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Object Recognition Using a 3D RFID System

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1. Introduction

We cannot 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 human being'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 (Weiss et al. 2001). 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.

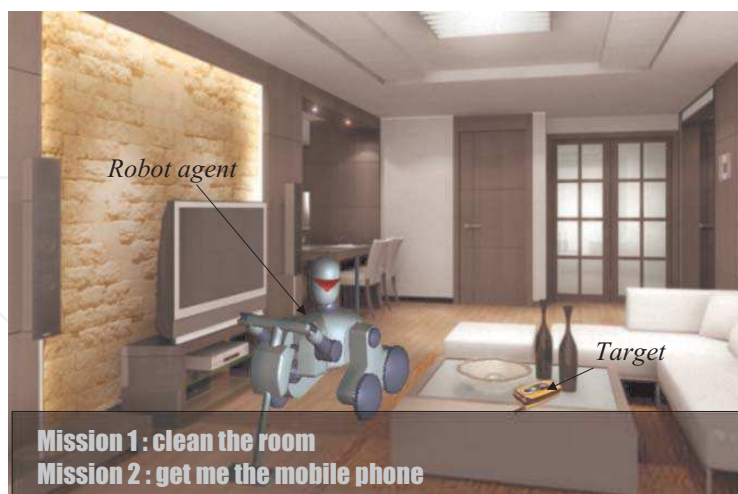


Fig. 1. Recognition for executing a task.

Suppose that a robot agent is commanded to clean the room as illustrated in Fig. 1. The robot has sensors such as ultrasonic, vision, and laser range finder. When executing the cleaning mission, it receives another order, that is, to bring the commander his/her mobile phone. Executing mission needs the classification of physical objects, which is to be kept or

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cleaned. At the same time, it should find the mobile phone. However, 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 despite every effort because the sensors cannot scan the target object, which is hidden by 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. The basic but powerful function of this technology is to identify the existence of the object. In the same mission, there is another robot with the RFID system and all objects have built-in tags. This tag gives to the robot the information about 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 this list, the robot has already knows 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, does not know where the target is because the sensors cannot detect the target, which is hidden by other objects, and the mission is not completed. Obviously, the target is there, but something is often thought not to exist if it is not detected. Unfortunately, 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 can identify the object, and estimate the object's position and orientation. Because of these characteristics, the robot with the automated systems can recognize objects easily and rapidly. Naturally, this recognition mechanism can also simplify other robot processes such as localization, navigation, and manipulation. The authors have developed the algorithm and application of such processes based on the proposed RFID system. In this chapter, we mainly focus on the fundamental principle and algorithm of this system. In Section 2, the basic idea of this system is addressed. Sections 3 and 4 describe the structure of the system and the 3D tag, which characterize the system. The algorithms for estimating the position and orientation of the target object are given in Section 5, and experimental results are briefly presented in Section 6.

2. Problem statement and idea

An RFID system has been used for the artificial landmark to obtain the geographical information for navigation and localization of the mobile robot (Yamano et al, 2004; Kulyukin et al, 2004; Ni et al, 2003; Kubitz et al, 1997; Tsukiyama, 2002; Hahnel et al, 2004; Ruff & Hession, 2001). Using this system, several researchers have developed the application of RFID system to support object recognition and manipulation (Boukraa & Ando, 2002; Mae et al, 2000; Chong et al, 2004). Their studies are very useful and practical, in that, the RFID system supplements the limitation of the robot's capability. Most of previous RFID systems have omni-directional read range. One RFID tag is embedded into one object, and this tag is detected by the antenna of the RFID system. This system informs the robot of the existence of an object. To recognize objects, however, a robot considerably depends on other sensors though it is equipped with the RFID system. For example, let us suppose the

missions described above. There are objects with new type tags called a 3D tag. This tag provides the robot with the position and orientation of the object. Since the orientations of objects and tags are the same, the robot can easily estimate the pose of the object when it detects the tags. To manipulate the target mobile phone, the robot directly approaches the target without the unnecessary scanning and sensing 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).

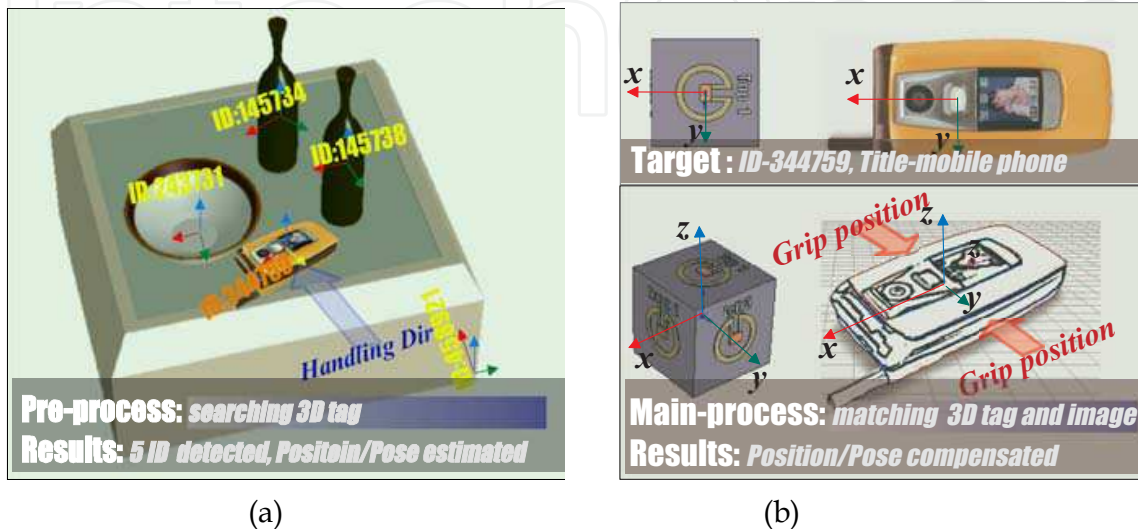


Fig. 2. The proposed idea. (a) Preliminary process for object recognition. (b) Main process for object recognition.

The robot determines the location and direction for moving so that it can handle the target without obstructing by obstacles. The robot has estimated the position and pose of the object from the information provided by the 3D tag, and already known the characteristics of the object such as the shape and size. Thus, it is simple to compare and match the real target and the 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 concept, the 3D tag and the 3D RFID system were developed.

3. Characteristics of the 3D RFID system

3.1 Recognition module

The DRP I (Dynamically Reconfigurable Personal Robot I) which is equipped with the RFID system is modularized, as shown in Fig. 3(a) (Roh et al, 2004). It is composed of four modules. Each module is functionally distributed and reconfigured. The proposed RFID system is a part of the module called a recognition module. The major function of this module together with the sensor module is to recognize, and judge from the existing state of objects. For more detail recognition, this module has also a vision and voice recognition system. These systems are physically synchronized as shown in Fig. 3(b). They simultaneously try to scan the object for the purpose of recognition. Especially, with the RFID system, the robot can identify and confirm targets easily, so that other recognition systems of the recognition module and the sensor module can perform their functions quickly.

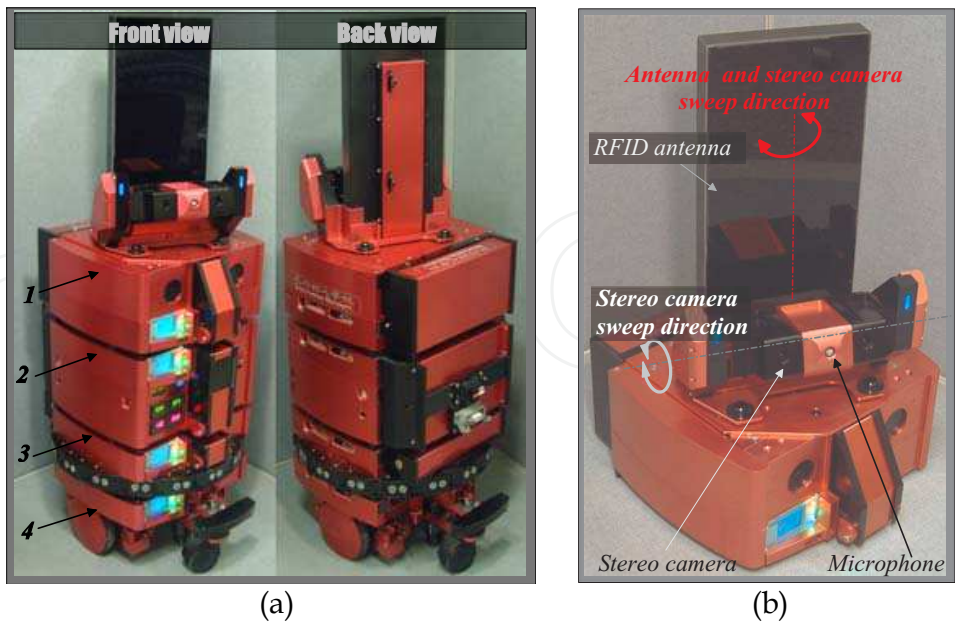


Fig. 3. 3D RFID-based robot. (a) Modularization of robot. 1, 2, 3, and 4 represent recognition, arbiter, sensor, and mobile module, respectively. (b) Structure of recognition module.

3.2 Sensing range of the 3D RFID system

The proposed RFID system is composed of an antenna and reader to detect the 3D tag (Roh et al, 2006). The antenna can be swept by the actuator in Fig. 3(b), and it has the uni-directional read range as shown in Fig. 4. These features are used for estimating the position and orientation of the 3D tag. The 3D tag is composed of several passive tags, which have the dipole antennas as shown in Fig. 4(b). It has no self-power source, so it has to obtain its required power through electromagnetic induction, especially magnetic field.

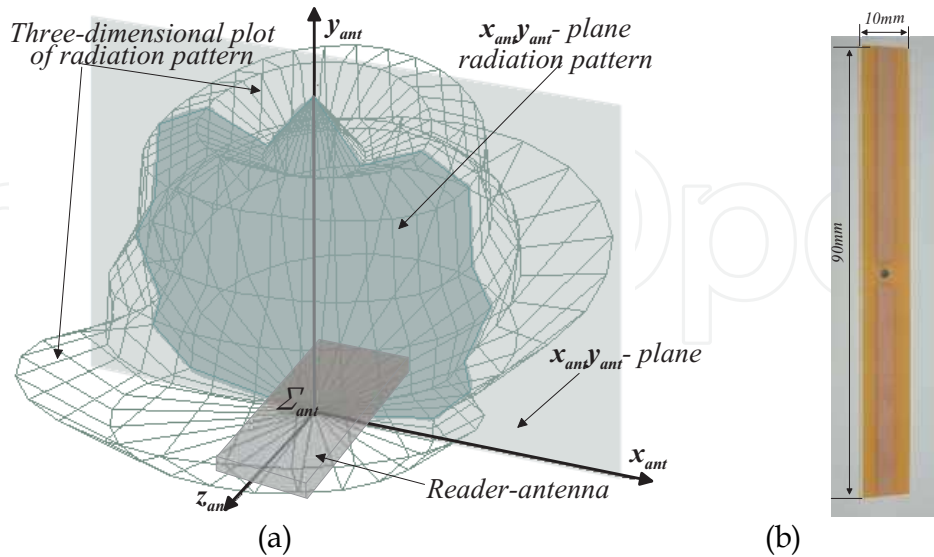


Fig. 4. RFID antenna and tag. (a) Simulated sensing range of the RFID antenna. (b) Tag with a small dipole antenna

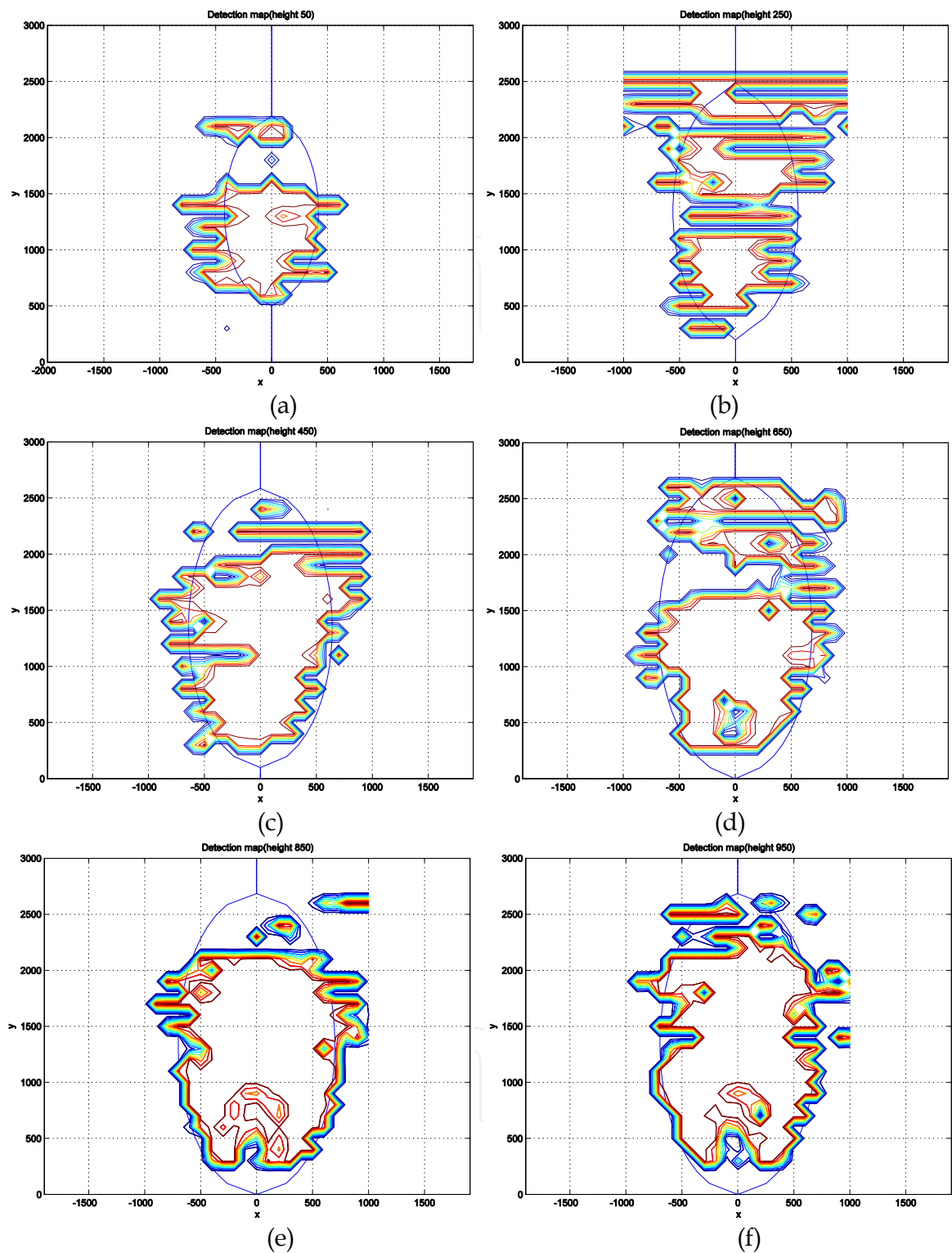


Fig. 5. Read range pattern of the RFID antenna according to the height of the tag. (a) $z=50\text{mm}$. (b) $z=250\text{mm}$. (c) $z=450\text{mm}$. (d) $z=650\text{mm}$. (e) $z=850\text{mm}$. (f). $z=950\text{mm}$.

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 cannot be sensed by the reader even if it is placed within the detectable distance. The specific detectable angle and distance

of the RFID system can provide the robot with more definite information. The authors measured the sensing range of the RFID antenna to the tag when the 3D RFID system was combined into the DRP I. To measure the range with respect to height and distance, the test space of (2000mm× 3000mm×1000mm) and 6-axis manipulator were used. In this experiment, the concept of a detection rate was introduced. The detection rate in this chapter means how many times an RFID-reader detects and counts a single tag per 1 second; the detection rate is 100% if the reader detects and counts the tag 20 times per 1 second. Fig. 5 shows sensing range pattern of the reader-antenna with respect to the tag height, depending on the detection rate. The experimental sensing range formed the geometry similar to the simulated sensing range. Based on the experimental results, the detectable range of our system was modeled as an ellipsoid as shown in Fig. 6.

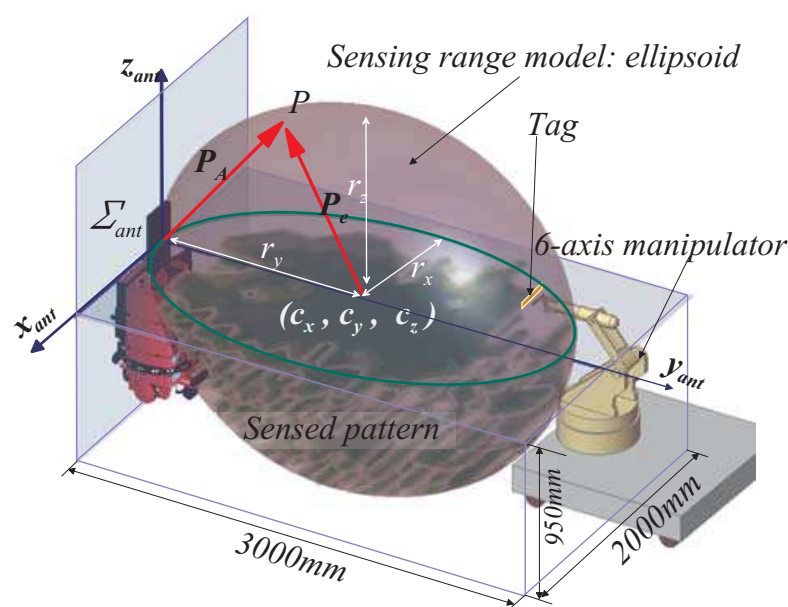


Fig. 6. Sensing model.

The equation of the ellipsoid is Eq.1. The reference frame is denoted by Σ_e . (c_x, c_y, c_z) , which is the center of the ellipsoid and r_x , r_y , and r_z are the radii of the ellipsoid, respectively.

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

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 suitable for the sweepable antenna. In spherical coordinates, Eq. (1) can be rewritten by

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

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 θ_e is the polar angle from the z_e -axis ($0 \leq \varphi_e \leq 2\pi$, $0 \leq \theta_e \leq \pi$). The position vector $\mathbf{p}_A$ inside the ellipsoid, of which the reference frame is Σ_{ant} , can be written by

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

where $\mathbf{C}_A$ is the vector from Σ_{ant} to Σ_e .

3.3 Detectable tag orientation

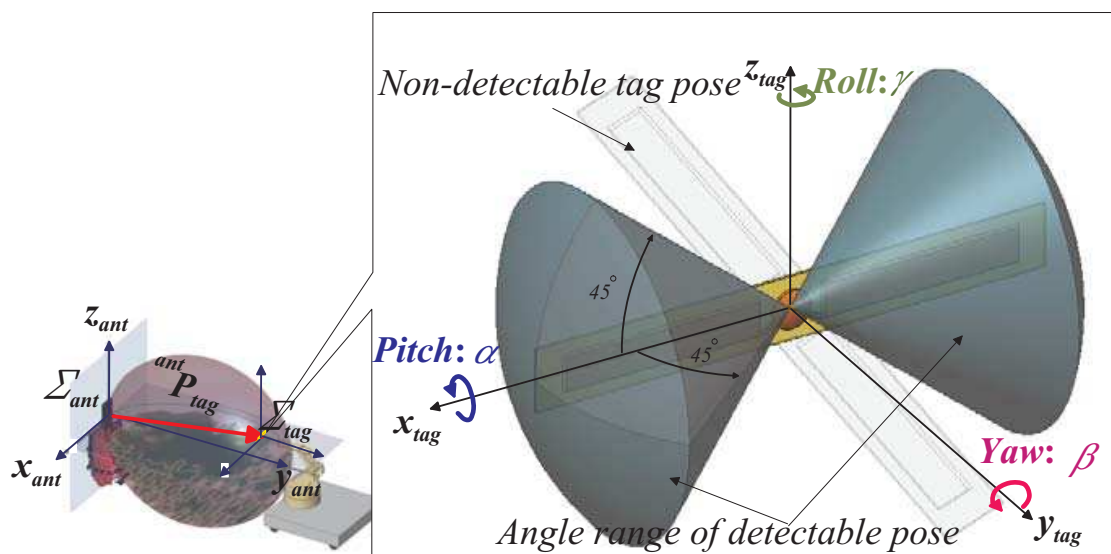


Fig. 7. Detectable tag orientation.

The detection rate of the tag changes with the angle between the tag in the sensing range and the antenna. Let us 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. 7 (Σ_{ant} and Σ_{tag} are the coordinate frames of the antenna and the tag, respectively). Each of the detection rate in the tag rotating around x_{tag} , y_{tag} and z_{tag} is measured as plotted in Fig. 8, so that the detectable angle range of tag is obtained as follows:

$$\begin{aligned} &[-180^\circ \leq \alpha \leq 180^\circ], \\ &[-45^\circ \leq \beta \leq 45^\circ, 135^\circ \leq \beta \leq 225^\circ], \\ &[-45^\circ \leq \gamma \leq 45^\circ, 135^\circ \leq \gamma \leq 225^\circ], \end{aligned} \quad (4)$$

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

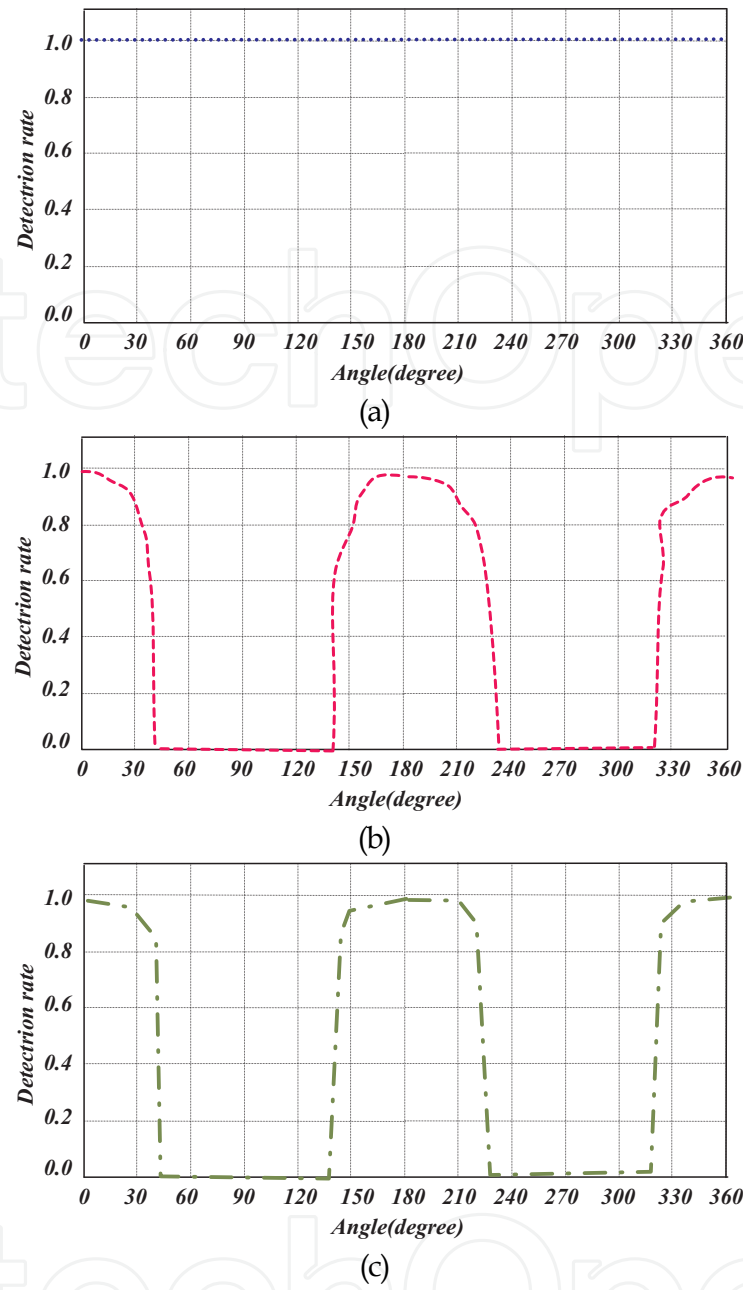


Fig. 8. Detectable angle range of a tag. (a) Pitch. (b) Yaw. (c) Roll.

4. 3D tag: union tag

The 3D tag is comprised of several tags called tag units. As illustrated in Fig. 9, 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. 9(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. Similarly, 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. 9(c).

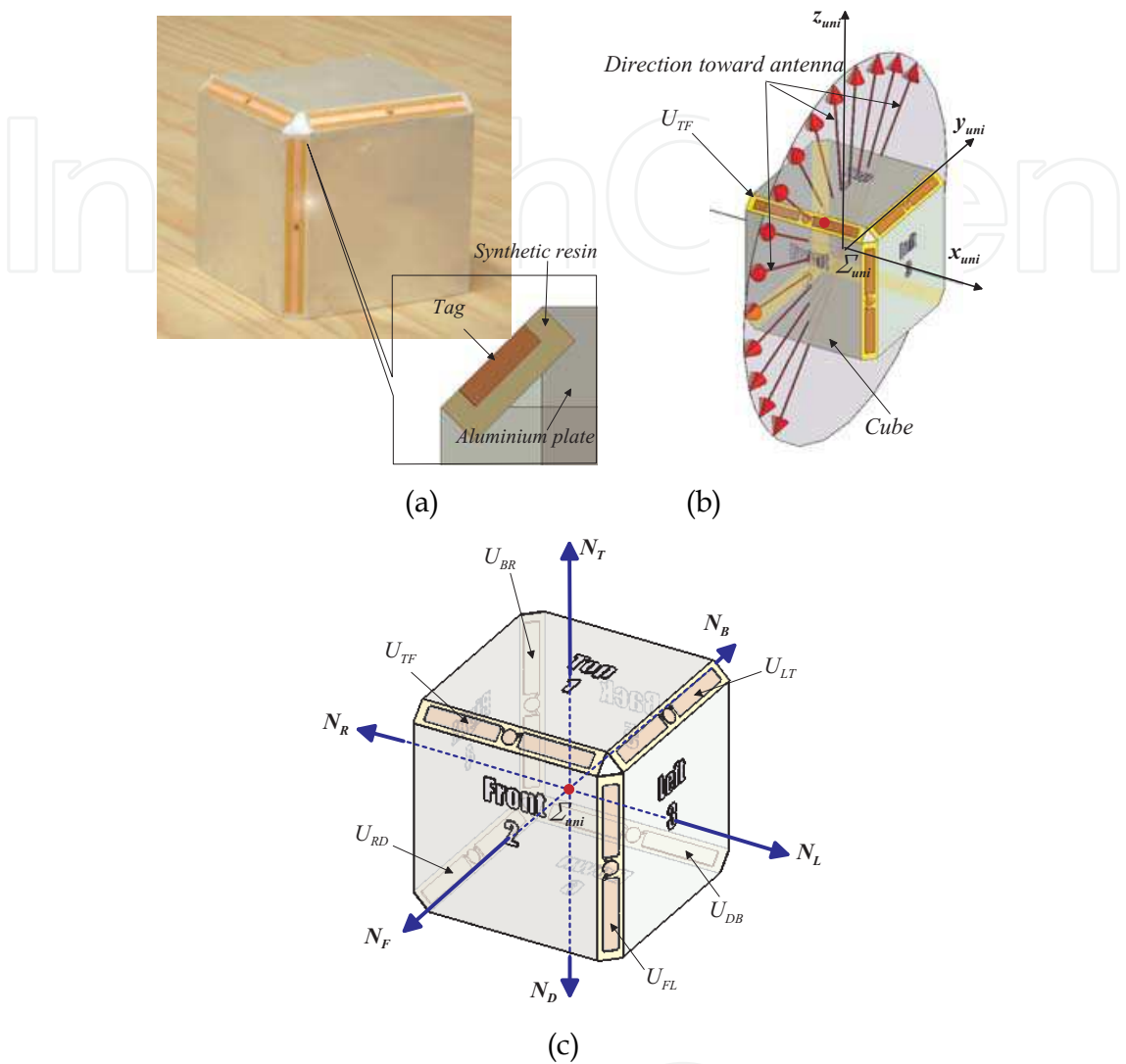


Fig. 9. Union tag. (a) Prototype of a union tag. (b) Antenna direction capable of detecting U_{TF} . (c) Notation of a union tag.

The proposed 3D tag composed of the tag units is named a union tag, and its detection angle range is characterized by the tag units. With this detectable angle range, the orientation of the union tag can be estimated, and 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. 10(a), an ordinary object has four postures per one face when the face is rotated in 90-degree increments. In this case, there are 24 kinds of poses of the object. The classification like this is useful in that a human being 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. For the tag unit U_{TF} , four kinds of object pose allows U_{TF} of the union tag to be detected, as shown in Fig. 10(b).

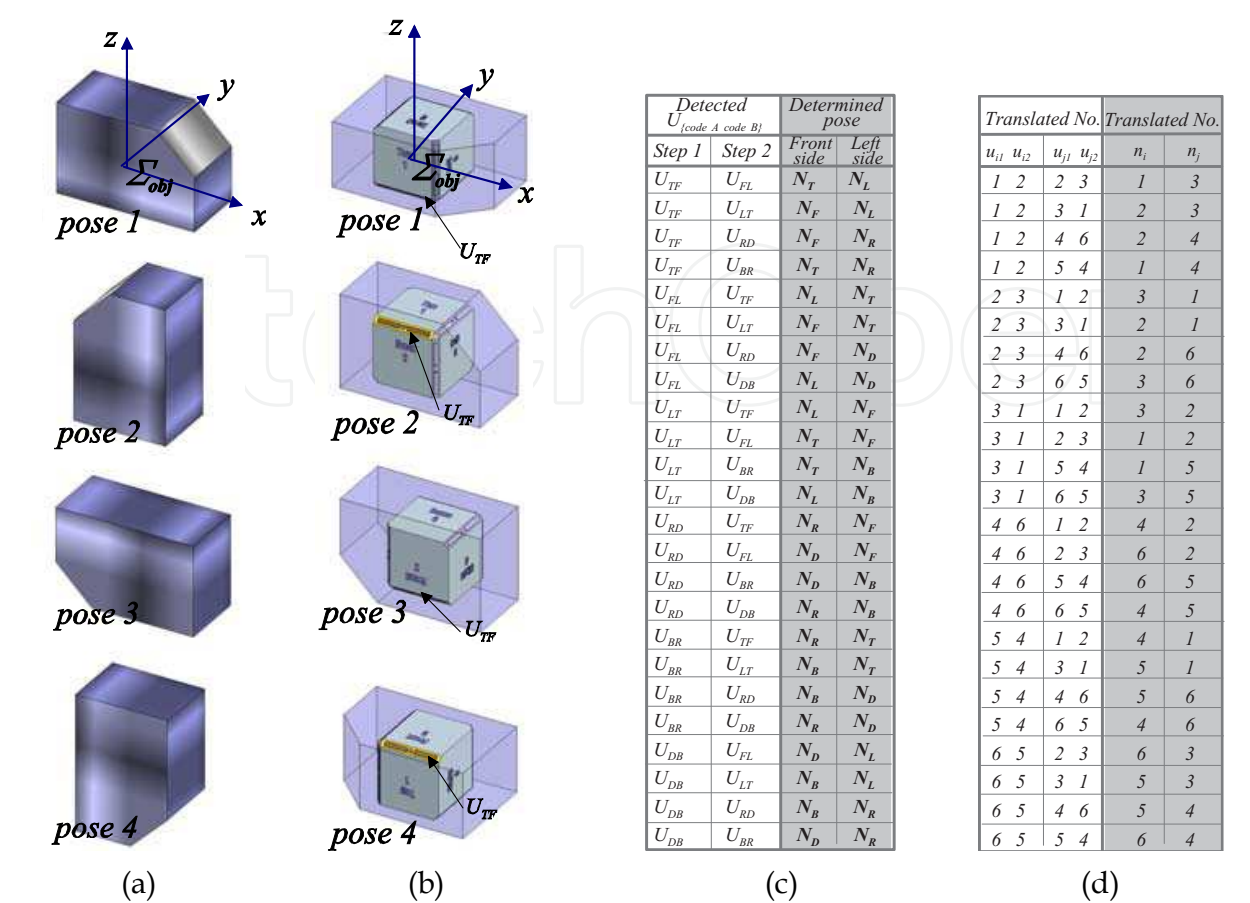


Fig. 10. Pose relation of 3D tag and object. (a) Orientation of normal object. (b) Object with built-in 3D tag. (c) Pose estimation. (d) Translation for pose estimation.

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 can be determined. The most effective method is to detect two neighboring tag units. Let us assume that the antenna of the robot detects the object from $-y_{uni}$ axis direction when the object is fixed, as shown in Fig. 9(b), and then it detects 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 the front and left, respectively (the subscripts F and L denote the front and left). The detection case by this order is only one. There are a total of 24 cases like this, as shown in Fig. 10(c) and each case determines the pose of the object. To generalize these cases, the authors developed an algorithm. We defined 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 shown in Fig. 10(d). The equations for the relations of these numbers are found through observation, and the relations can be written by

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

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

$$S_{MM} = \max(U_i) + \max(U_j)$$
$$S_{mm} = \min(U_i) + \min(U_j)$$
$$S_{mM} = \min(U_i) + \max(U_j)$$
$$S_{Mm} = \max(U_i) + \min(U_j)$$

$$\tag{6}$$

Using Eqs. (5) and (6), the orientation of the object with the built-in 3D tag can be determined.

5. Position and orientation estimation of object

5.1 Position estimation

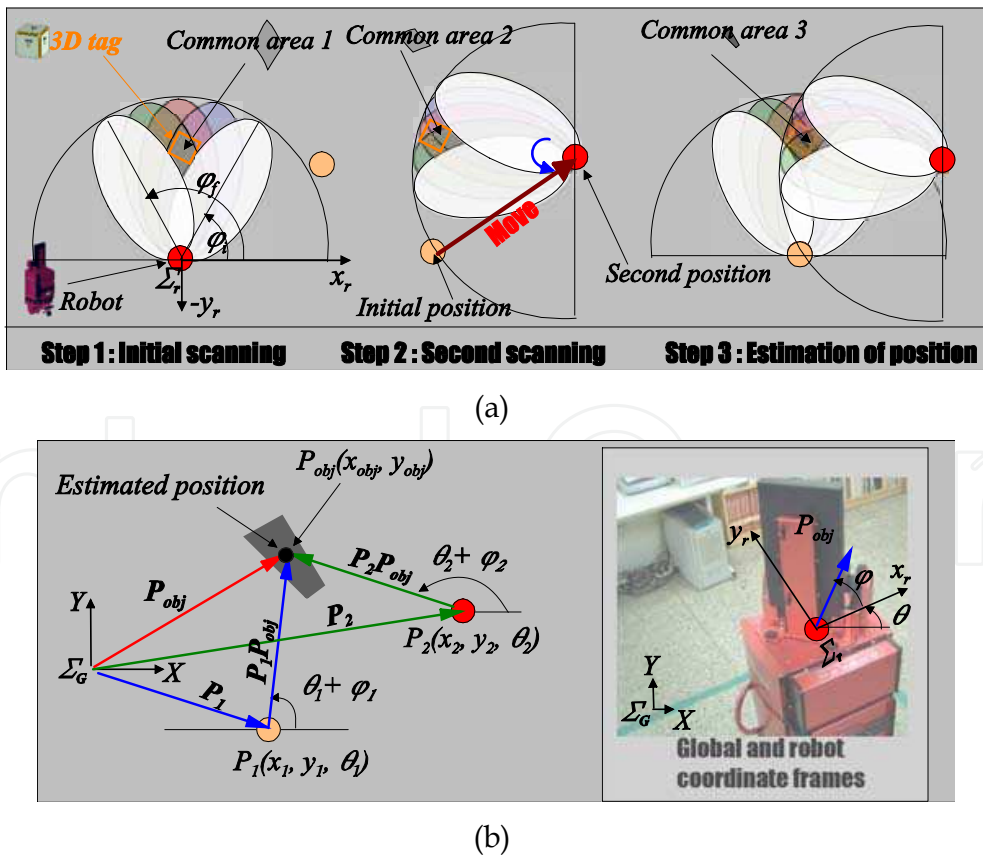


Fig. 11. Algorithm for position estimation. (a) Procedure for position estimation. (b) Relations between positions of target and robot.

To complete a mission for manipulating a target, the robot has to know the position of the target. Fig. 11 shows how the 3D RFID system is used. The proposed system can rotate the RFID antenna to scan for finding objects, and it can estimate the position of the 3D tag. As shown in Fig. 11(a), the robot rotates the antenna from the right-hand to the left-hand. The 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 steps 1 and 2, the position of the 3D tag is one point in the common area 3. Object detection by scanning has been used by the other robots, which have the sensors with a detection range. However, the results obtained from scanning of these sensors differ from the results of the 3D RFID system. For example, the main purpose of the procedure using ultrasonic sensors is to give the robot not the position but geometry data of the environments such as walls and obstacles (the position is already determined because the distance and direction of the object have been measured when detected), or the procedure is performed to compensate the error data when the sensor does not detect the object because the object is a sharp edgy 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 the sensor cannot identify target. On the other hand, the robot with the 3D RFID system can identify the target even if the scanning procedure by the 3D RFID system cannot exactly determine the position of the target because the RFID antenna itself does not have capability to read distance between the antenna and the tag. Thus, this scanning should be used not for determining, but for estimating the position of the target. The steps in Fig. 11(a) are the pre-process for the position determination by other sensors capable of distance measuring. The other sensors of the robot with the 3D RFID system can easily detect the object and determine rapidly the position because the robot already knows roughly the position of the object, whether the object exists or not, what the object is, and how it is posed. Fig. 11(b) shows the position estimation of the proposed system. In this figure, Σ_G and Σ_r are global and robot coordinates. $\mathbf{P}_{obj}$ is the position vector of the object in global coordinates. $\mathbf{P}_1$ and $\mathbf{P}_2$ are the position vectors of the robot at $\mathbf{P}_1$ and $\mathbf{P}_2$, respectively. $\mathbf{P}_{obj}$ can be written by

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

When the robot's pose and the direction of the RFID antenna are considered, Eq. (7) 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 $\mathbf{P}_1$ and $\mathbf{P}_2$. φ_1 , which means the 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 $\mathbf{P}_1$ and $\mathbf{P}_2$, respectively. Thus, we finally obtain

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

Eq. (10) is obtained from the relations of the steps 1 and 2. Theoretically, the position can be estimated with only step 1 because the common area 1 is determined with the two ellipsoids computed. The steps 1 and 2, however, are 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

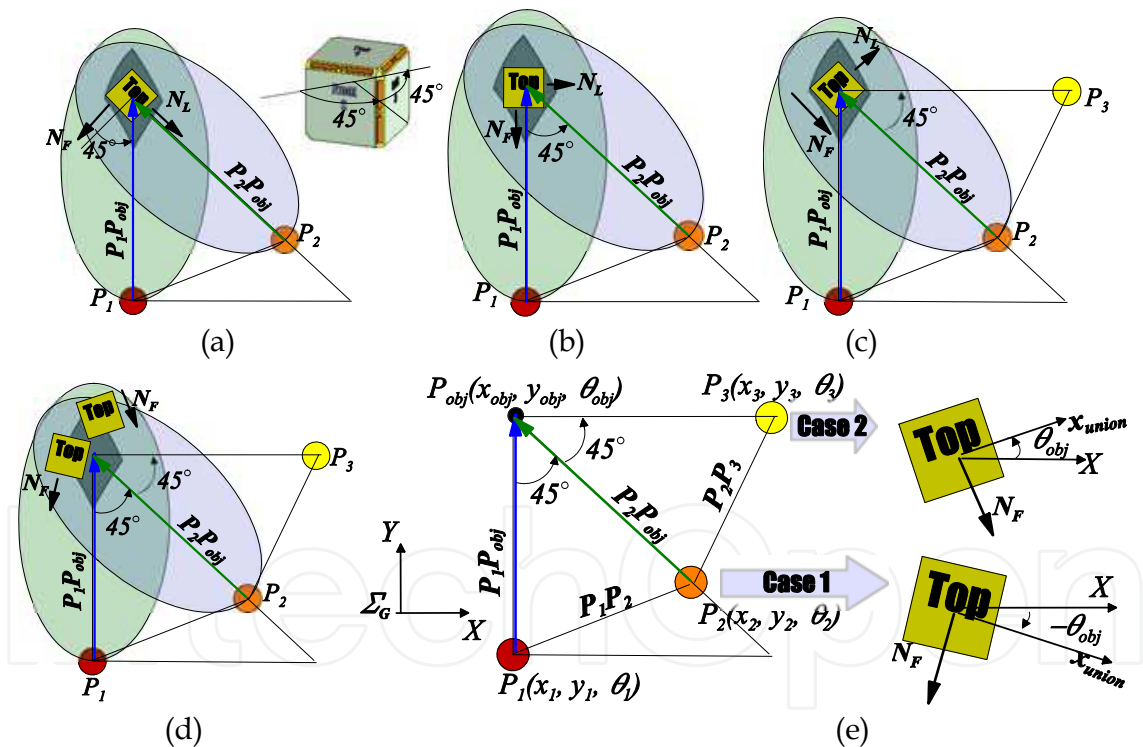


Fig. 12. Algorithm for orientation estimation. (a) Step 1. (b) Step 2. (c) Method of pose estimation. (e) Relation between the target pose and the robot position.

The proposed method for estimating the orientation of the object is based on the characteristic of the 3D tag: the 3D tag’s detectable angle is limited. To define the pose of the target, two sides of the 3D tag should be detected as mentioned in the section 4. If the robot detects the front side at the initial position $\mathbf{P}_1$, and then detects the left side at the second position $\mathbf{P}_2$, the 3D tag poses as shown from Fig. 12(a) to Fig. 12(c). To obtain the pose of the

target, the robot must determine the second position. If the second position is not chosen properly, the left side cannot be detected because the antenna has a limited direction and sensing range for detecting the 3D tag. The determination of the second position depends on the detectable angle range of the tag unit of the 3D tag; the maximum is 45° and the minimum -45° from Eq. (4). When the tag poses as shown in Fig. 12(a), the angle between the vectors N_F denoting the front side and $-\mathbf{P}_1\mathbf{P}_{obj}$ should be less than 45° to detect the front side of the 3D tag. In case of Fig. 12(b), N_L and $-\mathbf{P}_2\mathbf{P}_{obj}$ should be more than 45° 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 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 to obtain ϕ_1 , but the position of the area is not considered. In other words, this common area is used as a guide for the choice of P_2 to estimate the orientation even if the area is not used for the position estimation. Though the robot moves to P_2 , the left side of the 3D tag cannot be detected as shown in Fig. 12(c). In such a case, the robot moves to P_3 and detects the left side. As shown in Fig. 12(e), the positions of P_1 , P_2 , P_3 , and 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

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

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 by the following method. If the robot detects the front side of the 3D tag at the position $\mathbf{P}_1$ and detects the left side of the 3D tag at $\mathbf{P}_2$, as shown in the case 1 of Fig. 12(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 the 3D tag at the position $\mathbf{P}_1$, does not detect the left side of the 3D tag at $\mathbf{P}_2$, and then detects the left side of the 3D tag at $\mathbf{P}_3$, as shown in the case 2 of Fig. 12(e), the orientation θ_{obj} of the target can be written by

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

This result is satisfied wherever the target is placed in the common area 1 and how it is posed, as shown in Fig. 12(d).

6. Experiments

Figure 13 shows the procedure of the experiment based on the proposed algorithm. In the test space, the target is placed at the random position $\mathbf{P}_{\text{target}}$ (1040, 900, 0). The target is the box with the built-in 3D tag. The robot is initially located on $\mathbf{P}_r$ (500, 500, 0) in the global map. Using only the 3D RFID system, the robot DRP I searches and detects the target, and then, the robot estimates the position and orientation of the target. This experiment is repeated several times. Figure 14 shows the results of the position estimation. The results of the orientation estimation are always regular ($0^\circ \leq \theta_{obj} \leq 45^\circ$). Currently, the orientation of the object by using the 3D RFID system is estimated when the face is rotated in 45°

increments. This is because the detection rate cannot be matched to the change of continuous orientation of the object, as show in Figs. 8(b) and 8(c). If the RFID tag and antenna suitable for the stable detection rate should be developed, the object’s orientation estimation using the 3D tag can be extended to various automation systems.

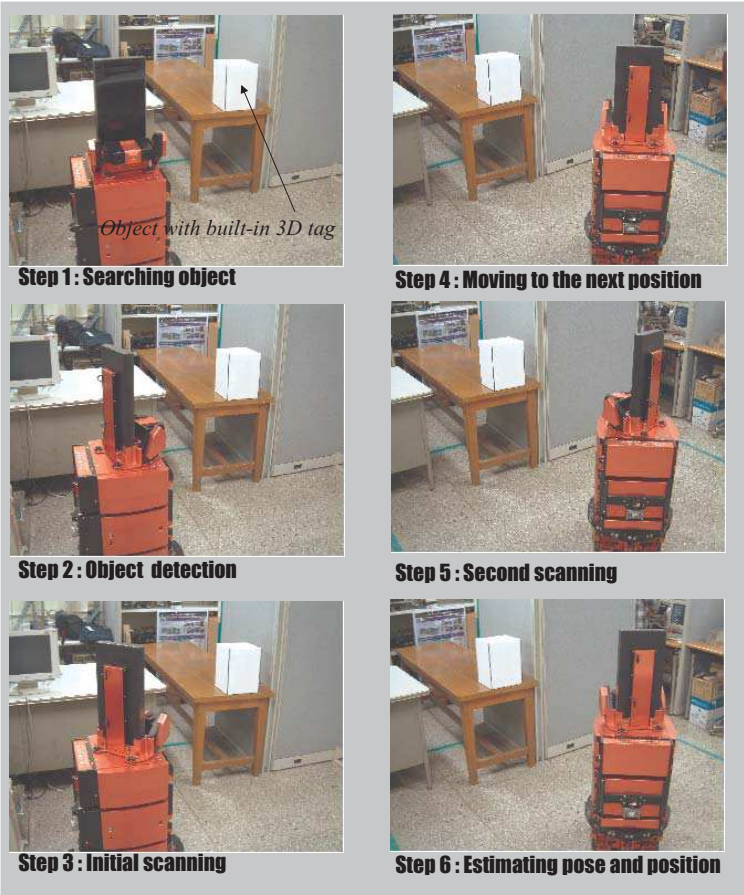


Fig. 13. Experiment of DRP 1.

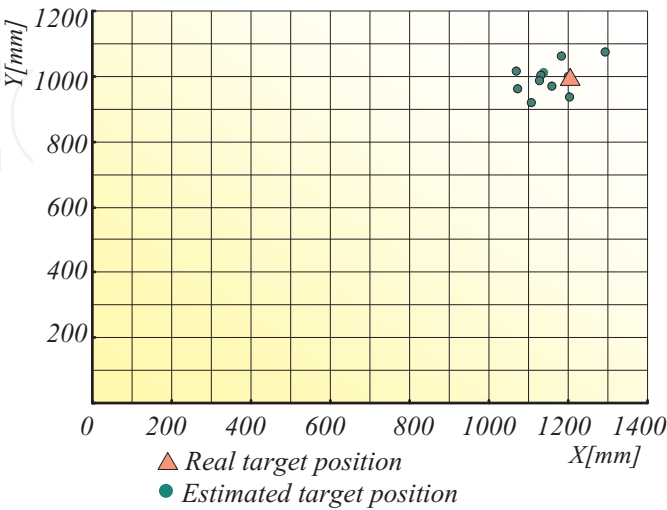


Fig. 14. Location estimation by only the RFID system.

7. Conclusions

Up to now, object recognition in robotics has been typically done by vision, ultrasonic sensors, laser ranger finders etc. Recently, RFID has emerged as a promising technology that can strengthen object recognition. In this chapter, the 3D RFID system and the 3D tag were presented. The proposed RFID system can determine if an object as well as other tags exists, and also can estimate the orientation and position of the object. This feature considerably reduces the dependence of the robot on other sensors such as vision systems required for object recognition. With the fast growth of RFID technology, the field of robotics will benefit greatly, and our research will support the investigation of its use in practical applications.

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The book generously covers a wide range of aspects and issues related to RFID systems, namely the design of RFID antennas, RFID readers and the variety of tags (e.g. UHF tags for sensing applications, surface acoustic wave RFID tags, smart RFID tags), complex RFID systems, security and privacy issues in RFID applications, as well as the selection of encryption algorithms. The book offers new insights, solutions and ideas for the design of efficient RFID architectures and applications. While not pretending to be comprehensive, its wide coverage may be appropriate not only for RFID novices but also for experienced technical professionals and RFID aficionados.

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