Localization and Navigation Using a Novel Artificial Landmark for Indoor Mobile Robots①

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Abstract

This paper presents a practical topological navigation system for indoor mobile robots, making use of a novel artificial landmark which is called MR code. This new kind of paper-made landmarks can be easily attached on the ceilings or on the walls. Localization algorithms for the two cases are given respectively. A docking control algorithm is also described, which a robot employs to approach its current goal. A simple topological navigation algorithm is proposed. Experiment results show the effectiveness of the method in real environment.

Key words: mobile robot, localization, navigation, artificial landmark, topological map

0 Introduction

The ability to navigate is obviously a major requirement for an autonomous mobile robot. Topological navigation allows overcoming some of the classical problems of geometric navigation of mobile robots, such as simultaneously reducing the uncertainty of localization and perception of the environment. On the other hand, topological navigation is heavily dependent on a powerful perception system to identify elements of the environment[1].

Using artificial landmarks is proved to be an effective way to improve the robustness of robot self-localization and navigation. Research works on artificial landmark have lasted for twenty years and several artificial landmarks have been proposed. Mansur R. et al. used a circle and bar codes to compose a landmark in [2], the circle is used for position determination and the bar codes provide an unique identity for each pattern. C. Becker et al. proposed a module as an artificial mark for robots, which consists of three elements: an outer circle, an opening in the circle, and an inner 3×3 grids of black and white tiles in [3]. Yasuo OGAWA et al. used a circular mark pattern around which the binary Grey codes were written in [4]. Yang Guo et al. designed a red pattern with symmetric rectangles and seven-part numbers in [5] which has the property of cross-ratio invariant under projective transformation. It is also shown that the detection of this pattern is robust under illuminant change and the geometrical variations such as camera zoom and the viewing direction change. However, the recognition of the seven-part numbers in the patterns is not reliable enough yet.

A new kind of artificial landmark called MR code and the detection-recognition algorithm for this MR code were proposed in our previous work[6]. In this paper, it will be shown that how a mobile robot with a visual system can complete a task of self-localization and navigation easily using this MR code. Localization algorithms for the case when the MR code is attached on the ceiling and the case when the MR code is attached on the wall vertically are given respectively. Primitive docking control behavior and topological navigation algorithm are described. Experiment results are also given to show the effectiveness of the proposed method for robot self-localization and navigation.

The following part of this paper is organized as follows. In section 1, a brief introduction of the design and the detection algorithm of the MR code is given, and, the localization algorithm using MR codes is also described. In section 2, a docking control algorithm is described. In section 3, a navigation algorithm is described. Some of the localization and navigation experiment results using the MR code are given in section 4 to show the effectiveness of the proposed method, and some discuss about our future work is given in section 5.

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1 Brief introduction of MR code system

1.1 Design of MR code system

C. Becker et al. pointed out that an efficient landmark should be designed so that its sensing system can achieve three key functions, namely, detection, recognition and localization in [3]. The MR code is designed to satisfy these rules.

In order to detect the landmark in a cluttered scene robustly, the landmark pattern should show invariant characteristics under different viewing angles and illumination conditions.

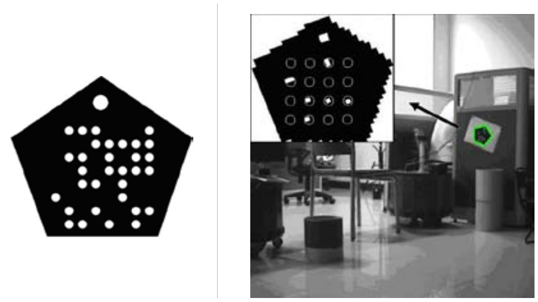
According to [7], a system of five general coplanar lines forms two invariants, and considering the fact that the outline of the module extracted by edge detector is robust under different illumination conditions, so the shape of the MR code is designed to be a pentagon, which is regular to reduce computing cost when detecting the pentagon.

In the design of MR code, the binary information is represented by its unit modules which are designed to be solid circles with certain distance from each other to assure that the binary image can still be recognized robustly under different viewing angles and different illumination conditions.

A 2D code system is adopted for the MR code so that they can represent enough different locations, objects, etc. The binary BCH code is adopted for our MR code system, which is a kind of linear circular block code and has powerful correcting ability[8].

Figure.1(a) shows a prototype of MR code with 8×8 unit modules. It uses BCH(63, 45, 3) toerzhihua encode the binary information of 45 bits data, which means that such a MR code can provide 2^{45} different landmarks. The number 3 means that even when some recognition error occurs, the binary information of 45 bits will not be influenced if the error is less than 3 of the 63 unit modules. The unit module on top of the MR code is used to denote the direction of the MR code, which is very helpful for the self-localization and navigation for mobile robot.

Detection-recognition algorithm of MR code was proposed in our previous work[6]. Figure.1(b) is a picture selected from one of our experiments to demonstrate the effectiveness of the proposed detection algorithm. It can be noticed that even a binarization error occurred, the result of decoding will not be influenced because the BCH code itself has the self-correcting ability.



(a) (b)

Figure. 1. (a)A prototype of MR code; (b) An example of detection and recognition(the MR code is rotated deliberately)

1.2 Localization using MR codes

Since the MR code can be printed on a paper and can be attached easily to places like ceilings, walls, surface of furniture, electronic appliances, etc., a mobile robot can identify its location or recognize an object using its vision system by simply recognizing the information represented by the MR code. Using the five vertexes of the extracted outline, the pose of the MR code relative to mobile robot can also be obtained. Therefore, a mobile robot can complete the task of self-localization based on the information provided by MR codes.

The pose estimating methods for the MR code attached to ceiling and a vertical surface are different and they will be described respectively in the following parts of this section.

1.2.1 MR codes attached to a ceiling

In this case, the MR codes are detected by an upward-looking camera, and the coordinate system is defined as shown in Figure.2(a). Here, (O_W, X_W, Y_W, Z_W) and (O_C, X_C, Y_C, Z_C) denote the world coordinate frame and the camera coordinate frame respectiviely, and O_W is the center of the MR code. The plane (O_W, X_W, Y_W) is identical with the plane of the ceiling Π_C, and Π_I denotes the image plane. P_i and $V_i (i=1,...,5)$ denote the vertexes' coordinate of MR code in the world coordinate frame and in the image coordinate frame respectively, and φ denotes the angle between X_W and X_C.

It is assumed that the image plane is parallel with the ceiling, and the relative pose (x, y, φ) can be estimated by follows:

$$\varphi = \pi(1-\tau) + \tau arc\cos\left(\frac{v_{loc} - v_c}{D}\right)$$
$$\begin{bmatrix} x \\ y \end{bmatrix} = k \begin{bmatrix} \cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi \end{bmatrix} \begin{bmatrix} (u_O - u_C) \\ (v_O - v_C) \end{bmatrix} \tag{1}$$

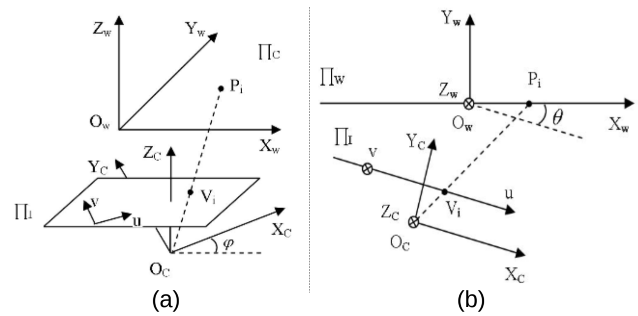


Figure. 2. Imaging model and all coordinate frames when MR codes are respectively attached to: (a) a ceiling; (b) a vertical surface

Where $D=\sqrt{(u_{loc}-u_c)^2+(v_{loc}-v_c)^2}$, (u_o, v_o) denotes the coordinate of image center, (u_c, v_c) the coordinate of MR code's centroid, (u_{loc}, v_{loc}) the coordinate of the vertex related to direction unit module, which are all in the image coordinate frame. τ is equal to -1 when $u_{loc} > u_c$ or 1 otherwise, k is a ratio coefficient, its unit is $mm / pixel$.

1.2.2 MR codes attached to a vertical surface

In this case, the vertex of the MR code related to direction unit module must be placed upward and the detection of the MR code is carried out by a forward-looking camera. The coordinate system is defined as shown in Figure.2(b). The plane (O_W, X_W, Z_W) is identical with the plane of the vertical surface Π_W , θ denotes the angle between Π_W and Π_I , and the definitions of other symbols are identical with those in Figure.2(a). The relative pose of a robot can be represented by (x, y, θ) .

Since the MR codes have a fixed size, the problem of detecting a MR code can be formulated as how to determine the coordinate of the optical center in world coordinate frame when the coordinates of five pairs of points in world coordinate frame and in image coordinate frame are known.

The problem has been solved in a more ordinary form by Chien-Ping Lu et al. in [9] who have given an iterative algorithm called OI algorithm. This algorithm is used to calculate the parameters of three rotations and three translations. The error function is defined as:

$$e(\mathbf{R},\mathbf{t}) = \sum_{i=1}^{n} \left\| (\mathbf{I}-\mathbf{V}_i)(\mathbf{R}\mathbf{p}_i+\mathbf{t}) \right\|^2 \tag{2}$$

Where $\mathbf{R}$ is a rotation matrix, t is a translation vector, $\{\mathbf{p}_i\}(i=1,2,...)$ denote the 3D coordinate in the world coordinate frame. Suppose $\{\mathbf{v}_i\}(i=1,2,...)$ denote the homogeneous coordinates of corresponding image points, $\mathbf{V}_i$ is defined by:

$$\mathbf{V}_i = \mathbf{v}_i \mathbf{v}_i^T / (\mathbf{v}_i^T \mathbf{v}_i) \tag{3}$$

In [9], the author uses the image points themselves as the hypothesized scene points in the initial absolute orientation iteration. But the solution does not always correspond to the true pose, and this is analyzed by Gerald Schweighofer et al. in [10]. In our case, the θ may converge to two values θ_1 and θ_2, and θ_2 is very close to $-\theta_1$. Therefore, we determine which one is reasonable in the following way.

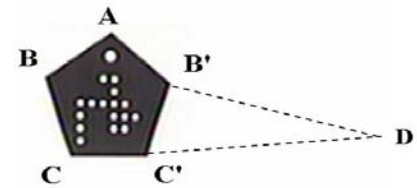


Figure. 3. Verifying the sign of θ by the vertexes in image

As shown in Figure.3, $\mathbf{A},\mathbf{B},\mathbf{B}',\mathbf{C},\mathbf{C}'$ denote the five vertexes of a MR code in the image respectively. The corresponding straight line of BB' in the world coordinate frame is parallel with the corresponding straight line of CC' , so we can verify the sign of θ by the relation of BB' and CC' . Suppose that the extension lines of BB' and CC' intersect at $\mathbf{D}$, and if $\mathbf{D}$ is at the right side of $\mathbf{A}$, θ is minus, otherwise, θ is plus. When the initial value of θ is not correct, substitute $-\theta$ into the error function and iterate again. Because $-\theta$ is very close to true value, the process does not cost much time.

2 Docking control

When the robot finds the MR code which is its current goal, it employs a docking control algorithm to approach to the distinctive place, which is near the projection point on the flat floor of the MR code. Based on the assumption that an indoor mobile robot navigates on a flat floor, it is feasible to describe this problem in a 2-D frame.

The proposed control algorithm is based on proportional control, which is a compact and fast algorithm for real-time applications.

The control model is shown is Figure.4(a). The origin of the world coordinate frame is at the center of the MR code. The pose of the robot is represented by (x, y, φ) , which is estimated by using the algorithm described in section 1.

γ represents the angle from the direction of the robot to the directed line between the robot and the origin. In order to obtain γ , we consider the robot coordinate frame. The vector of the MR code is represented by (x_M, y_M) , which can be obtained from the equation below:

$$\begin{bmatrix} x_M \\ y_M \end{bmatrix} = \begin{bmatrix} \cos(-\varphi) & \sin(-\varphi) \\ -\sin(-\varphi) & \cos(-\varphi) \end{bmatrix} \begin{bmatrix} -x \\ -y \end{bmatrix} \tag{4}$$

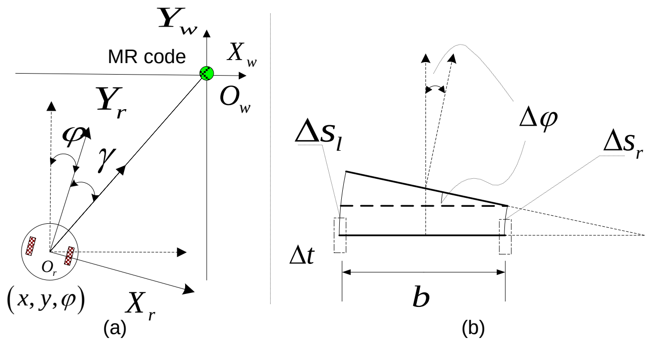


Figure. 4. (a) The docking control model; (b) The movement model

Thus, we obtain follows:

$$\gamma = \tau \arccos(\frac{y_M}{D_M}) \tag{5}$$

Where $D_M = \sqrt{x_M{}^2 + y_M{}^2}$;

$$\tau = \begin{cases} -1 & when \quad x_M > 0; \\ 1 & else \; ; \end{cases}$$

For a differential-drive robot with an instruction cycle Δt, its movement can be analyzed as Figure.4(b).

$$\Delta\varphi = \frac{\Delta s_r - \Delta s_l}{b} \tag{6}$$

When equation (6) is divided by Δt, we obtain follows:

$$\omega = \frac{v_r - v_l}{b} \tag{7}$$

Where

$\Delta\varphi$ = variation of the robot's direction angle;

Δs_r ; Δs_l = traveled distances of the right and left wheel respectively;

b = distance between the two wheels of differential-drive robot;

v_r ; v_l = velocity of the right and left wheels respectively;

ω = angular velocity of the robot.

In order to approach the MR code, the robot should change its direction in every instruction cycle according to γ. Here, proportional control is employed to adjust the robot's direction. ω is proportional to γ, and defined as follows:

$$\omega = k\gamma \tag{8}$$

Where k is the coefficient, which is related to v and Δt. v is the velocity of the robot, which is usually a constant in a period of time in the practical application, and obtained from follows:

$$v = \frac{v_r + v_l}{2} \tag{9}$$

Based on the v and w, v_r and v_l are the control parameters to the robot motion system. They can be obtained from the equation below:

$$\begin{bmatrix} v_r \\ v_l \end{bmatrix} = \begin{bmatrix} 1 & b/2 \\ 1 & b/2 \end{bmatrix} \begin{bmatrix} v \\ \omega \end{bmatrix} \tag{10}$$

The distinctive place is defined as Figure.5. d_s denotes the distance between the distinctive place and the MR code.

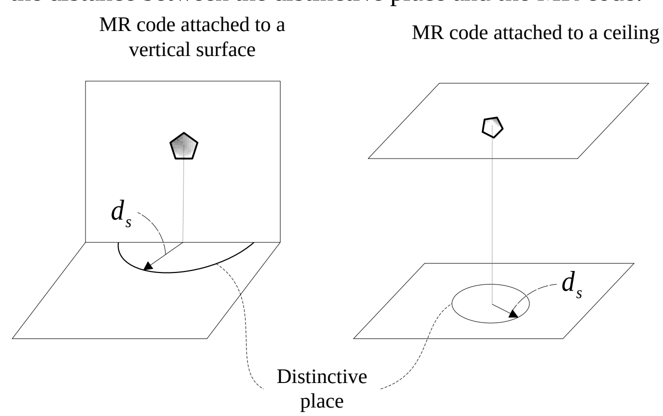


Figure. 5. Distinctive place

When $D_M <= d_s$,that means the robot has arrived at the distinctive place. Then v_r and v_l are set to 0, and the robot stops.

3 Navigation algorithm

Generally, topological navigation is more simple and natural for a behavior-based robot. It avoid direct measurement of geometric environment qualities, instead concentrating on characteristics of the environment that are most relevant to the robot for localization[11].

When the robot is placed in an indoor environment, it should perform the following procedures:

Step 1: A topological map is entered.

The nodes represent the distinctive places. The edges represent the costs between each pair of connected nodes.

The costs can be expressed as the approximate length or weights, which reflect preferences in constructing route. For example, the connections which navigating through are considerably more computationally expensive and unreliable are set at 2, and other connections which navigating through are relatively easier are set at 1.The set of weights should be deliberated. The overall control strategy is Coastal navigation[12].

Additional information is attached to edges: relative angle α from the positive direction (i.e. $\overrightarrow{O_w Y_w}$ in Section 1) of the current node to the directed line between the current node and the next node, appropriate abstract navigation behavior, distance between the distinctive place and the MR code (i.e. d_s in Section 2).

Step 2: The Cartographer is responsible for constructing the route according to a start node and a goal node.

It takes as input the start node and goal node, and produces a list of nodes representing the best path between the start and goal. The optimal path is computed using Dijkstra's single source shortest path algorithm, by considering the costs between each pair of connected nodes.

Step 3: The Task Manager maintains a pointer to the current node and the next intended node from the path, and determines the appropriate local control strategy by referring to the data stored in the map, which is the procedure for getting from the current node to the next node.

First, the robot estimate its direction angle θ using the algorithm described in section 1, then turn ϕ, where $\phi = \alpha - \theta$.

Second, The Task Manager selects appropriate abstract navigation behavior for traveling between the nodes.

Here, abstract navigation behavior includes navigating door behavior, navigating foyer behavior and navigating hall behavior.

When the robot finds the goal MR code, it calls primitive docking control behavior described in Section 2 to approach the goal.

4 Experiments

In order to validate our method, localization and navigation experiments were carried out using a mobile robot platform AIM developed in our lab as shown in Figure.6. The mobile robot platform AIM is equipped with a Intel Centrino microprocessor clocked at 1600MHz, two wheel encoders, one color CCD camera and 16 sonar sensors, etc..

Figure. 6. Experiment platform robot AIM.

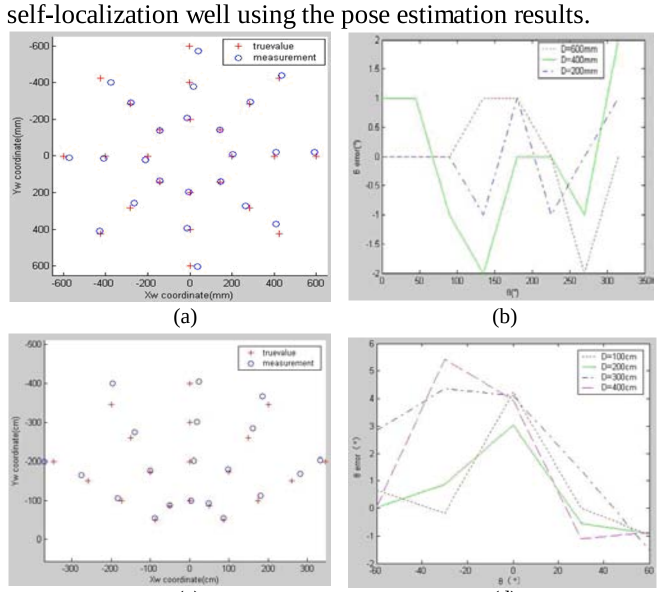
4.1 Localization Experiments

The localization experiments when MR codes are attached to the ceiling or the wall vertically are carried out respectively. The algorithm described in section 1 are used for the detection and pose estimation of the MR codes.

When MR codes are attached to the ceiling, the camera is set upward. The perpendicular distance between the optical center of the camera and the ceiling is 2m. Therefore, as shown in Figure.7(a,b), the distance between the optical center of the camera and the center of the MR code varies from 200mm to 600mm.

Figure.7(a) shows that the pose estimation errors increase a little with the increase of the distance, but the accuracy of position estimation is quite good. Figure.7(b) shows that the accuracy of angle estimation is also good enough to be used for robot self-localization.

When MR codes are pasted vertically, the camera is set forward. Figure.7(c,d) shows that although the accuracy of position estimation results are not as good as when the MR code is attached to a ceiling, it is still good enough for robot self-localization when the distance between the robot and the measuring point is not too far, e.g., less than 200mm. Therefore, a robot can still complete a task of self-localization well using the pose estimation results.



(a) (b)

(c) (d)

Figure. 7. Localization experiment results: for ceiling landmark - (a)position error, (b)angle error; for vertical landmark – (c) position error, (d)angle error.

4.2 Navigation Experiments

The MR code system and the navigation algorithm have been used successfully in the Robocup@home League of RoboCup China Open 2007.

The scenario is shown in Figure.8. It consists of a living room and a kitchen. There is also a door which represents the entrance to the kitchen from the living room.

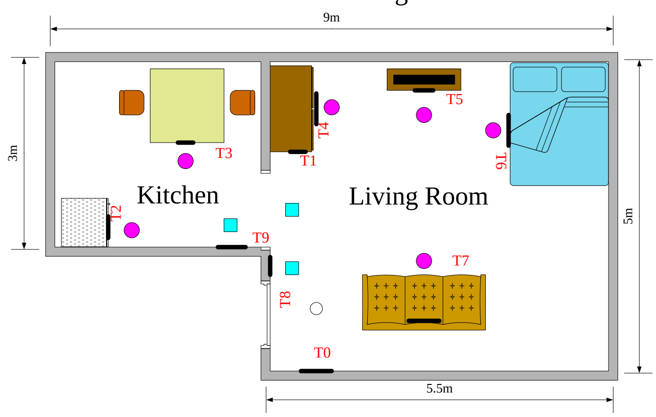


Figure. 8. Configuration of the scenario which is a home environment with the distribution of the nodes and the locations where MR codes are pasted (the black lines). The circles and squares denote the distinctive places where the robot should arrive at when it has reached the according nodes.

According to the rules, the robot has to safely visit 4 distinct places in the scenario with 10 minutes. The hollow circle represents the start position, and the solid circles represent places needed to be visited.

The solid and hollow circles are set as nodes, and MR codes need to be pasted on the surface of the objects accordingly. Considering the characteristics of MR code (such as region that MR code can be seen), several points near the door are also set as nodes, which are denoted by squares in Figure.8.

Here we build this map as a digraph. Some nodes take effect only when robot traverses from one zone to another. For example, with regard to the space relations, T8 is in the middle of T1 and T0. However, the robot can traverse from T1 to T0 without requiring traversal of T8, because the robot can see MR code T0 at point T1. But T8 is needed when the robot traverse from the right region of the living room (such as T7) to the start position T0.

The topological map is shown in Figure.9. We use the navigation algorithm described in Section 3 to complete this task. We take the route from T1 to T7 for example. The successive frames in the competition are shown in Figure.10. Only the key-point frames are captured from the video.

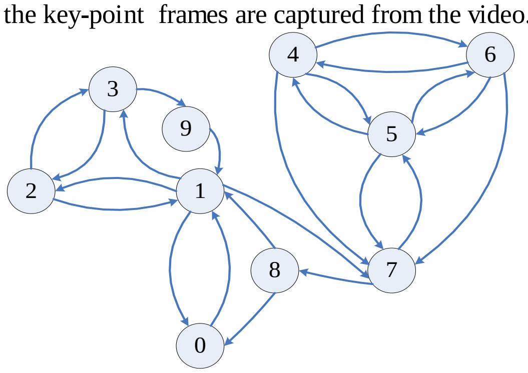


Figure. 9. Topological map of the scenario.

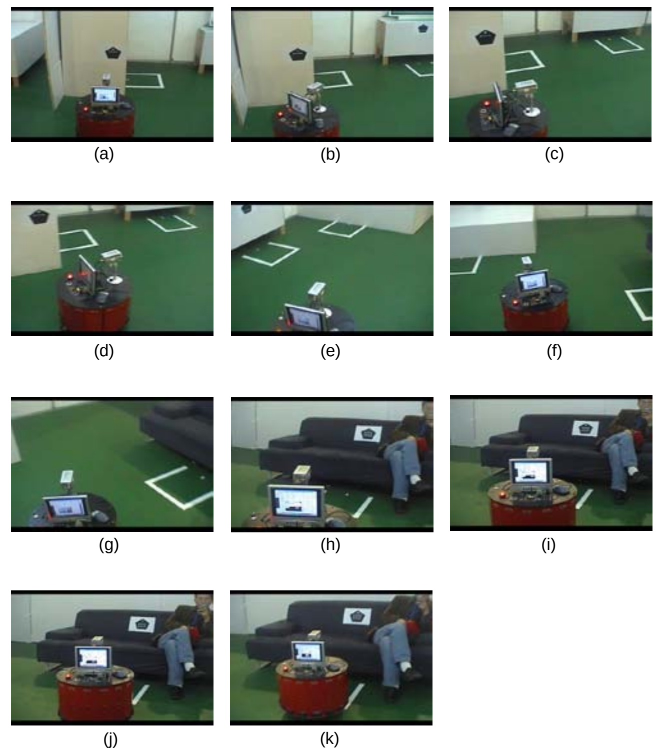


Figure. 10. The sequence of the frames in the figure is left-to-right and top-to-down. (a) The robot is at node T1, and estimating its direction angle θ. (b ~ c) The robot turns ϕ. (d ~ f) The navigating foyer behavior is triggered. (g ~ h) The robot is searching for the MR code. (i ~ k) When the MR code is found, the robot calls the primitive docking control behavior to approach the goal, and stops at the distinctive place.

5 Conclusions and Future Work

In this paper, it is shown that how a robot with a visual system can complete the tasks of self-localization and self-navigation using a set of MR codes as landmarks. Experiment results have shown that MR code is quite convenient and effective to be used as a set of artificial landmarks. Our future work will include the improvement of MR code design and its detecting algorithm, how to arrange the MR code more effectively for service robots, how to deal with the problem of SLAM when the MR code is used as the landmarks, etc. We are quite hopeful that this MR code system will be put into practical use soon for indoor service robot applications.

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