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천정 부착 셀코드 랜드마크에 기반한 이동 로봇의 정밀 위치 계산

(Precise Localization for Mobile Robot Based on Cell-coded Landmarks on the Ceiling)

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요 약

실내 로봇의 자율 운행에 효과적인 새로운 로봇 위치 계산 방법을 제안하였다. 천정에 칼라 코드로 만든 위치 지시용 랜드마크를 부착하고, 천정을 향해 설치된 카메라에 의해 랜드마크가 인식되게하는 구조이다. 칼라 랜드마크에 사용한 코드는 9개의 다른 조합이 되도록 하여 상대적 위치를 지시하게 하며, 위치 계산이 모듈로 9 계산에 의해 용이하도록 하는 특별한 배치 방법을 사용하였다. 천정에 부착된 랜드마크 인식을 기반으로 한 위치 계산 알고리즘이므로, 실내에서 사용하는 것을 특징으로 하며, 상대적인 위치 코드를 사용하므로 사용 넓이에 제한이 없다. 이 논문에서는 랜드마크의 구조와 인식방법을 소개하며, 위치계산 결과의 정확성 실험결과도 제시하였다.

Abstract

This paper presents a new mobile robot localization method for indoor robot navigation. The method uses color-coded landmarks on the ceiling and a camera is installed on the robot facing the ceiling. The proposed "cell-coded map", with the use of only nine different kinds of color-coded landmarks distributed in a particular way, helps reduce the complexity of the landmark structure. 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

I . Introduction

Capability of mobile robot localization 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

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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 on the ceiling as landmarks indicating the relative positions from the neighboring patches. 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. Proposed Localization

In a conventional vision based localization system, color patches as landmarks are arranged in a fixed pattern on the ceiling, as shown in Fig. 1, each dot representing a patch. Each patch containing different information (ID and orientaion) represents an absolute coordinate and the robot determines its position by identifying the nearest patch's information. As shown in Fig. 2, with a camera facing the ceiling installed on the robot, at any time, the robot first recognize the nearest patch's coordinate, then calculate the robot's relative position to identify its current absolute position. The distance d between every two neighboring patches must ensure camera can see at least one patch at any time.

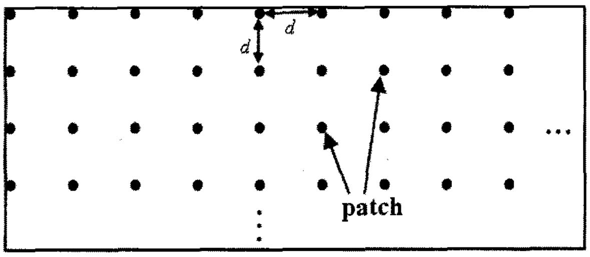


그림 1. 천정에 부착된 패치의 분포
Fig. 1. Patch distribution on the ceiling.

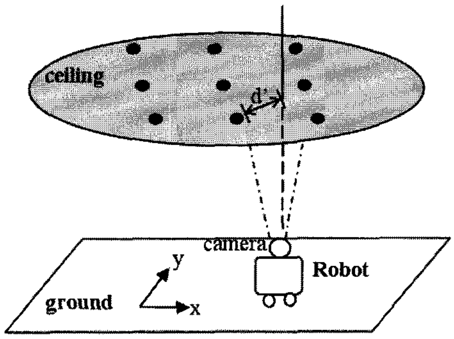


그림 2. 비젼 기반 위치 인식 시스템
Fig. 2. Vision-based localization system.

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

1. Landmark coding

In this paper, a new method is proposed to solve

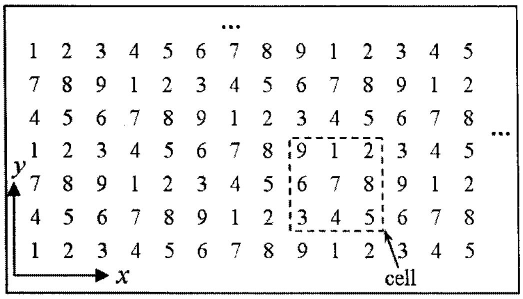


그림 3. 패치의 ID 분포
Fig. 3. Distribution of patch's ID

I_6	I_7	I_8
I_3	I_4	I_5
I_0	I_1	I_2

(a)

(-d,0)	(0,d)	(d,d)
(-d,0)	(0,0)	(d,0)
(-d,-d)	(0,-d)	(d,-d)

(b)

그림 4. 각 셀의 상대적 위치 (a) 각 셀의 ID (b) 각 셀의 상대적 위치
Fig. 4. Relative locations around a cell (a) IDs (b) relative locations.

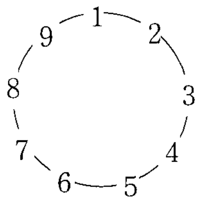


그림 5. ID 서클
Fig. 5. ID circle.

2	3	4
8	0	1
5	6	7

그림 6. 단일한 ID 순서
Fig. 6. uniform ID sequence.

this problem. We construct a new map, named "cell-coded map". In this map, each patch still represents an absolute coordinate. But the IDs of two patches at distance can be repeated, and here only 9 different IDs are used. Fig. 3 shows the distribution of these repeated IDs. Any 3x3 patches will be referred as a cell. The IDs are distributed in this way: In any row, IDs from 1 to 9 are orderly and periodically assigned to each patch and every following row is just shifted 3 numbers from the upper row. Then it could be seen that 9 IDs inside any cell are different. That means inside any cell, because of the uniqueness of each ID, we can define the relative position of each ID.

Let nine IDs in a cell be labeled $I_0 \cdots I_8$ as shown in Fig. 4(a). From Fig. 3, it can be seen that the sequence $[I_0 \cdots I_8]$ is assigned as a circular sequence as shown in Fig. 5 with a selected starting point. This rule is suitable for any cell. Since the relative position of the 9 IDs in the circular sequence is fixed, we can use this rule to define the relative position of the 9 IDs in the coordinate as shown in Fig. 4(b).

For any cell, if we substitute $I_0 \cdots I_8$ into equation (1), we will get a unique result as shown in Fig. 6. It's a 9 modular subtraction. Then look up in Table 1, we can get each patch's relative coordinate in one cell. Where, d is the distance of every two neighboring patches.

$$I_i' = (I_i - I_4 + 9)\%9, i \in 1,2,\cdots 9 \qquad (1)$$

Besides, substitute I0···I8 into equation (2) directly, without equation (1) and table 1, we can also get the same result.

$$\begin{pmatrix}\Delta x\\ \Delta y\end{pmatrix}^T = \begin{pmatrix}((I_i - I_4 + 9)\%3+1)\%3-1 \\ (((I_i - I_4 + 10)/3)\%3+1)\%3-1\end{pmatrix}^T d \qquad (2)$$
$$i \in 1,2,3,4,5,6,7,8,9$$

2. Robot position and orientation estimation

Since robot's localization system is a real-time system, assume that at the previous time, the ID

표 1. 상대적 위치 테이블
Table 1. Relative coordinate look-up table

ID	0	1	2	3	4	5	6	7	8
Relative coordinate($\Delta x, \Delta y$)	(0,0)	(d,0)	(-d,0)	(0,d)	(d,d)	(-d,-d)	(0,-d)	(d,-d)	(-d,0)

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. The position of ID a_i relative to that of ID a_{i-1} , $(\Delta x, \Delta y)$,could be known if the nine IDs are assigned in a systematical way as described in the previous paragraph.

Assume that the coordinate system is as shown in Fig. 3, the coordinate for ID a_{i-1} is $(x_{i-1}, y_{i-1})$and that for a_i is (x_i, y_i). The coordinates for ID a_i can be expressed as

$$\begin{pmatrix} x_i \\ y_i \end{pmatrix}^T = \begin{pmatrix} \Delta x + x_{i-1} \\ \Delta y + y_{i-1} \end{pmatrix}^T \qquad (3)$$

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.

Then assume Fig. 7 shows one possible image captured by the camera $"x-y"$ is the real coordinate system and $"x'-y'"$ is the image coordinate system. Since our patch contains its orientation information (patch structure will be explained in next section), patch's orientation in the image can be easily calculated as the angle θ_1, the orientation of the patch relative to the image center is θ_2, and the real distance from the image center to the patch center can be calculated as L. Then the robot's current position and orientation can be expressed by the following equation.

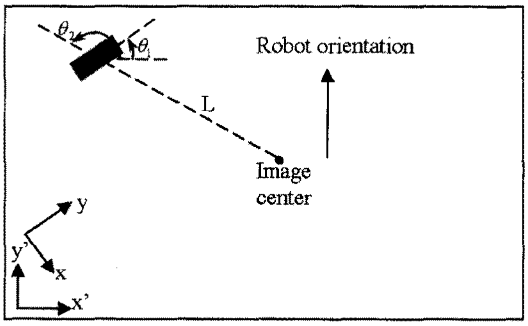


그림 7. 영상에서의 패치의 위치
Fig. 7. Possible patch location in an image.

Where, (x_r, y_r) is robot's current position and θ_r represents its current orientation in the real coordinate system.

III. Proposed Localization

For the constructed map in the previous subsection, only nine different patches will be needed. This can be done utilizing patch shape. For example, circle may code ID 1, triangle - ID 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. Colors with low similarity should be used. In this study, three colors: yellow, orange, and red were selected to form a patch. Our experiments show that these colors are well distinguishable using a camera. The permutation of three colors gives $3^3 = 27(\gg 9)$ distinct combinations (one color can be repeatedly used). Thus up to 27 different IDs can be coded by patches defined using this color scheme. For our purpose, only nine are needed.

And to determine the orientation of a patch, two

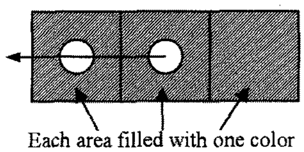


그림 8. 패치의 구조
Fig. 8. Patch structure.

$$\begin{cases} (x_r, y_r) = (x_i + L \times \cos(\theta_2 - \theta_1 - \frac{\pi}{2}), y_i + L \times \sin(\theta_2 - \theta_1 - \frac{\pi}{2})) \\ \theta_r = \frac{\pi}{2} - \theta_1 \end{cases} \qquad (4)$$

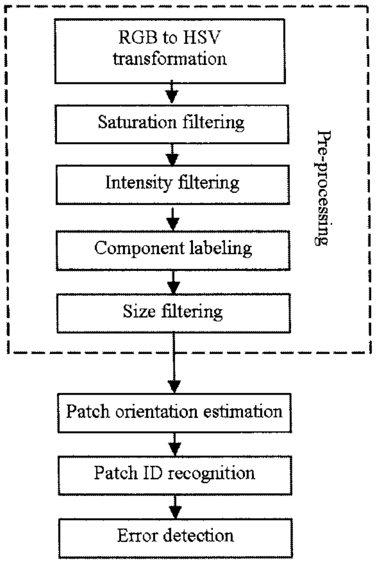


그림 9. 패치 인식을 위한 순서도
Fig. 9. Flow chart for the patch recognition.

white holes are also added one into each of two squares, as shown in Fig. 8. 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. 8.

Fig. 9 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. Image pre-processing

(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.

(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 3. The patch background is removed by application of saturation filter, as shown in Fig. 10. 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.

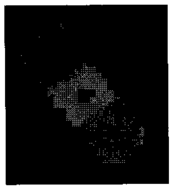


그림 10. 패치 영상의 예
Fig. 10. A sample of a patch image.

Assume that the centers of two holes in the image coordinate system are points (x_1, y_1) and (x_2, y_2), where 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. 9) can be calculated as equation (5) shows. Where ATAN2 is the four-quadrant inverse tangent function (undefined only if both arguments are zero).

$$\theta = ATAN2(y_1 - y_2, x_1 - x_2) \qquad (5)$$

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. 11 can be easily calculated by the following equation:

$$\begin{pmatrix} x_3 \\ y_3 \end{pmatrix}^T = \begin{pmatrix} 2x_2 - x_1 \\ 2y_2 - y_1 \end{pmatrix}^T \qquad (6)$$

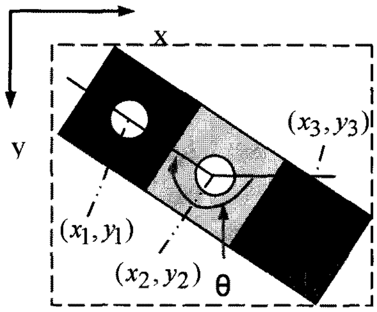


그림 11. 패치의 방향과 ID
Fig. 11. Direction and ID of a patch.

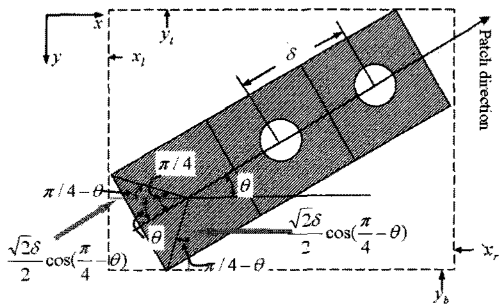


그림 12. 에러 검출을 위한 룰
Fig. 12. Illustration of error detection rules.

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:

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

The second rule: the (x_3,y_3) coordinate calculated from two different approaches should be the same; one of the methods is by equation (6) and the other is to be described below. As shown in Fig. 12, assume θ is the angle between the x-axis and the patch orientation vector, d 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 (8) can be applied to compute coordinates (x_3,y_3). Here (x_3,y_3) is replaced by (x_3',y_3').

This equation will depend on which quadrant θ belongs to. Result obtained using equation (8) can be compared with that estimated by equation (6). 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:

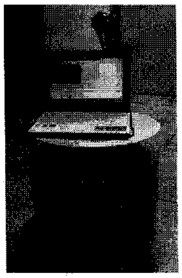
$$\sqrt{(x_3'-x_3)^2+(y_3'-y_3)^2} \le 0.5\times\frac{\sqrt{(x_1-x_2)^2+(y_1-y_2)^2}}{2} \quad (9)$$

If both inequalities in (7) and (9) are satisfied, the patch is considered to have been correctly detected.

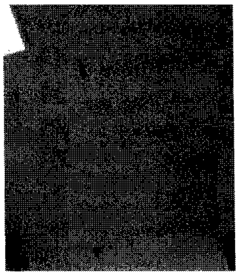
Ⅳ. Experiments

Fig. 13(a) shows our robot with a camera facing the ceiling. The robot diameter is 40cm. Fig. 13(b)

$$(x_3',y_3')=\begin{cases}(x_l+\frac{\sqrt{2}\delta}{2}\left|\cos(\frac{\pi}{4}-\theta)\right|, y_b-\frac{\sqrt{2}\delta}{2}\left|\cos(\frac{\pi}{4}-\theta)\right|), \theta\in[0,\frac{\pi}{2}) \\ (x_r-\frac{\sqrt{2}\delta}{2}\left|\cos(-\frac{\pi}{4}-\theta)\right|, y_b-\frac{\sqrt{2}\delta}{2}\left|\cos(-\frac{\pi}{4}-\theta)\right|), \theta\in[\frac{\pi}{2},\pi) \\ (x_r-\frac{\sqrt{2}\delta}{2}\left|\cos(\frac{\pi}{4}-\theta)\right|, y_t+\frac{\sqrt{2}\delta}{2}\left|\cos(\frac{\pi}{4}-\theta)\right|), \theta\in[-\pi,-\frac{\pi}{2}) \\ (x_l+\frac{\sqrt{2}\delta}{2}\left|\cos(-\frac{\pi}{4}-\theta)\right|, y_t+\frac{\sqrt{2}\delta}{2}\left|\cos(-\frac{\pi}{4}-\theta)\right|), \theta\in[-\frac{\pi}{2},0)\end{cases} \quad (8)$$



(a)



(b)

그림 13. 실험 환경 (a) 이동 로봇 (b) 천정 부착 칼라 패치

Fig. 13. Experiment environment. (a) mobile robot used in the experiments (b) color patches on the ceiling.

shows the color patches on the ceiling. The distance between two adjacent patches is 1m.

1. Patch ID recognition error

We tested about 1000 samples and check the patch ID recognition error. Table 2 shows the error when using different rules. From the result, we can see that, if we don't use any rules explained before, the recognition error is very frequently and only rule 1 and rule 2 also can't remove the error completely. But when we use the rules together, till now, we didn't find any error.

Analyzing all the possible condition of one ID mistake, the possible error is shown in the Table 3. Sometimes, after several steps, the error will be counteracted. If the error can't be counteracted, it will accumulate and the error is serious. So the previous two rigid rules are very important to remove such error although it looses some efficiency because of giving up error samples.

표 2. 다른 룰을 사용할 경우의 인식 률

Table 2. Patch recognition error with different

rule	neither	1	2	1 & 2
Error(%)	27%	5%	1%	0%

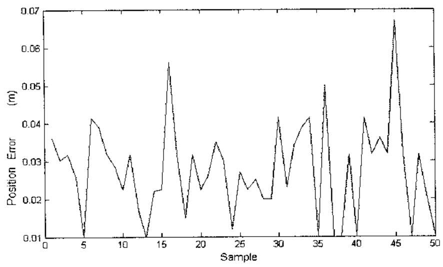
표 3. 단인 ID에 대한 에러

Table 3. Possible error of one ID mistake.

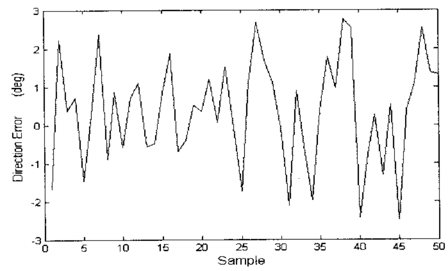
error	0	3d	$\sqrt{10}\,d$	$\sqrt{13}\,d$

2. Position and orientation estimation accuracy

Fifty positions have been tested at the velocity of 0.1m/s and the moving trace is a straight line (More complex trace is not necessary because it refers control algorithm). Fig. 14 shows the measurement 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 3o. This error is mainly created by the measuring error of distance L, which is from the robot to the current landmark and this error will not accumulate.



(a)



(b)

그림 14. 측정 에러 (a) 위치 에러 (b) 방향 에러

Fig. 14. Measured errors (a) position error (b) directional error.

V. Conclusions

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 orientation. 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. And the benefits of the proposed method over the existing ones are 1)the code locations can easily be computed with the proposed equation, 2) the size of the landmark could be smaller than others since it employs the relative coding, and therefore 3) it could be utilized in large working space.

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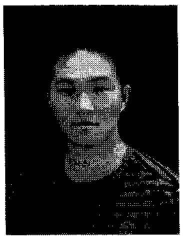

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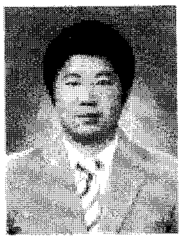

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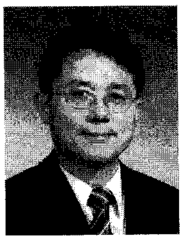

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