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# Multiple Omnidirectional Vision System and Multilayered Fuzzy Behavior Control for Autonomous Mobile Robot

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## 1. Introduction

In the research on multiple autonomous mobile robots such as RoboCup, some methods for obtaining the environmental information over all circumferences used an omnidirectional vision sensor, were proposed. In case of the research using the omnidirectional camera (called omni-camera), only one camera is almost used in general. However, the object image in the mirror is compressed according to the distance. If the height of the object is uncertain, the accurate distance measurement is generally impossible.

To solve these problems, some researches for the stereo vision system used two omni-cameras were also proposed. For example, the research for the stereo vision system which two omni-cameras are vertically fixed was proposed by J.Gluckman (Gluckman; Nayar & Thoresz, 1998), H.Koyasu (Koyasu; Miura & Shirai, 2002) and T.Matsuoka (Matsuoka; Motomura & Hasegawa, 2003). The other approach which two omni-cameras are horizontally fixed is proposed by R.Miki (Miki et al., 1999).

In our laboratory, we have developed a multiple omnidirectional vision system (called MOVIS) which three omnidirectional cameras are arranged on an autonomous soccer robot like as a horizontal and equilateral triangle (Shimizuhira & Maeda, 2003). As a result, the stereo-vision system by the principle of the triangulation is made by each two cameras. The purpose of this research is to realize the object recognition and the position measurement of the robot accurately in real time. Furthermore, we propose the real-time object position measurement and the self-localization method for the autonomous soccer robot with MOVIS.

On the other hand, there are some researches for the autonomous behavior under the complicated environment by using fuzzy reasoning. In the research of the behavior control in the RoboCup middle-size league, a control system based on the fuzzy potential method was proposed by R.Tsuzaki (Tsuzaki & Yosida, 2003), a multi-layered learning system was proposed by Y.Takahashi (Takahashi; Hikita & Asada, 2003). Generally, it is well known that an operator is easy to express his control knowledge by using fuzzy reasoning. We have already proposed a multi-layered fuzzy behavior control method that element behaviors of the robot are individually controlled with the behavior decision fuzzy rule in lower-layer, and combined them with the behavior selection fuzzy rule in higher-layer (Shimizuhira; Fujii & Maeda, 2004) (Maeda & Shimizuhira, 2005).

The goal of our work is to acquire the surrounding environment information overall circumferences under the complicated environment, and to realize the omnidirectional adaptive behavior in an autonomous mobile robot. In this paper, we propose the useful self-localization method for MOVIS in any environment. To confirm the efficiency of the proposed method and system, we performed the measurement and self-localization experiment by MOVIS carried on an actual autonomous soccer robot.

## 2. Multiple Omnidirectional Vision System

To acquire the surrounding information in dynamic environment, we developed the multiple omnidirectional vision system (MOVIS). Measurement of the distance and direction to an object by only vision sensor without active sensors (sonar, infrared sensor, etc.) becomes possible by using MOVIS.

### 2.1 Hardware of MOVIS

Three omnidirectional cameras ( $M_1$ ,  $M_2$ , and  $M_3$ ) with same performances respectively are used in MOVIS. In this system, the omni-cameras are horizontally arranged in the equilateral triangle on a soccer robot as shown in Fig.1. Sample images of three omni-cameras are shown in Fig.2. The center of gravity of the robot and the equilateral triangle vertically exist in the same point.

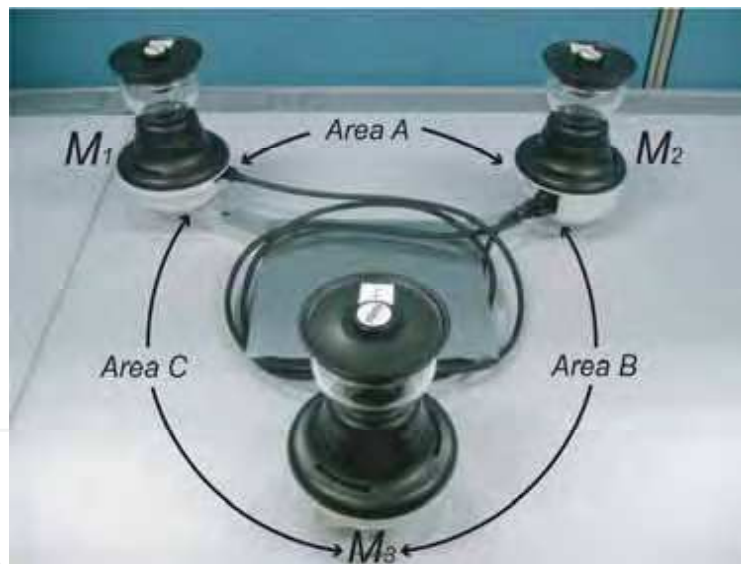


Figure 1. Overview of MOVIS

By the line extended from the center of gravity of the equilateral triangle to each vertex point, the range of the acquisition of images are divided into three areas which each two cameras perform as the stereo vision within 120 degrees (Area A, B and C in Fig.1). Stereo visions in each area provide the precise distance information by the principle of triangulation.

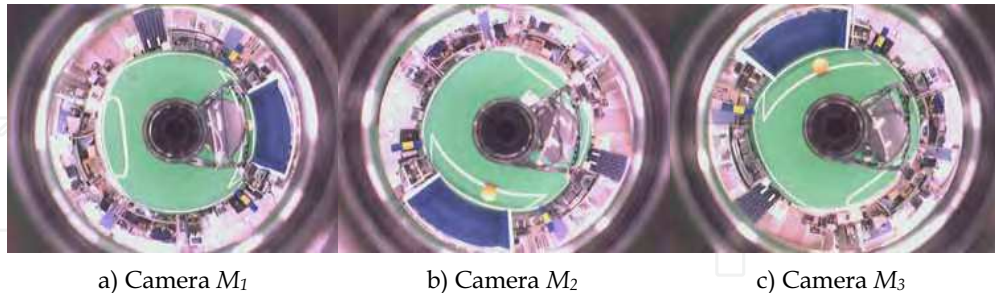


Figure 2. Camera Images of MOVIS

### 2.2 Scanning Method of Omni-directional Camera

In general, the extraction of the selection area in an image is performed after making a binary format image and saving an array. The scanning process on Cartesian coordinates includes some useless searches out of an image in the omni-directional camera, but scanning on Polar coordinates has the efficient search performance because of its circular image (see Fig.3). In this method, after scanning process on Polar coordinates, the color information in Cartesian coordinates is obtained by the following transformation. In this equation,  $\theta$  and  $r$  show the parameters in Polar coordinates and  $x$  and  $y$  in Cartesian coordinates.

$$x = r \cdot \cos\theta \quad (1)$$

$$y = r \cdot \sin\theta \quad (2)$$

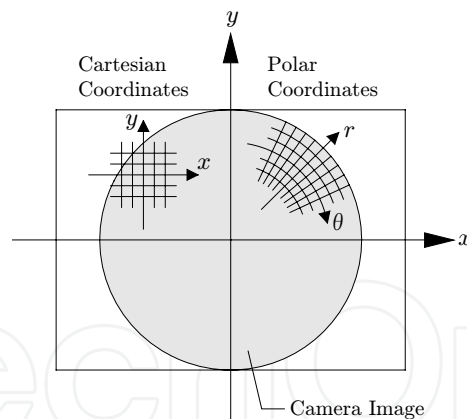


Figure 3. Scanning Method of Omni-directional Camera

### 2.3 Object Recognition by MOVIS

In our method, we adopted the scanning method based on Polar coordinates for the efficient image processing. At first, we count the number of extracted selection pixels in the binary format image in Polar coordinates and save it to the array arranged according to the orientation angle. Next, the panorama information for objects is obtained from the

histogram made by the extracted pixel number in the array. By setting up the threshold value of pixel number, we are able to find the desired object. Fig.4 shows a histogram example in Polar coordinates for three omni-directional cameras.

Generally, we must reduce noises in the preprocess of image by compressing and enlarging. However, by using this histogram, we easily recognize the object tuning the threshold adaptively except the noise reduction process. By this method, the load of image processing is decreased.

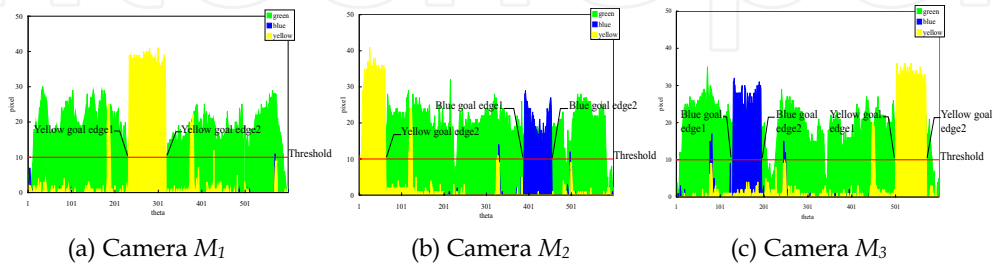


Figure 4. Extracted Pixel Histogram of Camera Image

#### 2.4 Position Measurement by MOVIS

Outline of the overall measurement process of MOVIS is shown as below. The measurement process of the object position and the self-localization used in MOVIS has four main processes.

1. Object Position Measurement in Robot Coordinates
2. Self-Localization in Absolute Coordinates
3. Self-Localization after Measurement Error Correction
4. Modification of Absolute Object Position

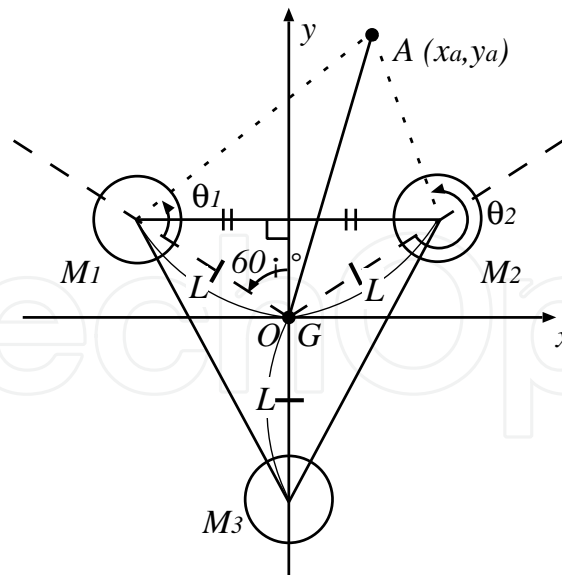


Figure 5. Structure of MOVIS

In the position measurement, an object position  $A(x_a, y_a)$  in Fig.5 is obtained by using omni-camera  $M_1$  and  $M_2$  in the robot coordinates. In the view point of  $M_1M_2$ , a slant angle of  $AM_1$  is  $(\theta_1 - \pi/6)[=\lambda_1]$ , that of  $AM_2$  is  $(\theta_2 - 5\pi/6)[=\lambda_2]$ . The distance between the center of gravity of the robot and the center of camera is assumed as  $L$ . As a result, a position  $(x_a, y_a)$  of the object  $A$  in the robot coordinates is calculated by the following equations.

$$x_a = \frac{\sqrt{3}}{2} L \cdot \frac{\tan \lambda_2 + \tan \lambda_1}{\tan \lambda_2 - \tan \lambda_1} \quad (3)$$

$$y_a = \frac{1}{2} L + \sqrt{3} L \cdot \frac{\tan \lambda_2 \cdot \tan \lambda_1}{\tan \lambda_2 - \tan \lambda_1} \quad (4)$$

### 3. Self-Localization by MOVIS

In this research, a half field of RoboCup middle-size robot league was constructed for the measurement experiment. The center and the corner of soccer goals were used as a landmark for the self-localization in this experiment. In this section, we propose two different measurement methods for the self-localization of a soccer robot and the mixed criterion of these methods.

#### 3.1 Method1

Method 1 is the measurement method used the center of both goals as the landmark. The coordinate axis in the absolute coordinates is shown in Fig.6. The origin point is fixed in the center of the soccer field.  $P$  and  $Q$  show the center of goals, and  $P_1, P_2, Q_1,$  and  $Q_2$  show the edge of goals with the width  $F_w$  and the depth  $F_d$  from the origin of the field. These absolute positions are used as landmarks in the proposed method.

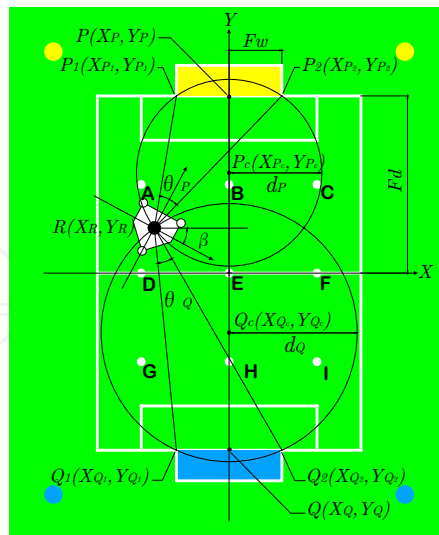


Figure 6. Self-Localization in Absolute Coordinates

Moreover, the absolute position of the center of gravity of the robot R is assumed as  $(X_R, Y_R)$  and the slant angle of x axis of the robot coordinates in the absolute coordinates is assumed as  $\beta$ .

In the robot coordinates, assuming that relative positions of the landmark P and Q obtained from the position measurement are  $p(x_p, y_p)$  and  $q(x_q, y_q)$  respectively, the landmark's absolute positions  $(X_P, Y_P)$  and  $(Y_Q, Y_Q)$  are described as the following equations.

$$\begin{pmatrix} X_P \\ Y_P \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta & X_R \\ \sin\beta & \cos\beta & Y_R \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_p \\ y_p \\ 1 \end{pmatrix} \quad (5)$$

$$\begin{pmatrix} X_Q \\ Y_Q \\ 1 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta & X_R \\ \sin\beta & \cos\beta & Y_R \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x_q \\ y_q \\ 1 \end{pmatrix} \quad (6)$$

where the yellow and blue goal are used as the landmark P( $X_P, Y_P$ ) and Q( $X_Q, Y_Q$ ) in the experiment respectively.

The center of the gravity position  $(X_R, Y_R)$  of a robot in the absolute coordinates is calculated by these equations as the following equations.

$$X_R = y_p \sin\beta - x_p \cos\beta \quad (7)$$

$$Y_R = Fd - x_p \sin\beta - y_p \cos\beta \quad (8)$$

$$X_R = y_q \sin\beta - x_q \cos\beta \quad (9)$$

$$Y_R = -Fd - x_q \sin\beta - y_q \cos\beta \quad (10)$$

$$\beta = \arctan \frac{x_p - x_q}{y_p - y_q} \quad (11)$$

By our experimental results, we confirmed that the self-localization performance in X axis orientation is relatively good in the accuracy of the position estimation, but the measurement in Y axis has some errors because the distance data error of MOVIS has quite larger than the direction data error.

### 3.2 Method2

Method 2 is the measurement method used the corners of both goals as the landmark. As Fig.6, after the robot measures the corner edge of both goals,  $\theta_P$  (=angle of  $P_1RP_2$ ) as the parallax angle for both edges of a goal P and  $\theta_Q$  (=angle of  $Q_1RQ_2$ ) as that of a goal Q are obtained. The radius of a circumscribed circle for triangles of  $\Delta P_1P_2R$  and  $\Delta Q_1Q_2R$  are shown in the following equations.

$$d_P = \frac{Fw}{\sin\theta_P} \quad (12)$$

$$d_Q = \frac{Fw}{\sin\theta_Q} \quad (13)$$

where  $F_w$  means the distance between a center and each corner edge of a goal.

Next, the absolute position of the center of each circumscribed circle  $P_C(X_{P_C}, Y_{P_C})$  and  $Q_C(X_{Q_C}, Y_{Q_C})$  is calculated as follows.

$$X_{P_C} = X_{Q_C} = 0 \quad (14)$$

$$\begin{aligned} Y_{P_C} &= Fd - \sqrt{d_P^2 - Fw^2} & (0 < \theta_P < \frac{\pi}{2}) \\ &= Fd + \sqrt{d_P^2 - Fw^2} & (\frac{\pi}{2} \leq \theta_P < \pi) \end{aligned} \quad (15)$$

$$\begin{aligned} Y_{P_C} &= Fd - \sqrt{d_P^2 - Fw^2} & (0 < \theta_P < \frac{\pi}{2}) \\ &= Fd + \sqrt{d_P^2 - Fw^2} & (\frac{\pi}{2} \leq \theta_P < \pi) \end{aligned} \quad (16)$$

where  $F_d$  means the distance between a center line and a goal line.

Therefore, the intersection of these circumscribed circles shows the robot position. The self-position of the robot  $R(X_R, Y_R)$  is decided by the following equations.

$$\begin{aligned} X_R &= -\sqrt{r_P^2 - (Y_R - Y_{P_C})^2} & (x_{P_1}^2 + y_{P_1}^2 \leq x_{P_2}^2 + y_{P_2}^2) \\ &= \sqrt{r_P^2 - (Y_R - Y_{P_C})^2} & (x_{P_1}^2 + y_{P_1}^2 > x_{P_2}^2 + y_{P_2}^2) \end{aligned} \quad (17)$$

$$Y_R = \frac{(r_P^2 - Y_{P_C}^2) - (r_Q^2 - Y_{Q_C}^2)}{2 \cdot (Y_{Q_C} - Y_{P_C})} \quad (18)$$

This method has relatively high performance of the self-localization for the Y axis orientation, but the measurement for X axis orientation includes some errors. As this reason, we consider that larger errors are generated in X axis orientation rather than Y axis orientation in the calculation for the intersection of these circumscribed circles.

### 3.2 Self-Localization Method

Two above-mentioned methods have merits and demerits. Therefore, we proposed a composed method with each merit in this research. By composing two method, the self-localization method with better performance in all measurement area is constructed. In this



method, we compose Method 1 with better performance in X axis orientation and Method 2 with better performance in Y axis orientation.

In the estimation of X position, we adopt Equation (7) and (9). For the improvement of the measurement accuracy, the absolute robot position in X axis is calculated with the average of these equations.

In the estimation of Y position, we adopt Equation (18) with better performance in Y axis orientation. Finally, the self-localization position of the robot is calculated by the following equation.

$$X_R = \frac{y_p \sin \beta - x_p \cos \beta + y_q \sin \beta - x_q \cos \beta}{2} \quad (19)$$

$$Y_R = \frac{(r_P^2 - Y_{Pc}^2) - (r_Q^2 - Y_{Qc}^2)}{2 \cdot (Y_{Qc} - Y_{Pc})} \quad (20)$$

## 4. Experiments

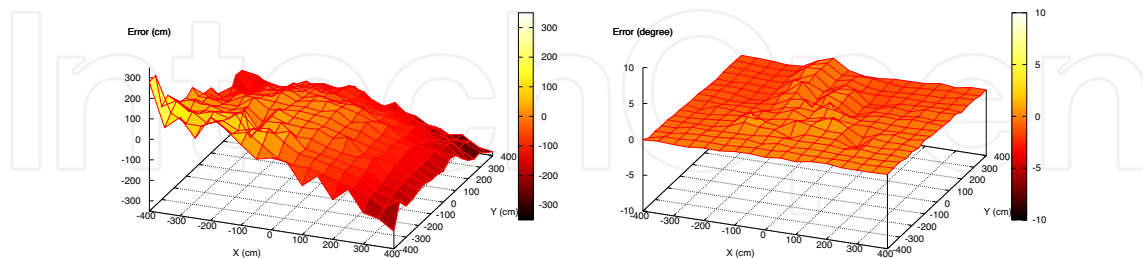
We actually performed the measurement experiment by MOVIS and the shoot experiment by a soccer robot with the multi-layered fuzzy behavior control method. The experiment was executed by using three IEEE1394 digital omni-cameras and a notebook PC with Celeron 600A MHz CPU and Vine Linux 3.0.

### 4.1 Experiment for Performance of MOVIS

In order to confirm the precision of MOVIS, we carried out the measurement experiment of the ball direction and distance from the robot with MOVIS. This experiment was performed at the wide space with a uniform light source. We used an orange soccer ball regulated in the RoboCup middle-size league as the measurement object. The origin of the absolute coordinates is a center of the measurement space within 800cm square and the measurement place are 289 lattice points at each 50cm interval from -400cm to 400cm. Omni-cameras were fixed at 25cm height from the floor during the experiment.

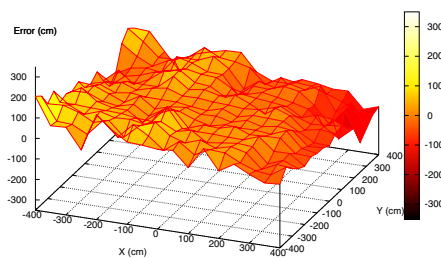
Fig.7 shows measurement results for the distance and direction error in polar coordinates. Results for a single omni-vision are shown in Fig.7a),b), the vertical stereo omni-vision (Koyasu, Miura & Shirai, 2002) in Fig.7c),d) and MOVIS with the error correction in Fig.7e),f). In the measurement experiment of the single omni-vision, large particular errors were found in the area around (-400, -400). We confirmed a single omni-vision has an individual difference such as this type of error. The absolute average of the distance error was 92.63 cm in this experiment. On the other hand, we confirmed the omni-vision has an ability of the precise measurement for the direction by the result that the absolute average of the direction error was 0.61 degrees.

In Fig.7c) to f), the absolute average of the direction error in the vertical stereo omni-vision and MOVIS was relatively small within -1.5 to 1.5 degrees as same as a single omni-vision. Moreover, the absolute average of the distance error in MOVIS was remarkably smaller than that of the vertical stereo omni-vision. By this results, we could confirm the performance of the precise distance measurement of MOVIS.

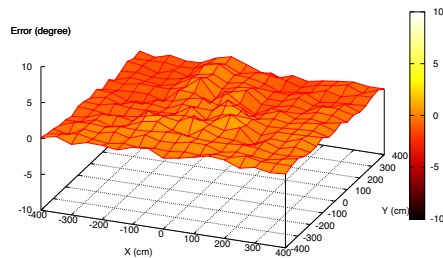


a) Single Omni-Vision (Distance Error)

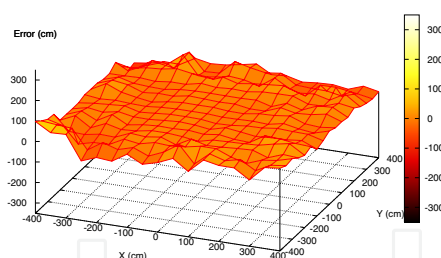
b) Single Omni-Vision (Direction Error)



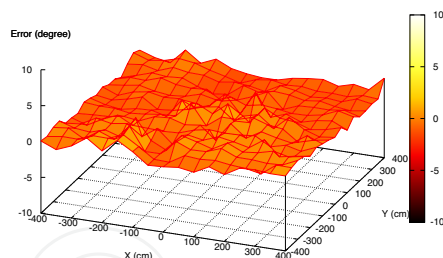
c) Stereo Omni-Vision (Distance Error)



d) Stereo Omni-Vision (Direction Error)



e) MOVIS (Distance Error)



f) MOVIS (Direction Error)

Figure 7. Results of Measurement Experiment

#### 4.1 Experiment for Self-Localization

Furthermore, Fig.8 to 16 shows the results for the measurement error of the self-localization. These results show the self-localization error measured on nine spots A to I in miniature field with 3.5m width and 4m depth while a robot rotates on a spot. In these figures, for example, Position A means the self-localization experimental result executed in place of point A in Fig.6. Left graph shows the position error estimated by the proposed self-localization method and right figure shows the real position plotted in the field.

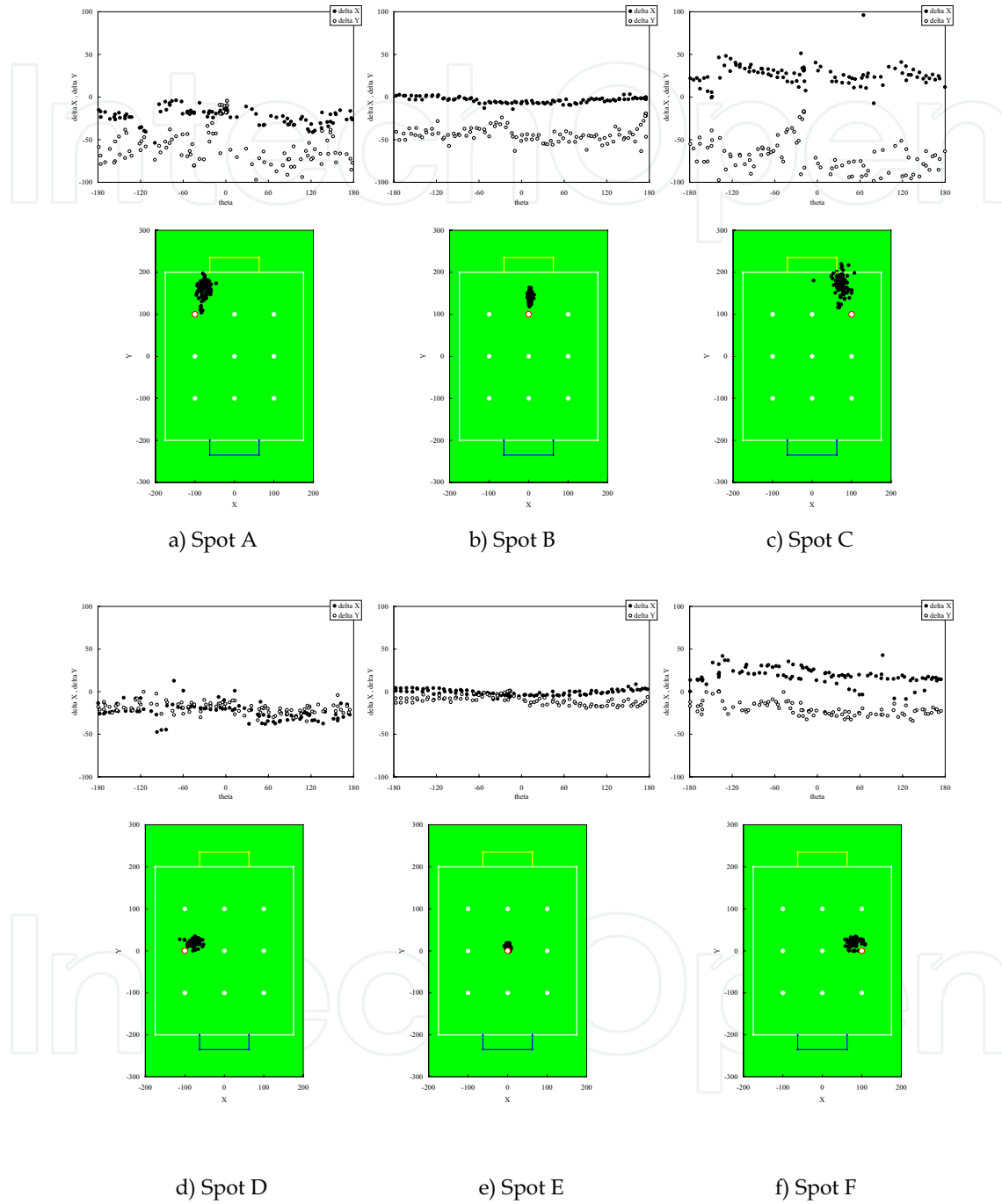


Figure 8. Experimental Result of Self-Localization (1)

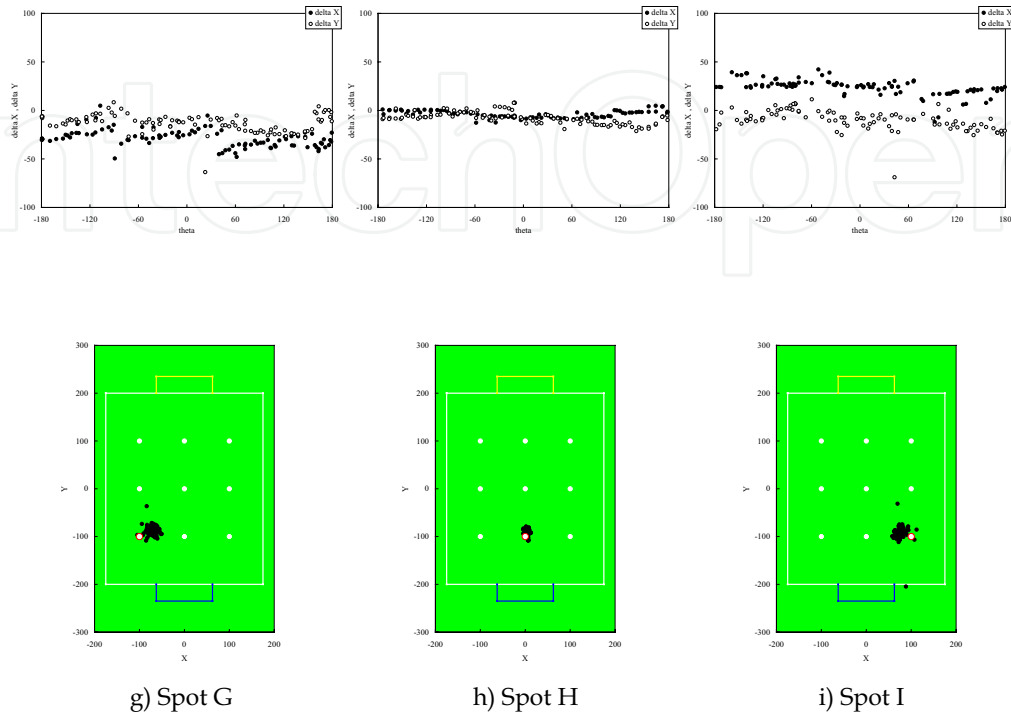


Figure 8. Experimental Result of Self-Localization (2)

As a result, we confirmed that the proposed method is useful for the self-localization. Especially, the performance of self-localization on Y axis (spot B, E, and H) was better than that on the other spots. Maybe we consider that the reason is caused by the measurement error of the distance in far area. In all results, the result on the spot A and C was the worse because the robot could not successfully execute the color extraction of blue goal near the yellow goal area. We think that we are able to make better the performance of these areas by improvement of lighting environment.

## 5. Conclusions

The multiple omnidirectional vision system (MOVIS) with three omni-cameras and its self-localization method for the autonomous mobile robot were proposed in this paper. Moreover, the experiment of the measurement performance and self-localization by MOVIS on the real miniature soccer field was carried out by using the proposed method. As a result, we confirmed that the measurement of MOVIS is remarkably more accurate than that of a single omni-vision and the vertical stereo omni-vision, and the self-localization performance is relatively useful in all area of soccer field. In the near future, we would like to develop the real soccer robot with MOVIS and the proposed self-localization method.

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## **Scene Reconstruction Pose Estimation and Tracking**

Edited by Rustam Stolkin

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This book reports recent advances in the use of pattern recognition techniques for computer and robot vision. The sciences of pattern recognition and computational vision have been inextricably intertwined since their early days, some four decades ago with the emergence of fast digital computing. All computer vision techniques could be regarded as a form of pattern recognition, in the broadest sense of the term. Conversely, if one looks through the contents of a typical international pattern recognition conference proceedings, it appears that the large majority (perhaps 70-80%) of all pattern recognition papers are concerned with the analysis of images. In particular, these sciences overlap in areas of low level vision such as segmentation, edge detection and other kinds of feature extraction and region identification, which are the focus of this book.

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