

Object Recognition of Robot Using 3D RFID System

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Abstract: Object recognition in the field of robotics generally has depended on a computer vision system. Recently, RFID(Radio Frequency Identification) technology has been suggested to support recognition and has been rapidly and widely applied. This paper introduces the more advanced RFID-based recognition. A novel tag named 3D tag, which facilitates the understanding of the object, was designed. The previous RFID-based system only detects the existence of the object, and therefore, the system should find the object and had to carry out a complex process such as pattern match to identify the object. 3D tag, however, not only detects the existence of the object as well as other tags, but also estimates the orientation and position of the object. These characteristics of 3D tag allows the robot to considerably reduce its dependence on other sensors required for object recognition the object. In this paper, we analyze the 3D tag’s detection characteristic and the position and orientation estimation algorithm of the 3D tag-based RFID system.

Keywords: RFID, Tag, Mobile Robot, Object Recognition

1. Introduction

We cannot even think about something if that something does not exist. If something exists, we can understand or imagine about it no matter what it may be. Understanding and imagination in this way fully depend on recognition. A humanbeing’s object recognition is executed in real time by identification intelligence, which is developed from experience, learning, and presumption. On the other hand, a robot’s object recognition is executed by sensation, perception, and identification. Sensation means the response to the stimulus and intensity of the object; for example, a vision system captures images obtained from a CCD camera [1]. Perception implies the estimation or acquirement of the object geometry, of which invariants are extracted from the two-dimensional luminance data. Identification matches and determines the object from a database based on the representations of the extracted geometry. These processes need to compute enormous data, so that real-time process is almost impossible. In addition, matching uncertainty is immanent in this recognition because the robot has much difficulty in identifying the existence of an object. Suppose that a robot agent is commanded to clean the room as illustrated in Fig. 1. The robot has sensors such as ultrasonic, vision,

despite every effort because the sensor cannot scan the target object, which is hidden by the bottles and a dish. Consequently, the robot cannot even confirm the existence of the target in the room and it will conclude that the target is in another room.

RFID is an attractive technology to supplement the limitation of robot faculty as such. The basic but powerful function of this technology is to identify the existence of the object. In the same missions, there is another robot with the RFID system and all objects have built-in tags. This tag gives to the robot the information which is the property or characteristic of the object. To clean the room, the robot easily chooses the objects which should be removed or kept. To execute the second mission, the robot searches the ID lists of objects which have been obtained while cleaning. Through the robot has already known that there is the target mobile phone in the room. To find the target, this robot moves to the position where the target has been detected, and then scans nearby objects using its sensors. Hence, the robot can complete its task more easily after object identification. The robot, however, hardly ever knows where the target is because the sensors cannot detect the target, which is hidden by other objects. Finally, the mission is not completed. Obviously the target is there, but something, however, is often thought not to exist if it is not detected. Hence, the RFID system also cannot present the solution for object recognition because it is not enough to identify and confirm the existence of the object.

In order to overcome this limitation, the authors have developed the advanced RFID system based on 3D tag. The proposed RFID system cannot only identify, but also estimate the position and orientation of the object. Owing to these characteristics, the automated systems together with robots can easily and rapidly recognize objects. Naturally, this recognition mechanism can also simplify other robot processes such as localization, navigation and manipulation. The authors have developed the algorithm and application for such processes of the robot on the basis of the proposed advanced RFID system. In this paper, we mainly focus on the fundamental principle and algorithm of this system. Firstly, the basic idea is addressed. Sections III and IV describe the structure of the system and the 3D tag which characterizes the system. The algorithms for estimating the position and orientation of objects are given in Section V, and experimental results are briefly presented.



Fig. 1. Recognition for executing a task

and laser range finder. When executing the cleaning mission, it receives another order, that is, to bring the commander his/her mobile phone. Executing this mission needs the classification of physical objects which is to be kept or cleaned. At the same time, it should find the mobile phone. But sensors that should recognize objects for cleaning are beyond their computational capacity. Thus, the robot stops cleaning, and then begins to find the mobile phone. First, it scans all objects using vision, sonar, etc., and then will try to compare the objects with the target mobile phone. It, however, cannot find the target

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2. Problem Statement and Idea

RFID system has been used for the artificial landmark to obtain the geographical information for navigation and localization of the mobile robot [2] – [8]. Using this system, several researchers have developed the application of RFID system to support object recognition [9] – [11] and manipulation [11]. Their studies are very useful and practical in that the RFID system supplements the limitation of the robot's capability.

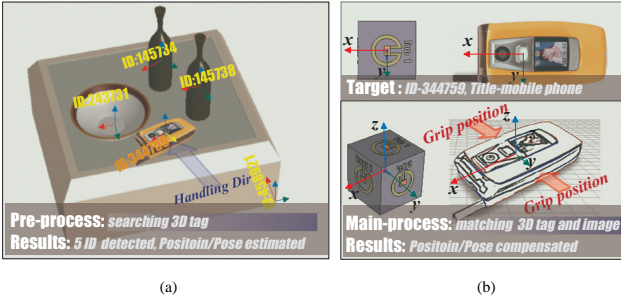


Fig. 2. The proposed Idea. (a)Preliminary process for object recognition. (b)Main process for object recognition. Because the orientations of objects and tags are same, the object pose is easily estimated when tags are detected.

Most of previous RFID systems have omni-directional read range and one RFID tag is embedded into one object which is detected by the antenna of the system. These systems can know whether the object exist or not. To recognize objects, however, a robot should considerably depends upon other sensors as ever though it is equipped with the RFID system.

Let's suppose the missions as described above. There are objects with new type tags called 3D tag. This tag provides the robot with the position and orientation of the object. To manipulate the target mobile phone, the robot directly approaches the target without the unnecessary scanning and sensing processes of other objects. The robot already knows the position and orientation of the target and some other objects(bottles and dish around the target) as shown in Fig. 2(a). The robot determines the location and direction so as to handle the target without obstructing of the objects. The robot estimate the position and pose of the object owing to 3D tag, and also already knows the characteristics of the object such as shape and size; to provide these characteristics is the basic merit of an ordinary tag. Thus, it is simple to compare and match the real target and a target model. The robot begins to manipulate the target considering the corrected position and orientation which are obtained from the match process, and deliberating the shape, weight, material and size of the target.

For the materialization of this idea, a novel tag called a 3D tag and the 3D RFID system have been developed.

3. Characteristics of 3D RFID System

3.1. Recognition Module

DRP I(Dynamically Reconfigurable Personal robot I) which equips RFID system are modularized as shown in Fig. 3(a) [12]. It is composed of four modules. Each module is functionally distributed and reconfigured. The proposed RFID system is a part of the module called Recognition Module. The major function of the module is to recognize, and judge from the existing state of things with Sensor Module. This function should be required so as to execute the task or mission of a robot as a agent. For the effective target or subject recognition, this module has also a vision and voice recognition system. The systems are physically synchronized as shown in Fig. 3(b). They simultaneously try to scan the object with the same intensity,

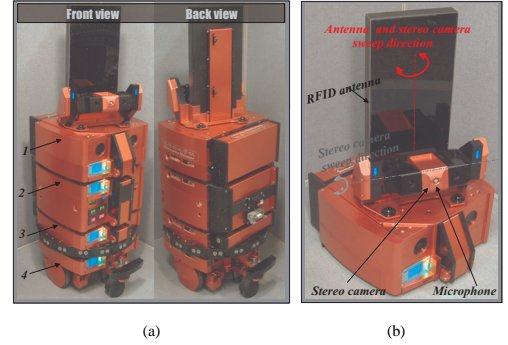


Fig. 3. 3D RFID-based robot. (a) Modularization of robot. 1, 2, 3, and 4 represent recognition, arbiter, sensor, and mobile module, respectively. (b) Structure of recognition module.

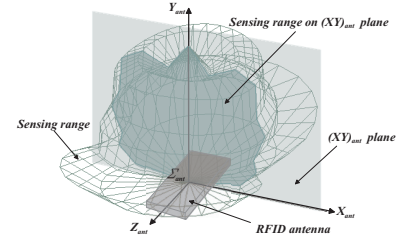


Fig. 4. Simulated sensing range of RFID antenna.

and also fill up the lock of each whatever the target is. Especially, RFID system makes identify and confirm targets easily, so that other recognition systems and Sensor Module can perform their functions fast.

3.2. Sensing Range of 3D RFID System

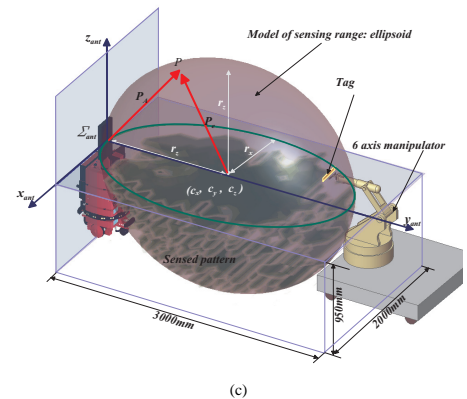
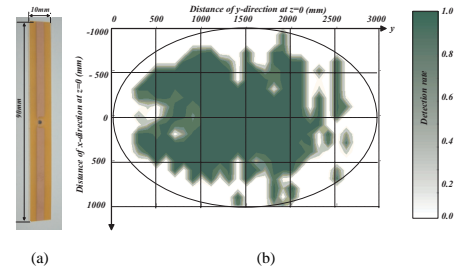


Fig. 5. Sensing model. (a)Tag with small dipole antenna(b)Read range pattern of RFID antenna at $z=0$ (c) Model of sensing range.

The proposed RFID system is composed of a antenna and reader to detect 3D tag. Antenna can be swept by the actuator as shown in Fig. 3(b) and has the uni-directional read range as shown in Fig. 4. These features are used for estimating the position and orientation of 3D tag. 3D tag is composed of several passive tags which have the dipole antennas as shown in Fig. 5(a). It has no self-power source, so that the required power is obtained through the electromagnetic induction, especially magnetic field. To induce sufficient operating voltage, the tag must be placed within the range of the detectable angle and

distance in the magnetic field of the electromagnetic wave from the antenna. If the tag is out of the range of detectable angle, it can not be sensed by the reader though it is placed in the detectable distance. The specific detectable angle and distance of RFID system can provide more definite information to the robot. The authors measure the sensing range of RFID antenna to the tag when 3D RFID system is combined into DRP I.

To measure the range in accordance with height and distance, the test space is $(2000mm \times 3000mm \times 1000mm)$ and 6 axis manipulator is used as illustrated in Fig. 5(c). The experimental sensing range is the geometry similar to the simulated sensing range. The fragmental non-detectable area, however, is present because of the effects of the robot body and ground as shown in Fig. 5(b). The sensor model including the fragmental area is designed so that the once detected tag should not be missed; even tag in the fragmental area is detected in a little time because the proposed RFID system is sweepable. The model should include all of range which can have the possibility to detect tags. This concept differs from that of the other sensor model such as sonar. The tag should not be neglected, if exists, because a matter of primary concern of RFID system is to determine the existence of the object.

Based on the experimental results, the detectable range of our system is modeled as an ellipsoid. The equation of the ellipsoid is Eq.1. The reference frame is denoted by Σ_e . (c_x, c_y, c_z) is the center of the ellipsoid and r_x, r_y , and r_z are the radius of the ellipsoid.

$$\frac{(x_e - c_x)^2}{r_x^2} + \frac{(y_e - c_y)^2}{r_y^2} + \frac{(z_e - c_z)^2}{r_z^2} = 1, \quad (1)$$

where $c_x = 0, c_y = 1350, c_z = 0, r_x = 700, r_y = 1350$, and $r_z = 1000$. This equation can be rewritten in order to be suitable for the sweepable antenna. In spherical coordinates of the center of the ellipsoid, Eq.(1) is rewritten by

$$\mathbf{P}_e(\varphi_e, \phi_e) = \begin{bmatrix} |\mathbf{P}_{x_e}| \cdot \cos \varphi_e \sin \phi_e \\ |\mathbf{P}_{y_e}| \cdot \sin \varphi_e \sin \phi_e \\ |\mathbf{P}_{z_e}| \cdot \cos \phi_e \end{bmatrix}, \quad (2)$$

where \mathbf{P}_e is the position vector inside the ellipsoid. $\mathbf{P}_{x_e}, \mathbf{P}_{y_e}$, and \mathbf{P}_{z_e} are x_e, y_e , and z_e vectors of \mathbf{P}_e , respectively ($|\mathbf{P}_{x_e}| \leq r_x, |\mathbf{P}_{y_e}| \leq r_y, |\mathbf{P}_{z_e}| \leq r_z$). φ_e is the azimuthal angle in the $x_e y_e$ -plane from the x_e -axis and ϕ_e is the polar angle from the z_e -axis ($0 \leq \varphi_e \leq 2\pi, 0 \leq \phi_e \leq \pi$). The vector \mathbf{P}_A of inside the ellipsoid, of which the reference frame is Σ_A , can be written by

$$\mathbf{P}_A = \mathbf{C}_A + \mathbf{P}_e(\varphi_e, \phi_e), \quad (3)$$

where \mathbf{C}_A is the vector from Σ_A to Σ_e .

3.3. Detectable tag orientation

The detection rate of the tag is changed in accordance with the angle between the tag in the sensing range and the antenna. Let's assume that the relation between the coordinate frames Σ_{ant} and Σ_{tag} is given by the vector ${}^{ant}\mathbf{P}_{tag}$ without rotation in Fig. 6(a) (Σ_{ant} and Σ_{tag} are the coordinate frames of the antenna and the tag, respectively). Each detection rate of the tag rotating around x_{tag}, y_{tag} and z_{tag} is measured as plotted in Fig. 6(b), so that the detectable angle range of tag is obtained as follows:

$$\begin{aligned} [-180 \leq \alpha \leq 180], \\ [-45 \leq \beta, \gamma \leq 45], \end{aligned} \quad (4)$$

where α, β , and γ are the angles of pitch, roll, and yaw, respectively. The results mean that the detection rate can estimate the pose of a tag

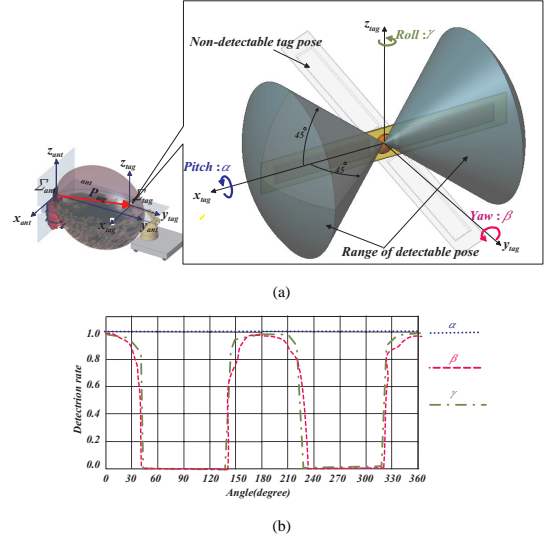


Fig. 6. Detectable tag pose. (a) Rotation of tag. (b) Detectable angle range of tag.

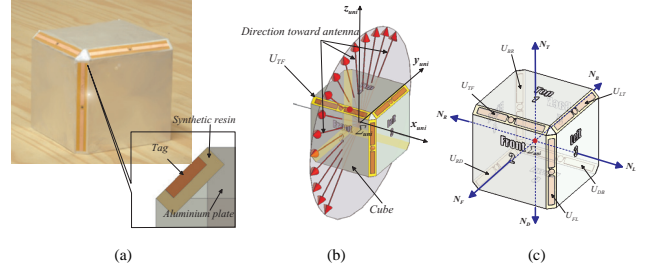


Fig. 7. Union tag range. (a) Prototype of union tag. (b) Antenna direction capable of detecting the tag unit U_{TF} . (c) Notation of union tag

within the limits. Furthermore, the orientation of the object with built-in tags can be estimated if the change of the detection rate in accordance with the axes can be properly combined. 3D tag is developed on the basis of this characteristic.

4. 3D tag: Union Tag

3D tag consists of several tags. They are called tag units in that they are the components of 3D tag. Two kinds of 3D tag are developed, which are union tag and cubic tag. As illustrated in Fig. 7, the tag units are attached to the six edges of a cube. The surface of the cube is covered with the radio shielding material. This shield limits the pitch angle for the detection of the unit tag, while it does not limit the roll and yaw angles. As shown in Fig. 7(b), the antenna, which can detect one tag unit U_{TF} of six units, should be placed within the angle range of 180° ; the other tag units have the same ranges 180° similarly to U_{TF} . This detection of U_{TF} means that the y -axis of Σ_{ant} (hereinafter referred to antenna direction) faces the side of the top or front or both; the letters T and F of U_{TF} denote top and front. In the same manner, $U_{FL}, U_{LT}, U_{DB}, U_{BR}$, and U_{RD} correspond to the front or left, left or top, down or back, back or right, and right or down, respectively as shown in Fig. 7(c). 3D tag composed of the tag units is named a union tag and its detection angle range is characterized by the tag units. This detectable angle range permits the orientation of the union tag to be estimated. Thus, the orientation of the object fitted with the union tag can be estimated because the union tag is aligned with the orientation of the object.

As shown in Fig. 8(a), an ordinary object has four postures per one face when the face is rotated in 90° increments, and all poses of the object

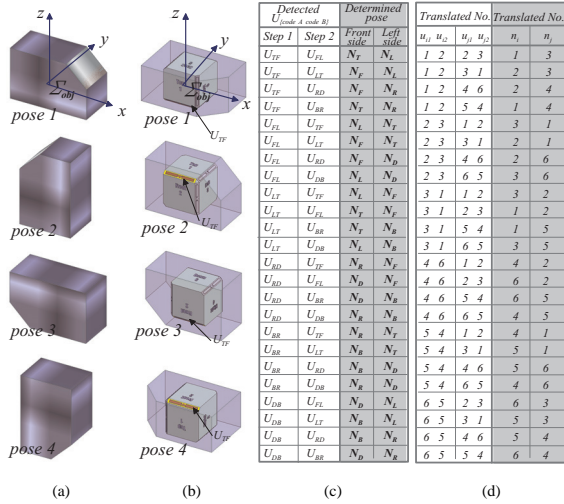


Fig. 8. Pose relation of 3D tag and object. (a) Orientation of normal object. (b) Object with built-in 3D tag. (c) Pose estimation (d) Translation of pose estimated

are twenty four kinds; the classification like this is useful in that a human frequently understands the pose of an object with the base of 90 degree such as top, bottom, front, back, left and right. On the other hand, the pose of the object with the built-in union tag is divided into twenty four classes from a different standpoint. Considering the tag unit U_{TF} , the pose of the object which allows U_{TF} of the union tag to be detected is four kinds as shown in Fig. 8(b). This detection of U_{TF} means the detection of one of the object's two faces: the front side or top side of the object. Owing to this feature, the orientation of the object cannot be determined by the detection of one tag unit. Two tag units at the least should be detected so that one of the twenty four poses is determined. The most effective method is to detect two neighboring tag units. Let's assume that the antenna of the robot detects the object from $-y_{uni}$ axis direction when the object is fixed as shown in Fig. 7(b), and then it does from x_{uni} axis direction. 3D RFID system reads U_{TF} and U_{LT} in order. This means that 3D RFID system detects the front side denoted by N_F , and then the left side by N_L . N_F and N_L also denote the direction vectors which are normal to the faces of front and left, respectively(the subscripts F and L denote the front and left). The detection case by this order is only one. The sum of cases like this is twenty four as shown in Fig. 7(c) and each case determines the pose of the object. To generalize these cases, the authors developed the algorithm. We define that U_i is the first detected tag unit and U_j the second where $U_i=(i1, i2)$ and $U_j=(j1, j2)$. T , F , L , R , B and D are denoted by 1, 2, 3, 4, 5 and 6, respectively. $[n_i n_j]$ which means the first and second face detected is as shown in Fig. 8(d). The relation equations of these numbers are found through observation, and the relations can be written by

$$[n_i n_j] = \begin{cases} [\min(U_i) \min(U_j)] & \text{if } S_{MM} \leq 7 \text{ or } S_{MM} > 9 \\ [\max(U_i) \max(U_j)] & \text{if } S_{mm} = 7 \\ [\max(U_i) \min(U_j)] & \text{if } S_{mM} = 7 \\ [\min(U_i) \max(U_j)] & \text{if } S_{Mm} = 7 \end{cases}, \quad (5)$$

where S_{MM} , S_{mm} , S_{mM} , and S_{Mm} are as shown below.

$$\begin{aligned} S_{MM} &= \max(U_i) + \max(U_j), \\ S_{mm} &= \min(U_i) + \min(U_j), \\ S_{mM} &= \min(U_i) + \max(U_j), \\ S_{Mm} &= \max(U_i) + \min(U_j). \end{aligned} \quad (6)$$

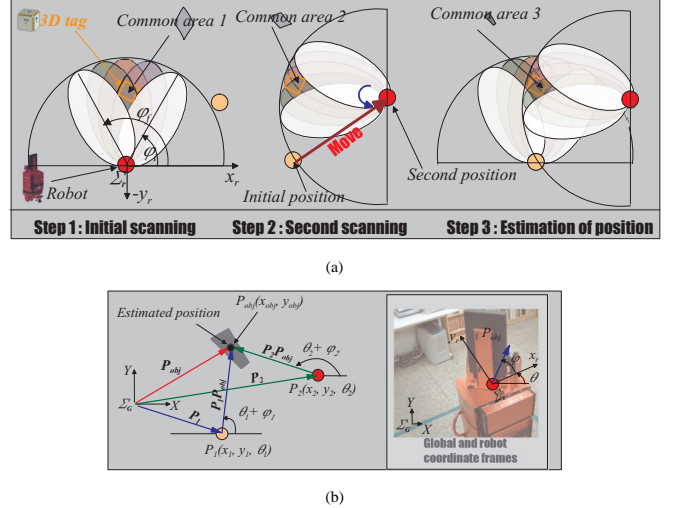


Fig. 9. Algorithm for position estimation. (a) Procedure for position estimation (b) Relation between positions of target and the robot

5. Position and Orientation Estimation of Object

5.1. Position Estimation

To complete the mission, the robot should know the position of the target. Fig. 9 shows how 3D RFID system is used. The proposed system can rotate the RFID antenna for scanning objects. This scanning ability makes the robot estimate the position of 3D tag or the object. As shown in Fig. 9(a), the robot rotates the antenna from the right-hand to the left-hand. 3D tag is initially detected when the direction angle of the antenna is φ_i , and the tag is detected until the angle is φ_f . Thus, it can be said that the tag will be placed in the common area 1 through this scanning procedure. In the next step, the robot moves to the second position, and then repeats the procedure. From the steps 1 and 2, the position of 3D tag is one point in the common area 3. Detecting objects by scanning has been used by the other robots which has the sensors with detection range. But the results obtained from scanning of these sensors differ from the results by the usage of 3D RFID system. For examples, main purpose of the procedures using ultrasonic sensors gives the robot not the position but geometry data of environments such as walls and obstacles(the position is already determined because the distance and direction of the object has been measured when detected). Or the procedure is performed so as to compensate the mistaken data when the sensor does not detect the object because the object is a sharpened edge shape, etc. The ultrasonic sensor or laser range finder is very useful for sensing unspecified objects such as mapping environments or avoiding obstacles, but these sensors cannot find and sense the specified target because what the target is. On the other hand, the robot with 3D RFID system what the target is, but the scanning procedure by 3D RFID system cannot determine the position of the target because RFID antenna itself cannot read distance and the position is always uncertain. Thus, the scanning should be used not for determining, but for estimating the position of target. The steps in Fig.9(a) are the pre-process for the position determination by other sensors capable of distance measuring. These sensors of the robot based on 3D RFID system can easily detect the object and determine rapidly the position because the robot has already known roughly the position of the object, moreover, whether or not the object exists, what the object is, and how it poses. Fig. 9(b) shows the position estimation of the proposed system. In this figure, Σ_G and Σ_r are global and robot coordinates. P_{obj} is the position vector of the object in global coordinates. P_1 and P_2 are the position vectors of the robot at P_1 and P_2 , respectively. P_{obj} can be written

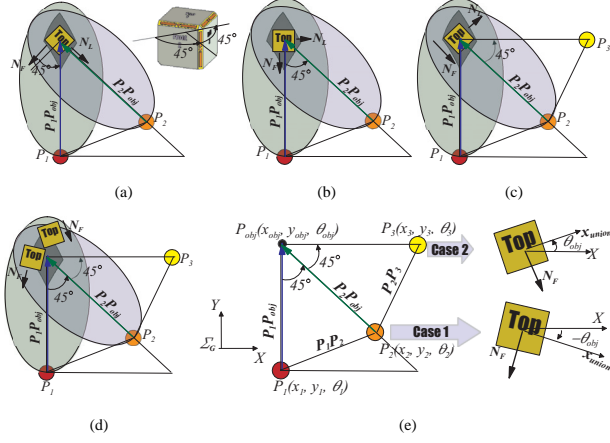


Fig. 10. Algorithm for orientation estimation. (a) Step 1. (b) Step 2. (c) Step 3. (d) Method of Pose estimation. (e) Relation between target pose and robot position

by

$$\mathbf{P}_{obj} = \mathbf{P}_1 + \mathbf{P}_1 \mathbf{P}_{obj}. \quad (7)$$

This can be rewritten by

$$\mathbf{P}_{obj} = \begin{bmatrix} x_1 + |\mathbf{P}_1 \mathbf{P}_{obj}| \cdot \cos(\theta_1 + \varphi_1) \\ y_1 + |\mathbf{P}_1 \mathbf{P}_{obj}| \cdot \sin(\theta_1 + \varphi_1) \end{bmatrix}, \quad (8)$$

where θ_1 and θ_2 are the angular differences between the global and robot frames at P_1 and P_2 . φ_1 , which means antenna direction angle is, the angle of $\mathbf{P}_1 \mathbf{P}_{obj}$ from the x_r -axis and φ_2 is the angle of $\mathbf{P}_2 \mathbf{P}_{obj}$ from the x_r -axis. $|\mathbf{P}_1 \mathbf{P}_{obj}|$ is rewritten by

$$|\mathbf{P}_1 \mathbf{P}_{obj}| = |\mathbf{P}_1 \mathbf{P}_2| \cdot \frac{\sin(\theta_2 + \varphi_2 - \psi)}{\sin(\theta_2 + \varphi_2 - \theta_1 - \varphi_1)}, \quad (9)$$

where ($\psi = \tan^{-1} \frac{y_2 - y_1}{x_2 - x_1}$) and φ_1 and φ_2 are obtained from $(\varphi_i + \varphi_f)/2$ at P_1 and P_2 , respectively. Thus, we finally obtain

$$\mathbf{P}_{obj} = \begin{bmatrix} x_1 + |\mathbf{P}_1 \mathbf{P}_2| \cdot \frac{\sin(\theta_2 + \varphi_2 - \psi)}{\sin(\theta_2 + \varphi_2 - \theta_1 - \varphi_1)} \cdot \cos(\theta_1 + \varphi_1) \\ y_1 + |\mathbf{P}_1 \mathbf{P}_2| \cdot \frac{\sin(\theta_2 + \varphi_2 - \psi)}{\sin(\theta_2 + \varphi_2 - \theta_1 - \varphi_1)} \cdot \sin(\theta_1 + \varphi_1) \end{bmatrix} \quad (10)$$

This Eq.(10) is obtained from the relations of the steps 1 and 2. Theoretically, the position can be estimated with the only step 1 because the common area 1 is determined with the two ellipsoid computed. The steps 1 and 2, however, should be required to execute the orientation estimation which will be presented in the next section. Since the orientation estimation is always accompanied with the position estimation and the position estimation by the two steps is more accurate, the position estimation using these steps is reasonable.

5.2. Orientation Estimation

The proposed method for estimating the orientation of the object is based on the characteristic which 3D tag's detectable angle is limited. To define the pose of the target, two sides of 3D tag should be detected as mentioned in the section V. If the robot detects the front side at the initial position P_1 , and then detects left side at the second position P_2 , the 3D tag poses from Fig. 10(a) to Fig. 10(c). To obtain the pose of the target, it is important for the robot to determine the second position. If the second position is not chosen properly, the left side is not detected because the antenna has the limited direction and sensing range for detecting 3D tag. The determination depends on the detectable angle range of the tag unit of 3D tag; the maximum is 45° and the minimum -45° from Eq.(5). When the tag poses as shown in Fig. 10(a), the angle between the vectors \mathbf{N}_F denoting the front side and $-\mathbf{P}_1 \mathbf{P}_{obj}$ should be less than 45° so as to detect the front side of 3D tag. In case if Fig. 10(b), \mathbf{N}_L and $-\mathbf{P}_2 \mathbf{P}_{obj}$ should be more than

45° so as to detect the left side. Thus, it is reasonable that the angle between $\mathbf{P}_1 \mathbf{P}_{obj}$ and $\mathbf{P}_2 \mathbf{P}_{obj}$ is 45° . In addition, when the robot is placed at the second position P_2 , the target should be within the sensing range of the antenna. Hence, the distance between the target position \mathbf{P}_{obj} and P_2 should be chosen properly. This distance is substituted with that between the common area 1 and P_1 . In the previous section, the common area 1 is used so as to obtain φ_1 but the position of the area is not considered. In other words, this common area is used as the guide for the choice of P_2 so as to estimate the orientation even if the area is not used for the position estimation. Though the robot move to P_2 , the left side of 3D tag cannot be detected as shown in Fig. 10(c). In such a case, the robot move to P_3 and detects the left side. As shown in Fig. 10(e), the positions of P_1 , P_2 , P_3 , and \mathbf{P}_{obj} are solved as follows.

\mathbf{P}_2 can be written by

$$\mathbf{P}_2 = \mathbf{P}_1 + \mathbf{P}_1 \mathbf{P}_2, \quad (11)$$

where $\mathbf{P}_1 \mathbf{P}_2$ is written by

$$\begin{aligned} \mathbf{P}_1 \mathbf{P}_2 &= \begin{bmatrix} \sqrt{2 - \sqrt{2}} \cdot |\mathbf{P}_1 \mathbf{P}_{obj}| \cdot \cos 22.5^\circ \\ \sqrt{2 - \sqrt{2}} \cdot |\mathbf{P}_1 \mathbf{P}_{obj}| \cdot \sin 22.5^\circ \end{bmatrix} \\ &= \begin{bmatrix} \frac{|\mathbf{P}_1 \mathbf{P}_{obj}|}{(1 - \frac{|\mathbf{P}_1 \mathbf{P}_{obj}|}{\sqrt{2}})} \end{bmatrix}. \end{aligned} \quad (12)$$

Thus, \mathbf{P}_2 becomes Eq.(13).

$$\mathbf{P}_2 = \begin{bmatrix} x_1 + \frac{|\mathbf{P}_1 \mathbf{P}_{obj}|}{\sqrt{2}} \\ y_1 + (1 - \frac{|\mathbf{P}_1 \mathbf{P}_{obj}|}{\sqrt{2}}) \end{bmatrix}. \quad (13)$$

\mathbf{P}_3 can be written by Eq.(14)

$$\mathbf{P}_3 = \mathbf{P}_1 + \mathbf{P}_1 \mathbf{P}_3, \quad (14)$$

where $\mathbf{P}_1 \mathbf{P}_3$ is given by

$$\mathbf{P}_1 \mathbf{P}_3 = \begin{bmatrix} |\mathbf{P}_1 \mathbf{P}_{obj}| \\ |\mathbf{P}_1 \mathbf{P}_{obj}| \end{bmatrix}. \quad (15)$$

Thus, \mathbf{P}_3 becomes Eq.(16).

$$\mathbf{P}_3 = \begin{bmatrix} x_1 + |\mathbf{P}_3 \mathbf{P}_{obj}| \\ y_1 + |\mathbf{P}_3 \mathbf{P}_{obj}| \end{bmatrix}. \quad (16)$$

Consequently, we finally obtain

$$\mathbf{P}_{obj} = \begin{bmatrix} x_1 + |\mathbf{P}_1 \mathbf{P}_2| \cdot \frac{\sin(\theta_1 + \varphi_1 + 22.5^\circ)}{\sqrt{2}} \cdot \cos(\theta_1 + \varphi_1) \\ y_1 + |\mathbf{P}_1 \mathbf{P}_2| \cdot \frac{\sin(\theta_1 + \varphi_1 + 22.5^\circ)}{\sqrt{2}} \cdot \sin(\theta_1 + \varphi_1) \\ \theta_{obj} \end{bmatrix}, \quad (17)$$

where $|\mathbf{P}_1 \mathbf{P}_2| = \sec 22.5^\circ (x_2 - x_1)$. The orientation θ_{obj} of the target can be obtained as the following method. If the robot detects the front side of 3D tag at the position P_1 and detects the left side of 3D tag at P_2 , as shown in the case 1 of Fig. 10(e), the orientation θ_{obj} of the target can be written by

$$-45^\circ \leq \theta_{obj} \leq 0^\circ. \quad (18)$$

If the robot detects the front side of 3D tag at the position P_1 , does not detect the left side of 3D tag at P_2 , and then detects the left side of 3D tag at P_3 as shown in the case 2 of Fig. 10(e), the orientation θ_{obj} of the target can be written by

$$0^\circ \leq \theta_{obj} \leq 45^\circ. \quad (19)$$

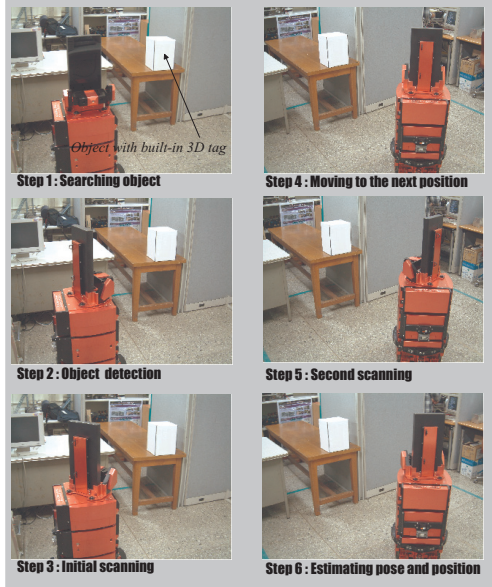


Fig. 11. Experiment of DRP 1.

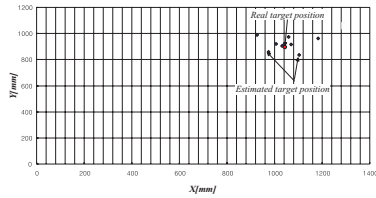


Fig. 12. Experimental results of position estimation by DRP 1.

This results is satisfied wherever the target placed in he common area 1 and how it poses as shown in Fig. 10(d). Fig. 11 shows the procedure of the experiment based on the proposed algorithm. In test space, the target is placed at the random position $P_{target}(1040, 900, 0)$. the target is the box with built-in 3D tag. The robot is initially located on $P_r(500, 500, 0)$ in the global map. Using only 3D RFID system, the robot DRP I searches and detects the target, and then then the robot estimates the position and orientation of the target. This experiment is repeated several times. Fig. 12 shows the results of the position estimation. The results of the orientation estimation are always regular ($0^\circ \leq \theta_{obj} \leq 45^\circ$).

6. Discussion

Currently, the proposed 3D tag is detected has the limitation of the pose estimation. In other words, the orientation is estimated when the face is rotated in 45° increments. The detection rate, however, will be matched to the change of continuous orientation of the object as show in Fig. 6(b). The authors have not succeed this matching process because the detection rate is unstable until now. Thus, RFID tag and antenna suitable for the stable detection rate should be developed. If it is possible, the usage of 3D tag to estimate the orientation of the object can be extended to various automation systems which need the object recognition.

7. Conclusion

In this paper, 3D RFID system and 3D tag is presented. The proposed RFID system supports not only to identify the existence of the object as well as other tags, but also to estimate the orientation and position of the object. This feature reduces considerably the dependence on other sensors such as vision required of recognizing object. The authors have developed the algorithm and application for the processes

on the basis of the proposed system.

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