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# Global Localization for a Small Mobile Robot using Magnetic Patterns

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*Abstract*— **In this paper, we present a global localization and local pose error compensation method in a known structured environment using magnetic landmarks. In previous our research, it was possible to compensate the pose error ($x_e$, $y_e$, $\theta_e$) of a mobile robot correctly on the surface of structured environment with magnetic landmarks. In this work, we propose a methodology of arranging magnetic landmarks on the map such that properly arranged magnetic patterns ease the global localization of a mobile agent. Among total six patterns of magnetic-bar in square arrangement, five unique landmarks are obtained. Therefore, a heuristic pattern search method is applied to build the virtual map using five landmarks. In order to obtain the global pose information, the robot identifies the pattern of magnets, and obtains the current global pose information by comparing the measured neighboring patterns with the map information that is saved in advance. Experimental results show the effectiveness of the magnetic-pattern landmarks for the global localization and local pose control of a mobile robot.**

## I. INTRODUCTION

The pose information of a mobile robot within its environment is the fundamental and essential piece of information to carry out any kind of missions in real world environment. In general, sensors provide the necessary information between the environment and the robot motion to confirm the location of the robot. However, because there is often a huge uncertainty in real applications such as the influence of external physical factors and internal programming limitations, such a localization issue still remains a great challenge.

Localization problems are usually classified into two categories; one is local localization (or tracking), and the other is global localization. Local localization is to successively track the pose of the mobile robot with a given initial pose, whereas global localization is to perceive the pose of the mobile robot with respect to its own representation of the environment without any prior knowledge about initial pose [1]. Various attempts have been made to solve the local and global localization problem. As a result, several strategies and algorithms have been proposed to reduce the global positioning error of a mobile robot.

The odometry error of a differential-drive mobile robot is unavoidable due to the mechanical formation of running gear. To solve this problem Borenstein proposed a method called "UMBmark" [2]. This method has shown the reduction of odometry errors that are caused by uncertainty regarding the effective wheelbase and unequal wheel diameters in a two-wheel differential driving mobile robot. Also, the position estimation is influenced by the uncertainty of sensor data. In order to estimate the position of a mobile robot, Dellaert proposed Monte Carlo Localization algorithm. The MCL reduces the computation and memory consumption for more efficient localization of the mobile robot [3]. The global localization need more decisive information to know the position of the robot accurately. The landmarks have a role of basis for a robot situated in an environment. Se presented a vision-based global localization by matching visual landmarks to a given data map [4]. Many other attempts proposed for global localization in a probabilistic approach, for example in [5]. Although these methods have achieved efficient error compensation and have generated localization algorithms based on a mathematical analysis, localization failures still exist because of inaccuracies in the detected sensor data. The development of methods that can precisely estimate the position of a robot is still an important goal in mobile robot localization.

When a mobile robot is to move to a final "goal" position in a known structured environment without any prior knowledge about its current position, global localization has to be solved first, and it inevitably subsumes the position tracking problem. According to these demands, we present a global localization method and position error compensation in a known structured environment using magnetic landmarks. Total six patterns of magnetic landmarks are formed by exhaustively arranging four magnetic bars in a rectangular configuration. These patterns of magnetic landmarks are placed on the floor of the experimental environment at regular interval to form a virtual map. The four magnetic hall sensors that are installed at the bottom of a mobile robot identifies a sequence of patterns of the neighboring magnetic landmarks in the environment. Then, the measured pattern sequence is compared with the map information that is given in advance to find the global position of the robot. First of all, the map building with a finite number of patterns of magnetic landmarks is an important problem because the performance of global localization depends on the quality of the map. In this work, a heuristic search method that can avoid repeated sequences of patterns is proposed in order to build a map with five patterns of magnetic landmarks such that minimizes the searching time and the traveling distance of the robot.

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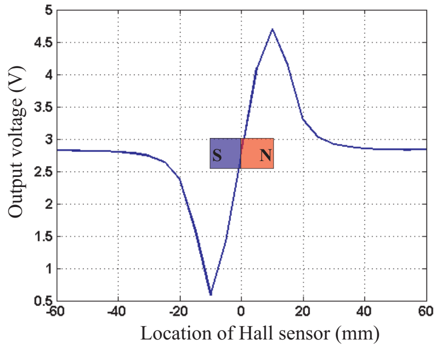



Fig. 1. The hall sensor output voltage according to the length direction of permanent magnet.

This paper is organized as follows. In section II, the basic concept for pose estimation is explained, In section III, the proposed global localization method and the pose error compensation method are presented, respectively. Then, in section IV, experimental procedures and results for evaluation of the performance of the proposed pose estimation method are presented. Finally, the paper is concluded with summary in section V.

## II. POSITION TRACKING USING MAGNETIC LANDMARKS

In our previous research, the problems of pose error compensation and the relative localization are solved by the proposed technique in [10] which makes use of a set of permanent magnets and hall sensors. Fundamentally, relative localization can be realized by counting the number of magnet sets from starting point to current point using position tracking technique. For the sake of completeness of the paper, the basic concept of pose estimation using four magnetic bars and hall sensors in a rectangular configuration is introduced in this section.

The hall sensors are the magnetic field sensor based on Hall effect, which detects the potential difference (Hall voltage), created by a magnetic field applied perpendicularly to the current. As shown in Fig. 1, one magnet and one hall sensor has the linear relationship between the location of hall sensor on the magnet and the output voltage of the hall sensor. Therefore, it can be recognized as a single direction or single axis. Moreover, different local coordinate system can be constituted by repeated arrangement of several magnets according to their placement configuration [10]. The coordinate system of magnet sets is arranged by forming repeatable patterns. Therefore, the current position information of robots can be easily obtained in accordance with the coordinate system. In the following section, a pose error compensation method that is related to the new global localization method will be emphatically presented.

Various configurations of magnet installation could be applied for a set of arranged magnets. However, because of the following considerations, such as 1) the use of minimum number of hall sensors to construct the coordinate system,

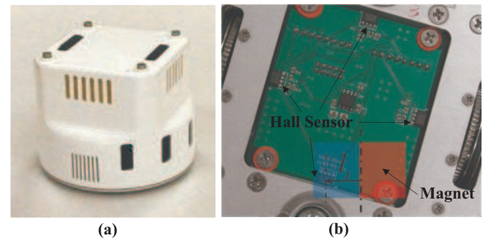



Fig. 2. The magnetic hall sensors that attach bottom of mobile robot. (a) small sized mobile robot, (b) the bottom of the mobile robot and hall sensors.

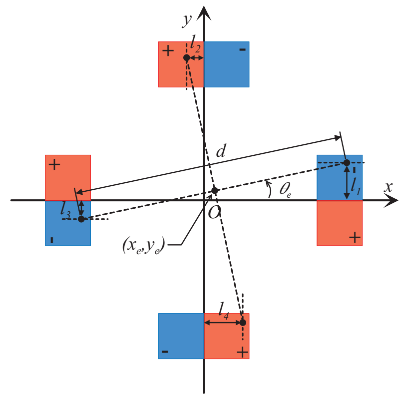


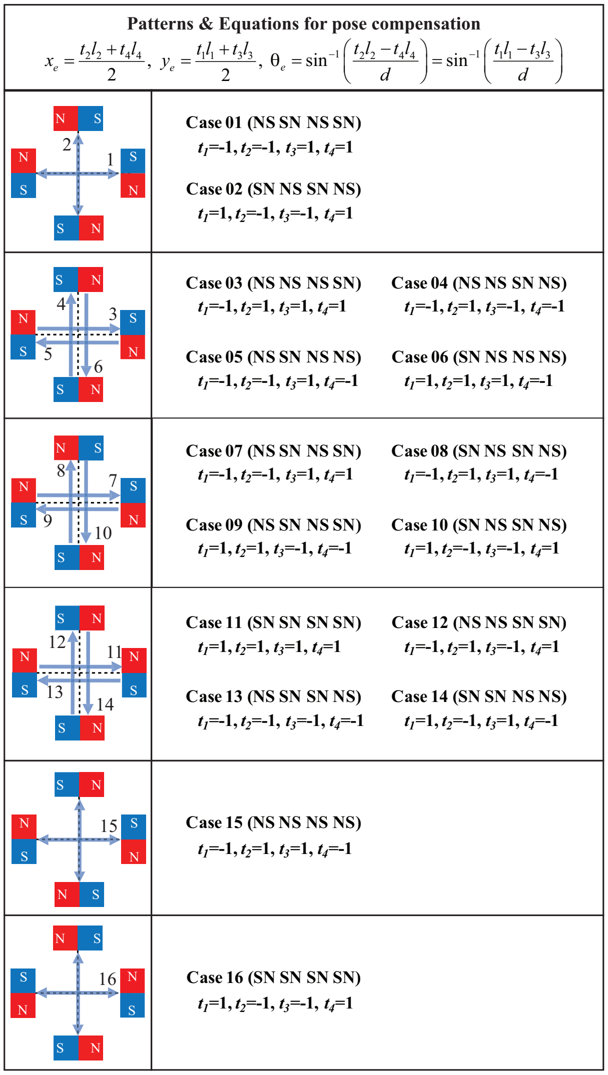

Fig. 3. The magnets arrangement of the rectangular configuration.

2) the problems of space interval by arrangement of magnets according to the reason why the linear measurement range of hall sensor is limited to inside the size of magnet, 3) the size of applied mobile robots, 4) Cartesian coordinate, the unique pattern had been simply considered. Therefore, we present the rectangular configuration using four magnets.

The basic concept of the position error compensation method is to measure the position difference between the coordination of the hall sensors of the mobile robot and the coordinate of the magnet set. The measured potential difference through hall sensors attached to the mobile robot is transformed to the distance value from the center of the magnet to the center of the hall sensor. Therefore, the translational and rotational errors of the mobile robot are found and calculated with respect to the current position. Based on the linear characteristics, we can acquire the data $l_1$, $l_2$, $l_3$, and $l_4$ for the rectangular configuration. Figure 2 shows one of the hall sensors to be attached to the bottom of the mobile robot which is located on the surface of the magnet in the case of the rectangular configuration. Therefore, we can determine that the distance $l_i$ from the central axis of the magnet to the center of the hall sensor is proportional to the voltage output $V_i$ of hall sensor with coefficient $k_i$. Figure 3 depicts the meaning of the distance $l_i$.

$$l_i = k_i V_i \qquad (i = number\ of\ magents) \tag{1}$$

If the non-holonomic mobile robot moves in a two dimensional plane, accumulated errors about the position variables of $x$, $y$, $\theta$ have been occurred continuously. Therefore, it



The direction of arrow = the traveling direction of robot (the front side of robot)

Fig. 4. The equations for compensation of pose errors.

is necessary that the errors of $x$, $y$, $\theta$ should be directly measured and unceasingly compensated.

For a rectangular configuration of the magnetic bar arrangement, we still have choices of polarity directions for each magnet. In total, we have six different patterns of the magnetic bar arrangement and the equations of the pose error as a function of the measurement are different one another. According to the arrangements of magnetic bars, the equations for pose error compensation can be expressed as shown in Fig. 4. Total sixteen equations are classified by the heading direction of robot because the sign of each error term depends on the reading sequence of the magnetic bars. As shown in Fig. 4, the direction of arrows stands for the heading direction of the robot.

When the pose error is detected at a landmark, it is compensated while moving to the neighboring landmark. We have proposed a method of pose error correction by applying Dubin's curve path planning and a simple tracking control in [19]. The idea is that the known pose error at a landmark provides sufficient information about the two circular paths that are tangent to each other, the current pose, and the final goal pose. Once this path is generated from the current pose error, the robot tracks the path using a standard control algorithm.

## III. GLOBAL LOCALIZATION METHOD

If the initial pose of the robot is unknown, the robot cannot estimate its current position directly from the position tracking method because the pattern of the magnetic landmarks is unknown to the robot which means that the pose error of the robot cannot be either computed nor compensated using the method described in the previous section. So, the key issue of the global localization in this work is for the robot to identify the pattern of magnetic landmarks where the robot is currently located. Once the robot identifies the pattern of the current landmarks, the position tracking is easily achieved. After this, global localization can be completed by identifying neighboring patterns of the landmarks. In this section, we also discuss the issue of composing a desirable global map using five patterns of magnetic landmarks.

### *A. Principle of global localization method based on magnetic patterns*

A new strategy for global localization using several patterns of magnetic landmarks is presented in this section. For one set of landmark is composed of four magnetic bars in rectangular configuration as shown in Fig. 4 where total six patterns can be obtained. When the robot is located at the center of the four-magnet landmark, it can easily read the polarity of the magnets while making a complete turn in one direction.

Notice that, when the robot reads the polarity of the magnetic bars while rotating in one direction, the sequence of the read polarities repeats at each complete turn of the robot because the sequence is circular. Also, notice that the sequence of the polarities of pattern 5 and 6 are identical if they are considered as a circular sequence, in other words, if we ignore the coordinate of the magnet placement. In fact, the shape of the magnetic field that corresponds to the pattern 5 is the same as that of the pattern 6 rotated by 45 degrees in clockwise direction.

In this paper, the patterns of magnetic landmarks are distributed in such a way of forming a grid-like global map as shown in Fig. 5 where the number inside of the grid stands for the type of the landmark pattern. It should be noted that once the pattern is identified, position tracking is easily done in this proposed framework.

The first step for global localization is to control the robot so to be situated on the range of magnetic landmarks. When fairly large size of magnets are used, the range of magnetic field is large enough. In this case, a simple random walk algorithm may situate the robot onto a proper location where the robot can read the four magnetic fields and begin the procedure of identifying the pattern of the landmark. Another approach is to use a gradient descent algorithm for one hall sensor so that one of four hall sensors is placed in the

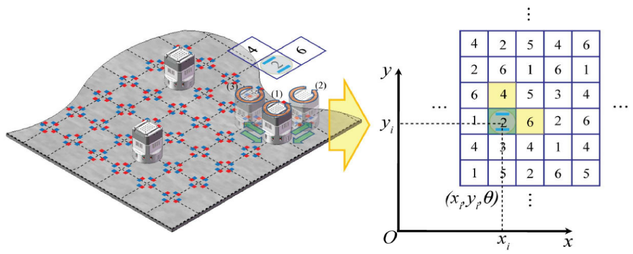



Fig. 5. The basic concept of global localization method for finding current position information of the robot. The robot identifies the pattern of the magnetic landmark of current pose and the neighboring patterns without any prior knowledge, then the robot compares the measured sequence of patterns with the map information to complete global localization.

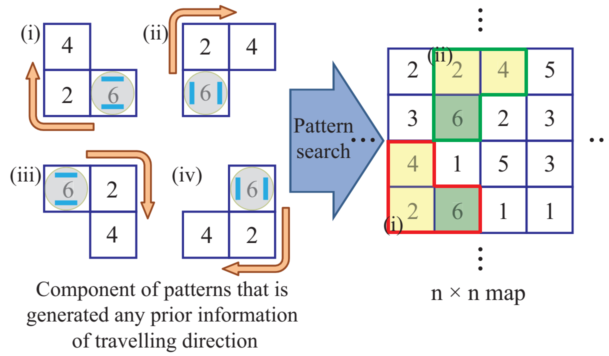



Fig. 6. Illustration of pattern compnent.

center region of the magnetic field which is generated by four magnetic bars. Although we have six different patterns of landmarks for a rectangular configuration, by placing one hall sensor at the center region of the magnetic field. While maintaining its pivoting at the center region and rotate the robot to measure the shape of the magnetic field by another hall sensor, we can find the accurate center point of magnetic field for each pattern. Once this is done, the robot can be controlled to a location where four hall sensors are properly located ontop of magnetic bars.

The robot identifies the pattern of magnetic landmark by reading the sequence of the magnetic polarities while rotating, and it obtains the current global position information. At this point, there still is ambiguity in current location of the robot because the number of patterns is not large enough to cover the entire grid-like map. However, once the robot recognizes the pattern of the current landmark, position tracking can be done afterward, thus the robot can move to the one of the neighboring grid with very small tolerable pose error. We propose that the robot identifies the patterns of the three neighboring landmarks in L shape. In the next section, we provide a map-building algorithm that generates 8 by 8 maps with unique three neighboring landmarks for global localization, in other words, identifying three neighboring landmarks in L shape is sufficient for global localization in such a map.

## *B. Distribution of magnetic landmarks patterns*

In the proposed global localization method, the uniqueness of the neighboring magnetic landmarks is highly significant because it is related to searching time and robot's traveling distance while robot compares the measured sequence patterns with the stored map. Therefore, the ideal $n \times n$ virtual map have to consist of unique patterns such that the sequence of neighboring magnetic landmarks are not repeated as less as possible. However, it is obvious that the distribution of landmark patterns is a complex issue because the lack of information on headig direction of the robot; the four different distribution of the landmark patterns can appear to be in fact identical to the robot as shown in Fig. 6. If we use more landmarks to make a single unique pattern, this problem will be simpler. However, the use of a lot of landmarks means that robot has to recognize more landmarks to localize itself, so it will inevitably spend more time.

To solve the distribution problem of patterns that minimizes the landmarks in repeated sequence in arrangement, first we apply a random method and a symmetric non-recurring De bruijn sequence [11] for the map construction. Secondly, a heuristic approach that is based on exhaustive search is considered to distribute patterns on the 8×8 virtual map. Especially, in order to distribute patterns on 8×8 virtual map, the heuristic approach has been realized by constructing four 4×4 submaps where three neighboring landmark patterns are unique, and then combines those four submaps to form an 8×8 virtual map. Note that the magnetic pattern 6 is not used in order to avoid ambiguity between the magnetic patterns 5 and 6.

TABLE I
MATLAB SIMULATION RESULTS

| Map construction method | overlapped patterns |
|---|---|
| Random | 70.8(Average:10) |
| Symmetric non-recurring De Bruijn sequence | 65 |
| Heuristic approach | 60 |

The Table I shows the results of MATLAB simulation about each map construction method. The result of random method has the most repeated patterns among the three methods. Also, the virtual map based on the symmetric non-recurring De Bruijn sequence has many repeated patterns on any coordinates inside of the map, as shown in Fig. 7(a). On the other hand, the virtual map which is built with the heuristic approach has repeated patterns of the smallest number because the repeated patterns of this virtual map exist on the boundary line or in other 4×4 submap, as shown in Fig. 7(b).

Avoiding the emergence of the repeated patterns is not obvious as ever even though a relatively small size virtual map such as the 8×8 size has been directly generated. One way to resolve this problem is to use smaller scale submaps such as 4×4, as mentioned above. However, the optimal solution of the large-scale virtual map with minimum repeated patterns is still a challenging issue in our ongoing research. Now, we are improving our heuristic approach by

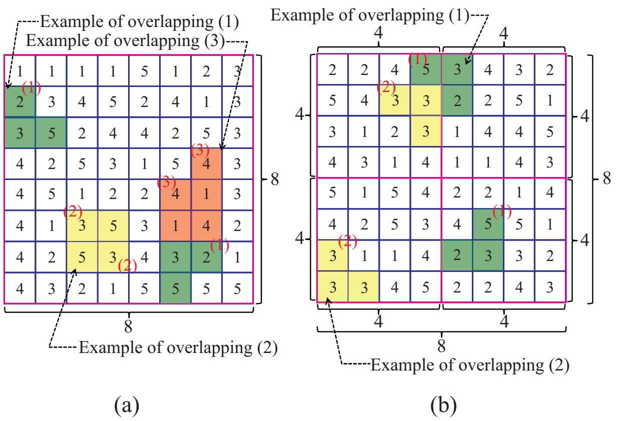



Fig. 7. Example of 8×8 virtual map constructed with (a)symmetric non-recurring De Bruijn sequence and (b)heuristic approach. (1)Example of repeated patterns, (2)Example of inner region repeat, (3)Example of boundary line repeat.

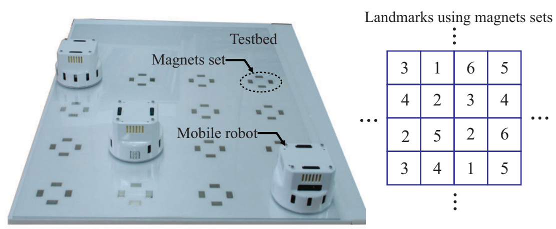



Fig. 8. Experimental environments

adding hierarchical stack schemes.

## IV. EXPERIMENTS

To evaluate the effectiveness and performance of the proposed method, the experimental environment which is composed of a test-bed with magnets and small-sized mobile robots is designed and fabricated, as shown in Fig. 8. The mobile robot is a differential drive type and hall sensors are attached to the bottom of the mobile robot. The workspace of the mobile robot is restricted to the test-bed which has arranged magnets under the test-bed surface. One set of magnetic landmark is composed of four magnets. These landmarks of arranged magnets offer the information of global coordinate as well as estimated pose error data for the mobile robot pose errors compensation.

In the first experiments, the sequential pose error compensation is presented, as shown in Fig. 9. Firstly, the error values ($x_e$, $y_e$, and $\theta_e$) of current pose are measured and calculated. Secondly, in order to compensate the y-directional error $y_e$, the mobile robot rotates to the angle of -90°-$\theta_e$. Then, moving direction of robot becomes to be parallel with $y$-axis of magnet coordinate, and robot approaches the $x$-axis of magnet coordinate by moving distance of $y_e$ that is error of $y$-axis. Moreover, in the similar method, in order to correct the $x$-directional error $x_e$, mobile robot rotate to the angle of 90°-$\theta_e$. Like the preceding, the traveling direction of robot becomes to be parallel with $x$-axis of magnet coordinate, and robot approaches the $y$-axis of magnet coordinate by moving distance of $x_e$ that is error of $x$-axis. Finally, robot measures the error value again at the current state. If the position error still remains after position error compensation, the robot reiterates the above sequence. If the measured error values come close to zero, the error compensation operation is completed. As shown in Table II, the proposed pose compensation method could reduce the pose error effectively.

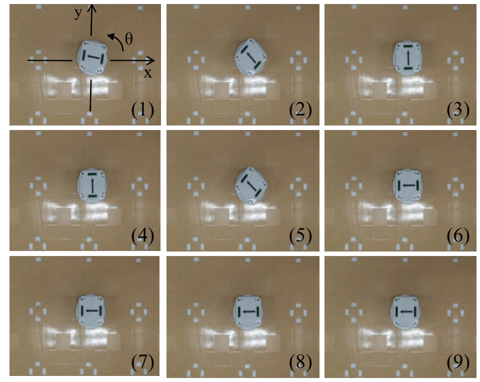



Fig. 9. The movement of mobile robot according to the position error compensation method((1): initial position with error, (1)∼(3): $y$ error compensation, (6)∼(8): $x$ error compensation, (4)∼(6), (9): $\theta$ error compensation).

TABLE II
REMAINING ERROR AFTER THE COMPENSATION[$mm$,$^o$]

| | $x$ | $y$ | $\theta$ |
|---|---|---|---|
| Max error (Absolute value) | 0.5 | 1.5 | 1.14 |
| Mean error | 0.23 | 0.66 | 0.31 |

To prove the performance of global localization technique using various patterns of magnetic landmarks, the experiments are carried out as shown in Fig. 10. The robot is placed in an arbitrary position in the map (the current pose of robot is unknown), then the robot makes turns in this position. During the rotation, four hall sensors look for changes of magnetic poles, and they identify the pattern of magnetic landmark. The robot moves to the two neighboring landmarks, one in forward direction and the other in left direction, and identifies the pattern of the neighboring landmarks using the four hall sensors. Based on these information, the robot compares the measured three neighboring patterns in an L shape with the map information that is saved in advance, then the robot estimates its current position. Also, as shown in Fig. 10, the robot calculates the $x_e$, $y_e$, $\theta_e$ of pose error by applying equations of pose error compensation using the according pattern of magnetic landmark in the current position.

## V. CONCLUSIONS AND FUTURE WORKS

In this paper, we have presented a method that can determine the global localization and compensate the position error that occurs in mobile robots using magnetic hall sensors

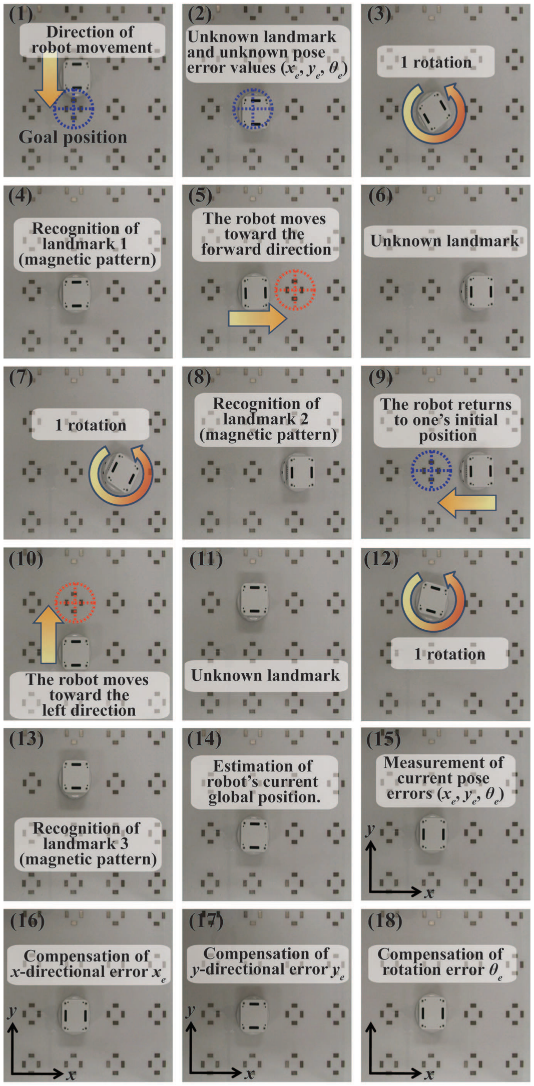



Fig. 10. The experiments to prove the performance of global localization technique using various patterns of magnetic landmarks, and the traverse of the mobile robot according to the position errors compensation.

while the current pose of the robot is unknown. First of all, the proposed global localization method is able to determine the position of robot on the global coordinate system. In addition, the robot can measure and compensate some error values of $x_e$, $y_e$, $\theta_e$ as comparing a desired position on the global coordinate system with current position of robot. Also, the heuristic search method was implemented to build the optimized virtual map. The experimental results show that the mobile root can recognize and compensate its current position on the global coordinates system to a more correct position. In the future, the proposed global localization method will be applied to multiple robot system. Also, a SLAM problem while considering the global localization will be studied and combined with a path planning algorithm for active SLAM.

## ACKNOWLEDGMENT

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