Experimental Evaluation of Gyro-based Odometry Focusing on Steering Characteristics of Wheeled Mobile Robot in Rough Terrain

*Takuma Nagata, Genya Ishigami

Keio University, Yokohama, Japan, E-mail: nagatatakuma@keio.jp, ishigami@mech.keio.ac.jp

ABSTRACT

Mobile robot used for planetary exploration has several scientific missions over a long distance travel and needs to have a high degree of autonomous mobility system because the communication delay from the Earth impedes its direct teleoperation. Robot localization is of particular importance on the autonomous mobility. Several techniques for the robot localization such as wheel odometry or visual odometry have been widely investigated and demonstrated, but they still possess a well-known trade-off between computational cost and localization accuracy. This paper proposes a simple but accurate gyro-based odometry method focusing on steering characteristics of a wheeled mobile robot. The mobile robot in rough terrain is often subject to large wheel slip or vehicle sideslip which is related with steering maneuver of the robot, and those degrade the robot localization accuracy. The basic approach of the proposed method is to exploit wheel odometry data as well as gyroscope data for the robot heading calculation; but each data set is the correlated with a weighting factor that depends on steering characteristics of a robot in rough terrain. The usefulness of the proposed method is examined through field experiments in Martian analogue site using a wheeled mobile robot testbed. The experimental result confirms that the proposed method accurately estimates the robot path.

1 INTRODUCTION

The planetary rover is required to travel towards area of interest with its autonomous mobility system since the teleoperation of the rover is not practical owing to the communication delay from the Earth to a target planetary body.

An autonomous mobile robot basically performs the following tasks to move around on unknown environment: (1) environment recognition (mapping), (2) path/motion planning, and (3) motion control and localization. First, a robot recognizes environment by stereo camera or laser range finder in order to identify hazardous area or possible obstacles ahead. Next, the robot generates a path to be traveled toward a location of interest according to terrain traversability. Subsequently, the robot guides itself with controlling the motion (driving and steering) of the robot to travel along the path while estimating the position and heading of the robot. The latter task is known as robot localization which tells where the robot is on a given map and how far or how accurate the robot has driven on the map.

There have been extensive researches and demonstrations in robot localization: some well-known localization methods are for wheel odometry, gyro-based odometry, and visual odometry. The wheel odometry estimates distance traveled by counting the number of wheel rotations using wheel encoders. The gyro-based odometry uses gyroscopes to estimate the robot heading while using wheel odometry for the distance traveled. The visual odometry tracks feature points on multiple time consecutive images taken by onboard cameras and estimates the robot motion from the displacement of the feature points. The visual odometry is particularly useful for a case in which the robot traverses in slippy environment, but it may require some computational efforts for data management of camera readout time and visual processing.

The mobile robots on the Mars, such as Spirit/ Opportunity operated by NASA, are required to maintain a position estimate accuracy that drifts no more than 10% during a 100 meters drive [1]. The gyro-based odometry secures real time localization with less complicated systems. Recent works related to this method have devoted to a direct estimation or correction of wheel slipping, resulting in an accurate localization [2-4], or others have coupled the gyro-based odometry with data from laser range finder [5-7], or applied Unscented Kalman Filter (UKF) for data acquired from gyroscope and wheel encoder [8]. Most of the abovementioned methods have employed empirical or statistical approach to determine its correlation between wheel odometry and gyroscope data, however, the performance of the methods have not been well discussed based on vehicle characteristics such as driving or steering maneuvers.

In this paper, we focus on a sideslip motion of wheel and vehicle, which are typical factors for a localization error, and propose a method that couples with a steering characteristics of a vehicle to the robot localization. The proposed method basically exploits a framework of classical gyro-based odometry but collocates weightings for wheel odometry and gyroscope data with the vehicle steering characteristics. The method is therefore relatively simple and easily implemented to any wheeled mobile robot. The usefulness of the proposed method is quantitatively verified through field experiment in Martian analogue site covered with scoria sand and slippy rocks.

The paper is organized as follows: In Section 2, the proposed gyro-based odometry with steering characteristics of wheeled mobile robot is introduced along with a classical gyro-based odometry. The proposed method is evaluated through two different sets of experiment using a wheeled mobile robot testbed: Section 3 describes an experiment in which steering angle of the robot is fixed so that the robot theoretically follows a constant turning radius. Section 4 reports a long-range travel experiment with several steering motions.

2 GYRO-BASED ODOMETRY

In this section, first, a general gyro-based odometry is introduced, and then, the proposed gyro-based odometry with steering characteristics is described, along with a stability factor which is widely used as an index for the steering characteristics of a wheeled vehicle.

2.1 Classical Method

In a conventional method of gyro-based odometry, or called gyrodometry, a distance traveled of a wheeled robot is calculated from a wheel odometry (counting wheel rotations), and a robot heading is estimated from two different data sets: one is given from a gyroscope data and the other is calculated by the wheel odometry data. An angular velocity of the robot heading calculated from the wheel odometry ω_{wo} is determined as follows: first, the steering geometry is given as:

$$\omega_{wo} = v/\rho \quad (1)$$

where v is the traveling velocity of the robot and ρ is the turning radius. Assuming that the robot steers front wheels with an angle of θ_{steer}, a general bicycle model of steering geometry rewrites ω_{wo} as:

$$\omega_{wo} = v\sin\theta_{steer}/l \quad (2)$$

where l represents the wheelbase of the vehicle. Then, the gyro-based odometry first compares the angular velocities measured by the gyroscope denoted by ω_{gy} and ω_{wo}:

$$\Delta\,\omega = \omega_{gy} - \omega_{wo} \quad (3)$$

Subsequently, given the threshold ω_{thres} having a certain value, the robot heading angle θ_i at the time step i is estimated with the following equation:

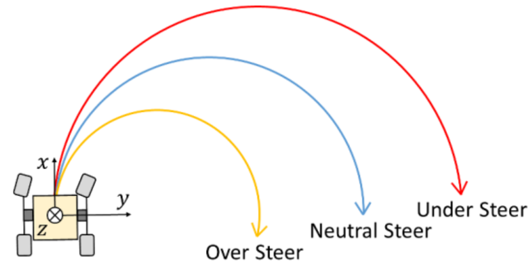

Figure 1: Stability Factor

$$\begin{cases} \theta_i = \theta_{i-1} + \omega_{gy}\Delta t & (|\Delta\omega| > \omega_{thres}) \\ \theta_i = \theta_{i-1} + \omega_{wo}\Delta t & (|\Delta\omega| \leq \omega_{thres}) \end{cases} \quad (4)$$

where Δt is the sampling time step of the measurement. The value of the threshold $\omega_{thres}$is usually tuned based on a pre-experimental test, or it is updated online during the robot travel.

The gyro-based odometry is well known as an accurate localization method for a robot traveling on hard ground; however, it may not be often applicable for a robot on rough terrain owing to wheel slippage (miscount of wheel rotation) or vehicle sideslip. These slips become remarkable while the robot steers, resulting in a localization error of the robot.

2.2 Gyro-based Odometry with Steering Characteristics

2.2.1 Stability Factor

The stability factor K_s given by the following equation [9] is a parameter that shows steering characteristics of a vehicle:

$$K_s = -\frac{m}{2l^2}\frac{l_f K_f - l_r K_r}{K_f K_r} \quad (5)$$

where m represents the mass of a robot, and l represents the wheelbase, and l_f and l_r represent the distance between the position of the center of gravity to the front or rear wheels, and K_f and K_r represent the cornering stiffness of the front wheel and rear wheels.

Figure 1 shows the steering characteristics of a vehicle with varied stability factor: when K_s is equal to 0 called Neutral Steer (NS), the vehicle steers along with a curve which is geometrically determined from a given steering angle; when K_s is greater than 0 as Under Steer (US), the turning radius becomes greater than that of NS; and when K_s is less than 0 as Over Steer (OS), the turning radius becomes smaller than that of NS. The cornering stiffness is generally used for a pneumatic tire of automobile to describe tire's dynamic response with respect to a slip angle of the tire. The value of the stiffness then depends on the tire characteristics as well as ground on which the tire rotates. Although the value of the cornering stiffness for a rigid wheel in rough terrain cannot be directly estimated, the work in this paper utilizes the idea of the stability factor. Here, assuming that two identical wheels (dimension and wheel surface pattern) travel on rough terrain, these wheels should possess same values of the cornering stiffness, namely $K_f = K_r$. Therefore, we derive the following equation from Eq. 5.

$$K_s = -\frac{m}{2l^2}\frac{l_f - l_r}{K} \tag{6}$$

This equation clearly shows that m l, and K determine a magnitude of K_s, and the sign of K_s only depends on the relationship of $l_f - l_r$.

2.2.2 Proposed Method

A wheeled mobile robot that makes a steering on skiddy terrain usually experiences wheel slippage. A wheel slippage in longitudinal direction degrades an accuracy of wheel odometry. A turning radius estimated by the wheel odometry then becomes smaller than that of a true one, which is similar to an over steer condition. On the other hand, a wheel slippage in lateral direction generates a vehicle sideslip which is mainly composed of a lateral translation of vehicle body without any/less rotation of the body. A gyroscope mounted on the robot does not accurately measure an angular velocity in such translation because the angular velocity may be often less than the sensor's signal to noise ratio, and therefore, a turning radius estimated by a gyro-based odometry becomes larger than that of a true one, which may be identical to an under steer condition. These tendencies as shown in Figure 2 are often observed in experimental tests using a wheeled mobile robot on rough terrain.

The angle of sideslip is measured by $\beta = \tan^{-1}(v_x/v_y)$. Here, v_x represents the robot's translational velocity in the longitudinal direction, and v_y represents that in the lateral direction (Figure. 3). A general wheel odometry defines the sideslip angle being 0° for its estimation. Therefore, the proposed method in this study first calculates a relative error ϵ between the robot heading angles estimated from a wheel odometry and a gyro-based odometry (Figure. 4):

$$\epsilon = \theta_{wo} - \theta_{gy} \tag{7}$$

Here, as noted above, the gyro-based odometry may be identical to an under steer condition. Therefore, it can be assumed that the gyro-based odometry underestimates the heading angle of the vehicle body, the value of which is w times smaller than that of true sideslip angle $\hat{\beta}$, namely:

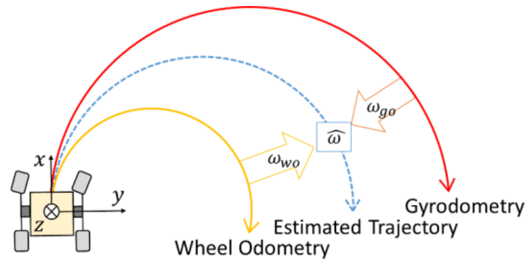

Figure 2: Approach of Proposed Method

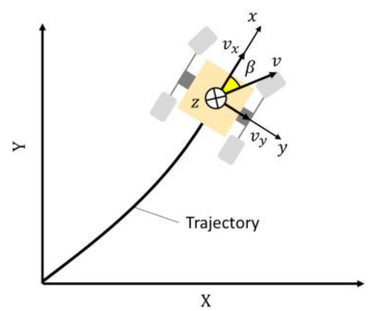

Figure 3: Side Slip Angle

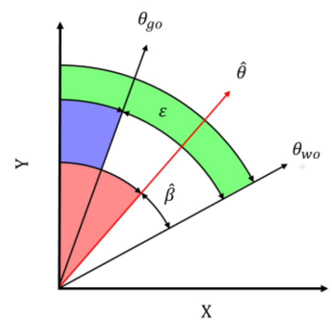

Figure 4: Heading Angle of Vehicle: Angles are measured from Y-Axis

$$\hat{\beta} = w\epsilon \tag{8}$$

Then, the true heading angle $\hat{\theta}$ is calculated by the following equation:

$$\begin{aligned} \hat{\theta} &= \theta_{wo} - \hat{\beta} \\ &= \theta_{wo} - w\epsilon \end{aligned} \tag{9}$$

An angular velocity of the vehicle used in the proposed method can be derived by the time derivative of Eq. 9:

$$\widehat{\omega} = (1 - w)\omega_{wo} + w\omega_{go} \quad (0 \le w \le 1) \tag{10}$$

Eq. 10 means that the angular velocity of the robot heading is estimated by combining the wheel odometry and the gyroscope data, each of which is respectively weighted in accordance with steering characteristics of the robot (Figure 2). A well-known approach in [10] for a gyro-based

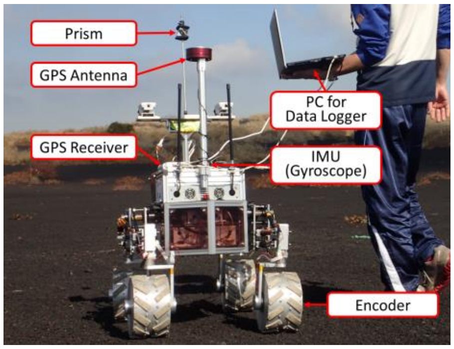

Figure 5: Experimental setup of the robot testbed

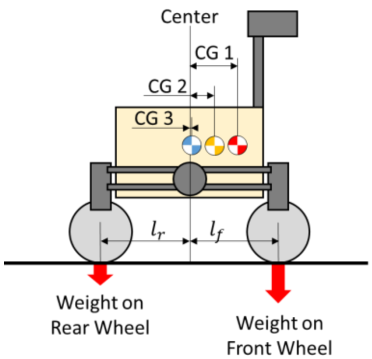

Figure 6: Illustration of the center of gravity of the robot

odometry utilizes a maximum likelihood estimation to calculate a value of the weighting factor from time-varied covariance values between wheel data and gyroscope data. In contrast, it is clear that the weighting factor in the proposed method is determined based on steering characteristics of a vehicle, which depends on terrain, position of robot's center of gravity, and steering angle. Therefore, the value of the weighting factor can be assumed to be constant while a robot travels on a uniform terrain with constant velocity and fixed steering angle.

3 EXPERIMENTAL VALIDATION OF THE PROPOSED METHOD

In the experiment described in this section, the robot steers with a fixed steering angle. The center of gravity of the robot is tuned with three different positions. This is because the steering characteristics depends on the position of the center of gravity as described in Section 2. Therefore, the usefulness of the proposed method can be discussed along with the relationship between localization accuracy of the proposed method, steering characteristics, and weighting factor used for Eq.10.

Table 1. Specification of mobile robot

Overall length	800×630 ×950 mm
Wheelbase	600 mm
Track width	460 mm
Wheel diameter	200 mm
Maximum velocity	100 mm/s
Continuous running time	4 hours

Table 2. Position of the center of gravity

	CG 1	CG 2	CG 3
Front load [kg]	21.14	19.14	19.76
Rear load[kg]	17.88	17.44	19.26
- [%]	4.2	2.3	0.6
l_f [mm]	275	386	296
l_r [mm]	325	314	304

3.1 Experimental Setup and Condition

The robot testbed used in the experiment is shown in Figure 5 and the specification is summarized in Table 1. An inertial measurement unit (IMU) mounted on the upper side of the robot measures the 3-axis accelerations and angular velocities of the robot. The ground truth data of the robot trajectory is measured by a total station. The total station automatically collimates its ranging laser toward the prism mounted on the robot and provides accurate measurement of ±3 mm in distance. The experimental field is volcanic area where scoria, skiddy rock covers. The terrain feature is gentle slope with its many uphill/downhill and there are little flat area.

The experiments were performed with three different steering angles with three different center of gravities of the robot. The center of gravity of the robot is adjusted by attaching 2 kg weight on front side or rear side of the robot (Figure 6, Table 2.) The steering angle is fixed on 5°, 8°, or 10° in each CG position, and the robot is controlled to maintain constant traveling velocity of 0.1 m/s.

3.2 Proposed Method Validation

The experimental results for the steering angle of 5°, 8°, or 10° are respectively shown in Figure 7, Figure 8, and Figure 9. In each graph, the true trajectory, and three trajectories estimated from the wheel odometry, the classical gyro-based odometry, and the proposed method are illustrated.

Note that these results are the case of CG 1 and the other cases for CG 2 and CG 3 are almost identical to that for CG 1. This is because that terrain stiffness dominantly effects on the steering characteristics rather than the change of the center gravity in rough terrain. As defined in Eq. 6, assuming that the cornering stiffness K which is highly related to the terrain stiffness becomes large as compared to the value of $l_f - l_r$, the change of the stability factor with

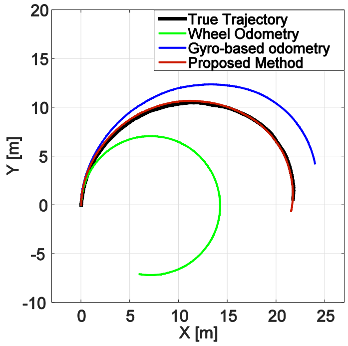

Figure 7: Experimental result: steering angle = 5 deg

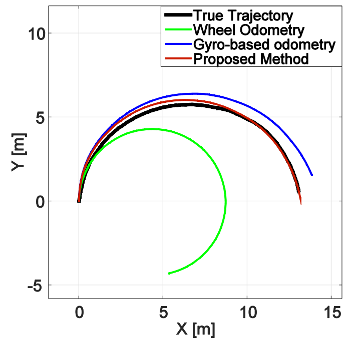

Figure 8: Experimental result: steering angle = 8 deg

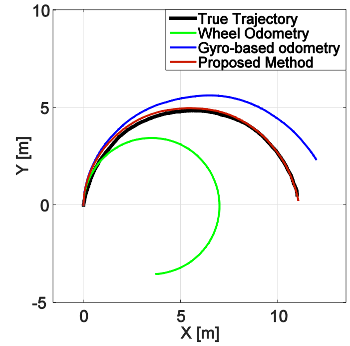

Figure 9: Experimental result: steering angle = 10 deg

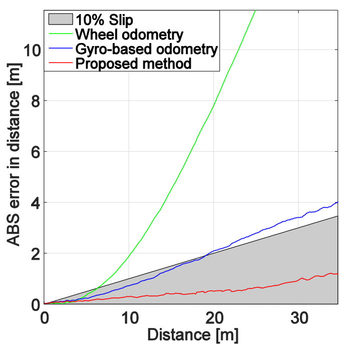

Figure 10: Accumulated error: steering angle = 5 deg

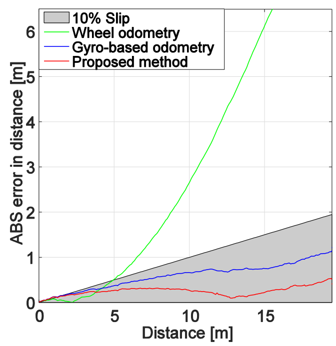

Figure 11: Accumulated error: steering angle = 8 deg

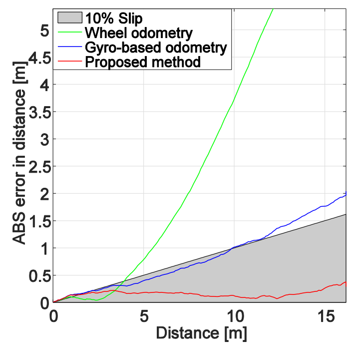

Figure 12: Accumulated error: steering angle = 10 deg

respect to the change of the CG is not remarkable. Therefore, the small difference of the CG affects small change to the steering characteristics. From the above, the steering characteristics in rough terrain is mainly determined by terrain type and rarely by the change of center of gravity.

The accumulated error along with the distance traveled are depicted in Figure 10, Figure 11, and Figure 12. The gray-colored area indicates an allowable error due to a case of 10% wheel slippage as noted in Section 1. The accumulated error of the proposed method falls within the allowable error during the experimental run.

The proposed method improved the localization accuracy in every case of nine experiments (Table 3.) The error rate at the goal area was 3.34% at a maximum and 0.09% at a minimum. Here, the weighting factor is determined such that the error of the localization becomes minimum. Therefore, the weighting factor becomes large for a case in which the classical gyro-based odometry shows good performance. However, the value of the weighting factor ***w*** is within the small range from 0.80 to 0.91 (Table 4.) This result implies that the proposed method can still estimate relatively accurate trajectory of the robot traveling on that terrain with arbitrary CG position once a weighting factor is selected from that range.

Table 3. Error rate of Experiment

		Proposed method	Gyro-based odometry	Wheel odometry
CG 1	5°	3.34 %	11.65 %	50.25 %
	8°	2.08 %	6.26 %	46.67 %
	10°	1.80 %	12.62 %	51.20 %
CG 2	5°	1.16 %	10.47 %	47.89 %
	8°	1.52 %	7.48 %	50.12 %
	10°	0.09 %	9.44 %	50.98 %
CG 3	5°	0.99 %	9.75 %	50.55 %
	8°	0.73 %	13.37%	52.14 %
	10°	0.39 %	14.19 %	51.90 %

Table 4. Weighting factors of Experiment

	CG 1	CG 2	CG 3
5°	0.80	0.83	0.85
8°	0.88	0.91	0.82
10°	0.82	0.87	0.82

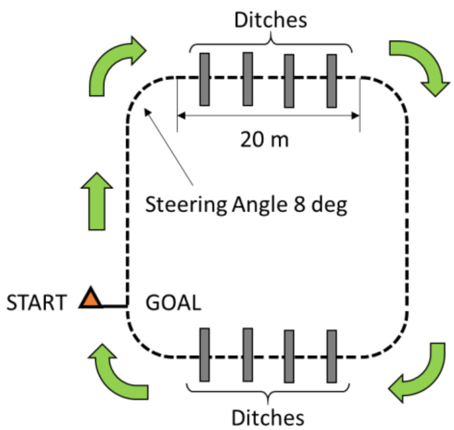

Figure 13: Long-range travel experiment: schematic illustration of the robot trajectory

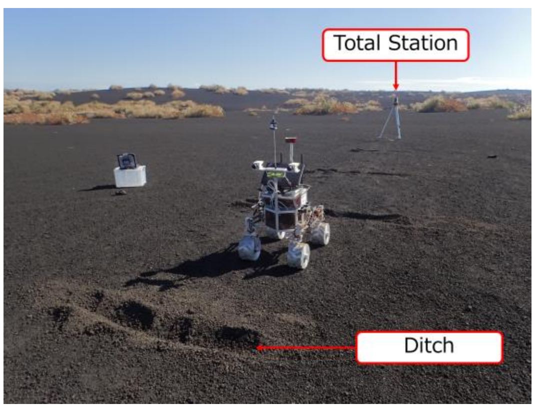

Figure 14: Long-range travel experiment: overview of the experimental field

4 LONG-RANGE TRAVEL EXPERIMENT

This section describes an experimental evaluation of the proposed method in a long-range travel experiment. The experiment was performed in a volcanic area with skiddy terrain.

4.1 Setup and Condition for Long-range Travel Experiment

The basic setup of the robot testbed is same as that described in Section 3.1. During the experiment, the robot was controlled to travel along a predetermined course including straight and curve motions (Figure 13.) The experimental environment is shown in Figure 14. The predetermined course is square trajectory having four steering corners and eight ditches as imitating obstacles. At each corner, the steering angle was controlled to maintain mainly 8°, or 5° for trajectory correction maneuver. A pivot motion was occasionally used after the curve motion to adjust the robot's heading. The CG of the robot is selected as CG 2. The experiments were performed three times, each of which took 45 minutes.

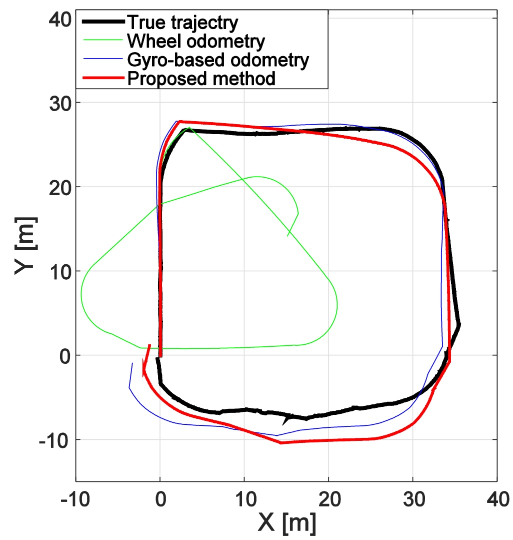

Figure 15: Trajectory of experiment No. 1

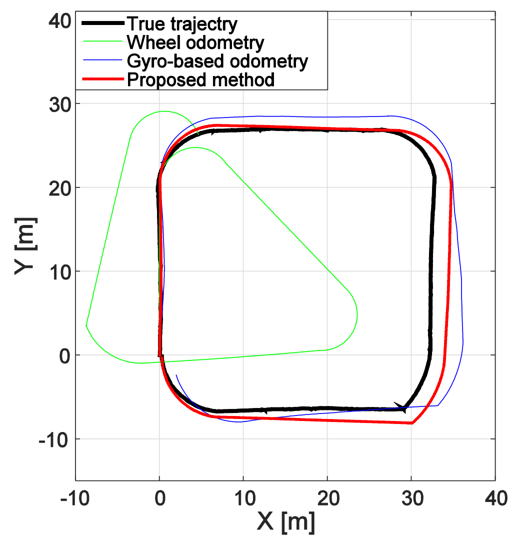

Figure 16: Trajectory of experiment No. 2

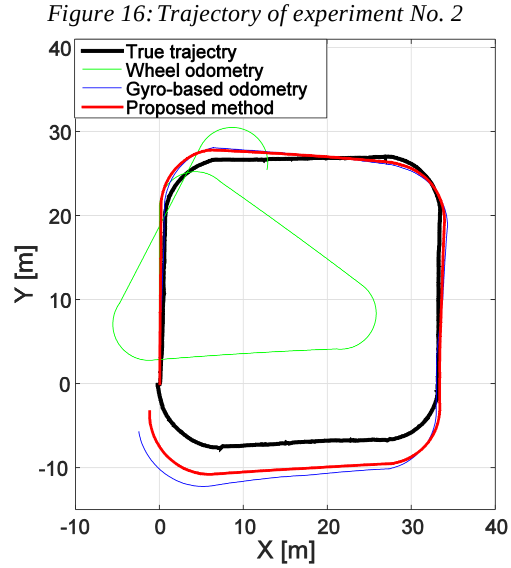

Figure 17: Trajectory of experiment No. 3

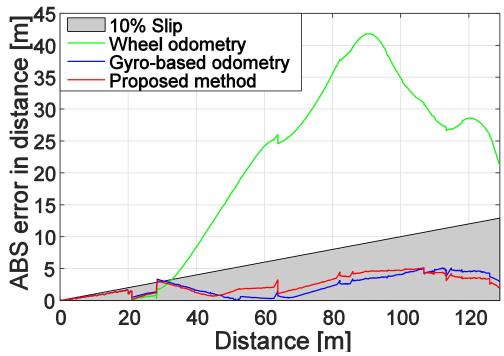

Figure 18: Accumulated error of experiment No. 1

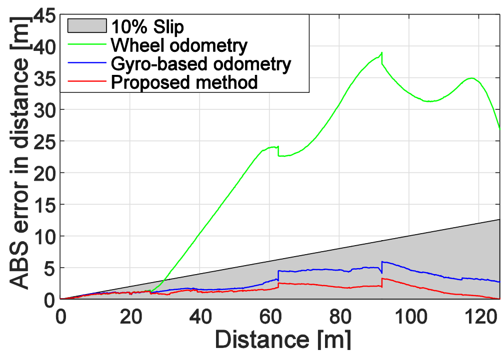

Figure 19: Accumulated error of experiment No. 2

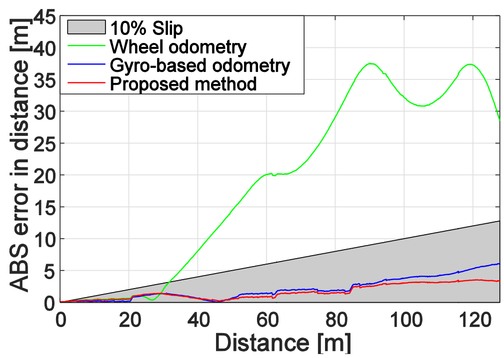

Figure 20: Accumulated error of experiment No. 3

4.2 Result and Discussion

The experimental results are shown in the Figures 15, 16, and 17. The error rate is summarized in Table 5. The accumulated errors are also shown in Figures 18, 19, and 20. The black curve shows the true trajectory measured by the total station, the green curve shows the trajectory estimated by the wheel odometry, the blue curve shows the trajectory estimated by the classical gyro-based odometry, and the red curve shows the trajectory estimated by the proposed method.

Table 5. Error rate of long-range travel experiment

Trial #	Proposed method	Gyro-based odometry	Wheel odometry
No. 1	1.45 %	2.30 %	16.33 %
No. 2	0.17 %	2.26 %	21.21 %
No. 3	2.62 %	4.76 %	22.28 %

Table 6. Weighting factor

Trial #	Straight motion	Curve motion	Pivot motion
No. 1	020	1.00	0.95
No. 2	0.25	0.90	1.00
No. 3	0.25	0.90	1.00

It can be clearly seen that the wheel odometry completely deviates from the true robot trajectory. On the other hand, the proposed method accurately estimates it. Between the three trials of the experiment, the proposed method fairly improves the classical gyro-based odometry.

Table 6 shows the weighting factors used in the experiment. Note that the weighting factor at the curve motion is 1.0 for the first trial, which indicates that the proposed method in this case completely relies on the angular velocity measured by the gyroscope, and does not use the angular velocity estimated from the wheel odometry. This may be due to the fact that the robot motion at each corner was not smooth all the time and requires some heading correction with the pivot motion. The reliability on the wheel odometry then becomes less, resulting in such large weightings. On the other hand, the weighing factors for the other trials are 0.90 which is within the range determined from the steering experiment in Section 3. Therefore, once a preliminary test of a simple steering motion of a robot is performed and a best-fit weighting factor for a robot trajectory is determined, the same value of the weighting factor may be applicable for any localization that includes similar steering maneuvers.

5 GENERAL DISCUSSION

The usefulness of the proposed method in rough terrain has been verified in Section 3. Moreover, Section 4 has showed that the proposed method can estimate the trajectory more accurate than the classical gyro-based odometry in such long-range travel.

In general, a range of possible value for the weighing factor that provides accurate localization of a robot is assumed from a preliminary test, and it may be able to correlated with steering characteristics of the robot: the weighting factor for the robot in the rough terrain may have a value from 0.80 to 0.91 (as described in Section 3.2) and it can be still useful for the long-range travel.

The proposed method still includes open issues. One particular issue is how to determine a unique value of the weighting factor. The value would be then quantitatively correlated with steering characteristics or a value of stability factor of a vehicle. The stability factor as defined in Section 2 is a function of the cornering stiffness K that is gradient of the cornering force w.r.t the slip angle of a wheel. Therefore, a wheel characteristics should be also clarified to further discuss the relationship between the stability factor and the weighting factors. Once the value of stability factor is determined from the wheel characteristics, it is well known that a vehicle sideslip is theoretically estimated based on a bicycle model of steering geometry [9].

The other open issue is related to the zero-yaw motion of the vehicle since the angular velocity in that motion is too small for the gyroscope to measure. One possible solution for this issue is to employ an additional sensor such as the one using the optical mouse technique [11]. To mount this optical sensor on the vehicle body may enables an accurate measurement of planar translational motion.

6 CONCLUSION

In this paper, the gyro-based odometry with steering characteristics of wheeled mobile robot has been proposed and evaluated through the field experiments. The basic idea of the proposed method is to selectively use an angular velocity of a vehicle estimated from a wheel odometry or that measured by a gyroscope: a weighting factor is used to tune the dependency between them, the value of which is correlated with the vehicle steering characteristics. The experimental results have confirmed that the proposed method estimates the robot trajectory more accurately than the conventional method such as the classical gyro-based odometry. The smallest absolute error of the localization by the proposed method is 0.17% in the long-range travel experiment including straight motion, curve motion, and pivot motion. The main contribution of this work is to propose a simple but accurate localization method for a robot in rough terrain. Also the work clarifies the steering characteristics of the robot in rough terrain which is correlated with the range of the weighting factor used for an accurate localization.

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