넓은 실내 공간에서 반복적인 칼라패치의 6각형 배열에 의한 이동로봇의 위치계산

Mobile Robot Localization Based on Hexagon Distributed Repeated Color Patches in Large Indoor Area

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Abstract : This paper presents a new mobile robot localization method for indoor robot navigation. The method uses hexagon distributed color-coded patches on the ceiling and a camera is installed on the robot facing the ceiling to recognize these patches. The proposed "cell-coded map", with the use of only seven different kinds of color-coded landmarks distributed in hexagonal way, helps reduce the complexity of the landmark structure and the error of landmark recognition. This technique is applicable for navigation in an unlimited size of indoor space. The structure of the landmarks and the recognition method are introduced. And 2 rigid rules are also used to ensure the correctness of the recognition. Experimental results prove that the method is useful.

Keywords : mobile robot navigation, localization system, color image processing, landmark, hexagon distribution

I. INTRODUCTION

Capability of mobile robot localizations is required for robot navigation and path tracking. Development of a reliable and efficient mobile robot localization system has long been an interest of many researchers. Previously, the dead reckoning method has been widely used for most wheeled mobile robots to calculate their location with respect to an inertial frame of reference [1]. This method is simple but the accumulation of errors caused by wheel slippage is a problem. To overcome this drawback, ultrasonic sensors could be used. A robot can measure time-of-flight (TOF) temporal data from its surroundings by using several ultrasonic sensors. Given a known or partially recognized structured environment, the temporal information can be processed to obtain the robot's spatial location by means of barrier test [2-4], extended Kalman filtering with environment models [3-6], fuzzy fusion logic [7], or neural networks [8]. The efficiency of this method relies on the amount of a priori knowledge about the environment. This results in complexity in system implementation and practical use.

More recently, several research studies proposed the use of landmarks. One of those is based on RFID (Radio Frequency Identification) technology. A collection of RFID tags used as artificial landmarks are distributed in the environment. Mobile robot carries a RFID reader, which reads the RFID tags to localize the mobile robot. Each RFID tag stores its own unique position, which is used to calculate the position of the mobile robot [9-11]. Another technique is based on visual landmarks. Vision sensor recognizes the feature of artificial or natural landmarks to calculate the robot position. The technique in [12] used ceiling lights as natural landmarks to navigate and that in [13] designed 64 different landmarks, each with a unique ID, installed on the ceiling. Through identifying different ID, a mobile robot calculates its real position. But if the indoor space is very large, 64 different landmarks used in [13] will be insufficient.

This paper presents a method that uses coded color patches as landmarks on the ceiling. One advantage of the proposed scheme is that the size of the indoor space is not limited. Patch images are acquired by a camera that faces the ceiling mounted on the mobile robot. Based on image analysis, the robot can recognize the patches and estimates its position with good and reliable accuracy.

II. DEFINITION OF THE COLOR CODED MAP

1. Map construction

With a vision based localization system using landmarks, at any time, the robot determines its position by first identifying the landmark ID. At any time, the camera must be able to see at least one landmark. For simplicity, it is desired that the number of landmarks is minimized. Fig. 1 shows the distribution of patches on the ceiling. Each dot represents a patch with a certain ID. Assume the distance between every two neighboring patches is d', which is selected to ensure that camera can see at least one patch at any time. From the patch's position in the camera's view, a robot can calculate its real position.

Patches with different IDs must have different features, such as different colors or different geometrical shapes. When more distinguishable IDs are needed, features used for patches become more complicated. For instance, more colors or more complex shapes must be used. These create complexity in implementation

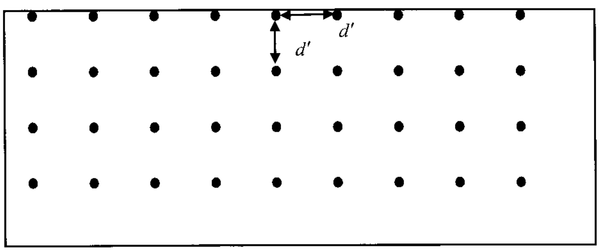

그림 1. 천장에 부착하는 패치 배치.
Fig. 1. Patch distribution on the ceiling.

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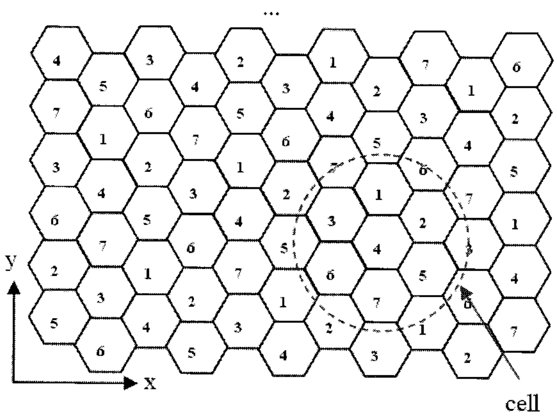


그림 2. 6 각형 패치의 ID 배치.

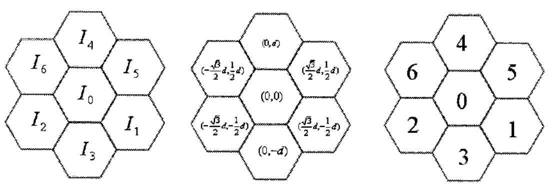
Fig. 2. Distribution of hexagonal patch's ID.

and lower the reliability in patch recognition. This will be a problem especially for navigation in very large indoor space.

In this paper, a new method is proposed to solve this problem. We construct a new map, named "cell-coded map", in which, the IDs of two patches at distance can be repeated. Fig. 2 shows the distribution of seven patch's ID. Any 7 neighboring patches will be referred as a cell. In Fig. 2, it could be seen that IDs inside any cell are different and in the whole map, only 7 different IDs are needed. The way to construct and use the landmark map will be explained below.

Let seven IDs in a cell be labeled I_0.. I_6. as shown in Fig. 3(a).

The sequence $[I_0 \cdots I_6]$ must be assigned values using the circular sequence as shown in Fig. 4 with a selected starting point. Fig. 2 illustrates the map assigned in this way. Fig. 3(b) shows the coordinates of each patch, with the center of the cell as the origin of the reference frame. Where d is the distance of every two neighboring patches.



(a) One cell (b) Patch coordinates (c) Subtraction resut

그림 3. 각 셀의 모양.

Fig. 3. Feature of each cell.

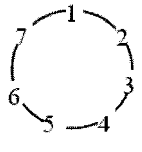


그림 4. 원형으로 연결된 ID.

Fig. 4. Circular chained ID.

The robot's localization system is a real-time system. Assume that at the previous time, the ID recognized is a_{i-1}, and currently the ID recognized is a_i. Then a_i and a_{i-1} must be inside the same cell with a_{i-1} at the center, as long as the robot's moving distance at the interval is smaller than d. Since both are inside the same cell, their IDs are different. The position of ID a_i relative to that of ID a_{i-1} could be known if the seven IDs are assigned in a systematical way as described in the previous paragraph. Equation (1) can be used for such computation.

$$\Delta ID = a_i - a_{i-1}, \quad a_i, a_{i-1} \in \{1,2,3,4,5,6,7\} \tag{1}$$

Substituting each ID inside a cell into equation (1), for any arbitrary cell, will result in values given in Fig. 3(c).

For all these IDs in Fig. 3(c), looking up in a table, as shown in table 1, will result in values given in Fig. 3(b). These values represent the relative coordinate $(\Delta x, \Delta y)$ from a_{i-1} to a_i.

Assume that the coordinate system is as shown in Fig. 2, and the coordinate for ID a_{i-1} is (x_{i-1}, y_{i-1}) and that for a_i is (x_i, y_i). Using equation (1), and for the result values, looking up in table 1, the coordinates for ID a_i can be expressed as

$$\begin{pmatrix} x_i \\ y_i \end{pmatrix}^T = \begin{pmatrix} \Delta x + x_{i-1} \\ \Delta y + y_{i-1} \end{pmatrix}^T \tag{2}$$

So as long as the initial coordinate is given at the very beginning, any later landmark's coordinate could be calculated depending on the previous one. This map is applicable for unlimited indoor space.

2. Patch design

For the constructed map in the previous subsection, only seven different patches will be needed. This can be done utilizing patch shape. For example, circle may code digit 1, triangle - digit 2 and so on. However, such a choice is not the best. The acquired image can contain other ceiling elements with size and shape similar to the patches, and geometric distortions, shape scaling and orientation, etc. will significantly increase the computational complexity in patch identification and also lower the identification accuracy. Thus in the proposed approach a patch is characterized only by color information. Permutations of different colors allow coding of each unique number. As usually most ceilings are of a solid color (white, tinge or gray with relatively low intensity and texture variations), their color saturation represented in HSV color space is quite low. The background in acquired images (which represents the ceiling) can be then easily removed by the saturation filter.

Colors with low similarity should be used. In this study, two colors: yellow, orange were selected to form a patch. Our experiments show that these colors are well distinguishable using

표 1. ΔID-상대위치의 룩업 테이블.

Table 1 ΔID -relative coordinate look-up table.

ΔID	0	1	2	3	4	5	6
Relative coordinate	$(0,0)$	$(\frac{\sqrt{3}}{2}d, -\frac{1}{2}d)$	$(-\frac{\sqrt{3}}{2}d, -\frac{1}{2}d)$	$(0,-d)$	$(0,d)$	$(\frac{\sqrt{3}}{2}d, \frac{1}{2}d)$	$(\frac{\sqrt{3}}{2}d, -\frac{1}{2}d)$

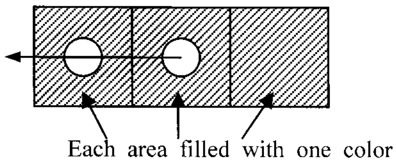


그림 5. 패치의 구조.

Fig. 5. Patch structure.

a camera. The permutation of three colors gives 2^3=8 (>7) distinct combinations (one color can be repeatedly used). Thus up to 8(>7) different IDs can be coded by patches defined using this color scheme. For our purpose, only seven are needed.

To determine the orientation of a patch, two white holes are also added one into each of two squares, as shown in Fig. 5. The patch orientation is defined by the vector from the center of the hole in the middle square to that of the side one, as indicated by the arrow in Fig. 5. Because the holes are white, they can be easily extracted from the image by application of saturation filter.

III. PATCH IMAGE ANALYSIS

Fig. 6 shows the flow chart of patch image analysis. It implements the following functions: image pre-processing, estimation of patch orientation, ID recognition and error detection.

1. Pre-processing of Image

1) Transformation of RGB to HSV color space.
2) Application of the saturation filter to remove the ceiling background by thresholding.
3) Application of intensity filter to remove any potentially detected light sources (lamps) that have a very high intensity image region. Again, this is done by image thresholding.

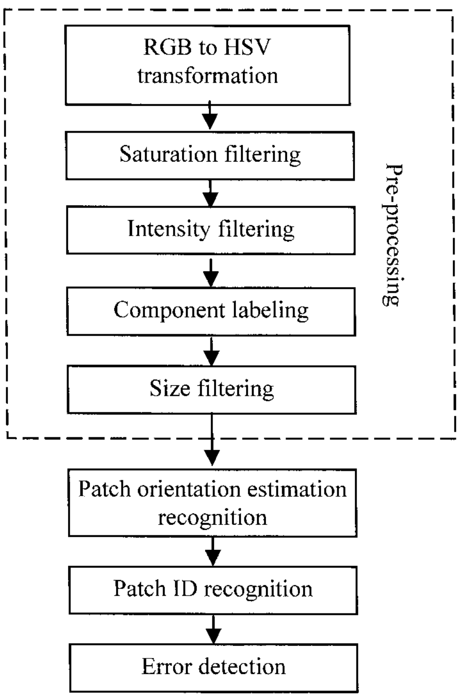


그림 6. 패치 인식을 위한 플로우 차트.

Fig. 6. Flow chart for the patch recognition.

4) Artifact removal by finding patch objects only. This is done using connected component labeling, which finds the candidate region that could represent the patch.
5) Since many patches can be detected in a single image, size filtering is used to find the bigger one (based on its area) and to remove the smaller remaining objects.

2. Estimation of patch orientation

Patch orientation is estimated using the locations of two detected white holes as described in subsection 2.2. The patch background is removed by application of saturation filter, as shown in Fig. 7. Then connected component labeling is used to extract the holes from the patch. To localize the holes, a scan inside the boundary of the blue rectangle (that delineates the patch) is performed. Elements found close to the boundary are discarded , and finally size filtering is used to select the biggest two components as the holes.

Assume that the centers of two holes are points (x_1, y_1) and (x_2, y_2), whereas the center of the blue rectangle is point (x_c, y_c). Then the two distances from each hole to point (x_c, y_c) are calculated. The one closer to (x_c, y_c) is concluded to be the middle hole. Supposing that its center is determined to be (x_2, y_2), then the angle between x axis and the patch orientation vector (see Fig. 8) can be calculated as

$$\theta = ATAN2(\ y_1 - y_2, x_1 - x_2\ ) \tag{3}$$

where ATAN2 is the four-quadrant inverse tangent function (undefined only if both arguments are zero).

3. ID recognition based on patch colors

The coordinates of patch's third square's center point (x_3, y_3) as shown in Fig. 8 can be easily calculated by the following equation:

$$\begin{pmatrix} x_3 \\ y_3 \end{pmatrix}^T = \begin{pmatrix} 2x_2 - x_1 \\ 2y_2 - y_1 \end{pmatrix}^T \tag{4}$$

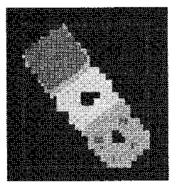


그림 7. 패치 영상의 예.

Fig. 7. A sample of a patch image.

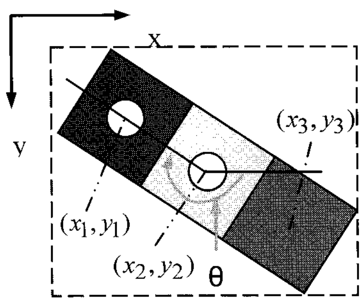


그림 8. 패치의 방향과 ID 결정.

Fig. 8. Estimation patch's direction and ID.

Computing the median hue value in a given neighborhood around points (x_1, y_1), (x_2, y_2) and (x_3, y_3), three patch colors can be evaluated. Then the number coded by this patch can be extracted from the predefined codebook.

4. Error detection

Reliability and robustness are important in robot localization. Patch detection errors could occur even with the proposed simple patch structure. If an error is detected, the localization system must reprocess to find a valid localization result. In the discussed system, two rigid rules are used to ensure that the result is correct.

The first rule: the position of the center hole should be close to the center of the blue rectangle that delineates the patch. The following condition is checked:

$$\sqrt{(x_2 - x_c)^2 + (y_2 - y_c)^2} \le 0.5 \times \frac{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}{2} \quad (5)$$

The second rule: the (x_3, y_3) coordinate calculated from two different approaches should be the same; one of the method is by equation (4) and the other is to be described below. As shown in Fig. 9, assume θ is the angle between the x-axis and the patch orientation vector, δ is the distance between points (x_1, y_1) and (x_2, y_2), x_l and x_r represent the x coordinates of the rectangle's left and right border, y_t and y_b represent the y coordinates of the rectangle's top and bottom border. Because each of the patch components is a square, equation (6) can be applied to compute coordinates (x_3, y_3). Here (x_3, y_3) is replaced by (x_3', y_3').

$$(x_3', y_3') = \begin{cases} \left(x_l + \frac{\sqrt{2}\delta}{2}\left|\cos(\frac{\pi}{4} - \theta)\right|, y_b - \frac{\sqrt{2}\delta}{2}\left|\cos(\frac{\pi}{4} - \theta)\right|\right), & \theta \in [0, \frac{\pi}{2}) \\ \left(x_r - \frac{\sqrt{2}\delta}{2}\left|\cos(-\frac{\pi}{4} - \theta)\right|, y_b - \frac{\sqrt{2}\delta}{2}\left|\cos(-\frac{\pi}{4} - \theta)\right|\right), & \theta \in [\frac{\pi}{2}, \pi) \\ \left(x_r - \frac{\sqrt{2}\delta}{2}\left|\cos(\frac{\pi}{4} - \theta)\right|, y_t + \frac{\sqrt{2}\delta}{2}\left|\cos(\frac{\pi}{4} - \theta)\right|\right), & \theta \in [-\pi, -\frac{\pi}{2}) \\ \left(x_l + \frac{\sqrt{2}\delta}{2}\left|\cos(-\frac{\pi}{4} - \theta)\right|, y_t + \frac{\sqrt{2}\delta}{2}\left|\cos(-\frac{\pi}{4} - \theta)\right|\right), & \theta \in [-\frac{\pi}{2}, 0) \end{cases} \quad (6)$$

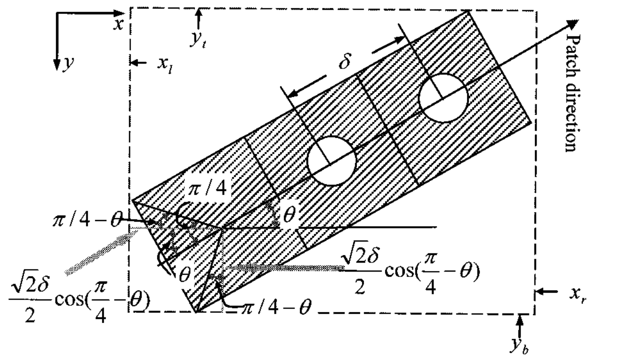


그림 9. 에러 검출 규칙의 예.

Fig. 9. Illustration for error detection rules.

This equation will depend on which quadrant θ belongs to.

Result obtained using equation (6) can be compared with that estimated by equation (4). The evaluated center point coordinates (x_3', y_3') should be close to the values (x_3, y_3). To check this, the following condition is checked:

$$\sqrt{(x_3' - x_3')^2 + (y_3' - y_3')^2} \le 0.5 \times \frac{\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}}{2} \quad (7)$$

If both inequalities in (5) and (7) are satisfied, the patch is considered to have been correctly detected.

IV. EXPERIMENT AND RESULT

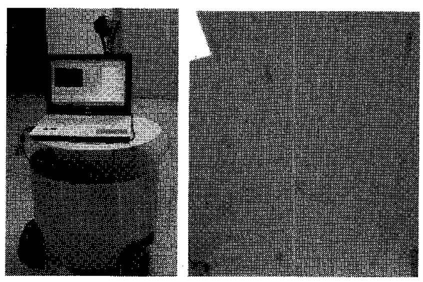
Experiments have been conducted with our experimental system to test the feasibility of the proposed cell-coded localization system.

1. Localization process

Fig. 10(a) shows our robot with a camera pointing toward the ceiling. Fig. 11(b) shows the color patches on the ceiling. The distance between two adjacent patches is 1 m.

At the very beginning, the robot's initial position with respect to a reference frame is known and given. The robot can then move in any random way. The localization system analyzes the patches in real time and calculates the position of any later observed patch using equation (2). The robot's coordinates can always be calculated.

Fig. 11 shows one patch acquired by the camera. Assume that the center point of each patch in real coordinate system is (x_{pr}, y_{pr}), the center point of camera in real coordinate system is



(a) (b)

그림 10. (a) 실험에 사용된 이동 로봇 (b) 천장에 부착된 칼라 패치.

Fig. 10. (a) mobile robot used in the experiments (b) color patc hes on the ceiling.

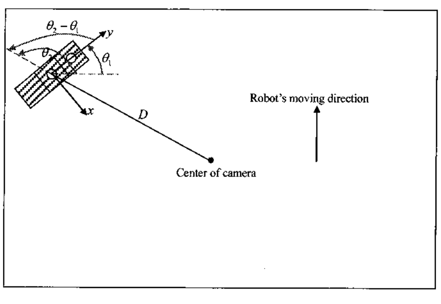
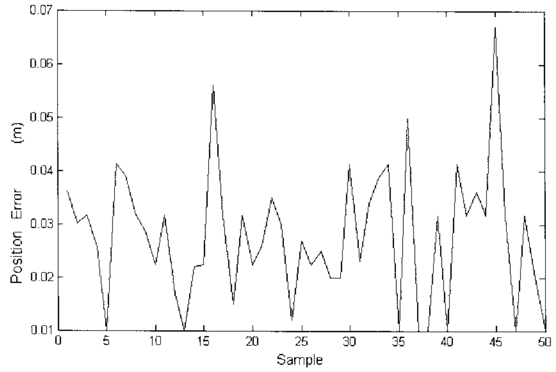
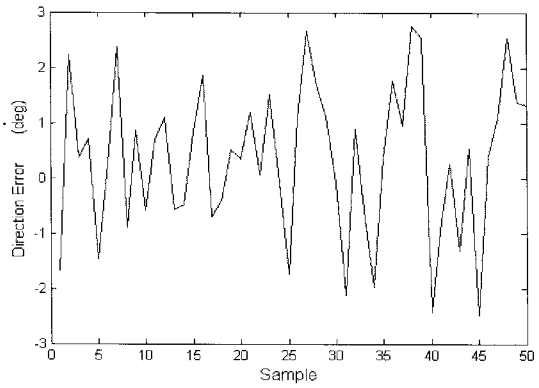


그림 11. 패치 위치 계산 예.

Fig. 11. Computation of the sample patch location.



(a) Position error



(b) Direction error

그림 12. 측정된 에러.
Fig. 12. Measured errors.

(x_r, y_r) and the real distance from center of camera (which denote accurate robot position projected onto the ceiling) to the patch center is D. Then, equation (8) can be used for estimation of accurate robot location:

$$(x_r, y_r) = \left(x_{pr} - D \times \cos(\theta_2 - \theta_1 - \frac{\pi}{2}), y_{pr} + D \times \sin(\theta_2 - \theta_1 - \frac{\pi}{2}) \right) \quad (8)$$

The robot movement direction is then defined by the angle $\pi/2 - \theta_1$.

2. Results

Fifty positions have been tested at the velocity of 0.1m/s. Fig. 12 shows the estimation error for each sample. From this figure, we can see, in most conditions, the estimation error is less than 5 cm and direction error is less than 3°.

V. CONCLUSION

In this paper, a new system for mobile robot localization was presented. In this localization system, very simple patches were created on the ceiling as landmarks to facilitate a special map named "cell-coded map". Using the patches as reference, a mobile robot can find its position and moving direction. Experimental results demonstrated that the proposed system provides accurate estimation of robot position. The evaluated localization error is within the range of 5 centimeters while the direction error is less than 3 degrees. This makes the proposed system reliable for practical applications.

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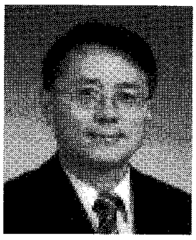

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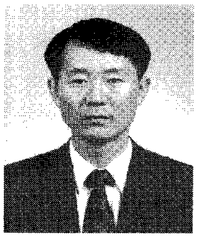

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