the environmental conditions including the effect of the distance [8], [9], [10]. As the shape of the induced voltage level is ideally the Arabic numeral eight in polar coordinates, the bearing of the transponder can be determined if we know the antenna angle at which the voltage level is minimized or maximized [11]. For instance, from Eq. (1), the voltage level can be minimized when the rotation angle of the antenna and the bearing of the transponder are coincident. Then the location of the transponder can be triangulated with the bearings of the transponder at multiple positions. In principle, however, the directional antenna requiring the scanning of the environment at a fixed position about the azimuth axis can find the direction of a transponder only when the transponder is stationary. Also the signal pattern is easily distorted by the environmental effects such as obstacles and people. Thus, the single antenna approach might not be suitable for use in cluttered environments.

B. Dual Antenna System

To cope with the problems of the single directional antenna, we design a dual directional antenna system. The dual antenna is a set of antennas consisting of two identical loop antennas proportionally positioned to each other as shown in Fig. 1-(b). A 90 degree phase shift occurs between the received signal at two antennas. We can then obtain a dimensionless parameter $v_{1,2}$ defined as the ratio of the received signal strength of one antenna to that of the other antenna given by

$$\begin{aligned} & v_{1,2} = V_1/V_2 = \left|\tan(\theta-\varphi)\right|, \\ \text{where} \quad & V_1 \propto CSB_0\left|\sin(\theta-\varphi)\right|, \qquad (2) \\ & V_2 \propto CSB_0\left|\sin(\theta-\varphi+90)\right|. \end{aligned}$$

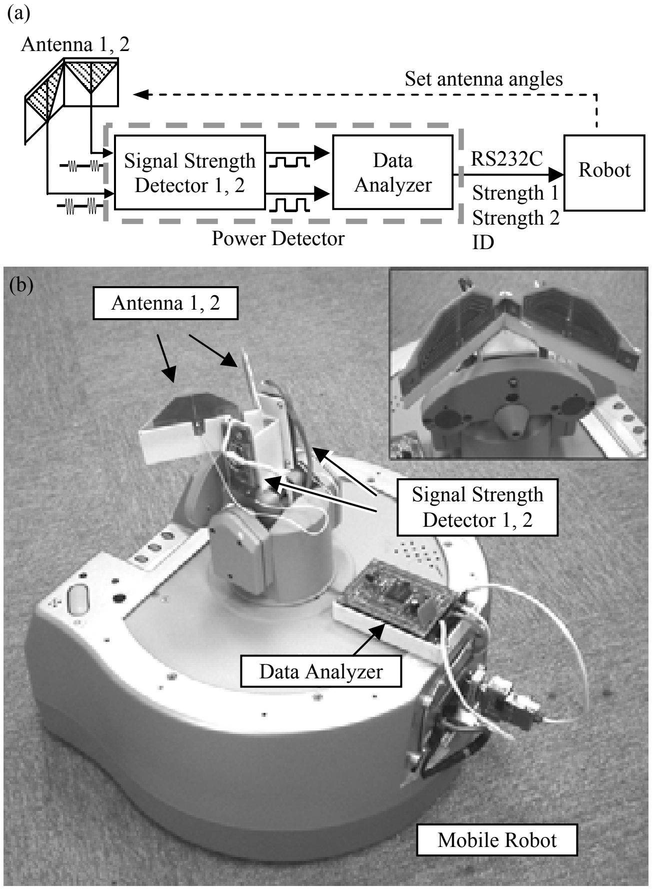
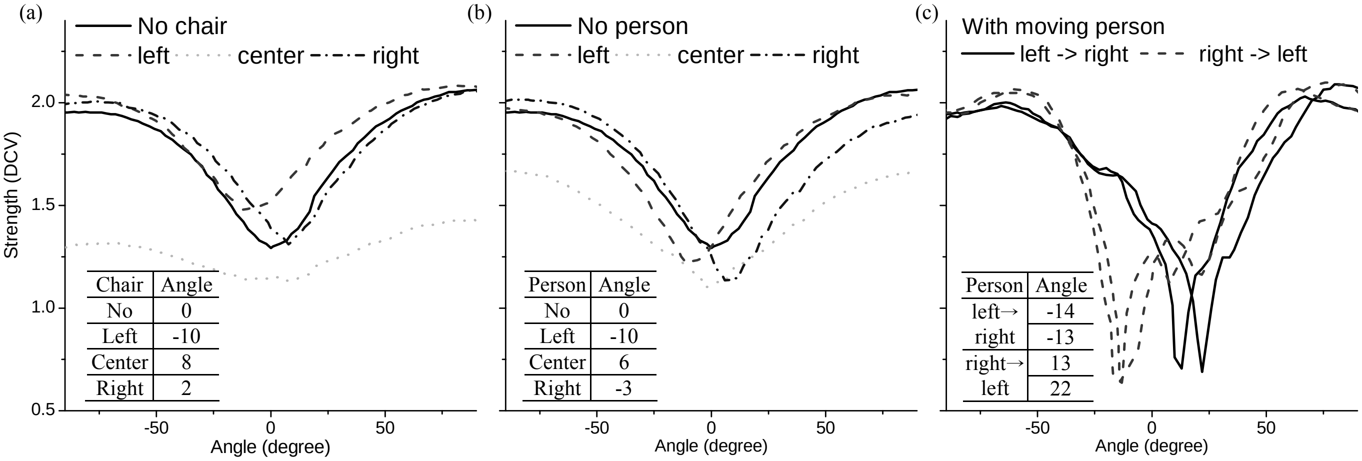


Fig. 2 Experimental System (a) Schematic (b)



Chair	Angle
No	0
Left	-10
Center	8
Right	2

Person	Angle
No	0
Left	-10
Center	6
Right	-3

Person	Angle
left→	-14
right	-13
right→	13
left	22

Fig. 3 Received signal pattern at the single antenna in the presence of (a) chair, (b) person, and (c) person moving

Thus, the bearing of the transponder can be determined without scanning the environment if we measure $v_{1,2}$ and θ from the above equation. Moreover, since we can eliminate C , the bearing measurement is much more robust to environmental disturbances. Based on the current analysis, we develop the prototype system.

3 Experimental Setup

Fig. 2-(a) shows the schematic of the dual antenna RFID prototype consisting of two directional antennas and their power detector. The power detector has two identical signal strength detectors and a data analyzer. An RF signal received at each antenna is fed to the signal strength detector. The signal strength detector converts the signal within a range of -120 dBm to -45 dBm to a DC voltage with a range of 0 to 5 V. This DC voltage is transmitted to the data analyzer that generates the digitalized signal strength and ID code of the transponder. Finally, the generated signal strengths and ID code together with an antenna facing angle are provided to the robot through a serial communication interface. Then the direction of a target transponder can be determined by the ratio of the signal strength of the two antennas.

Fig. 2-(b) shows an off-the-shelf mobile robot platform equipped with the dual antenna RFID system. The dual antenna setup has two electrically small loop antennas manufactured by printed circuit board etching, each of which has a width of 78 mm and a height of 32 mm. Their rear side is shielded and perpendicularly opened to improve the signal receiving sensitivity in the horizontal plane. Each antenna is attached to an acrylic plate that is fixed to the pan and tilt head of the robot. The center of the dual antenna setup is set to zero degree. The test results of the dual directional antenna system are shown in the following section.

4 Result

Analyzing the change in the received signal strength pattern under various test conditions, we investigate the errors in bearing measurements with the dual antenna RFID system. The measurements were performed in a 7 m x 9 m unoccupied room. The transponder was located 2 m away from the antenna, that is (0, 2) m in the antenna coordinate system.

4.1 Effect of Obstacles

The received signal by a single antenna usually is attenuated and distorted in the presence of stationary or moving obstacles as depicted in Fig. 3. Fig. 3-(a) shows the strength patterns distorted by a metallic chair. The metallic chair is placed at (-1, 1), (0, 1), and (1, 1) m, respectively, heading -45, 0, and +45 degrees in the antenna coordinates. The black solid line is the signal pattern without the chair that is used as the reference signal. The red dashed line shows the pattern when the chair is located at -45 degrees, the green dotted line 0 degree, and the blue dash-dotted line +45 degrees. It can be observed from the figure that the antenna facing angle, at which the received signal strength is minimum, was shifted by -10 to 8 degrees in the presence of the chair. Also, the level of the strength decreased dramatically when the chair was positioned at 0 degree that definitely blocked the path of the signal.

In Fig. 3-(b), a person replaces the chair. All other conditions remain the same. The minimum and maximum levels of the signal strength varied as is the case with most obstacles including the metallic chair. The minium strength antenna angle also varied within a similar range. It has been reported in [7] that the errors in bearing measurements of a stationary transponder was within ±4 degrees in a real environment when there is no signal blocking obstacles. But, the accuracy becomes worse when there is an obstacle causing signal distortions. The distortion level varies according to the characteristics of the obstacle. However, as the stationary obstacles constantly affect the signal when

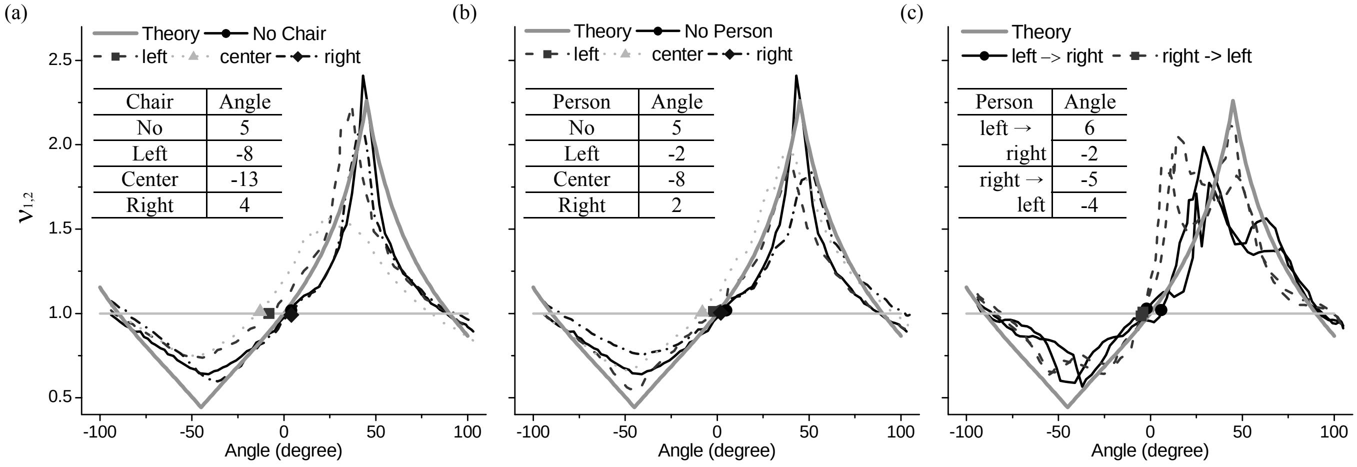


Fig. 4 Received signal pattern at the dual antenna in the presence of (a) chair, (b) person, and (c) person moving

the antenna scans the environment, the signal is likely to exhibit a typical pattern to some extent.

Fig. 3-(c) shows the results of signal patterns when a person moves right from left depicted by the solid black line and vice versa (*i.e.*, left from right) depicted by the dashed red line. The minimum level of the signal strength dropped abruptly and the corresponding antenna angle varied over a wide range. A moving obstacle does not affect the signal constantly, thus the signal is likely to be distorted unpredictably and varies with time.

In contrast, the dual antenna system can minimize the effects of signal blocking obstacles causing the errors in bearing measurements. The relative ratios of the received signal strengths are shown in Fig. 4, where the values of the signal strength of Antenna 1 divided by that of Antenna 2 are plotted on a logarithmic scale. The tests were performed under the same condition as the single antenna case. The center between the two antennas is set to zero degree. The trajectory shows how the ratio varies with the angle between the antenna facing direction and the actual transponder direction. The orange thick line is the theoretical value calculated from Eq. (2). The table in the figure shows the antenna angle of zero degree at which the strength ratio is 1.0. The angles designate the points that the trajectories meet the gray threshold line. Taking account of a slight discrepancy between two strength detectors in the prototype, the direction finding accuracy is almost the same with the single antenna case for the stationary obstacles. However, with a single antenna, it is quite difficult to find the direction of a transponder when there is a moving obstacle in the environment. Since the term related to the environmental effects was eliminated in the dual antenna system given by Eq. (2), the direction finding accuracy is maintained even in the case of moving obstacles. This can be observed from Fig. 4-(c) that that the antenna angle is within the range of reasonable estimates.

4.2 Moving Transponder

The dual antenna can determine the bearing of the transponder without scanning the environment. This will enable a robot to track a moving target continuously. The received signal strength patterns at the dual antenna from a moving transponder are shown in Fig. 5. In each row, the left graph shows the direction of the transponder movement, the center the signal pattern according to the antenna angle, and the right the relative ratio of the signal strength of the antenna while the antenna faces front at 0 degree. The gray line is the theoretical value calculated from Eq. (2). In Fig. 5-(a), the antenna is positioned at the origin and the transponder moves straight away along the y-axis from (0, 1) to (0, 5) m. Since the direction of the transponder remains unchanged, irrespective of the distance between the transponder and the antenna, the signal strength ratio is close to 1 in the right graph.

Fig. 5-(b) shows the pattern while the transponder moves from (-1, 1) to (1, 1) m, changing the initial angle from -45 degrees to 45 degrees. While the transponder moves, the strength ratio changes gradually. When the transponder is at -45 degrees, the ratio is significantly higher than the threshold of 1.0 implying that Antenna 1 induces stronger signals than Antenna 2 does due to the difference in their direction of signal arrival. The ratio is 1.0 as the transponder is located in front of the antenna, and goes down below the threshold of 1.0 as the transponder moves toward +45 degrees direction.

Fig. 5-(c) shows the pattern while the transponder moves upward along the slope from (-1, 0) to (1, 2) m. As the transponder moves, the angle of the transponder direction from the antenna facing angle changes from -90 degrees to 26.6 degrees. When the transponder is at (-1, 0), -90 degrees, the strength ratio is close to 1.0, and increases as the transponder moves to (-0.5, 0.5), -45 degrees, and decreases as the transponder moves through (0, 1) and (0.5, 1.5), toward (1, 2). It is verified that the dual antenna can obtain the heading direction estimates of the transponder movement from the changes in the strength ratio.

In effect, the accuracy of the dual antenna is unlikely to be improved significantly compared with the single antenna. However, the dual antenna system is much more robust to

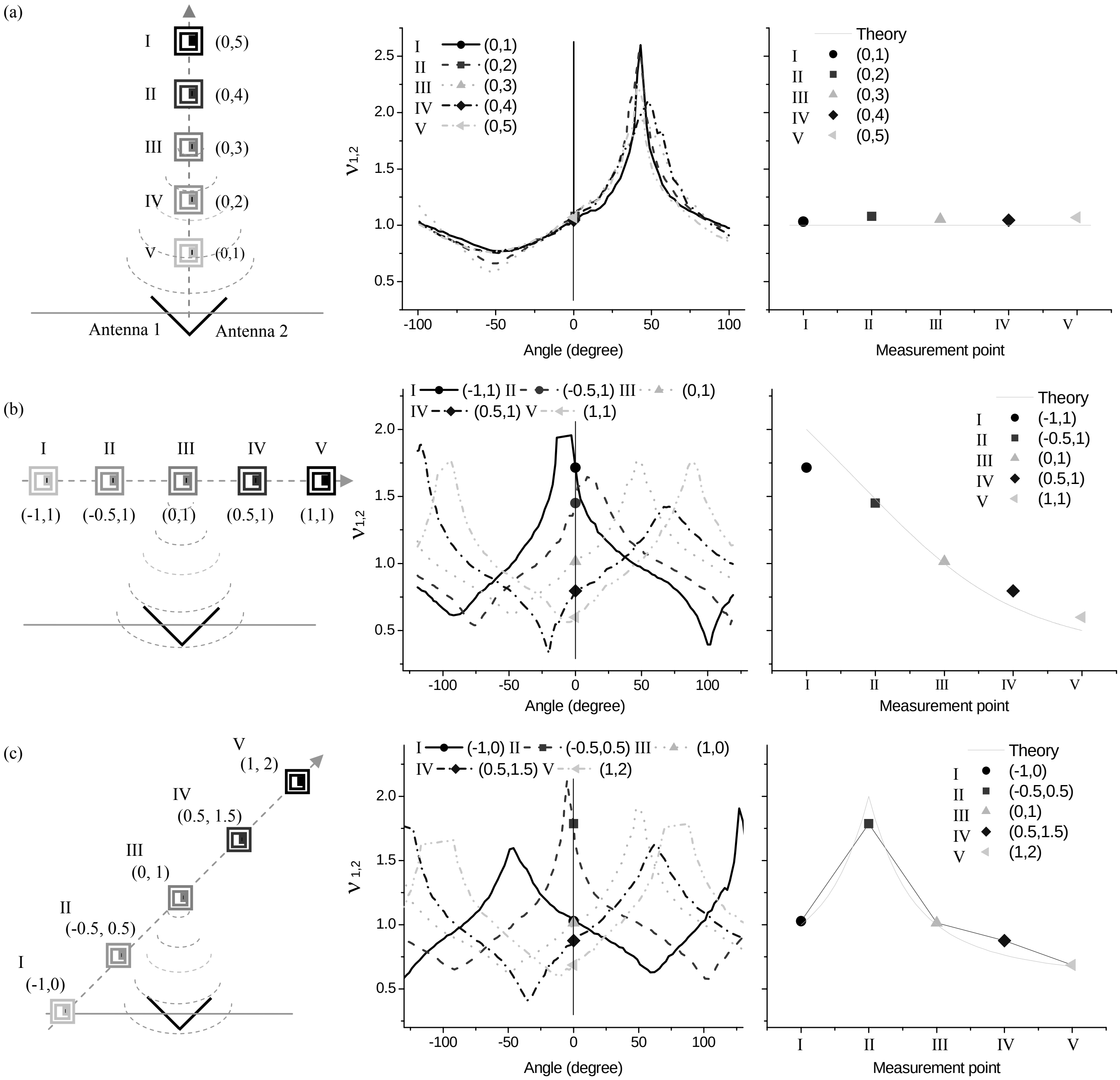


Fig. 5 Received signal pattern from a transponder moving (a) backward, (b) right from left, (c) upward along a slope

the signal distortion by moving obstacles and can track the moving transponder, thus it can enhance the location sensing capability of current RFID systems.

4.3 Application to robot navigation

Fig. 6 shows the robot navigation experiments guided by the proposed dual antenna system. Fig. 6-(a) shows how the robot modifies its path reflecting the antenna strength ratios. The varying ratios of the signal strength level of the two antennas are also shown in the figure. In effect, the relative strength ratio indicates the angle between the robot heading and the transponder direction. In Fig. 6-(a1), the strength ratio was initially close to 1.0, since the transponder was located in front of the robot. During the robot approached the transponder, the transponder position was changed in Fig. 6-(a2). With a single antenna system, it would be impossible to recognize this change in the transponder position without scanning the environment again at a stationary position. However, with the dual antenna system, the robot can detect the direction of the transponder movement in real time. The key to guiding the robot motion is to keep the antenna strength ratio close to 1, or zero facing angle, during the course of navigation. In this experiment, the strength ratio went down below the threshold line as the transponder moved right. This informed the robot where to move, and enabled it to turn right accordingly until the ratio returned to the threshold line. By repeating this as shown in Fig. 6-(a3), the robot

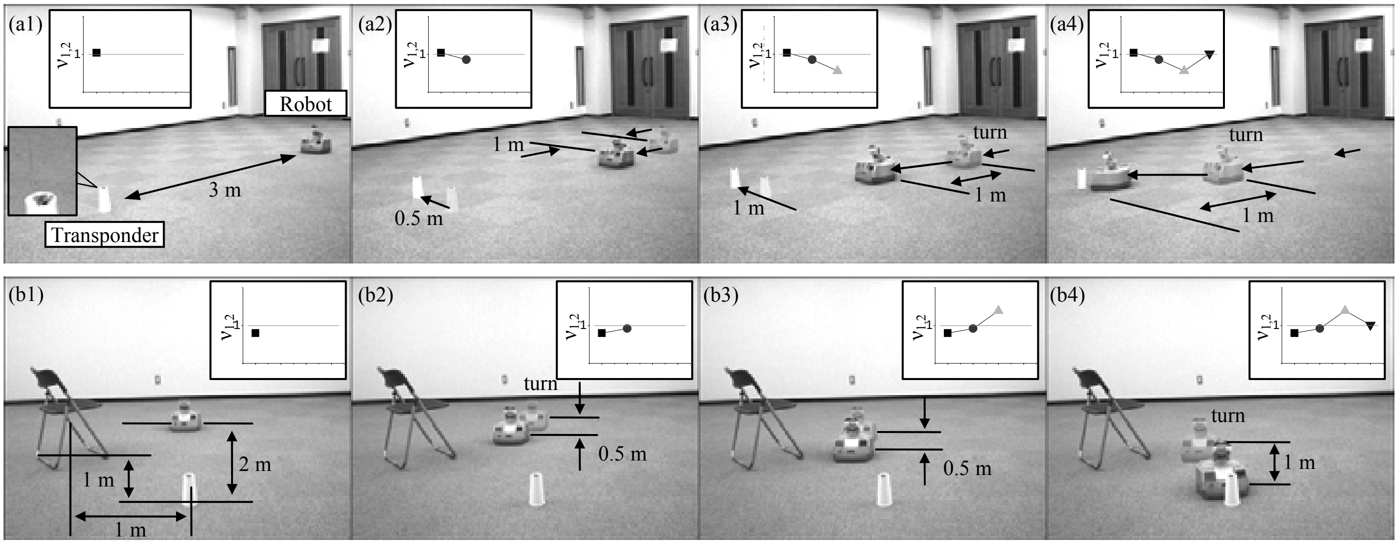


Fig. 6 Transponder tracking using the dual antenna (a) moving transponder (b) stationary transponder interfered with by a metallic chair

reached the zero facing angle and moved forward again toward the transponder. Finally, the robot arrived at the transponder position in Fig. 6-(a4).

Fig. 6-(b) shows the navigation result in an environment that includes a signal reflecting metallic chair at right 45 degrees with respect to the robot. The relative strength ratio was below the threshold line in Fig. 6-(b1). Thus, the perceived direction was shifted toward the direction of the chair and the robot approached the chair incorrectly in Fig. 6-(b2). As shown in Fig. 6-(b3), if the robot moved out of the range where the signal was affected by the obstacle, the path could be modified again toward the transponder. Finally, the robot arrived at the transponder position in Fig. 6-(b4) through appropriate heading modifications in real time.

The dual directional antenna system can be applied straightforwardly in the presence of multiple obstacles causing multiple distortion effects. In obstacle-cluttered environments, the estimated heading direction of the robot could be shifted by uncertain environmental effects. However, since the dual directional antenna adjusts the heading direction to keep the strength ratio within the vicinity of the threshold line, the robot can finally reach the target object. Likewise, being able to read multiple read-only transponders is quite a challenge. Therefore, a new activation and sending control enabled transponder is to be developed.

5 Conclusion

We have developed a novel RFID system using a dual directional antenna. The proposed RFID system offers significantly enhanced location sensing capabilities in a real world environment. The system consists of two individual loop antennas arranged perpendicularly to each other to provide a 90 degree phase shift. The direction of arrival of a signal can be determined by measuring the relative strength ratio of the received signal at the dual antenna. We installed the system in an indoor mobile robot to verify the effectiveness of the system. Our major contributions can be summarized as: 1) The proposed directional antenna does not need to scan the environment for direction finding and target localization that enables a robot to track the moving transponder. 2) It was shown to be robust to a wide variety of signal distortions in a real environment. Our future effort includes developing a model for the angle of arrival in multi-path propagation to solve the problem of multi-path interference and a controllable active transponder for handling multi-transponders. We will finally develop an efficient and effective approach to RFID guided navigation and planning for indoor mobile robot applications.

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