Calibration of Kinematic Parameters for Two Wheel Differential Mobile Robots by Using Experimental Heading Errors

Regular Paper

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Abstract Odometry using incremental wheel encoder sensors provides the relative position of mobile robots. This relative position is fundamental information for pose estimation by various sensors for EKF Localization, Monte Carlo Localization etc. Odometry is also used as unique information for localization of environmental conditions when absolute measurement systems are not available. However, odometry suffers from the accumulation of kinematic modeling errors of the wheel as the robot's travel distance increases. Therefore, systematic odometry errors need to be calibrated. Principal systematic error sources are unequal wheel diameters and uncertainty of the effective wheelbase. The UMBmark method is a practical and useful calibration scheme for systematic odometry errors of two-wheel differential mobile robots. However, the approximation errors of the calibration equations and the coupled effect between the two systematic error sources affect the performance of the kinematic parameter estimation. In this paper, we proposed a new calibration scheme whose calibration equations have less approximation errors. This new scheme uses the orientation errors of the robot's final pose in the test track. This scheme also considers the coupled effect between wheel diameter error and wheelbase error. Numerical simulations and experimental results verified that the proposed scheme accurately estimated the kinematic error parameters and improved the accuracy of odometry calibration significantly.

Keywords Calibration, Mobile robots, Odometry, Pose estimation, Systematic errors.

1. Introduction

In autonomous navigation, the position of a mobile robot needs to be estimated accurately. In general, the localization of a robot is based on the measurement of the traveled distance recorded by the wheel's incremental encoders. Odometry information using the encoder is the most widely used navigation method for mobile robot positioning. However, odometry has a well-known drawback : its errors accumulate over time as the robot moves. In order to reduce the odometry errors with increase of travel distance, the odometry errors need to be corrected.

Odometry error sources are classified into systematic errors and non-systematic errors [1-3]. Systematic error sources include unequal wheel diameters, uncertainty of the effective wheelbase, misalignment of wheels, etc. These are vehicle specific and do not usually change during navigation. Therefore, it is essential to reduce these errors by calibrating systematic kinematic parameters. The calibration scheme of kinematic parameters is the major focus of this paper.

Non-systematic error sources result from environmental conditions, which are probabilistic. Examples are uneven floors, unexpected objects on the floor, wheel slippages etc., which are significant problems in the practical application of robots. The uncertainty of these errors can be modeled by using the absolute position of the robot obtained from external sensors [4-6].

Calibration of systematic odometry errors have been discussed in many studies. Kelly [7] suggested a general solution for linearized systematic error propagation for an optional trajectory. Antonelli [8] proposed least-square estimations to approximate odometric parameters. Abbas [9] introduced a bi-directional circular path test, in which the robot is driven along a circular reference path in both directions. Ivanjko [10] proposed off-line odometry calibration based on optimization used to compensate calibration parameters from distinct systematic errors. Bostani [11] suggested a simple method based on two experiments, in which the robot is programmed to move back and forth in a straight line to estimate the kinematic parameters and the wheel diameter's scaling error E_s.

Doh [12] proposed an odometry calibration procedure called the PC-method that is based on the concept of sensor-based navigation through the GVG path. Roy and Thrun [13] suggested a statistical technique which uses the robot's sensors to automatically calibrate odometry errors as a robot operates. Martinelli [14] proposed an algorithm for an on-line estimation of the odometry errors during navigation in unknown environments. They adopted an Augmented Kalman Filter (AKF) that estimates both the robot's pose and the kinematic parameters to characterize the odometry errors. For the calibration scheme of a car-like mobile robot, the test track design and the calibration equations are presented in [15-16].

The UMBmark method [1] is the conventional calibration scheme of two-wheel differential mobile robots. The wheel diameter error and wheelbase error can be calibrated by driving the robot along a bi-directional square path, and by using the start and final position errors. This approach identifies the odometric kinematic parameters – wheel diameter error and wheelbase error. Although [1] is a practical calibration method for

measuring and reducing the odometry errors that are caused by the two systematic error sources, it is ineffective for large magnitudes of systematic errors due to the approximation errors from the calibration equations. The calibration accuracy decreases as kinematic modeling errors become large. In addition, the assumption that the average actual wheel diameter is equal to the nominal wheel diameter does not corresponded with the actual wheel.

In this paper, we propose a new calibration strategy by extending the conventional UMBmark. Our first objective is to propose a new calibration scheme, in which the final orientation errors of a robot on a test track are used for calibration accuracy. The proposed scheme remarkably reduced the approximation errors.

The second objective is to derive new accurate calibration equations from the limitation of [1]. In [17], we proposed approaches for the accurate calibration of kinematic parameters. The calibration equations of [17] were derived by investigating the coupled effect between the wheel diameter error and the wheelbase error for a robot turning 90° on a test track. Based on the research reported in [17], the coupled effect for a straight path in a test track is also considered. The presented numerical simulations showed that the reduction of the approximation errors in the calibration equations and the consideration of the coupled effects between the two error sources were essential for improving calibration accuracy.

This paper is organized as follows. In Section 2, an overview of the UMBmark method [1] is presented and the proposed calibration equations are derived. Section 3 explains the advantages of the proposed calibration scheme by numerical simulations. In Section 4, experimental results are given for the evaluation of the proposed method and for the comparison of the proposed method with other previous calibration schemes. Finally, conclusion is provided in Section 5.

2. Accurate Calibration of Kinematic Parameters

2.1 Illustrations of the UMBmark method [1], Bostani's method [11] and Lee's method [17].

Fig. 1 shows the UMBmark method [1] procedure for correcting systematic odometry errors in bi-directional square path experiments. The robot moves over a 4mx4m pre-programmed square path in both clockwise (CW) and counter-clockwise (CCW) directions to overcome the concealed dual-error problem from an uni-direction path. After the runs, the absolute final position errors of the robot are measured. Then, the kinematic error parameters, namely the wheel diameter error and wheelbase error, are calculated from the calibration equations.

(a) Type A errors
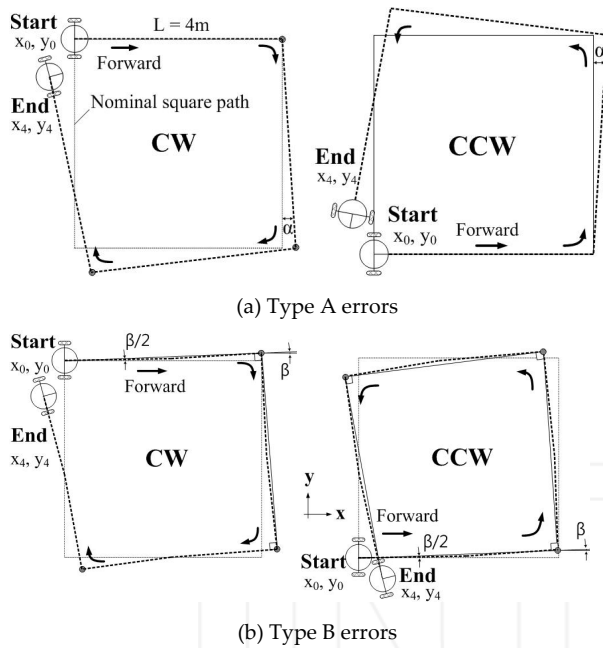
(b) Type B errors

Figure 1. Illustration of final position errors by (a) Type A errors and (b) Type B errors in CW, CCW directions from [1].

Fig. 1 (a) illustrates the Type A errors due to an incorrect wheelbase and the amount of orientation error α during rotation at each nominal 90° turn. The error parameter E_b is defined as $b_{actual} / b_{nominal}$, where b is the wheelbase of the robot. Fig. 1 (b) shows the Type B errors due to unequal wheel diameters and the orientation errors β during straight motion. The parameter E_d is defined as d_R / d_L, the ratio between the actual right and left wheel diameters.

In [1], as shown in Fig. 1, the final positions x_4, y_4 from Type A and B errors in the square path test for the CCW directions are simply calculated using the approximations for small angles: $L\sin\gamma \approx L\gamma$, $L\cos\gamma \approx L$. (L: track size, γ:small angle)

$$\text{Type A errors(CCW)} : x_4 \approx -2L\alpha \,,\, y_4 \approx \; 2L\alpha$$
$$\text{Type B errors(CCW)} : x_4 \approx \;\; 2L\beta \,,\, y_4 \approx -2L\beta \quad (1)$$

The actual final position of the robot x_{CCW}, y_{CCW} are obtained by superposition of the Type A and B errors.

$$x_{CCW} : -2L\alpha + 2L\beta = -2L(\alpha - \beta) = x_{c.g.,CCW}$$
$$y_{CCW} : \;\; 2L\alpha - 2L\beta = \;\; 2L(\alpha - \beta) = y_{c.g.,CCW} \quad (2)$$

The orientation errors α and β are estimated from the final position errors x and y for CW and CCW motions as follows.

$$\alpha = avg\left(\frac{x_{c.g.,CW} + x_{c.g.,CCW}}{-4L}, \frac{y_{c.g.,CW} - y_{c.g.,CCW}}{-4L} \right)$$
$$\beta = avg\left(\frac{x_{c.g.,CW} - x_{c.g.,CCW}}{-4L}, \frac{y_{c.g.,CW} + y_{c.g.,CCW}}{-4L} \right) \quad (3)$$

In [1], the kinematic error parameters E_b and E_d are calculated from the orientation errors α and β using the final position of the test experiments in CW, CCW directions by eqs. (1)-(3). However, odometry calibration accuracy can be reduced by the approximation errors when the kinematic modeling errors become large. Therefore, it is unsuitable for large magnitudes of systematic odometry errors. Furthermore, the calibration equation of [1] is based on the assumption that the effects of wheel diameter error and wheelbase error are totally independent in test motion. This is not true because of the coupled effect between the two error sources in practical application.

In Lee's method [17], the reference track is a 2mx2m square path for the experimental conditions. The robot is driven 5 times in CW and CCW directions, respectively. The final position errors are measured and applied for the calibration of systematic odometry errors. The calibration equations are derived with consideration of the coupled effect of wheel diameter error and wheelbase error at each 90° turning motion on the test track. In [17], however, the calibration scheme include the approximation errors and the coupled effect for a straight motion was not considered.
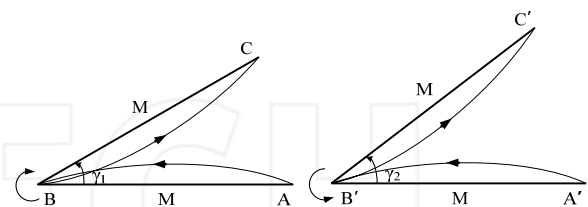
**Figure 2.** Traveling paths for two experiments of the Bostani's method [11].

Fig. 2 shows the Bostani's method [11], which has no approximations in its calibration procedure. In [11], the robot is commanded to move back and forth along a straight path. The robot rotates on the spot by 180° in the CW direction for the first test and in the CCW direction for the second test. The orientation errors γ_1 and γ_2 were calculated and used for odometry calibration. The test was repeated 5 times to reduce non-systematic errors. In [11], however, the coupled effect between wheel diameter and wheelbase error in rotation motion was not considered in the calibration experiment. Table 1 summarizes the limitations of previous calibration schemes.

Calibration Scheme	Limitations
UMBmark method [1]	- It is assumed that the average values of wheel diameters are known.
	- The approximation errors of the calibration equations are from the trigonometric functions.
	- The test track size is not considered for calibration performance.
Bostani's method [11]	- It does not consider the coupled effect in rotation motion in the calibration experiments.
	- The test track size is not considered for calibration.
Lee's method [17]	- It does not consider the coupled effect in straight motion on the test track.
	- The approximation errors of the calibration equations are from the trigonometric functions.

Table 1. Comparison of the odometry calibration schemes.

2.2 The calibration equations by considering the orientation errors of final robot pose and the coupled effects of two errors

The proposed calibration scheme considers the orientation errors of the final robot pose on a square path test track to reduce the approximation errors. The calibration equations are derived with no approximations, unlike those of the UMBmark method [1]. It is useful and practical because it only needs to measure the robot's initial and final heading errors in an open loop motion test. In addition, by considering the coupled effects between wheel diameter and wheelbase error in straight motion and 90° turning motion, the proposed calibration scheme can estimate the kinematic error parameter more accurately.
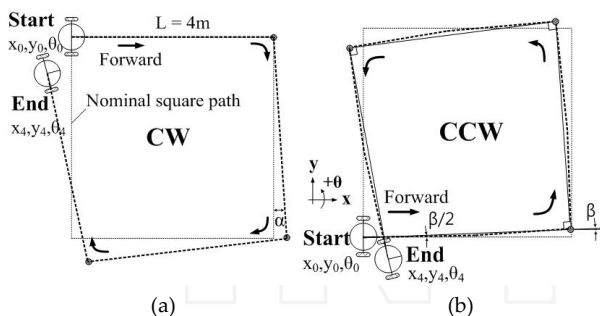
Figure 3. Illustration of the final robot pose errors by (a) Type A errors (CW) and (b) Type B errors (CCW) from [1].

Fig. 3 shows the final robot poses in CW, CCW experiments with Type A and B errors, respectively. The orientation errors of the final robot pose are simply calculated by using α, β from the two errors as follows.

$$\text{Type A errors}: \theta_{4,CW} = 4\alpha, \ \theta_{4,CCW} = -4\alpha$$
$$\text{Type B errors}: \theta_{4,CW} = 4\beta, \ \theta_{4,CCW} = 4\beta \quad (4)$$

The resultant orientation errors θ_{CW}, θ_{CCW} of the final pose in CW, CCW experiments are obtained by superposition of Type A and B errors as follows.
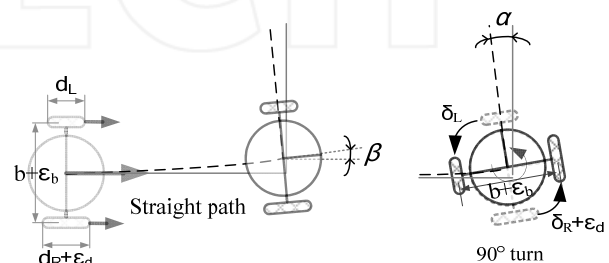
$$\theta_{CW} : \ 4\alpha + 4\beta = \theta_{c.g.,CW}$$
$$\theta_{CCW} : -4\alpha + 4\beta = \theta_{c.g.,CCW} \quad (5)$$

From eq. (5), α_{ε_b}, β_{ε_d} due to the wheelbase error ε_b and the wheel diameter error ε_d can be derived as follows.

$$\alpha_{\varepsilon_b} = \frac{\theta_{c.g.,CW} - \theta_{c.g.,CCW}}{8} \quad (6)$$

$$\beta_{\varepsilon_d} = \frac{\theta_{c.g.,CW} + \theta_{c.g.,CCW}}{8} \quad (7)$$

The orientation errors α_{ε_b}, β_{ε_d} are estimated without approximation equations, unlike [1], meaning that the error parameters can be calculated accurately.

(a) Heading error β after translation (b) Heading error α after 90° turn

Figure 4. Heading errors after motions caused by Type A, B errors in test track.

In a practical application, Type A and B errors will occur together. Fig. 4 shows that the orientation errors due to the coupled effects of the two errors after a straight motion and a 90° turning motion in the CCW experiment. The resultant robot orientation errors are newly defined as follows.

$$\theta_{error,90° turn} \quad : \alpha = \alpha_{\varepsilon_b} + \alpha_{\varepsilon_d}$$
$$\theta_{error,straight path} : \beta = \beta_{\varepsilon_d} + \beta_{\varepsilon_b} \quad (8)$$

From Fig. 4 (b), it can be seen that the orientation error α_{ε_d} due to the wheel diameter error ε_d affects the nominal 90° turning motion. α_{ε_d} can be computed as in [17] using eq. (7).

$$\alpha_{\varepsilon_d} = \frac{\pi \cdot b_{nominal}}{4L} \cdot \beta_{\varepsilon_d} \quad (9)$$

Finally, the expression for the E_b error parameter can be derived as follows. The orientation error α of 90° turning motion in [1] is newly defined, and it is used for computing the wheelbase error E_b.

$$E_b = \frac{90°}{90° - (\alpha_{\varepsilon_b} + \alpha_{\varepsilon_d})} \qquad (10)$$

The robot travels slightly in a curved trajectory of turning radius R in a straight path as shown in Fig. 4 (a). The orientation error β_{ε_d} due to the wheel diameter error ε_d is affected by the wheelbase error ε_b as eq. (8). β_{ε_b} is caused by the wheelbase error ε_b. In order to compute β_{ε_b}, the actual wheelbase b_{actual} is derived using $b_{nominal}$ and the E_b of eq. (10). According to eq. (8), the expression for the E_d error parameter can be derived as follows. The orientation error β of straight motion in [1] is newly defined, and it is used for computing the wheel diameter error E_d.

$$E_d = \frac{R + \dfrac{b_{actual}}{2}}{R - \dfrac{b_{actual}}{2}} = \frac{\dfrac{L/2}{\sin(\beta_{\varepsilon_d}/2)} + \dfrac{(b_{nominal} \times E_b)}{2}}{\dfrac{L/2}{\sin(\beta_{\varepsilon_d}/2)} - \dfrac{(b_{nominal} \times E_b)}{2}} \qquad (11)$$

3. Simulations

The numerical simulation is carried out to verify the proposed calibration scheme. The first objective is to show the advantages of the presented calibration scheme, using the robot's final orientation errors and the coupled effects of Type A and B errors of the test track as in eqs. (10)-(11). The second objective is to evaluate the calibration accuracy of the proposed calibration scheme for various systematic error cases.

In numerical simulation, we concentrate on the effect of the systematic errors; therefore, the non-systematic errors were not included. The calibration accuracy is evaluated as the difference between the actual and estimated kinematic error parameters E_b and E_d for different test track sizes. Since the y-axis represents the estimated kinematic parameter's errors compared to their actual values after calibration, a smaller y is desirable. The actual kinematic modeling errors of the wheels are defined to set the values of the parameters used in the simulation.

Initially, E_b = 0.976 and E_d = 0.992. Fig. 5 shows the estimated kinematic parameter's errors by [1]. The parametric errors increase as the track size increases due to the approximation errors. In [1], a 4mx4m track was adopted for systematic odometry calibration. The E_b and E_d still contain parametric errors after calibration, E_b = 0.725% and E_d = 0.030%. For this reason, the effect of the calibration performance with respect to the approximation errors of the calibration equations and the coupled effects of two error sources are explained in section 2.1.
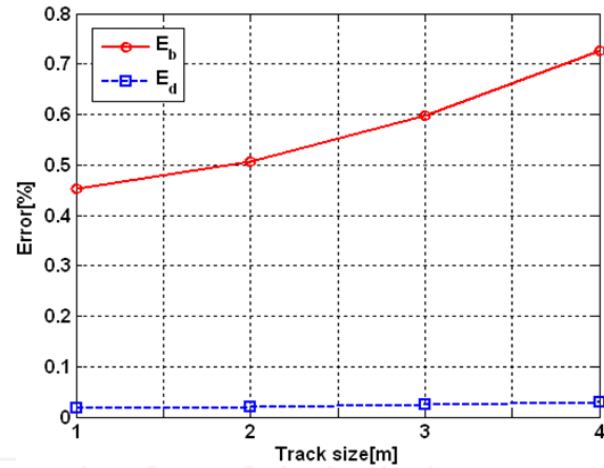

Figure 5. E_b and E_d parameter errors after calibration by UMBmark method [1].

To validate the accuracy of the resultant kinematic parameters, the calibrated robot was driven along the 4mx4m square path track. The larger value of the final position errors in CW, CCW directions, $E_{max,syst}$ = max($r_{c.g.,CW}$;$r_{c.g.,CCW}$), as obtained from the simulation results, is 0.164m.
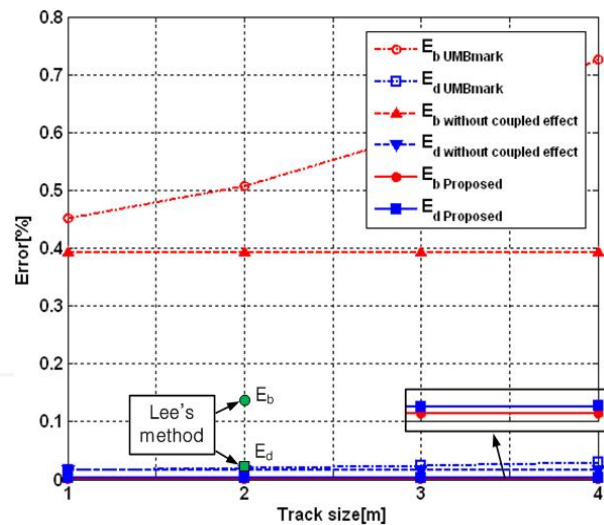

Figure 6. The E_b and E_d kinematic parameter errors after calibration (UMBmark method [1], Lee's method [17] and Proposed calibration scheme).

Fig. 6 shows the resultant kinematic parameter errors for different calibration schemes under the same E_b=0.976, E_d=0.992 condition. In Fig. 6, the dashed dot line indicates the kinematic parameter errors of [1], and the dashed line represents the errors obtained using the robot's final orientation errors. The kinematic parameter errors are significantly reduced to E_b = 0.392% and E_d = 0.016%. The solid line shows the errors with additional consideration of the coupled effects between the two error sources as explained in section 2.2 (proposed method).

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Error (%)	E_b:1.025, E_d:0.987 (case I)			E_b:0.970, E_d:0.985 (case II)		
	A	B	C	A	B	C
E_b	0.930	0.091	**0.001**	1.829	0.371	**0.001**
E_d	0.056	0.017	**0.009**	0.125	0.063	**0.003**

A: UMBmark method [1], B: Lee's method [17], C: Proposed method

Table 2. Calibration results for various error parameters cases.

With the consideration of the coupled effects between the wheel diameter error and the wheelbase error in the test track, the odometry calibration accuracy improved. The parametric errors by the proposed scheme reduced to E_b = 0.001% and E_d = 0.003%. The $E_{max,syst}$ was within 0.01m. This result shows that the E_b and E_d parameters were accurately calibrated by the proposed scheme.

When Lee's method [17], which considered the coupled effect of wheel diameter error and wheelbase error in 90° turning motion on a 2mx2m test track, was applied, t he resultant E_b was decreased from 0.725% (UMBmark) to 0.133% (Lee's). However, the parametric errors still remained due to the approximation errors from calibration equations. These results show that the proposed scheme corrected the parametric errors more accurately.

Table 2 shows the resultant parametric errors of E_b and E_d after odometry calibration with different kinematic error parameters. Numerical simulations evaluated the calibration accuracy of the proposed calibration scheme for E_b larger than 1.0 (case I) and relatively large kinematic modeling errors (case II).

For case I, the resultant parametric errors using the UMBmark method [1] were E_b = 0.930%, E_d = 0.056%. By Lee's method [17], the errors were reduced to E_b = 0.091%, E_d = 0.017%. Therefore, the odometry calibration accuracy was improved when the coupled effects of the two errors were considered in the 90° turning motion for a 2mx2m track. The resultant parametric errors from the proposed method were significantly decreased to E_b = 0.001%, E_d = 0.009%. The proposed scheme of odometry calibration was more accurate than those of [1] and [17]. Furthermore, in case II, which had the large systematic errors, the resultant parametric errors using [1] were E_b = 1.829%, E_d = 0.125%. When [17] was applied, the parametric errors reduced to E_b = 0.371%, E_d = 0.063%. On the other hand, the proposed method decreased the resultant parametric errors to E_b = 0.001%, E_d = 0.003%.

To validate the accuracy of the estimated error parameters for each calibration method, the calibrated robot was driven along the same 4mx4m square path in

CW, CCW directions. The final position errors, $E_{max,syst}$, were compared. The resultant values of cases I, II are as follows. In case of [1], the $E_{max,syst}$ were 0.203m, 0.458m and in case of [17], 0.037m, 0.132m. The odometry accuracy was improved 5.5 and 3.5 times when [17] was applied. However, the $E_{max,syst}$ were all within 0.01m after calibration by the proposed method. The results clearly show that the proposed calibration scheme significantly improved the odometry accuracy for normal systematic odometry errors.

4. Experimental Results

4.1 Experimental setup

Figure 7. The robot used in experiments.

A commercially available two-wheel differential mobile robot [18] was used in the experiments as shown in Fig. 7. The robot's configurations were as follows: wheel diameter = 150mm; wheelbase = 385mm; and wheel width = 30mm. Each wheel was equipped with incremental optical encoders of 10,000 pulses/rev resolution. The commercialized STARGAZER system [19] was adopted to monitor the real pose of the robot. It measures the absolute position of the robot within the standard-deviation of errors; x=0.17mm, y=0.24mm and θ=0.37° with regard to the static state.

4.2 Calibration experiments and performance comparison

In order to evaluate the systematic odometry calibration of the proposed scheme, we carried out the experiments and compared the performances. The robot was driven in an open loop along a 4mx4m square path in CW and CCW directions. To minimize the non-systematic errors due to the environmental condition, the robot was made to travel slowly at 0.2m/s five times. The robot's initial and final absolute poses were fully utilized by the calibration equations of UMBmark method [1] and the proposed method. In a successful odometry calibration, the final position after calibration would converge to the

initial position. The pose distributions of the CW and CCW runs are the result of non-systematic errors.

Before calibration, the final position errors were 2.84m / 1.57m (CW / CCW) and the final orientation errors were -53.84°/ -36.39° (CW / CCW). The proposed scheme required relatively accurate measurements of the robot's orientation in the experiments. In order to measure the robot's experimental heading errors, a commercial on board compass can also be available. From the final position and orientation errors of the robot, the kinematic error parameters of E_b and E_d were estimated. The calibration equations in eqs. (10)-(11) were used by the proposed scheme to estimate the kinematic parameters.

In addition, the performances of the two calibration schemes of Bostani [11] and Lee [17] were compared.

Error parameters	UMBmark method	Bostani's method	Lee's method	Proposed method
E_b	0.97945	0.96391	0.96361	0.97635
E_d	0.98338	0.98120	0.98095	0.98146

Table 3. Kinematic error parameters from UMBmark method, Bostani's method, Lee's method and Proposed method.

The values of the kinematic error parameters from the four calibration experiments are listed in Table 3. The four calibration schemes gave different values of the kinematic error parameters. In order to validate the accuracy of these values, the robot was driven along the same 4mx4m square path 5 times in CW, CCW directions, respectively.
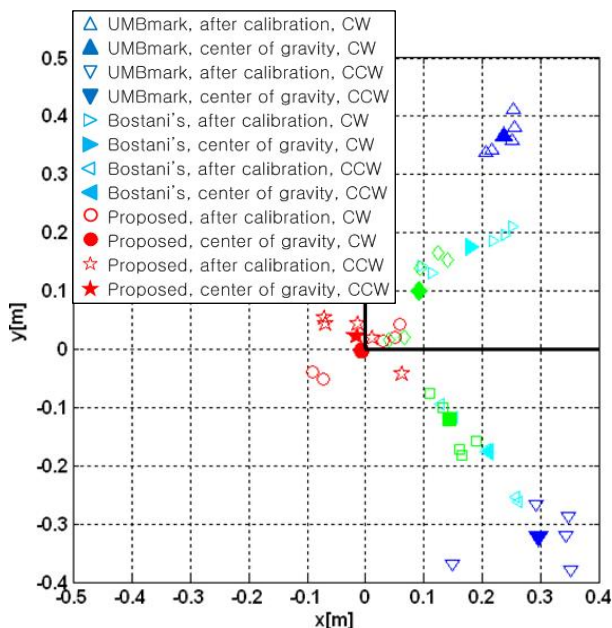
Figure 8. Comparison of the final position errors for 4mx4m test track (UMBmark method / Bostani's method / Lee's method / Proposed method).

Fig. 8 and Table 4 show the final position errors of experiments. Each calibration scheme reduced the final position errors of the test track in both directions. The average final position errors were 0.44m (UMBmark), 0.26m (Bostani's), 0.16m (Lee's) and 0.03m (Proposed), respectively.

Compared with the other methods, the proposed method significantly decreased the final position errors. The final position errors of five runs in both directions were within 0.1m. The odometry accuracy of the proposed scheme was 14.7 times higher than that of [1], therefore, the proposed calibration scheme is advantageous over the previous calibration schemes.

Fig. 9 compares the odometry errors of the final position from the experiments. Odometry accuracy was remarkably improved by the proposed calibration scheme.

Experi -ment	Final Position Errors (m)			
	UMBmark method	Bostani's method	Lee's method	Proposed method
CW	0.43	0.25	0.13	**0.02**
CCW	0.44	0.27	0.18	**0.04**
Average	0.44	0.26	0.16	**0.03**

**Table 4.** Results of the odometry accuracy after calibration.
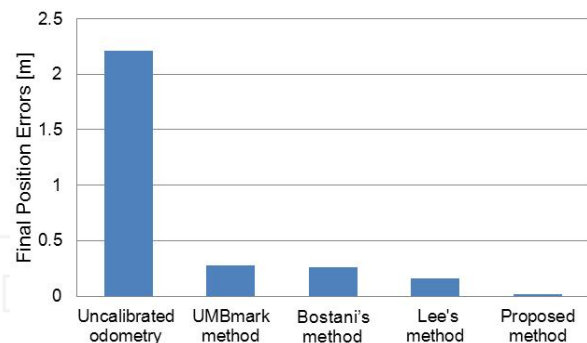
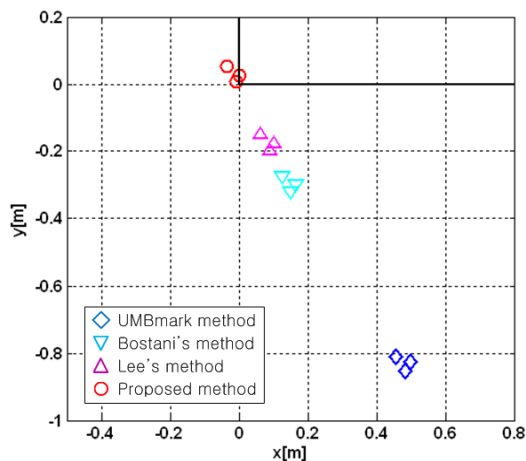**Figure 9.** Comparison of the final position errors.

In order to evaluate the effectiveness of proposed calibration scheme, we designed a 11.5mx5.8m rectangle test track. The robot was manually controlled to move the test track 3 times in the CCW direction at 0.2 m/s. The robot position was estimated from the calibrated odometry.

Fig. 10 shows the experimental results. Without calibration, the average final position error of the 3 runs was large (7.82m), as shown in Fig. 10 (a). After calibration, the final position errors were reduced to 0.97m (UMBmark method), 0.33m (Bostani's method), 0.19m (Lee's method) and 0.05m (Proposed method), respectively. The odometry accuracy was remarkably improved by the proposed calibration scheme within 0.1m errors of the robot's final

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position. The experimental results showed that the calibration accuracy of the proposed scheme was the highest of the four methods.
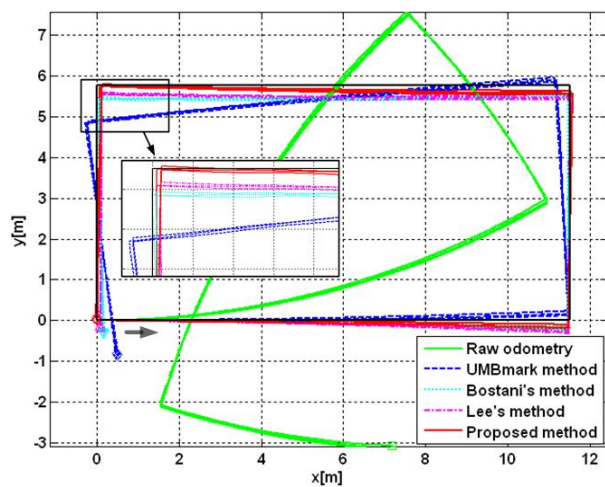
(a) 11.5mx5.8m (reference path)

(b) The final position errors

Figure 10. Comparison of the odometry accuracy among four calibration schemes (UMBmark / Bostani's / Lee's / Proposed).

5. Conclusion

Recently, the application area of service robots has been expanding in [20]-[25]. This paper proposed a calibration scheme to improve the odometry accuracy of a two-wheel differential mobile robot to overcome the limitations of conventional calibration scheme [1]. The new calibration equations use the robot's final orientation errors of a test track. The proposed equations remarkably reduced the approximation errors of the calibration equations in [1]. Furthermore, the proposed scheme considered the coupled effects between wheel diameter error and wheelbase error of the test track in the calibration experiments. The numerical simulations and experimental results showed that the proposed scheme improved the odometry accuracy significantly.

7. References

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