2008 IEEE International Conference on
Robotics and Automation
Pasadena, CA, USA, May 19-23, 2008

Calibration of Distributed Vision Network in Unified Coordinate System by Mobile Robots

Tsuyoshi Yokoya, Tsutomu Hasegawa, and Ryo Kurazume

Abstract— **This paper proposes a calibration method of a distributed vision network in a unified world coordinate system. The vision network system is conceived to support a robot working in our daily human life environment: the system provides with visual observation of the dynamically changing situation surrounding the robot. Vision cameras are rather sparsely distributed to cover a wide area such as a block of a town. Position, view direction and range of view are the camera parameters of principal importance to be estimated by the proposed method. A set of calibration data for each distributed camera is provided by a group of mobile robots having a cooperative positioning function and visually distinguishable markers mounted on the body of the robot.**

I. INTRODUCTION

The distributed vision network system has various applications: tracking the flows of pedestrians, and observation of intruders. Structuring the ordinary daily life environment in informative way would be a promising approach to an intelligent robot working in the environment together with humans [1]. In such application (Fig.1) vision cameras are distributed and set up in a daily life environment to observe and measure moving objects including robots. All the cameras are connected to a management system through network. The management system collects vision information from the distributed cameras, unifies results of observation from different view, and updates them to provide robot with its surrounding situation about moving and static obstacles. Vision data processing of a fixed camera is much easier than that of a camera mounted on a dynamically moving robot. This paper proposes a new method of calibration of distributed vision network by mobile robots.

Once many cameras are distributed and installed within a wide outdoor area or indoor area, they must be calibrated in the unified coordinates system to integrate environmental information obtained by each camera into a comprehensive whole information. Initial one-time calibration may not be sufficient. Re-calibration is often required because the cameras will be moved due to the strong wind, or accidental contacts with objects accompanied to daily human activities.

Generally a camera can be calibrated using some features adequately distributed within the field of view of the camera, if the accurate 3D position of features in cartesian space and their corresponding 2D position on the image plane of the camera are obtained [2], [3]. However, obtaining these data is not straightforward when the vision network is composed of many cameras distributed in a wide area. It is tedious and time-consuming for a human worker to collect data for calibration from the real world in the unified coordinate system. To overcome this problem, we have developed a robotic calibration system for the vision network covering the wide area.

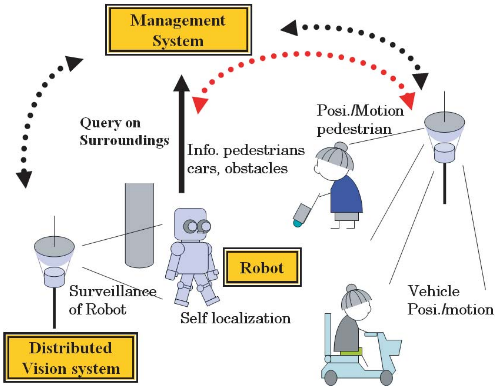

Fig. 1. Intelligent robot working in a daily life environment: distributed vision network supports the robot by providing with information of the surrounding situation composed of static obstacles and moving object.

Various calibration methods have been proposed so far. They are, for example, methods based on recognition of an artificial calibration pattern placed in the camera view [4], [5], and methods based on visually distinguishable landmarks already existing in the environment [6], [7]. Although these methods still suffer from difficulty in recognition, they well work for a single camera. For multiple cameras of vision network, however, problem of accurately positioning the calibration pattern or measuring position of the landmarks with respect to the unified coordinate system must be solved for each cameras. The problem can be relaxed if the fields of view of the camera overlap with each other [8], [9]. However, the overlapping of the field of view of the cameras is a too strong constraint for the vision network in general applications.

We use a simple and general method for the robotic calibration system described in this paper. A group of mobile robots calibrates cameras. A mobile robot equipped with visual marker moves to arbitrary points in the field of view. The marker is easily and reliably detected on the imaging plane from vision information of cameras, while the marker's 3D position is measured in unified coordinate system by other mobile robot using a precision measuring machine

---

Tsuyoshi Yokoya is with Graduate School of Info. Scie. and Elec. Engi., Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395 Japan `yokoya@irvs.is.kyushu-u.ac.jp`

Tsutomu Hasegawa, Ryo Kurazume are with Faculty of Info. Scie. and Elec. Engi., Kyushu University, 744 Motooka, Nishi-ku, Fukuoka, 819-0395 Japan `{hasegawa, kurazume}@irvs.is.kyushu-u.ac.jp`

978-1-4244-1647-9/08/$25.00 ©2008 IEEE.

mounted on it. The group of mobile robots visits the distributed cameras one after another to calibrate them(Fig.2).

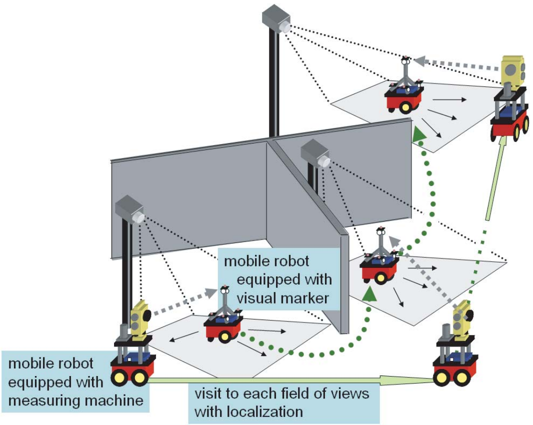

Fig. 2. Calibration of distributed vision network by a group of mobile robots

The accuracy of calibration of our method depends on the accuracy of localization of mobile robots. The localization of mobile robot itself is the most fundamental problem and various approaches have been proposed so far. However, the dead reckoning by odometry can't be applied due to large error [10]. Localization based on the sensory observation of the environment cannot achieve sufficient accuracy [11], [12]. Besides it requires precise map of observable landmarks, which is not always available depending on the application. Another approach is found in previous research on SLAM: the calibration process of a distributed sensor network is generally formalized as a relaxation on a mesh [13]. However the mesh itself is a rather strong constraint. To achieve good accuracy of localization with less constraint on the application environment, we use the cooperative positioning system (CPS) [14] which has originally been developed by one of the authors of this paper. In contrast to the previous work, our system proposed in this paper works in deterministic and straightforward manner without relaxation. It is applicable to any topology of sensor distribution in our daily life environment.

Thus the robotic calibration system has been developed. It is useful not only for initial construction of the distributed vision network but also for maintenance of it for permanent operation. The paper is structured as followings. Section two shows the principle of the method. Section three explains actual implementation of the group robot for camera calibration. Result of experiments is demonstrated in section four. Then we conclude the paper in section five.

II. CALIBRATION OF DISTRIBUTED CAMERAS

A. Calibration of Camera

Camera parameters are calibrated by using at least seven points distributed within a field of view of the camera. Required data for each point are 3D position in the world coordinate frame and corresponding 2D position in the image coordinate frame [15]. Usually we need more data points to overcome errors of measurement. However it is tiresome to obtain a large number of such data of points appropriately distributed within a view field of a camera, since the view field of the camera in our application is rather large compared with the size of the robots and human body. Furthermore there exist multiple cameras distributed far and widely in the area for daily human activities.

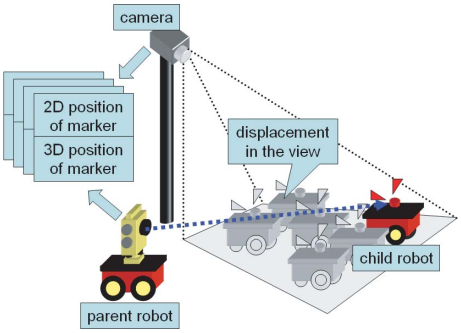

Fig. 3. Data acquisition for camera calibration: position of visibly distinguishable marker on a child robot is measured by the camera while 3D position of the marker is measured by a parent robot using precision measuring machine.

We have developed a calibration system with a group of robots. The group is composed of a parent robot and child robots. The parent robot is equipped with a precision 3D measurement machine that uses laser. The child robots are equipped with visible markers made of LED (Light Emission Diode) and with corner cubes for laser reflection. The 3D position of the corner cube is accurately measured by using the 3D measurement machine on the parent robot. Since the mutual spatial relationship between the LED markers and the corner cubes on a child robot is fixed and known, 3D position of the LED marker is accurately measured. Corresponding position of the marker on the 2D imaging plane of the camera is also obtained by image processing of the camera.

The calibration data set for each camera is obtained as followings (see Fig.3). The child robot positions itself at an appropriate point on the floor within the view field of a camera to be calibrated. Then the parent robot measures the 3D position of the corner cubes mounted on the child robot. The position of the LED marker is calculated from position data of the corner cubes. At the same time, the corresponding position of the LED on the 2D imaging plane of the camera is obtained by image processing. Once the measurement is accomplished, the child robot moves to another point within the view field of the camera. Thus, repeating displacement of the child robot and measurement of markers, necessary number of data set is obtained.

B. Cooperative Positioning System with Multiple Robots

Since cameras are distributed widely and rather sparsely in the environment, the fields of view of all cameras cannot be seen from one unique viewpoint (Fig.4). The fields of view are not overlapping either. Therefore, the group of calibration robots must travel a long way to visit the field of view of the cameras one after another along traversable outdoor passages

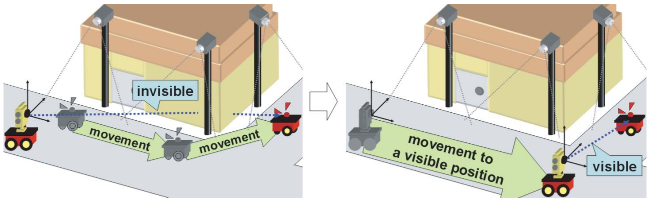

Fig. 4. Calibration of widely distributed camera: a group of robots travels a long way to overcome occlusion.

or indoor corridors while avoiding collisions with obstacles. However, actual path planning method is beyond the scope of this paper. We simply assume that a reference route is generated by a planner, and that the planner uses a map which roughly describes distribution of cameras. Such a map is to be made when the cameras were installed.

We use the cooperative positioning system (CPS) to accurately localize all the robots of the group in a unified world coordinate system. This automatically guarantees the accurate calibration of the cameras in a unified world coordinate system. The principal idea of the cooperative positioning is as followings (Fig.5).

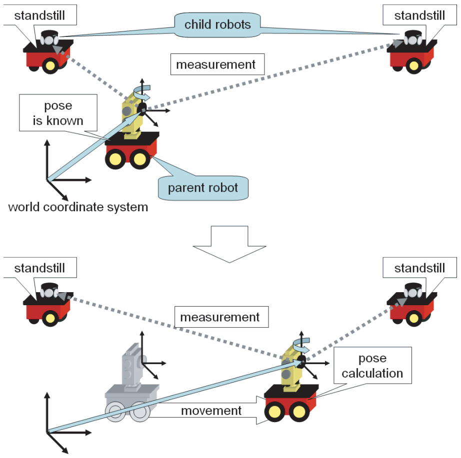

Fig. 5. Principle of cooperative positioning

1) Initial pose of the parent robot is identified with respect to the world coordinate system. It may be given from an external pose sensing system, or it may be obtained by robot itself by measuring external landmarks whose position is known.
2) The child robots travel certain distance along the given reference route, then stop.
3) Pose of the child robots is accurately measured by the parent robot.
4) The child robots remain stationary, while the parent robot travels a certain distance towards its goal.
5) Pose of the child robots is again accurately measured by the parent robot at the new position, and then the pose of the parent robot is calculated with respect to the world coordinates system.
6) Steps 2) through 5) are repeated until each robot achieves their goal for camera calibration.

C. Calculation of Robot Pose in Cooperative Positioning System

The parent robot and the child robots execute incremental move towards their goals alternately in the cooperative positioning process as described in section II.B.

Two-axes inclination sensor is mounted on the parent robot to compensate the inclination of the robot body on the uneven ground. Thanks to this compensation, the coordinate system of the parent robot is defined such that x-axis coincides with the forward motion direction of the robot and that z-axis orients perpendicularly upwards. The pose of the parent robot is defined by rotation angle ${}^{w}\phi_p$ around z-axis and translation vector ${}^{w}\mathbf{P}_p$ with respect to the world coordinate system.

Thus the measured position ${}^{m}\mathbf{P}_c$ of the child robot using the measuring machine is transformed to be ${}^{w}\mathbf{P}_c$ with respect to the world coordinate system by

$$ {}^{w}\mathbf{P}_c = \mathbf{R}({}^{w}\phi_p)\ {}^{m}\mathbf{P}_c + {}^{w}\mathbf{P}_p \qquad (1) $$

where

$$ \mathbf{R}(\phi) = \begin{bmatrix} \cos\phi & -\sin\phi & 0 \\ \sin\phi & \cos\phi & 0 \\ 0 & 0 & 1 \end{bmatrix}. $$

We assume that the parent robot is localized in the very first position. The position of the two child robots is obtained as ${}^{w}\mathbf{P}_{c1}$, ${}^{w}\mathbf{P}_{c2}$ respectively using equation (1) with measured position. After the incremental move of the parent robot, the position of the child robots is measured as ${}^{m}\mathbf{P}_{c1}$, ${}^{m}\mathbf{P}_{c2}$ respectively. Then using unknown rotation angle ${}^{w}\phi_p$ and unknown position ${}^{w}\mathbf{P}_p$ of the parent robot, we obtain

$$ {}^{w}\mathbf{P}_{ci} = \mathbf{R}({}^{w}\phi_p)\ {}^{m}\mathbf{P}_{ci} + {}^{w}\mathbf{P}_p \qquad (i = 1, 2). $$

From these equations $(i = 1, 2)$ we obtain

$$ {}^{w}\mathbf{P}_{c1} -{}^{w}\mathbf{P}_{c2} = \mathbf{R}({}^{w}\phi_p)\,(\,{}^{m}\mathbf{P}_{c1} - {}^{m}\mathbf{P}_{c2}). \qquad (2) $$

Soving equation (2) we obtain the rotation angle and the position by

$$ \begin{aligned} {}^{w}\phi_p &= atan2({}^{w}y_{c1} - {}^{w}y_{c2},\ {}^{w}x_{c1} - {}^{w}x_{c2}) \\ &\quad -atan2({}^{m}y_{c1} - {}^{m}y_{c2},\ {}^{m}x_{c1} - {}^{m}x_{c2}) \\ {}^{w}\mathbf{P}_p &= {}^{w}\mathbf{P}_{c1} - \mathbf{R}({}^{w}\phi_p)\ {}^{m}\mathbf{P}_{c1} \end{aligned} $$

where

$$ \begin{aligned} {}^{w}\mathbf{P}_{ci} &= [\ {}^{w}x_{ci}\ \ {}^{w}y_{ci}\ \ {}^{w}z_{ci}\ ]^T \\ {}^{m}\mathbf{P}_{ci} &= [\ {}^{m}x_{ci}\ \ {}^{m}y_{ci}\ \ {}^{m}z_{ci}\ ]^T \qquad (i = 1, 2). \end{aligned} $$

Repeating this process, the pose of the paraent robot is calculated after every incremental movement.

An example of alternative move of the parent robot and the child robots in cooperative positioning is shown in Fig.6. At the initial configuration, the pose of the parent is known with respect to the world coordinate system (upper left frame of the figure). The three robots aligned in series in a long corridor of a building. The parent robot measures position of the two child robot. Then it moves certain distance towards the goal and stops (upper middle frame). Again the parent measures position of the child robots and calculate its pose (upper right frame). Then two child robots move to next

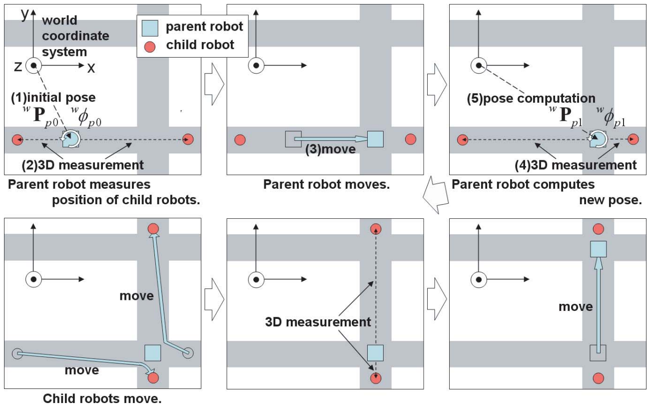

Fig. 6. Alternative move of parent robot and child robots in cooperative positioning in a passage of a building

planned positions respectively, and stop (lower left frame). The parent robot measures two child robots at their new positions (lower middle frame), and then it moves to certain distance and stops (lower right frame). These steps are repeated until the parent robot achieves its goal. In this way, accurate pose of the parent is maintained even if the robots must travel a long distance in a floor surrounded by walls and obstacles.

III. IMPLEMENTATION OF GROUP ROBOT

A. 3D Measurement Machine

Accurate 3D measurement has principal importance in twofold: 3D measurement of LED markers for camera calibration and 3D measurement of robot position in the cooperative positioning system. We use Total Station GTS-820A made by TOPCON inc., a laser measuring machine for the construction and civil engineering. This machine measures 3D position of a reflection point of the laser based on the time-of-flight measurement together with precise angle of laser deflection. A corner cube made of optical prism is attached at the point to be measured, then the measuring machine automatically searches for the corner cube and measures its position if the machine direction is adjusted within 5 degrees with respect to the correct direction to the corner cube. Direction of the machine is controlled by a computer for approximate adjustment toward the target corner cube. The specification of measurement is shown in Table I.

TABLE I

SPECIFICATION OF LASER MEASUREMENT

Distance measurement	Range	1.3-2200 m
	Precision	±(2 mm + 2 ppm×Distance)
	Output resolution	0.2 mm
Angle measurement	Precision	5 sec
	Output resolution	1 sec
Automatic aim	Range of search	±5 deg

B. Assembly of LED Markers and Corner Cubes

Geometric configuration of LED markers and the corner cubes is shown in Fig.7. The LED-corner cube assembly is mounted on a child robot. Since the robot moves around mostly on a planer floor, we use 4 LEDs attached on the assembly at different height in order to obtain calibration points adequately distributed in 3D volume, which enable to obtain camera parameters with good accuracy.

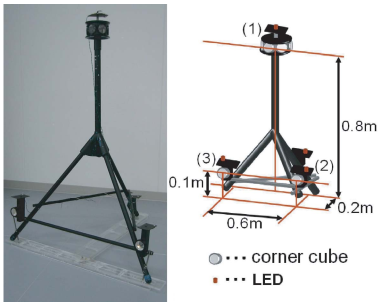

Fig. 7. Arrangement of LEDs and corner cubes

The 3D positions of three corner cubes are accurately measured by using the 3D measurement machine on the parent robot. Since the mutual spatial relationship between the LED markers and the corner cubes on a child robot is fixed and known, 3D positions of the LEDs are obtained from 3D position measurement of three corner cubes. Three corner cubes guarantee to obtain 3D position of LEDs even if the orientation of the robot changes during its travel.

C. Detection and Measurement of Marker Position on 2D Image

The image subtraction is used to measure 2D position of the LED markers on the imaging plane of a camera under the ordinary lighting condition of the daily human life environment. Since light-on and light-off control of the LEDs is made by the robot, 2D position of the LED markers is obtained reliably and accurately by subtraction of images corresponding to the light-on and the light-off respectively.

D. Parent Robot and Child Robots

A wheeled mobile robot (PIONEER3-AT, 50cm×49cm×26cm, 30kg max.load) is used as the parent robot body. The LED markers and corner cubes assembly is mounted on a smaller wheeled robot (PIONEER3-DX, 44cm×38cm×22cm, 23kg max.load) to be used as the child robot (Figs.8,9).

Fig. 8. Parent robot

Fig. 9. Child robot

IV. EXPERIMENTS

The calibration robot system has been evaluated through experiments. Figs.10 and 11 show the setups of the experiment in an entrance hall of the department building of our university. Three cameras are distributed and fixed in a large indoor space having 60m depth, 15m width and 8m height. The grey areas in Fig.10 are stairs and other structures surrounded by wall and inaccessible to robots. Each camera is fixed near the wall with 2.5m height, observing the floor with view direction of approximately 20 degrees downward with respect to the horizontal level.

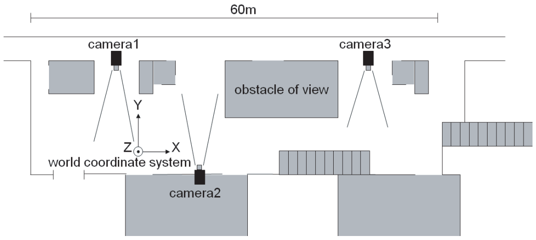

Fig. 10. Experiment setup (top view)

Fig. 11. Experiment space (oblique view)

The parent robot cannot simultaneously observe all the area of view of the three cameras at any single location on the floor. Therefore the parent robot travels around the floor to sequentially calibrate the cameras one by one as shown in Fig.12. Total traveling distance of the parent robot is approximately 85 m with two 90-degrees-turns. During the travel, the group of robots calibrates camera1, camera2, camera3, and then camera2 again and finally camera1 again. Thus we evaluate position errors of CPS in a long distance travel.

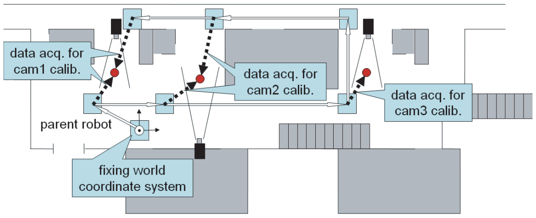

Fig. 12. Experiment sequence of cooperative positioning and data acquisition for camera calibration. Red small circle represent the child robot within the field of view of the camera.

Detail of the calibration process is as followings:

1) The parent robot is located at the initial position before starting the camera calibration travel. The coordinate system attached to the measuring machine on the parent robot at its initial position is used as the unified world coordinate system (See Fig.12).
2) At the initial position, the parent robot observes and measures the pose of the child robot which moves and positions within view areas in camera1 and camera2. Synchronously, position of LED markers on the child robot is measured with respect to the image coordinate system. Thus we obtain two dataset composed of 70 points of the LED markers in 3D coordinate system and 2D image coordinate system for each camera. These data sets are reference data to evaluate the calibration accuracy later.
3) The parent robot moves to the first position to calibrate camera1 by using cooperative positioning method with two child robots. Then the parent robot observes and measures the position of the child robot moving and positioning within the view area of the camera1. Position of LED markers is also measured in the image plane coordinate of the camera. Using these dataset, the camera1 is calibrated.
4) The parent robot moves to the next position for camera calibration using cooperative positioning method and obtains dataset for calibration with the child robot. This step is repeated until all the cameras are calibrated.

Table II shows camera parameter obtained through the experiment. The result of calibration can be analyzed from several different points of view. Position error of the camera is one of evaluation indices. Error of camera1 and camera2 are calibrated twice: at the first part and the last part of the round travel with traveling distance of 85m. Difference of calibrated position of camera1 is (37.7mm 18.9mm -1.1mm) with respect to the world coordinate system. Difference of calibrated position of camera2 is (39.0mm -24.57mm -10.56mm).

TABLE II

CALIBRATED PARAMETERS OF THE CAMERAS

parameter \ camera		1(1st)	2(1st)	3	2(2nd)	1(2nd)
focus length / pixel size [pix]		770.3	761.8	754.2	770.4	763.9
center of image	x-axis [pix]	160.0	170.3	159.9	142.6	154.7
	y-axis [pix]	120.1	109.1	120.0	111.9	115.4
1st order radial lens distortion coefficient[1/mm^2]		4.33E-7	8.08E-8	7.02E-7	1.98E-7	2.82E-7
position	X-axis [mm]	-3355.1	12506.6	42900.6	12545.6	-3318.4
	Y-axis [mm]	10625.5	-1101.1	9298.2	-1125.7	10644.4
	Z-axis [mm]	2117.4	2079.2	2075.6	2068.7	2116.3
rotation	around X-axis [deg]	115.5	-112.4	-123.5	-112.6	115.6
	around Y-axis [deg]	-2.9	2.9	2.6	0.7	-2.7
	around Z-axis [deg]	178.2	-1.6	-173.5	-1.7	178.1

Error of calibration is also evaluated by average error distance between measured 3D position of the LED marker and the corresponding computed line of view using the calibrated parameters with 2D marker position on the image plane. Average pixel error is obtained by computing 2D projection of 3D point on the image plane of the camera using the calibrated parameters. We use the reference dataset measured for camera1 and camera2 by the parent robot at the origin of the world coordinate system. Each dataset is composed of 70 data points in 3D and 2D, which are regarded as the ground truth.

TABLE III

EVALUATION OF CAMERA ERROR

camera		1(1st)	2(1st)	2(2nd)	1(2nd)
world coordinate system	pixel error [pix]	1.02	1.33	4.04	8.54
	3D error [mm]	7.53	11.47	32.35	60.24
local coordinate system	pixel error [pix]	0.62	0.81	0.75	0.66
	3D error [mm]	4.39	6.54	6.20	4.69

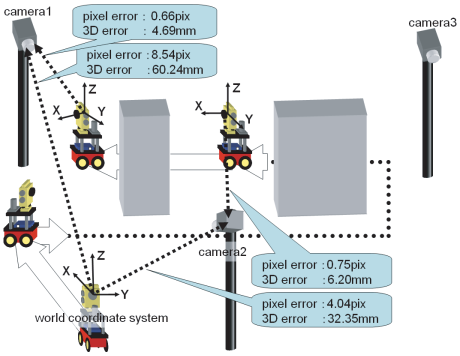

Fig. 13. Evaluation of parameters

Upper two rows in Table III show average position error of measurement by camera with respect to the world coordinate system. Error is increased according to the traveling distance of the parent robot. This is due to the nature of the position measurement by CPS: position error is accumulated along the repetition of robot motion and relative position measurement. However, the error is very small compared with the long distance travel of 85m.

Lower two rows in Table III show average position error of measurement by camera with respect to the local coordinate system when the parent robot located itself at the measuring position for each camera calibration during its travel. The errors are small and almost constant regardless of traveling distance.

In our application of the distributed camera, robots and other moving objects like pedestrians are visually observed and their mutual positions are measured within a view area of a camera. The results of the measurement are sent to the robots so that the robots can take appropriate action like local collision avoidance. The camera calibration error with respect to the local coordinate system is sufficiently small for this purpose. On the other side, the robots plan global motion passing through the view area of different cameras so that they are visually supported by the distributed vision system. The camera calibration error with respect to the world coordinate system is sufficiently small for this purpose. Especially mutual error between two adjacent cameras is negligibly small.

V. CONCLUSIONS

This paper proposes a calibration method of a distributed vision network in a unified world coordinate system. A group of mobile robots has been developed to obtain a set of calibration data for each camera distributed and installed in a wide area of the human daily life environment such as a block of a town or a big floor of hospital. The child robot equipped with LED vision markers and corner cubes moves around within a view field of a camera so that 2D positions of the LED markers on the imaging plane of the camera are measured, while the parent robot equipped with a precision range finder measures the 3D position of the corner cubes to calculate corresponding 3D position of the LED markers. The camera parameters are estimated from the set of data point thus obtained within the view field. The group of robots visits every view field of the cameras traveling a long way while measuring the pose of the parent with respect to the unified world coordinate system using the cooperative positioning system. The result of experiments demonstrates effectiveness of the method and the system.

REFERENCES

[1] Tsutomu Hasegawa and Kouji Murakami, “Robot Town Project: Supporting Robots in an Environment with Its Structured Information”, *Proc. of The 3rd International Conference on Ubiquitous Robots and Ambient Intelligence*, pp.119-123, Seoul, Korea, Oct. 2006.

[2] Tsai, Roger Y, “An Efficient and Accurate Camera Calibration Technique for 3D Machine Vision”, *IEEE Conference on Computer Vision and Pattern Recognition*, pp.364-374, 1986.

[3] Z.Zhang, “A Fiexible New Technique for Camera Calibration”, *IEEE Trans. on Pattern Analysis and Machine Intelligence*, Vol.22, No.11, pp.1330-1334, 2000.

[4] X.Meng and Z.Hu, “A New Easy Camera Calibration Technique Based on Circular Points”, *Pattern Recognition*, Vol.36, pp.1155-1164, 2003.

[5] Ryan White and D.A.Forsyth, “Deforming Objects Provide Better Camera Calibration”, *Technical Report*, No.EECS-2005-3, EECS Department, University of California, Berkeley, 2005.

[6] Q.Chen, H.Wu and T.Wada. “Camera Calibration with Two Arbitrary Coplanar Circles”, *IEEE Conf.on ECCV’04*, pp.521-532, 2004.

[7] S. Ikeda, T. Sato and N. Yokoya, “Geometric Registration in Outdoor Environments Using Landmark Database Generated from Omnidirectional Videos and GPS Positions”, *Int. Workshop on Mixed Reality Technology for Filmmaking*, pp.8-13, Oct. 2006.

[8] A.Azarbayejani and A.Pentland, “Real-Time Self-Calibrating Stereo Person Tracking Using 3-D Shape Estimation from Bolb Features”, *13th ICPR*, vol.3, pp.627-632, 1996.

[9] X.Chen,J.Davis and P.Slusallek, “Wide Area Camera Calibration Using Virtual Calibration Objects”, *CVPR2000*, vol.2, pp.520-527, 2000.

[10] Ryo Kurazume and Shigeo Hirose, “Study on Cooperative Positioning System - Optimum Moving Strategies for CPS-III -”, *IEEE Int.Conf.on Robotics and Automation*, Vol.4, pp.2896-2903, 1998.

[11] Andreas Nuchter and Hartmut Surmann, “6D SLAM with an Application in Autonomous Mine Mapping”, *IEEE International Conference on Robotics and Automation*, pp.1998-2003, 2004.

[12] Stephen Se, David Lowe and Jim Little, “Mobile Robot Localization and Mapping with Uncertainty Using Scale-Invariant Visual Landmarks”, *International Journal of Robotics Research*, August, 2002.

[13] Andrew Howard,Maja J Mataric and Gaurav S.Sukhatme, “Relaxation on a Mesh: a Formalism for Generalized Localization”, *IEEE/RSJ Int.Conf.on Intelligent Robots and Systems*, pp.1055-1060, 2001.

[14] Ryo Kurazume, Shigemi Nagata and Shigeo Hirose, “Cooperative Positioning with Multiple Robots”, *IEEE Int.Conf.on Robotics and Automation*, Vol.2, pp.1250-1257, 1994.

[15] Berthold K.P.Horn, “Tsai’s Camera Calibration Method Revisited”, *Department of Electrical Engineering and Computer Science Massachusetts Institute of Technology*, 2000.