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Trajectory Tracking Using Environmental Magnetic Field for Outdoor Autonomous Mobile Robots

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Abstract—**This paper describes a trajectory tracking method using environmental magnetic field for outdoor autonomous mobile robots. In this research, a 3-axis magnetic sensor is used to scan DC magnetic field in the outdoor environment to build a database. The robot then performs trajectory tracking based on the database. The experimental results show that by applying the proposed method the robot is possibly able to navigate in the outdoor environment with a reliable accuracy.**

I. INTRODUCTION

The variation of outdoor environment such as weather, illumination, and changes of vegetation characteristic cause difficulty in developing a navigation system for outdoor autonomous mobile robot that is able to navigate all the time in all conditions. Even if several researches have been done in this field so far, it still remains as a major challenge. Generally, GPS is well known as one of the most feasible position measuring sensor for outdoor navigation. However, GPS does not currently offer a sufficient navigation resolution to allow it to be used as a standalone global navigation method for mobile robot. It is because of the ionosphere and the troposphere which may cause the error of time delay of signal from satellite and multi-path phenomenon which occurs when the GPS signal is reflected off objects such as tall buildings or large surfaces before it reaches the receiver. Thereby, this only allows GPS to act as a coarse position fixing aid to other localization methods to get an adequate position. Ohno *et al.* [1] present a differential GPS and odometry-based outdoor navigation of a mobile robot. The mobile robot actually localizes based on odometry and the positions obtained from differential GPS are used to correct the cumulative error made by odometry. Odometry is also used to discard the erroneous differential GPS data. However, failure in discarding erroneous differential GPS data and interception of GPS signal cause failure of navigation. On the extended work, Moracles *et al.* [2] present autonomous robot navigation in outdoor cluttered pedestrian walkways. A landmark recognizing method is used to solve problems in [1] where the landmarks such as trees and buildings are scanned by laser scanner sensors. Howard *et al.* [3], Burguera *et al.* [4] and Guivant *et al.* [5] also present the similar method of landmark recognizing using laser scanner sensors. Since such landmarks are not unchanged and on the other hand, in the pedestrian walkways the obstacles such as people, bicycles and cars may appear during the navigation, mismatching of landmarks can be occurred. Botenstein *et al.* [6] provide an idea of using magnetic compass to compensate the localization based on landmarks recognizing and Chiaju *et al.* [7] provide a method of using magnetic compass to compensate the localization based on GPS to make the navigation system be more reliable. However, magnetic compass is distorted near power lines or steel structures [8]. Odometry-based navigation can also be compensated by gyroscope to approve its accuracy. For instance, Brenstein *et al.* [9], [10] present a new method for combining data from gyros and odometry and an experimental evaluation of a fiber optics gyroscope for improving dead-reckoning accuracy in mobile robots. The method in [9] and [10] works fine in the indoor environment with a reliable accuracy. However, for outdoor environment where the terrain is uneven the cumulative error of orientation of mobile robot can be occurred. The vision-based navigation is also well known as one of the fundamental skills for outdoor environment. Lynch [11] provides experimental evidence of the extent to which people use landmarks when finding their way around cities. Morita *et al.* [12] present panoramic view-based navigation in outdoor environments based on support vector learning. The robot is placed in positions to be recognized where the image features such as color and edge are extracted and then sent to a set of SVMs, each of which is trained to recognize objects of a specific class. The output vectors from all SVMs are concatenated to produce the final recognition result. The interesting point is only the upper-half part of the image where the unmoved objects such as trees or buildings exist is used in the method. Konolige *et al.* [13] provide outdoor mapping and navigation using stereo vision. A 3D map is built relied on visual odometry to provide good localization, ground-plane analysis to help detect obstacles and sight lines to identify distant regions that are likely to be navigable. The robot is possibly able to locate a goal position several hundred meters away. However, water and ditches are two robot-killers and augment from GPS for global consistency is required, because it would give finer adjustment in the robot position and safer navigation.

This paper introduces a method of using environmental magnetic field for outdoor autonomous mobile robot naviga-

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tion [14]. Even if, the navigation using magnetic field is still not widely used, it is also known as one of the fundamental skills in robotics. Xu *et al.* [15] present a magnetic guidance method for intelligent vehicles. The magnetic markers are embedded under the path along a defined trajectory and the vehicle navigates by using magnetic sensor to scan position information from magnetic markers when it moves along the trajectory. In America, the California PATH has already launched the navigation system based on magnetic markers embedded under the vehicle path into a commercial system [16]. However, installing operation of magnetic markers under the path of vehicle contributes significantly to costs and in some restricted environments this might cause difficulty. In this research, we take into account the usage of environmental magnetic field instead of magnetic markers by applying a 3-axis magnetic field sensor to scan environmental magnetic field to build a database. The robot then navigates by performing trajectory tracking based on the database.

II. MOBILE ROBOT PLATFORM

The autonomous mobile robot applied in this research is shown in Fig. 1. The robot has a control computer, four batteries, a magnetic sensor, a range-finder sensor, two casters on the backside and two front driving wheels which can be controlled independently by control computer through a serial interface. The size of the robot is 1.01m length, 0.66m height and 0.80m width with the total weight of approximate 70kg. When the armor is equipped as shown in Fig. 2, it is able to transport two people with the approximate total weight of 100kg with the maximum velocity of 3km/h for approximate 3 hours. The 3-axis magnetic sensor, 3DM-DH, is installed in the middle of the robot with the orientation of x-axis to forward direction, y-axis to the right and z-axis to downward of the robot. It has a calibration function which can avoid the magnetic influence from control computer, motors and other devices. The magnetic sensor is shown in Fig. 3 and its specification is shown in Table I. The range-finder sensor, PBS-03JN, is installed at the low frontal part of the robot, 0.2m above ground level and oriented sideway in order to detect obstacles. The range-finder sensor is shown in Fig. 4 and its specification is shown in Table II.

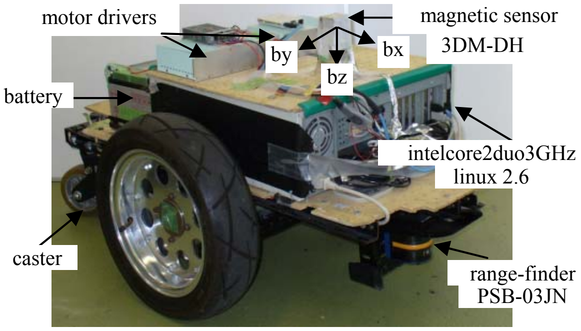


Fig. 1. Mobile robot [ERIE]

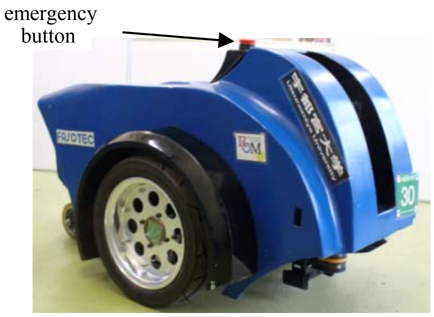


Fig. 2. Mobile robot with armor

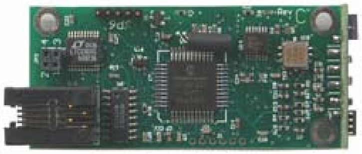


Fig. 3. 3-axis magnetic sensor [3DM-DH]

TABLE I
MAGNETIC SENSOR SPECIFICATION

Size [mm]	28×67×8
Angle output [degree]	yaw : ±180, pitch : ±180, roll : ±70
Raw output	bx, by, bz magnetic field ax, ay, az accelerometer
Angle resolution [degree]	yaw : 0.5, pitch : 0.3, roll : 0.25
Update rate [Hz]	45

Fig. 4. Range-finder sensor [PBS-03JN]

TABLE II
RANGE-FINDER SENSOR SPECIFICATION

Size [mm]	70×75×60
Range [degree]	180
Distance [m]	0.2-3.0
Source	red LED (800nm)
Hysteresis	less than 10% of detection distance (not less than 66mm)
Update rate [Hz]	10

III. NAVIGATION SYSTEM

Fig. 5 illustrates the navigation module of this research. It is divided into two phases of database building phase and navigating phase.

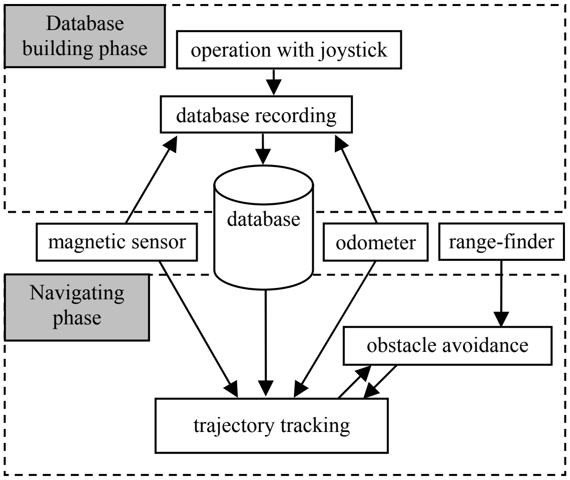


Fig. 5. Navigation module

A. Database building phase

The database built with the robot operated with a joystick. It contains the robot coordinates, the intensity of three axes of magnetic field and the state of magnetic field at each area of the path. Authors will describe details on the magnetic field and its state in the next section. The robot coordinate is recorded in the polar coordinate system (l, θ) instead of (x, y), where l is the robot travel distance which is calculated by counting the right and the left wheel rotation of the robot and θ is the robot azimuth angle which it is equivalent to yaw angle of the magnetic sensor. The data stored in the database with the sample rate of 10Hz. The structure of database is shown in Table III.

TABLE III
STRUCTURE OF DATABASE

Position (l, θ) [m, degree]		Magnetic field (bx, by, bz) (raw)			State of magnetic field
l[0]	θ[0]	bx[0]	by[0]	bz[0]	0, 0, 1
l[1]	θ[1]	bx[1]	by[1]	bz[1]	0, 0, 1
		⋮			
l[50]	θ[50]	bx[50]	by[50]	bz[50]	-1, 0, 1
l[51]	θ[51]	bx[51]	by[51]	bz[51]	-1, 0, 1
		⋮			
l[n]	θ[n]	bx[n]	by[n]	bz[n]	0, 0, 0

In order to evaluate the feasibility of the proposed method, we built a database on pedestrian walkways in Utsunomiya University campus as shown in Fig. 6 where the robot started and finished on the same position. The trajectory of database is shown in Fig. 7. In Fig. 7, the dash line illustrates the trajectory of database plotted with the value of (x, y) coordinate from odometer and the solid line illustrates the trajectory of database plotted with the value of (l, θ) of the robot travel distance and azimuth angle. The result shows that by using combination between the robot travel distance and the azimuth angle, the desired database trajectory can be achieved.

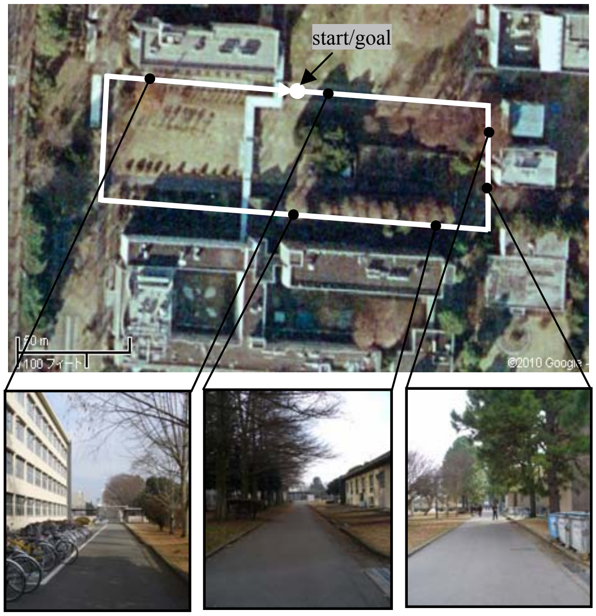


Fig. 6. Path viewed in Google Maps with snapshots (Utsunomiya Univ. campus)

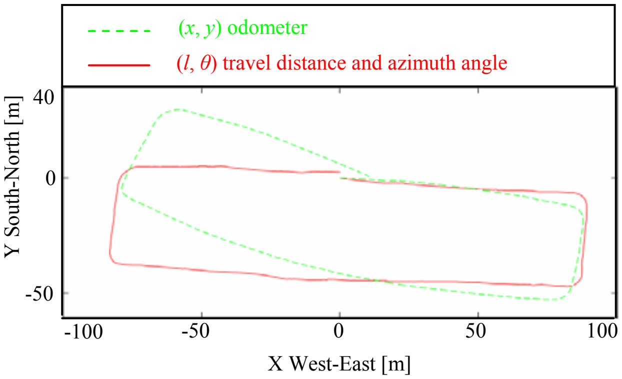


Fig. 7. Trajectory of database

B. Navigating phase

The database built in the previous section will be used here to perform the navigation. As shown in Fig. 5, the navigating phase is performed based on two processes of trajectory tracking and obstacle avoidance.

1) Trajectory tracking

In this process, the robot uses its current travel distance to match against the travel distance stored in the database to load the azimuth angle and magnetic field data from the database to perform trajectory tracking. The control system of trajectory tracking is shown in Fig. 8. Basically, the robot is able to perform trajectory tracking based on the travel distance and azimuth angle. However, in the outdoor cluttered pedestrian walkways, the uneven terrain and instantaneous influence of magnetic sensor from disturbances such as passing bicycles, cars, and other magnetic materials may cause the robot goes off the target trajectory as shown in

Fig. 9. In this research, the magnetic field and its state are used to possibly keep and return the robot into the target trajectory.

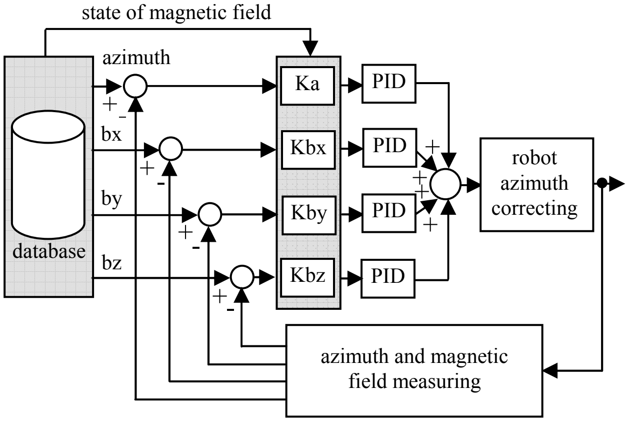


Fig. 8. Control system of trajectory tracking

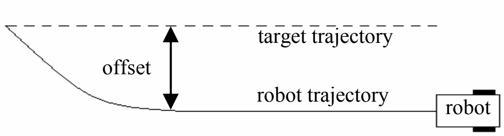
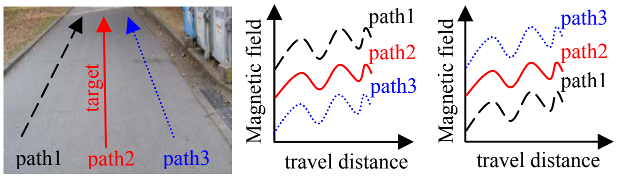


Fig. 9. Offset conducted by instantaneous influence or wheel slippage

The DC magnetic field occurred in the environment is known that it is the composition of geomagnetism and environmental magnetic field conducted by residual current of the magnetic materials in the environment. Since it is time invariant [17] and its strength depends on the distance from the magnetic materials, these gave us idea to apply it for keeping and returning the robot into its target trajectory when it goes off the target trajectory in some cases. However, the magnetic materials such as buildings and power poles in some areas are located on the left and in some areas are located on the right of the robot which causes difficulty for robot to recognize to which direction its target trajectory located depending on the strength of magnetic field when performing navigation. In this research, as shown in Fig. 10(a), the environmental magnetic field on other two trajectories along the target trajectory is also scanned in order to investigate the states of magnetic field at each area of the path. The states of magnetic field are divided into two states as shown in Fig. 10(b-c) and they are defined by 1 and -1 in the database. For the states which are not applied to the two states shown in Fig. 10(b-c) are defined by 0 in the database. The gain *Kbx*, *Kby* and *Kbz* of PID controller in Fig. 8 of the trajectory tracking control process will be multiplied by these states value in order to keep and return the robot into the target trajectory. Fig. 11 illustrates magnetic field scanned on 70m of a distance from the start position of the database trajectory and the states of magnetic field definition. In Fig. 11, the vertical axis represents raw data of the magnetic field and the horizontal axis represents the robot travel distance. Authors used raw data of the magnetic field because authors consider that it is not important to convert the raw data of the magnetic field into a magnetic unit. The important points are time invariant and waveform property of the magnetic field.



(a) Investigation paths (b) State (1) (c) State (-1)

Fig. 10. States of magnetic field definition

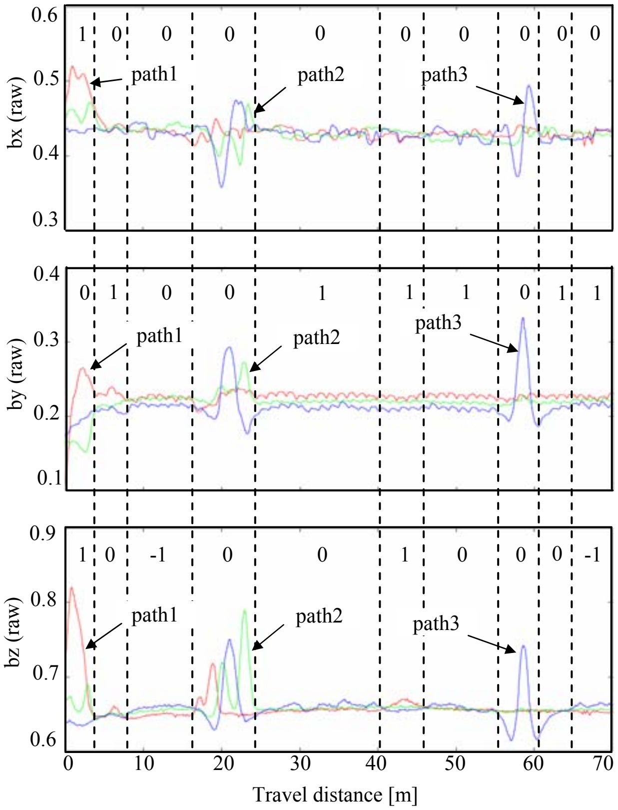


Fig. 11. State of magnetic field investigation

2) *Obstacle avoidance*

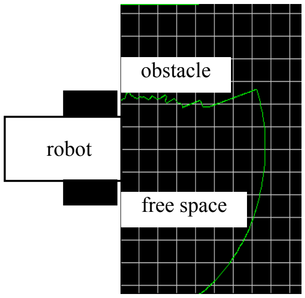


Fig. 12. Range-finder based obstacle avoidance

In the outdoor cluttered pedestrian walkways, obstacle avoidance is actually necessary to handle people, bicycles and other obstacles that appeared during the trajectory tracking. In this research, the obstacle avoidance is performed based on range-finder sensor where it is installed in the low frontal part of the robot, 0.2m above ground level and oriented sideway as shown in Fig. 1. Fig. 12 illustrates a scene when the robot located an obstacle. The obstacle avoidance is performed when the robot is at least 1m close to the obstacle. The program of obstacle avoidance is simple. It needs just to locate the free space when there are obstacles appear in front of the robot. In Fig. 12, the robot found an obstacle in its left side, in this case the robot will move to the free space in the right side to pass the obstacle. After the robot passed the obstacle, the navigation will return to trajectory tracking process. The interesting point of this research is, since authors use azimuth angle of the magnetic sensor in trajectory tracking, the robot always knows the direction of its target trajectory. On the other hand, with the magnetic field and its states are also applied in the trajectory tracking, the robot is always possible to return into its target trajectory.

IV. EXPERIMENTS

The experiments conducted on the different date to the date when the database was built. There are two purposes authors want to illustrate with the experiment results. Firstly, authors want to illustrate the different between trajectory tracking without support from magnetic field and the supported one. Secondly, authors want to illustrate the robot is able to navigate almost all the time in all conditions based on the proposed method. The database was built on 12th of Jan. 2010 in daytime with cloudy weather where the robot was operated by joystick with the velocity of 0.3m/s. The navigation experiments conducted on two different days, on 26th of Jan. 2010 in daytime with the weather clears up and on 2nd of Feb. 2010 in nighttime with cloudy weather where the robot navigated with the velocity of 0.4m/s. Since the robot navigated by performing trajectory tracking, the robot velocity in database building process should be lower than the velocity in trajectory tracking process in order to increase accuracy of navigation. Fig. 13 illustrates the experiment result when the robot navigated by performing trajectory tracking based on travel distance and azimuth angle without using magnetic field data. The result shows that without using magnetic field to compensate trajectory tracking, the robot conducted offset between the robot trajectory and database trajectory and this offset is increased when the magnetic sensor was affected by disturbances or wheel slippage of the robot is occurred. Fig. 14 illustrates the experiment result when the robot navigated by performing trajectory tracking with support from magnetic field. By using magnetic field to compensate the trajectory tracking, the robot is able to perform trajectory tracking with a more reliable accuracy.

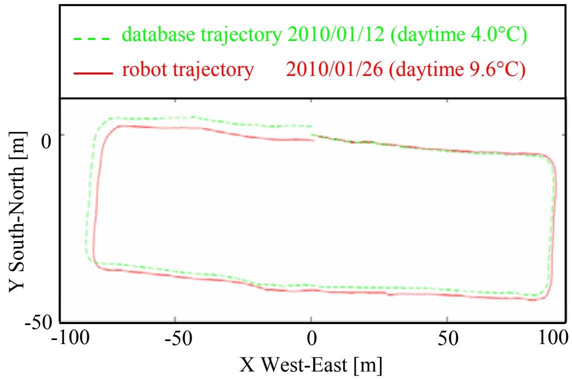


Fig.13. Trajectory tracking without support from magnetic field

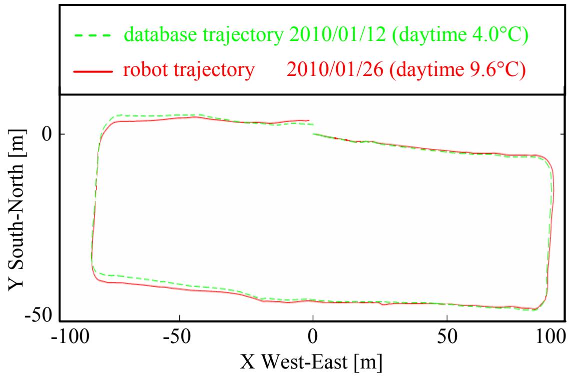


Fig. 14. Trajectory tracking with support from magnetic field

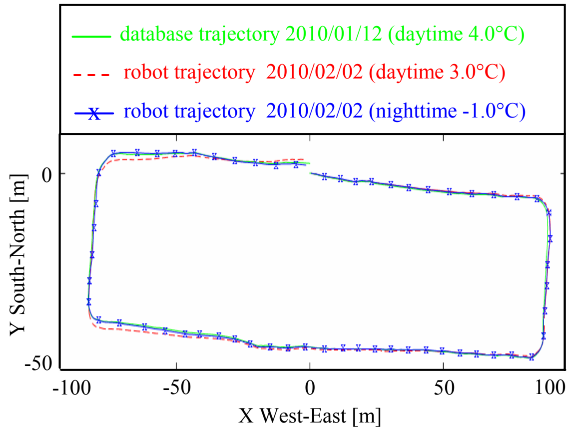


Fig. 15. Trajectory tracking with support from magnetic field in nighttime

Fig. 15 illustrates the comparison between experiment results conducted in the daytime and the nighttime. The result shows that in nighttime when there are not any disturbances such as bicycles or cars appear during the navigation, the robot is able to navigate with a higher accuracy than in daytime. This result also shows that the robot is able to navigate in all the time in all conditions with the proposed method. Depending on the results, it is enough to prove that the proposed method is feasibility.

V.CONCLUSIONS AND FUTURE WORKS

In this paper a trajectory tracking method based on environmental magnetic field was described. The experiment results showed that the robot is able to navigate in all the time in all conditions based on the proposed method. The proposed method was also applied in the so called "Real World Robot Challenge 2009" (or Tsukuba Challenge 2009) where our mobile robot finished 1km autonomous run with the time of 51m07s [18]. However, some problems have been occurred during the navigation experiment. Even if the results showed that the robot is possibly able to return to its target trajectory by using the magnetic field to compensate the trajectory tracking when it goes off its target trajectory in some cases, this will cause error between the robot travel distance and the travel distance in the database and this error will be increased when the robot keep returning into its target trajectory. It is therefore necessary to compensate this error by measuring position of the robot relative to known objects in the environment. A method of using GPS is well known as one of the most feasible method for outdoor navigation. However, signal of GPS is easily blocked by trees, tall buildings or large surfaces. Thereby, GPS is required to be stuck out and lifted to a high position. Since the mobile robot used in this research is designed for transportation which can allow two people ride on, sticking sensors out is something authors try to avoid. Therefore, a position measuring method without sticking sensors out should be required in order to increase the accuracy of proposed method. Another problem is, when the robot performed obstacle avoidance at the areas where the strength of magnetic field are strong, this caused failure in navigation. This is because of the magnetic sensor could not provide correct azimuth angle to the robot since it is completely influenced by magnetic noise. During the navigation experiment, authors also learned the error of odometer. The mobile robot applied in this research uses pneumatic tires and the odometer calculates the travel distance by counting the right and the left wheel rotation of the mobile robot. Thereby, the change of tire size caused by change of temperature or air leak can conduct error to odometer. The high change of temperature especially in the summer may also affect the proposed method. The magnetic field conducted by the magnetic materials in the outdoor environment such as buildings, manholes or power poles is partly changed by high temperature. Since the azimuth angle is calculated based on geomagnetism, this change of the magnetic field affected to azimuth angle of magnetic sensor which plays an important role in the proposed method.

As future works, authors plan to apply a position measuring method using image process or method using environmental magnetic field [14] which does not need to stick sensors out to compensate the error of travel distance occurred when the robot keep returning into its target trajectory. Authors also plan to use optical-fiber gyroscope to compensate the error of azimuth angle caused by magnetic noise or change of temperature. Beside that, authors also plan to investigate the change of the magnetic field and azimuth angle caused by change of temperature especially in the summer.

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