Navigation Planning of Autonomous Mobile Robots with Multiple Observation Strategies

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Abstract In this paper, we propose a new navigation planning method for autonomous mobile robots with multiple observation strategies. The robot estimates its position by observing landmarks attached on the environment with two active cameras. It chooses the optimal landmark-observation strategy depending on the number and the configuration of visible landmarks in each place. The effectiveness of our proposed method is shown through simulations.

Keywords mobile robot, navigation, landmark, planning

1 Introduction

In this paper, we propose a new navigation planning method for autonomous mobile robots with multiple observation strategies to realize the positioning of the robots with high accuracy.

The robot navigation is a very important technology for the robots to execute various tasks. The navigation is usually executed while the robots move and estimate their positions and orientations by using the information from several sensors.

A dead reckoning is a method that can estimate the position and the orientation of the robot with internal sensor [1]. The robot estimates its movement from the rotational angle of each motor. This method does not need the entire world map and the computational time is very fast. However, the direction in which the robot travels, as well as its velocity depends on a lot of parameters such as floor structure, previous wheel positions and so on. Therefore, the error of estimated position and orientation is accumulated in proportion to the traveling distance and the recovery of the error is impossible only with the internal sensors.

Therefore, an image-based method is always utilized for the robot navigation. In this method, the robots obtain the environment information with external sensor such as cameras. The robot observes characteristic points in the environment and measures the relationship between these points and the robot itself. The characteristic point is always called "landmark" (Fig.1). When the robots observe landmarks, the problems are how to measure the accurate position and orientation of landmarks and which landmarks the robots should observe while there are multiple landmarks.

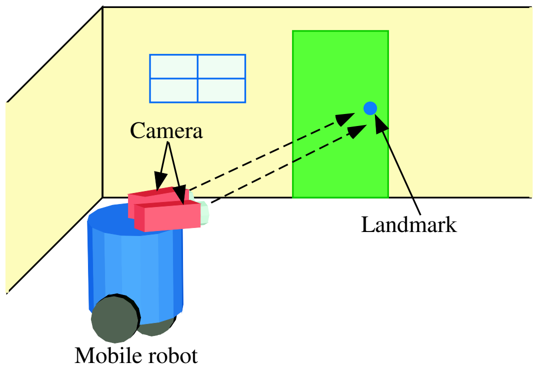


Fig. 1: Robot navigation with landmarks.

As to the former problem, there are a lot of studies that improve the accuracy of 3-D measurement, *i.e.*, [2]. However, there is a limit in accuracy when the robot always observes the same landmark regardless of the distance between the robot and the landmark.

Therefore, the latter problem is very important for the robot navigation. This means that the robot must choose the observing landmarks according to its position while it moves.

Komoriya *et al.* proposed the planning method of observing landmarks when there are multiple landmarks in the robot's field of view [3]. Nagatani and Yuta proposed the path and sensing point planning method. In this method, the cost function for the mobile robot's path that minimizes the risk of collision was settled, and the algorithm to find the optimal path and sensing points was constructed [4]. Moon *et al.* proposed an online viewpoint planning method for a mobile robot to reach a goal position safely and quickly [5]. In this method, the viewpoint was adaptively determined according to the clutteredness of the nearby environment. Additionally, there are several approaches for the outdoor navigation of the mobile robots [6, 7, 8]. For example, Ohno *et al.* utilized different colors in a walkway and lawn area along side the walkway. Olson *et al.* proposed the probabilistic self-localization techniques for mobile robots that are based on the principle of maximum-likelihood estimation.

On the other hand, the design of the optimal arrangement of artificial landmark is very important in the indoor environment [9]. Takeuchi *et al.* proposed a method to dispose artificial landmarks in the environment, and to navigate a mobile robot there [10]. The landmarks are disposed so that the robot can observe at least one landmark at any positions, and the robot plans the observation so that they can observe landmarks.

These methods consider the observing landmark(s) or viewpoints of cameras while there are several landmarks in the robot's field of view. However, these methods do not consider multiple observation strategies. If the number of the camera is more than two and the number of visible landmarks is also more than two, the robot can observe landmarks in the several way. For example, when two landmarks (landmark 1 and 2) are in the robot's field of view, the robot can observe one selected landmarks (landmark 1 or 2) with two cameras by using the stereo observation method. Besides the above-mentioned stereo observation, the robot can observe landmark 1 with the left camera and landmark 2 with the right camera.

In this paper, the robot uses the information from two active cameras that can change their directions independently. They can observe landmarks with several types of the observation strategies to change the cameras directions.

The accuracy of multiple observation strategies depends on the positions of landmarks that can be observed. Therefore, the robot must choose the optimal landmark-observation strategy to consider the number and the configuration of visible landmarks in each place. We analyze the errors of the landmark shape and the position in images. The evaluation of each observation strategy is executed to consider the accuracy of the observation when the image errors occur. The optimal observation strategy is defined as the one that contains the minimum error when there is the image error. The directions of cameras and the landmarks that are observed are decided to plan the optimal observation strategy by using the environment map that indicates the positions of the landmarks.

2 Observation Strategies

2.1 Problem Settlement

We make the assumptions for the planning of the robot navigation.

The robot can move in all direction at any time and uses the information from two active cameras that can change their directions independently (Fig.2). The environment map that indicates the positions of walls, obstacles, and landmarks is also previously provided to the robot.

Fig. 2: Mobile robot system. An omni-directional mobile robot mechanism [11] is adopted as the robot base and two pan-tilt-zoom cameras that can change their direction independently are set on the top of the robot.

Every landmarks whose heights are same with those of robot's cameras are attached to the environment (Fig.3). The shape of the landmark is circle and the radius of each landmark is constant (r mm). Each landmark can be distinguished with each other. All landmarks cannot be seen from the back side because they are attached on walls. We define (x_i, y_i) as the position of the landmark i, and d_{ij} as the distance between the landmark i and j.

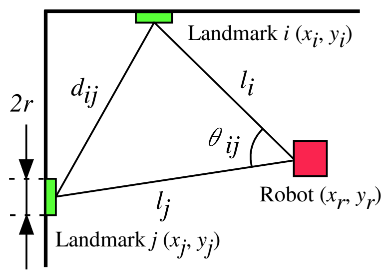
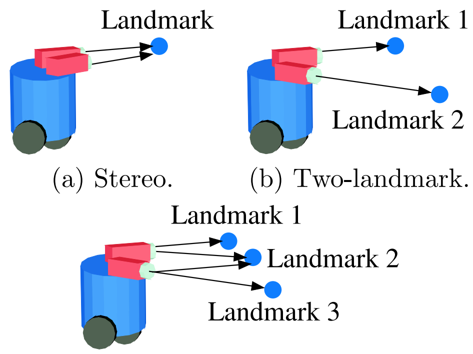


Fig. 3: 2-D model of the environment.

The position of the robot (x_r, y_r) is estimated by using the images from two cameras. Let l_i be the distance between the robot and the landmark i, and θ_{ij} be the angle between the landmark i and j from the robot position (x_r, y_r) (Fig.3). l_i can be estimated from the size of landmark i in the image. θ_{ij} can be estimated from the center position of landmark i and j in the images.

We develop three observation strategies: (a) stereo observation (Fig.4(a)), (b) two-landmark observation (Fig.4(b)), and (c) three-landmark observation (Fig.4(c)).

Te stereo observation can be executed when one landmark is inside the robot's field of view. The robot estimates its position and orientation with the triangulation.



(a) Stereo. (b) Two-landmark.

(c) Three-landmark.

Fig. 4: Three observation strategies. (a) Stereo observation strategy. (b) Two-landmark observation strategy. (c) Three-landmark observation strategy.

The two-landmark observation can be executed when two landmarks are inside the robot's field of view. The distance between the robot and nearer landmark that is observed is estimated from the size of the landmarks in images. The relationship between two landmarks and the robot is estimated from the coordinate value of the center of the landmarks in images. The position and the orientation of the robot are decided by combining the information mentioned above.

The three-landmark observation can be executed when more than three landmarks are inside the robot's field of view. The relationship between three landmarks and the robot is estimated from the coordinate value of the center of the landmarks in images.

2.2 Stereo Observation

The robot estimates its position and orientation with the triangulation when a landmark is observed with two cameras simultaneously (Fig.5).

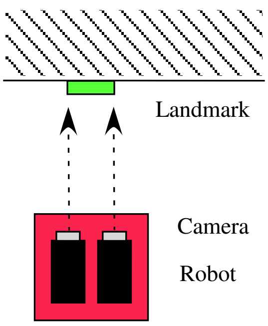


Fig. 5: Overview of stereo observation.

Here, the camera coordinate is defined (Fig.6). Let s, w, t be the coordinate axis while original point is set on the centered point of two cameras' principle points. Then the landmark's position in the case of parallel stereo model is calculated as follows:

$$s = \frac{b(u_l + u_r)}{2d} \quad (1)$$

$$w = \frac{b(v_l + v_r)}{2d} \quad (2)$$

$$t = \frac{bf}{d} \quad (3)$$

where (u_l, v_l) and (u_r, v_r) are the coordinate value of left and right images, respectively, b is the baseline length, f is the image distance, and $d = u_r - u_l$ is the disparity.

The positions of multiple characteristic points on the landmark can be measured with the triangulation. Therefore, the position and orientation of the robot can be calculated from these information.

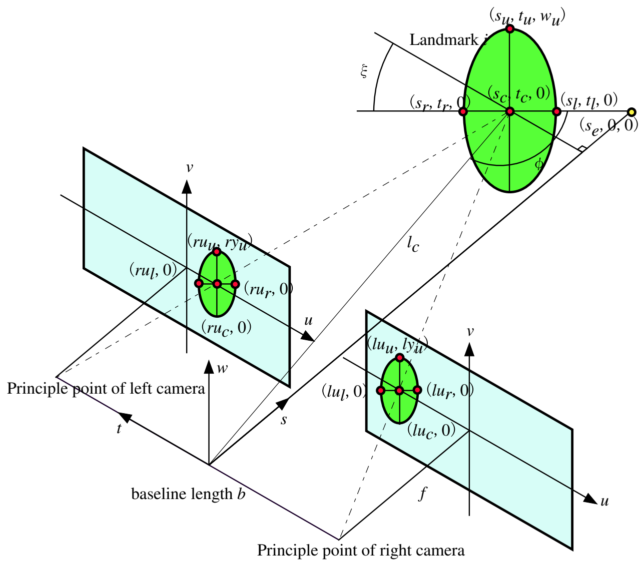


Fig. 6: Image of landmark in the case of stereo observation.

2.3 Two-Landmark Observation

The distance between the robot and nearer landmark l_i and the angle θ_{ij} are estimated from two camera images (Fig.7).

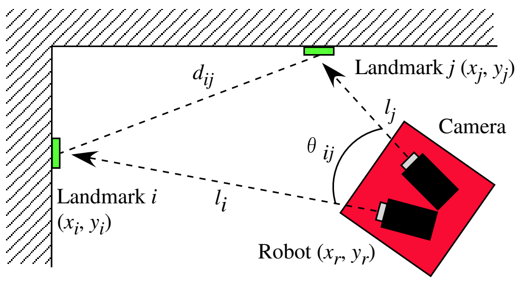


Fig. 7: Overview of two-landmark observation.

l_i can be estimated by considering the ratio between the size of the actual landmark and the size of the landmark in the image (Fig.8). θ_{ij} can be estimated from positions of two landmarks' center points of two images. Then, l_j is calculated from θ_{ij}, l_i and d_{ij}.

The robot position is located on the circle whose center is (x_i, y_i) and whose radius is l_i in the world coordinate.

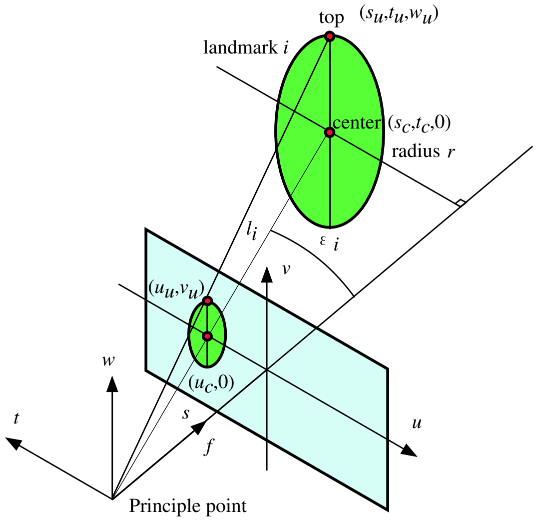


Fig. 8: Image of landmark in the case of two-landmark observation. There are two images that project one landmark.

The robot is also located on the circle whose center is landmark j.

$$
\begin{aligned}
(x_r - x_i)^2 + (y_r - y_i)^2 &= l_i^2 \qquad (4)\\
(x_r - x_j)^2 + (y_r - y_j)^2 &= l_j^2 \qquad (5)
\end{aligned}
$$

Therefore, the robot position is estimated as intersection points of two circles. There are two intersection points, however, we can decide the robot position by considering the moving history of the robot.

2.4 Three-Landmark Observation

The angle θ_{ij} and θ_{jk} are estimated from two camera images that projects three landmarks (Fig.9).

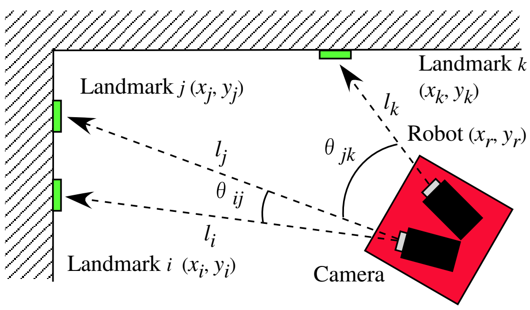


Fig. 9: Overview of three-landmark observation.

θ_{ij} and θ_{jk} can be estimated from positions of two landmarks' center points of one or two images (Fig.10).

Therefore, the robot position is calculated from the following equations.

$$
\begin{aligned}
\tan^{-1}\frac{y_j - y_r}{x_j - x_r} - \tan^{-1}\frac{y_i - y_r}{x_i - x_r} &= \theta_{ij} \qquad (6)\\
\tan^{-1}\frac{y_k - y_r}{x_k - x_r} - \tan^{-1}\frac{y_j - y_r}{x_j - x_r} &= \theta_{jk} \qquad (7)
\end{aligned}
$$

This estimation method uses only the center position of the landmarks. Therefore, the accuracy of the estimated position and orientation become very high as compared with the other observation methods.

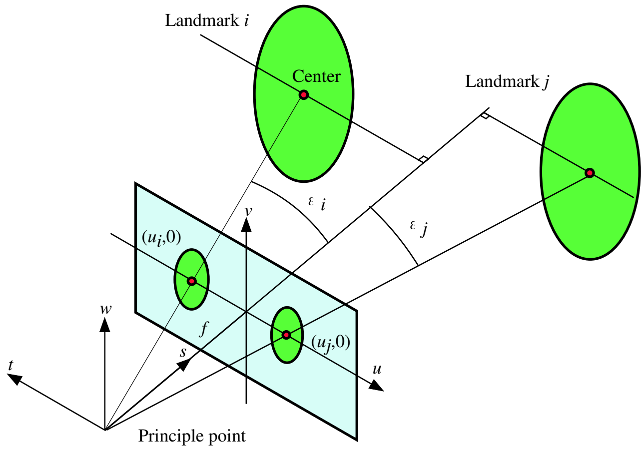


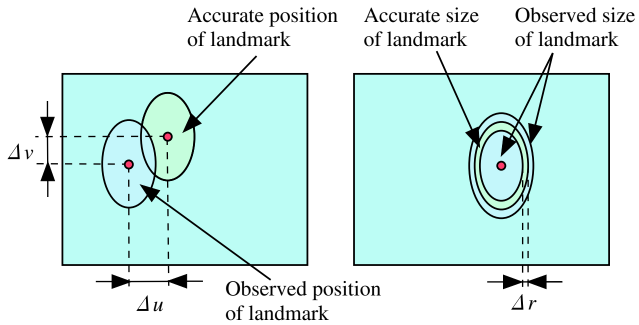
Fig. 10: Image of landmarks in the case of three-landmark observation. There is one image that projects more than two landmark and one image that projects more than one image.

3 Navigation Planning

The robot chooses the optimal landmark-observation strategy that can estimate its position and orientation precisely. The optimal strategy is planned with off-line by using the environment map that indicates the positions of landmarks.

At first, the visible landmarks in each place are selected to consider the robot's field of view. The robot cannot observe landmarks when obstacles are between the robot and landmarks and cannot observe them from the back side.

Incidentally, the error of image such as quantization error always occurs. Then, the theoretical estimation errors of robot's position and orientation are calculated by considering the situation that the errors of landmark's position and size (shape) in images occur (Fig.11).



(a) Position error. (b) Size error.

Fig. 11: Image error.

We assumed that the position error of the landmark's center point in the image is $(\Delta u, \Delta v)$. The size error of the landmark in the image Δr is also considered. It means that the observed landmark's position in the image may shift $(\pm\Delta u, \pm\Delta v)$ from the true position at the maximum. The observed radius may also shift $\pm\Delta r$ from the true size.

The robot estimates how the position and orientation errors occur in the world coordinate about all combination of visible landmarks when the errors occur in the images (image coordinates) of two cameras (Fig.12).

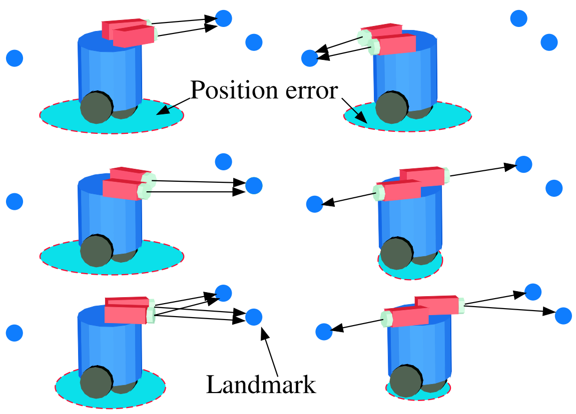
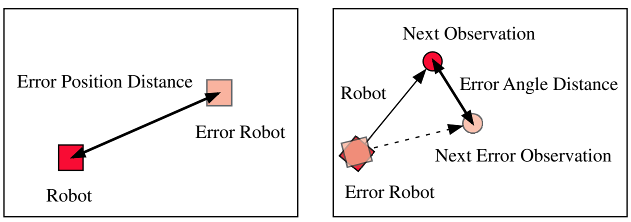


Fig. 12: Position error of each observation strategy.

However, the position error and the orientation error are not compared directly because the dimensions of them are different from each other. The position error is expressed as the dimension of length, *i.e.*, [mm], and the orientation error is expressed as the dimension of angle, *i.e.*, [deg].

Therefore, we transform the orientation error (the dimension of angle) into the position error (the dimension of length). The total sum of the error when the robot moves at a certain distance while the position and orientation error occur is calculated (Fig.13). This means that the total error at the next time's position of the robot when it moves is the sum of the position error (Fig.13(a)) and the incorrect moving distance under the influence of the orientation error (Fig.13(b)).



(a) Position error. (b) Orientation error.

Fig. 13: Position and orientation error of robot.

In this way, the estimated error of the robot position in the world coordinate that is caused by the image error is calculated. The optimal observation strategy is equal to the observation method that has minimum position estimation error.

The direction of two camera is decided by selecting the optimal observation strategy in each place. Therefore, the navigation planning of the mobile robot can be executed.

4 Simulation Results

Fig.14 and Table 1 show the simulation results of the optimal observation strategies of each place under the condition of $\Delta u = 1$, $\Delta v = 1$, and $\Delta r = 1$. I – V mean the positions where the robot observes landmarks, 1 – 5 mean landmark number, and A – C mean the selected optimal observation strategies; A: stereo observation, B: two-landmark observation, C: three-landmark observation.

At the position I, it is possible to adopt the stereo observation and the two-landmark observation. The total sum of error of the stereo observation is 143mm, and that of the two-landmark observation is 48mm. Therefore, the latter strategy is selected to estimate the robot position.

Note that the error seem to be large, however, the value of the position error in the world coordinate depends on that of the image error. Therefore, the smaller the image error becomes, the smaller the position error becomes. In this simulation, size relations between three observation strategies are important.

In the same way, observation strategies that have the minimum errors are selected at the each place. At the position III, all strategies can be executed. Three-landmark observation strategy is chosen because the accuracy of the position estimation is very high.

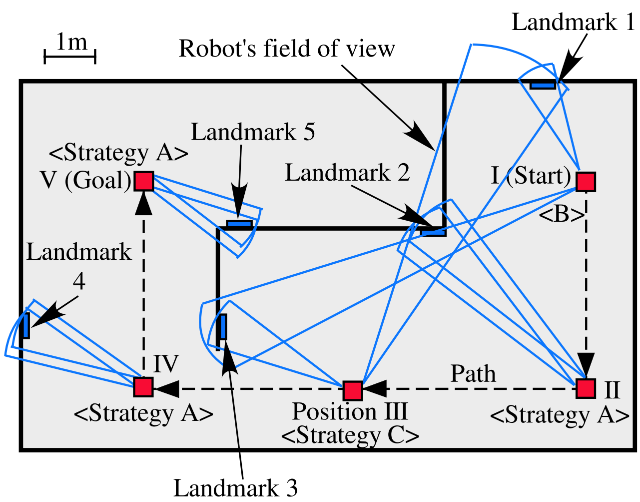


Fig. 14: Simulation results of optimal observation strategy.

As the result, it is shown that the three-landmark observation strategy is the best method in all situation if more than three landmarks can be seen. The accuracy of the two-landmark observation strategy depends on the angle between two visible landmarks. If the angle is large, the two-landmark observation strategy is adopted, and if it is small, the stereo observation strategy is selected as the optimal observation method.

Table 1: Simulation results of optimal observation strategy. The optimal observation strategy at each position is expressed in **boldface type**.

Position	Strategy	Observing Marks	Total error	Position error	Orientation error
I	A	1	143mm	53mm	1.6deg
	B	**1, 3**	**48mm**	**39mm**	**0.3deg**
	B	–	–	–	–
II	**A**	**2**	**259mm**	**133mm**	**1.9deg**
	B	1, 2	305mm	237mm	2.6deg
	C	–	–	–	–
III	A	3	237mm	101mm	2.4deg
	B	1, 3	93mm	81mm	0.7deg
	C	**1, 2, 3**	**5mm**	**2mm**	**0.1deg**
IV	**A**	**4**	**178mm**	**80mm**	**2.0deg**
	B	–	–	–	–
	C	–	–	–	–
V	**A**	**5**	**22mm**	**22mm**	**0.7deg**
	B	4, 5	35mm	35mm	0.6deg
	C	–	–	–	–

5 Conclusions

In this paper, we propose a new navigation planning method for autonomous mobile robots with multiple observation strategies. The robot estimates its position by observing landmarks attached on the environments with two active cameras. They choose the optimal landmark-observation strategy depending on the number and the configuration of visible landmarks in each place. The optimal strategy that minimizes the estimation error of the robot position can be selected properly. The effectiveness of our proposed method is shown through simulations.

As the future works, the path of the robot and the sensing points must be planned. Experiments with real robot system must be also performed for evaluating our proposed method.

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