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A Self-Position Estimation Algorithm for Multiple Mobile Robots Using Two Omnidirectional Cameras and an Accelerometer

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Abstract: This paper proposes a self-position estimate algorithm for the multiple mobile robots; each robot uses two omnidirectional cameras and an accelerometer. In recent years, the Great East Japan Earthquake and large-scale disasters have occurred frequently in Japan. From this, development of the searching robot which supports the rescue team to perform a relief activity at a large-scale disaster is indispensable. Then, this research has developed the searching robot group system with two or more mobile robots. In this research, the searching robot equips with two omnidirectional cameras and an accelerometer. In order to perform distance measurement using two omnidirectional cameras, each parameter of an omnidirectional camera and the position and posture between two omnidirectional cameras have to be calibrated in advance. If there are few mobile robots, the calibration time of each omnidirectional camera does not pose a problem. However, if the calibration is separately performed when using two or more robots in a disaster site, etc., it will take huge calibration time. Then, this paper proposed the algorithm which estimates a mobile robot's position and the parameter of the position and posture between two omnidirectional cameras simultaneously. The algorithm proposed in this paper extended Nonlinear Transformation (NLT) Method. This paper conducted the simulation experiment to check the validity of the proposed algorithm. In some simulation experiments, one mobile robot moves and observes the circumference of another mobile robot which has stopped at a certain place. This paper verified whether the mobile robot can estimate position using the measurement value when the number of observation times becomes 10 times in π/18 of observation intervals. The result of the simulation shows the effectiveness of the algorithm.

Key words: Multiple mobile robots, omnidirectional cameras, self-position estimation algorithm.

1. Introduction

In recent years, the Great East Japan Earthquake and large-scale disasters have occurred frequently in Japan. From this, development of the searching robot which supports the rescue team to perform a relief activity at a large-scale disaster is indispensable.

Until now, various disaster relief robots have developed [1-3]. This research is developing the system which searches the wide area by two or more robots in a disaster relief task. When searching the wide area using a searching robot, it becomes important to know a robot's position correctly. Then, this paper proposes the position estimate algorithm for a mobile robot group. Each robot is equipped with two omnidirectional cameras and an accelerometer.

In this research, each mobile robot uses two omnidirectional cameras to observe the surrounding mobile robot and get the relative position between mobile robots. A mobile robot presumes its own position using this relative position and the

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three-dimensional coordinate acquired from an accelerometer.

Here, it becomes important that each mobile robot gets correctly the distance between the mobile robots obtained from two omnidirectional cameras. In order for a mobile robot to know correctly the distance between the mobile robots obtained from two omnidirectional cameras, each parameter of the omnidirectional camera and the position and posture between two omnidirectional cameras have to be calibrated in advance. If there are few mobile robots, the calibration time of each omnidirectional camera does not pose a problem. However, if the calibration is separately performed when using two or more robots in a disaster site etc., it will take huge calibration time. Then, this paper proposes an algorithm for each mobile robot to perform position estimate simultaneously with presumption of the position and posture between two omnidirectional cameras.

Until now, the position estimate technique of the mobile robot using two omnidirectional cameras performs the mobile robot's position estimate by acquiring the three-dimensional information on observation space using the azimuth difference of the picture obtained from two cameras [4]. A mobile robot makes obstacle avoidance, etc. possible using this three-dimensional information.

However, in this research, a mobile robot observes the surrounding mobile robot with two omnidirectional cameras, and gets the distance between mobile robots. A mobile robot performs position estimate using the information from this distance and an accelerometer. The algorithm proposed by this research is an extension of Nonlinear Transformation (NLT) Method. NLT Method is the calibration technique which presumes the position and posture between the fixed cameras used for motion capture, etc. In NLT Method, it is known that there is no restriction in calibration pattern form [5]. This research assumes that two or more mobile robots operate simultaneously. When treating two or more mobile robots simultaneously, the surrounding mobile robot is observed as a calibration pattern, and a mobile robot presumes the position and posture between two omnidirectional cameras and distance to the circumference mobile robot simultaneously, using the information observed on the circumference and obtained from the sensor. This paper conducted the simulation experiment of the proposed position estimate algorithm.

In a simulation experiment, a mobile robot moves on a plane and alone the concentric circle centered by other mobile robots counterclockwise. The mobile robot observes the mobile robot which is present in a center. Moreover, this simulation experiment uses the parameter of the actually manufactured omnidirectional mirror attachment and the focal length of commercial PC camera. On this condition, this paper verified whether the mobile robot can estimate position.

The result shows that position estimate was possible using the measurement value when the number of observation times becomes 10 times in $\pi/18$ of observation intervals.

The paper is organized as follows: Section 2 describes formulation of the problem in this research; section 3 describes the self-position estimation algorithm which used two omnidirectional cameras; section 4 describes simulation experiment; section 5 describes discussion; and section 6 is conclusions.

2. Problem Formulization

The subject of this research is to estimate the position and posture of two omnidirectional cameras equipped in the mobile robot and position of a mobile robot simultaneously. In this research, a mobile robot equips as shown in Fig. 1 the two omnidirectional cameras up and down. A mobile robot observes the marker equipped on the surrounding mobile robots by this omnidirectional camera. The robot estimates the position between the lower omnidirectional camera and the markers of other mobile robots using the information acquired at this time.

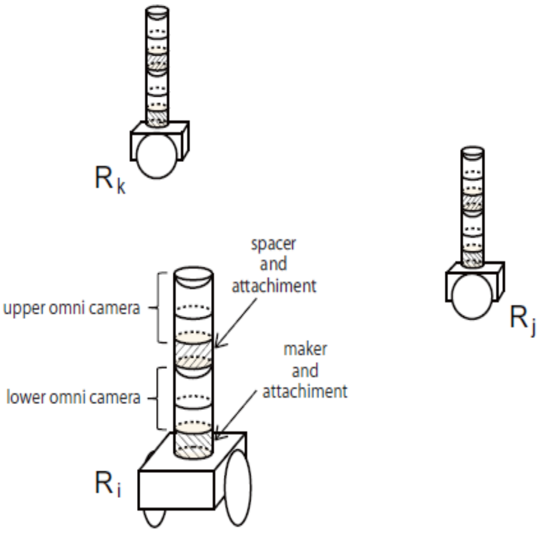

Fig. 1 Outline of the distance measurement using two omnidirectional cameras.

Fig. 2 shows the geometric relation between two omnidirectional cameras equipped the robot Ri and the marker equipped robot Rj. $\mathbf{X}_j$ (X_j, Y_j, Z_j) in Fig. 2 is an absolute coordinate of the marker equipped mobile robot j which mobile robot Ri observes. ${}^{i1}\mathbf{u}_{1j}$ (${}^{i1}u_{1j}$, ${}^{i1}v_{1j}$) and ${}^{i2}\mathbf{u}_{2j}$ (${}^{i2}u_{2j}$, ${}^{i2}v_{2j}$) are the picture coordinates of the up-and-down omnidirectional cameras, with which the mobile robot Ri observed the marker equipped the mobile robot Rj.

The subscript 1 shows the lower omnidirectional camera equipping on the mobile robot, and 2 shows the upper part. $i1$ and $i2$ express the coordinate system of the up-and-down omnidirectional camera equipped on the mobile robot Ri. ${}^{i1}\mathbf{d}_{1j}$ expresses the vector to the marker of the mobile robot Rj from the lower omnidirectional camera on the mobile robot Ri. ${}^{i2}\mathbf{d}_{2j}$ expresses the vector to the marker of the mobile robot Rj from the upper omnidirectional camera of the mobile robot Ri. ${}^{i1}\mathbf{d}_{12}$ expresses the vector between up-and-down omnidirectional cameras.

In Fig. 2, the relation between the absolute coordinate of the marker with which the mobile robot Rj was equipped, and the picture coordinates of the up-and-down omnidirectional camera with which the mobile robot Ri was equipped as Eqs. (1)-(2) and (4)-(5).

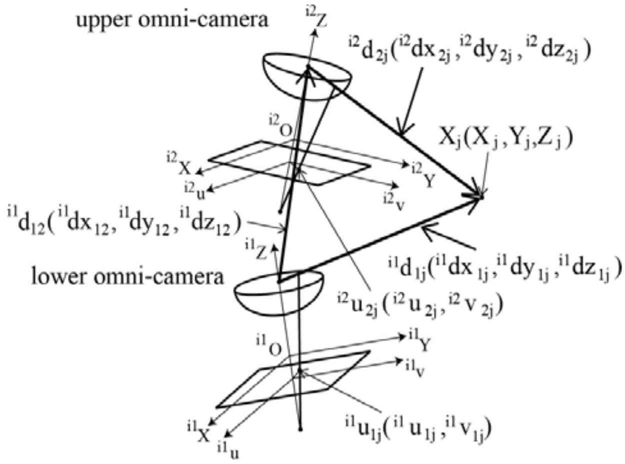

Fig. 2 The geometric relation of two omnidirectional cameras equipped on the robot Ri and the marker equipped robot Rj.

$$ {}^{i1}u_{1j} = \frac{{}^{i1}dx_{1j} f_1 (b_1^2 - c_1^2)}{(b_1^2 + c_1^2)\,{}^{i1}dz_{1j} - 2b_1 c_1 D_1} \tag{1} $$

$$ {}^{i1}v_{1j} = \frac{{}^{i1}dy_{1j} f_1 (b_1^2 - c_1^2)}{(b_1^2 + c_1^2)\,{}^{i1}dz_{1j} - 2b_1 c_1 D_1} \tag{2} $$

where D_1 is

$$ D_1 = \sqrt{({}^{i1}dx_{1j})^2 + ({}^{i1}dy_{1j})^2 + ({}^{i1}dz_{1j})^2} \tag{3} $$

$$ {}^{i2}u_{2j} = \frac{{}^{i2}dx_{2j} f_2 (b_2^2 - c_2^2)}{(b_2^2 + c_2^2)\,{}^{i2}dz_{2j} - 2b_2 c_2 D_2} \tag{4} $$

$$ {}^{i2}v_{2j} = \frac{{}^{i2}dy_{2j} f_2 (b_2^2 - c_2^2)}{(b_2^2 + c_2^2)\,{}^{i2}dz_{2j} - 2b_2 c_2 D_2} \tag{5} $$

where D_2 is

$$ D_2 = \sqrt{({}^{i2}dx_{2j})^2 + ({}^{i2}dy_{2j})^2 + ({}^{i2}dz_{2j})^2} \tag{6} $$

In Eqs. (1)-(2) and (4)-(5), ${}^{i1}dx_{1j}$, ${}^{i1}dy_{1j}$, ${}^{i1}dz_{1j}$, ${}^{i2}dx_{2j}$, ${}^{i2}dy_{2j}$, and ${}^{i2}dz_{2j}$ express each ingredient of vector ${}^{i1}\mathbf{d}_{1j}$ and ${}^{i2}\mathbf{d}_{2j}$ to the marker of the mobile robot Rj from the up-and-down omnidirectional camera on the mobile robot Ri. Vector ${}^{i1}\mathbf{d}_{1j}$ of Eqs. (1) and (2) can be expressed as follows using distance vector ${}^{i2}\mathbf{d}_{2j}$ and ${}^{i1}\mathbf{d}_{12}$ shows in Fig. 2:

$$ {}^{i1}\mathbf{d}_{1j} = {}^{i1}\mathbf{d}_{12} + {}^{i2}\mathbf{d}_{2j} \tag{7} $$

Vector ${}^{i2}\mathbf{d}_{2j}$ of Eqs. (3)-(4) and (7) performs coordinate conversion as follows using coordinate conversion procession ${}^{i1}\mathbf{T}_{i2}$:

$$ {}^{i1}\mathbf{d}_{2j} = {}^{i1}\mathbf{T}_{i2}\,{}^{i2}\mathbf{d}_{2j} \tag{8} $$

Using above Eqs. (7) and (8), Eqs. (1)-(2) and (4)-(5) are rewritten as

$$
\begin{aligned}
&((b_1^2 - c_1^2) f_1)^{i1} dx_{2j} - ((b_1^2 + c_1^2)^{i1} u_{1j})^{i1} dz_{2j} \\
&+ ((b_1^2 - c_1^2) f_1{}^{i1} dx_{12} - (b_1^2 + c_1^2)^{i1} u_{1j}{}^{i1} dz_{12}) \\
&+ (2 b_1 c_1{}^{i1} u_{1j}) \grave{D}_1 = 0
\end{aligned} \tag{9}
$$

$$
\begin{aligned}
&((b_1^2 - c_1^2) f_1)^{i1} dy_{2j} - ((b_1^2 + c_1^2)^{i1} v_{1j})^{i1} dz_{2j} \\
&+ ((b_1^2 - c_1^2) f_1{}^{i1} dy_{12} - (b_1^2 + c_1^2)^{i1} v_{1j}{}^{i1} dz_{12}) \\
&+ (2 b_1 c_1{}^{i1} v_{1j}) \grave{D}_1 = 0
\end{aligned} \tag{10}
$$

$\grave{D}_1$ becomes the following:

$$
\begin{aligned}
\grave{D}_1 = (&({}^{i1}dx_{12} + {}^{i1}dx_{2j})^2 + ({}^{i1}dy_{12} + {}^{i1}dy_{2j})^2 \\
&+ ({}^{i1}dz_{12} + {}^{i1}dz_{2j})^2)^{1/2}
\end{aligned} \tag{11}
$$

$$
\begin{aligned}
&((b_2^2 - c_2^2) f_2 t_{11} - (b_2^2 + c_2^2)^{i2} u_{2j} t_{31})^{i1} dx_{2j} \\
&+ ((b_2^2 - c_2^2) f_2 t_{12} - (b_2^2 + c_2^2)^{i2} u_{2j} t_{32})^{i1} dy_{2j} \\
&+ ((b_2^2 - c_2^2) f_2 t_{13} - (b_2^2 + c_2^2)^{i2} u_{2j} t_{33})^{i1} dz_{2j} \\
&+ (2 b_2 c_2{}^{i2} u_{2j}) \grave{D}_2 = 0
\end{aligned} \tag{12}
$$

$$
\begin{aligned}
&((b_2^2 - c_2^2) f_2 t_{21} - (b_2^2 + c_2^2)^{i2} v_{2j} t_{31})^{i1} dx_{2j} \\
&+ ((b_2^2 - c_2^2) f_2 t_{22} - (b_2^2 + c_2^2)^{i2} v_{2j} t_{32})^{i1} dy_{2j} \\
&+ ((b_2^2 - c_2^2) f_2 t_{23} - (b_2^2 + c_2^2)^{i2} v_{2j} t_{33})^{i1} dz_{2j} \\
&+ (2 b_2 c_2{}^{i2} v_{2j}) \grave{D}_2 = 0
\end{aligned} \tag{13}
$$

$\grave{D}_2$ becomes the following:

$$
\begin{aligned}
\grave{D}_2 = (&(t_{11}{}^{i1}dx_{2j} + t_{12}{}^{i1}dy_{2j} + t_{13}{}^{i1}dz_{2j})^2 \\
&+ (t_{21}{}^{i1}dx_{2j} + t_{22}{}^{i1}dy_{2j} + t_{23}{}^{i1}dz_{2j})^2 \\
&+ (t_{31}{}^{i1}dx_{2j} + t_{32}{}^{i1}dy_{2j} + t_{33}{}^{i1}dz_{2j})^2)^{1/2}
\end{aligned} \tag{14}
$$

t_{11}-t_{33} of Eqs. (12)-(14) express each ingredient of coordinate conversion procession ${}^{i1}\mathbf{T}_{i2}$. In Eqs. (9)-(10) and (12)-(13), it is assumed that each parameter a_1, b_1, c_1, f_1, a_2, b_2, c_2, f_2, ${}^{i1}\mathbf{d}_{12}$, and ${}^{i1}\mathbf{T}_{i2}$ of the up-and-down cameras of the mobile robot Ri are exact. By this condition, the mobile robot Ri observes the mobile robot Rj, and gets picture coordinates ${}^{i1}\mathbf{u}_{1j}$ and ${}^{i2}\mathbf{u}_{2j}$. At this time, Eqs. (9)-(10) and (12)-(13) become four equations in which each elements of vector ${}^{i1}\mathbf{d}_{2j}$ from the mobile robot Ri to the mobile robot Rj are an unknown.

The parameters a_1, b_1, a_2, and b_2 are the form of an omnidirectional mirror. Each value of these parameters is determined at the time of design. Each value of c_1 and c_2 is determined by a_1, b_1, a_2, and b_2. And, f_1 and f_2 are the focal lengths of a camera. Each value of f_1 and f_2 uses the value of commercial PC camera in this research. From above, it is assumed that a_1, b_1, c_1, f_1, a_2, b_2, c_2, and f_2 are exact in this research.

Next, the vector ${}^{i1}\mathbf{d}_{12}$ and the coordinate conversion procession ${}^{i1}\mathbf{T}_{i2}$ between up-and-down omnidirectional cameras are the parameters which determine the position and posture between up-and-down omnidirectional cameras. This parameter determines a value by performing a calibration.

Here, if there is little number of the mobile robots, performing a calibration to each mobile robot will not pose a problem. However, if the number of mobile robots increases, performing a calibration will require time.

Then, this research proposes the algorithm which estimates parameter ${}^{i1}\mathbf{d}_{12}$ and ${}^{i1}\mathbf{T}_{i2}$ which determine the position and posture between up-and-down omnidirectional cameras and position of a mobile robot. The algorithm proposed by this research extends NLT Method.

3. Position Estimation Algorithm

The flow chart of the algorithm proposed by this research is shown in Fig. 3, where the mobile robot Ri observes mobile robot Rj. At this time, a mobile robot acts according to a certain action plan, and assumes that the mutual position is transmitted.

Firstly, mobile robot Ri observes the marker of robot Rj which exists in a range of observations, and the mobile robot Ri gets picture coordinates of an up-and-down omnidirectional camera ${}^{i1}\mathbf{u}_{1j,t}$, ${}^{i2}\mathbf{u}_{2j,t}$. The lower right subscript $1j$ means that the lower omnidirectional camera equipped on the mobile robot Ri observed the mobile robot Rj. $2j$ means that the upper omnidirectional camera equipped on the mobile robot Ri observed the mobile robot Rj. t expresses the number of times of observing the mobile robot Rj. The mobile robot Ri calculates unit direction cosine vector ${}^{i1}\mathbf{du}_{1j,t}$, and ${}^{i2}\mathbf{du}_{2j,t}$ to the marker which is on the surrounding mobile robot using picture coordinates ${}^{i1}\mathbf{u}_{1j,t}$ and ${}^{i2}\mathbf{u}_{2j,t}$. The mobile robot Ri calculates this unit

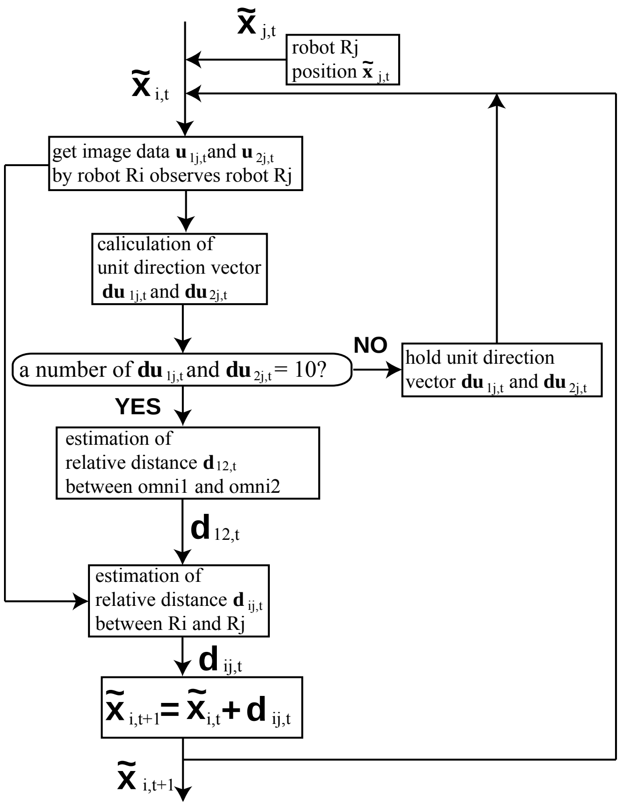

Fig. 3 The flow chart of the self-position estimation of the mobile robot.

direction cosine vector, while moving alone the mobile robot's Rj circumference. And the mobile robot Ri holds this unit direction cosine vector until a certain number of times. In the case of Fig. 3, it is 10 times.

Secondly, each ingredient ${}^{i1}dx_{12,t}$, ${}^{i1}dy_{12,t}$, ${}^{i1}dz_{12,t}$ of vector ${}^{i1}\mathbf{d}_{12,t}$ between two omnidirectional cameras are set up by the following Eqs. (15)-(17) using the coefficient K which rectifies the parameter of a camera system.

$$ {}^{i1}\tilde{d}x_{12,t} = \frac{{}^{i1}dx_{12,t}}{K} \quad (15) $$

$$ {}^{i1}\tilde{d}y_{12,t} = \frac{{}^{i1}dy_{12,t}}{K} \quad (16) $$

$$ {}^{i1}\tilde{d}z_{12,t} = \frac{{}^{i1}dz_{12,t}}{K} \quad (17) $$

Thirdly, mobile robot Ri presumes the optimal solution of ${}^{i1}\tilde{\mathbf{d}}_{12,t}$ and ${}^{i1}\mathbf{T}_{i2}$ from the following Eq. (18) using unit direction cosine vector ${}^{i1}\mathbf{du}_{1j,t}$ and ${}^{i2}\mathbf{du}_{2j,t}$ obtained by several observations and ${}^{i1}\tilde{\mathbf{d}}_{12,t}$ obtained from Eqs. (15)-(17).

The Levenberg-Marquart Method which is a least-squares method was used for the optimization of Eq. (18). At this time, Eq. (18) is a function which optimizes the parameter of each ingredient of ${}^{i1}\tilde{\mathbf{d}}_{12,t}$ and the rotation angle (ω, θ, κ) of each axis like Eq. (19). ω expresses the rotation angle of the circumference of an x-axis, θ expresses the rotation angle of the circumference of a y-axis, and κ expresses the rotation angle of the circumference of a z-axis.

$$ E_{12,t} = \frac{\left| r^{i1}\tilde{d}x_{12,t} + s^{i1}\tilde{d}y_{12,t} + t^{i1}\tilde{d}z_{12,t} \right|}{\sqrt{r^2 + s^2 + t^2}} \quad (18) $$

$$ \chi_{12,t} = E_{12,t}({}^{i1}\tilde{d}_{12,t}, \omega_{12,t}, \theta_{12,t}, \kappa_{12,t}) \quad (19) $$

Here, r, s, and t of Eq. (18) are as follows:

$$ r = {}^{i1}duy_{1j,t}\,{}^{i1}duz_{2j,t} - {}^{i1}duz_{1j,t}\,{}^{i1}duy_{2j,t} \quad (20) $$

$$ s = {}^{i1}duz_{1j,t}\,{}^{i1}dux_{2j,t} - {}^{i1}dux_{1j,t}\,{}^{i1}duz_{2j,t} \quad (21) $$

$$ t = {}^{i1}dux_{1j,t}\,{}^{i1}duy_{2j,t} - {}^{i1}duy_{1j,t}\,{}^{i1}dux_{2j,t} \quad (22) $$

The unit direction cosine vector ${}^{i1}\mathbf{du}_{2j,t}$ from an upper omnidirectional camera to an observation marker performed coordinate conversion as follows using coordinate conversion procession ${}^{i1}\mathbf{T}_{i2}$:

$$ {}^{i1}\mathbf{du}_{2j,t} = {}^{i1}\mathbf{T}_{i2}\,{}^{i2}\mathbf{du}_{2j,t} \quad (23) $$

Fourthly, the mobile robot Ri calculates the vector from Eq. (18) between the upper omnidirectional cameras and the marker equipped on the mobile robot Rj by Eqs. (9)-(10) and (12)-(13). At this time, the mobile robot Ri uses picture coordinates ${}^{i1}\mathbf{u}_{1j}$ and ${}^{i2}\mathbf{u}_{2j}$ obtained when the mobile robot Rj is observed.

And, parameter K, which rectifies the scale of the camera system of Eqs. (15)-(17), is rectified from the following Eq. (24) using the position $\mathbf{x}_{j,t}$ transmitted from mobile robot Rj and this vector ${}^{i1}\tilde{\mathbf{d}}_{2j,t}$.

$$ K = \frac{l_{ij,t}}{\hat{l}_{ij,t}} \quad (24) $$

$$ l_{ij,t} = \left\| \left(\tilde{\mathbf{x}}_{j,t} - \tilde{\mathbf{x}}_{i,t} \right) \right\| $$

$$ \hat{l}_{ij,t} = \left\| {}^{i1}\hat{\mathbf{d}}_{2j,t} \right\| $$

${}^{i1}\mathbf{d}_{12,t}$ are rectified from Eqs. (15)-(17) using K rectified by Eq. (24). And ${}^{i1}\tilde{\mathbf{d}}_{12,t}$ estimated Eq. (18). The vector ${}^{i1}\tilde{\mathbf{d}}_{2j,t}$ is estimated using the ${}^{i1}\mathbf{d}_{12}$ by solving Eqs. (9)-(10) and (12)-(13).

Finally, the vector ${}^{i1}\tilde{\mathbf{d}}_{1j,t}$ from the omnidirectional camera to the mobile robot Rj's marker as in Eq. (25) is calculated using vector ${}^{i1}\mathbf{d}_{12}$ between the up-and-down omnidirectional cameras and the vector ${}^{i1}\tilde{\mathbf{d}}_{2j,t}$ from an upper omnidirectional camera to the robot Rj's marker.

$$ {}^{i1}\hat{\mathbf{d}}_{1j,t} = {}^{i1}\mathbf{d}_{12,t} + {}^{i1}\hat{\mathbf{d}}_{2j,t} \quad (25) $$

The mobile robot Ri updates its own position ${}^{i1}\tilde{\mathbf{x}}_{i,t+1}$ using the position ${}^{i1}\tilde{\mathbf{x}}_{i,t}$ obtained from accelerometer and this vector ${}^{i1}\tilde{\mathbf{d}}_{1j,t}$.

The robot group repeats the above algorithm during movement.

4. Simulation Experiment

This paper conducted the simulation experiment, in order to verify the validity of the position estimate algorithm of the mobile robot group which equips two omnidirectional cameras and an accelerometer described in the third chapter. In this simulation experiment, when mobile robot Ri observed mobile robot Rj, it was verified whether the mobile robot Ri can estimate position. This paper shows an example of a simulation experiment.

The initial positions of mobile robot Ri is (0.0, 1.0,1.0). The initial positions of mobile robot Rjis (0.0, 0.0,1.0). Before mobile robot Ri observes mobile robot Rj, the space coordinates at that time of mobile robot Ri are transmitted the position of mobile robot Rj. And, the image coordinates ${}^{i1}\mathbf{u}_{1j}$ and ${}^{i2}\mathbf{u}_{2j}$ obtained using these space coordinates when mobile robot Ri observes mobile robot Rj are calculated using a general omnidirectional camera model. Here, ${}^{i2}\mathbf{u}_{2j,t}$ are calculated using vector ${}^{i1}\mathbf{d}_{12}$ and (ω, θ, κ) between the up-and-down omnidirectional cameras. The value of vector ${}^{i1}\mathbf{d}_{12}$, and (ω, θ, κ) use in Table 1.The noise according to Gaussian distribution is added to calculated image coordinates ${}^{i1}\mathbf{u}_{1j}$ and ${}^{i2}\mathbf{u}_{2j}$.

Table 1 Common simulation condition.

Symbol	Quantity	Value
a_1, a_2	Mirror geometry parameter	1.09407
b_1, b_2	Mirror geometry parameter	1.21500
f_1, f_2	Focal length	0.007

On this condition, when mobile robot Ri observed the surroundings of mobile robot Rj 10 times at π/18 of intervals concentrically, it was verified whether mobile robot Ri could presume an own position. At this time, mobile robot Ri moves only a plane. The mobile robot Rj dose not move.

The omnidirectional camera parameter used by the simulation experiment is shown in Table 1. a_1, b_1, a_2, and b_2 of Table 1 are the Miller shape parameter of an omnidirectional camera. Each value of a_1, b_1, a_2, and b_2 is determined when designing an omnidirectional camera. The value of Table 1 is the parameter of the omnidirectional camera manufactured in order to use it by this research. Next, f_1 and f_2 are focal lengths, and each value used the focal length of commercial PC camera.

In this research, parameter ${}^{i1}\mathbf{d}_{12}$ and (ω, θ, κ) which determine the position and posture between up-and-down omnidirectional cameras are a value which a mobile robot presumes. Then, the values shown in Tables 2-3 were assumed.

The results of simulation conditions 1-3 are shown in Figs. 4-7. Figs. 4 and 6 show xy coordinate plane. Figs. 5 and 7 show xz coordinate plane. Each square of Figs. 4-7 shows the actual place where mobile robot Ri performed position estimate. Each circle of Figs. 4-7 shows the result of which mobile robot Ri performed the position estimate. And the asterisk mark is a position of mobile robot Rj. The triangle is an initial position of mobile robot Ri. The character A, B, C, D, E, and F are the place which the robot Ri estimated self-position. These character of Figs. 4 and 6 are corresponding Figs. 5 and 7.

In Figs. 4-5, the place A, B and E which performed each position estimate, the mobile robot Ri can check that estimate is possible. In Figs. 6-7, the places A and B which performed each position estimate, the mobile robot Ri can check that estimate is possible.

5. Discussion

Tables 4-5 show the result is the mobile robot's omnidirectional camera parameter d_{12} of simulation

Table 2 Simulation condition 1.

Symbol	Quantity	Value
dx_{12}	x component of the vector between up-and-down omnidirectional cameras	0.05
dy_{12}	y component of the vector between up-and-down omnidirectional cameras	-0.02
dz_{12}	z component of the vector between up-and-down omnidirectional cameras	0.33
ω_{12}	The rotation angle of the circumference of the x-axis between up-and-down omnidirectional cameras	2.0
θ_{12}	The rotation angle of the circumference of the y-axis between up-and-down omnidirectional cameras	5.0
κ_{12}	The rotation angle of the circumference of the z-axis between up-and-down omnidirectional cameras	3.0

Table 3 Simulation condition 2.

Symbol	Quantity	Value
dx_{12}	x component of the vector between up-and-down omnidirectional cameras	-0.05
dy_{12}	y component of the vector between up-and-down omnidirectional cameras	0.01
dz_{12}	z component of the vector between up-and-down omnidirectional cameras	0.4
ω_{12}	The rotation angle of the circumference of the x-axis between up-and-down omnidirectional cameras	5.0
θ_{12}	The rotation angle of the circumference of the y-axis between up-and-down omnidirectional cameras	3.0
κ_{12}	The rotation angle of the circumference of the z-axis between up-and-down omnidirectional cameras	1.0

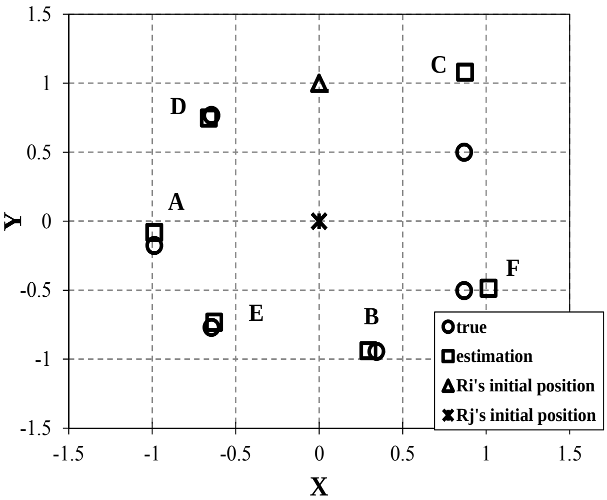

Fig. 4 A simulation condition 1 result (xy-coordinates).

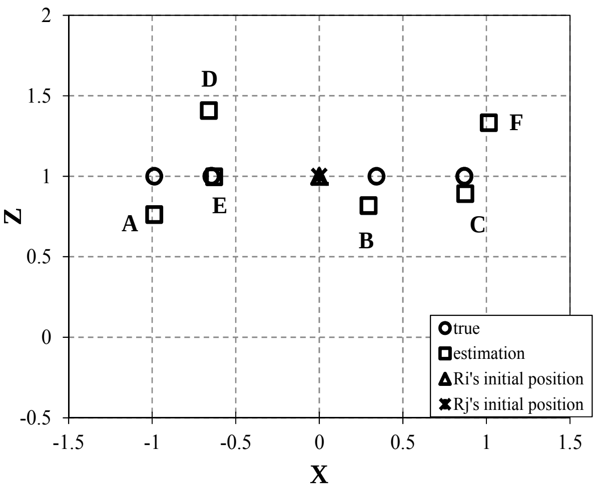

Fig. 5 A simulation condition 1 result (xz-coordinates).

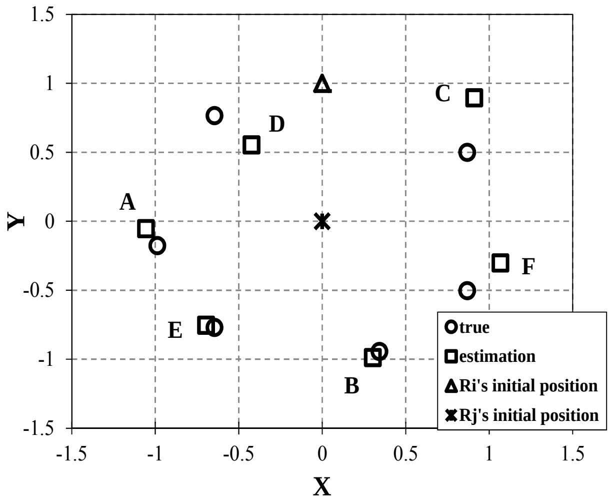

Fig. 6 A simulation condition 2 result (xy-coordinates).

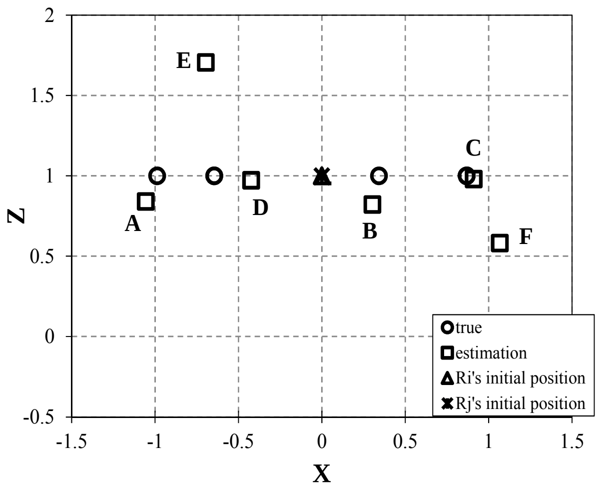

Fig. 7 A simulation condition 2 result (xz-coordinates).

Table 4 The result d_{12} of simulation condition 1.

	True	A	B	C	D	E	F
dx_{12}	0.05	0.012	0.015	0.025	0.036	0.049	0.072
dy_{12}	-0.02	-0.012	-0.015	-0.024	-0.036	-0.049	-0.072
dz_{12}	0.33	0.362	0.467	0.736	1.07	0.68	1.01
ω_{12}	2.0	2.86	5.47	5.461	5.5	5.5	5.49
θ_{12}	5.0	2.86	3.02	3.05	2.42	2.4	2.42
κ_{12}	3.0	2.87	3.24	3.22	3.09	3.09	3.09

Table 5 The result d_{12} of simulation condition 2.

	True	A	B	C	D	E	F
dx_{12}	-0.05	-0.013	-0.015	-0.022	-0.026	-0.042	-0.049
dy_{12}	-0.01	0.013	0.015	0.022	0.025	0.042	0.05
dz_{12}	0.4	0.38	0.45	0.66	0.77	1.27	0.59
ω_{12}	5.0	2.86	2.86	2.85	2.85	2.84	2.84
θ_{12}	3.0	2.86	3.03	3.01	3.01	3.01	3.01
κ_{12}	1.0	2.87	2.86	3.49	3.51	3.51	3.51

condition 1 and 2. The characters A, B, C, D, E, and F of Tables 4-5 are corresponding Figs. 4-7.

From this result, if the mobile robot's omnidirectional camera parameter d_{12} is estimated almost exactly, the mobile robot can estimate self-position.

From this, the mobile robot can estimate position by the proposed position estimate algorithm in this paper.

And when the mobile robot cannot estimate self-position and omnidirectional camera parameter d_{12}, it has to consider optimization method.

6. Conclusions

This paper proposed the position estimate algorithm of the mobile robot group which equips two omnidirectional cameras and an accelerometer. The position estimate algorithm extends NLT Method.

This paper performed simulation verification, in order to verify the validity of the position estimate algorithm of the proposed mobile robot group. In simulation verification, one mobile robot observes at $\pi/18$ of intervals, while moving a concentric form around one mobile robot stopping on that occasion. The mobile robot performed position estimate using the measurement value between the mobile robots obtained from two omnidirectional cameras, when the number of times of observation became 10 times.

The mirror geometry parameter of the omnidirectional camera and the focal length of the camera used by simulation verification used the focal length of the mirror geometry parameter of the omnidirectional mirror attachment which actually manufactured, and commercial PC camera by this research.

As a result, one mobile robot which observed the mobile robot stopped at the spot can estimate position.

From now on, it verifies whether position estimate is possible, increase the number of mobile robots and changes a mobile robot's action pattern. And the physical experiment is also due to do.

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