Highly Accurate Dynamic Position Measurement for Wheeled Mobile Robot Using Laser Beacon Measurement System*

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The present research concerns a compensation method for dynamic measurement error (DME) using the laser beacon measurement system (LBMS), which is necessary for highly accurate positioning control and trajectory tracking control of a wheeled mobile robot (WMR). The LBMS uses particular laser beacons, each of which emits two symmetrical laser beams traveling in opposite directions around the beacon and is placed at two reference positions. Receiving beams from these beacons, a photo sensor incorporated in the sensor unit of a WMR yields four time intervals that are necessary to calculate the position of the WMR. From four time intervals, the position of a standing WMR can be measured with high accuracy by LBMS. However, using this method, the position of a moving WMR can't be measured as accurately, because the above-mentioned four time intervals change slightly owing to motion of the WMR, and DME arises consequently. The proposed method compensates the position of a moving WMR measured by LBMS, making use of the DME calculated from four different time intervals. In this paper, we report on this compensation method which has been found to yield satisfactory results in terms of accuracy and repeatability after various simulations and experiments.

Key Words: Mobile Robot, Measurement, Accuracy, Sensor, Trajectory Tracking Control

1. Introduction

In order to achieve trajectory tracking control of a wheeled mobile robot (WMR), it is necessary to measure the position of the WMR (self-positioning) within a short sampling time. A method of self-positioning called "dead reckoning", wherein an internal sensor is attached to the WMR, is popular and easy to use. However, the dead reckoning method has a serious problem in that position error increases in magnitude with increasing distance traveled by the WMR. Recently, some external sensors have been developed to solve this problem⁽¹⁾⁻⁽⁷⁾. Among those external sensors, the laser beacon measurement sys-

tem (LBMS) is expected for use as a highly accurate positioning device of the WMR. It has been reported that LBMS is suitable for use in static measurements⁽¹⁾, however, the specifications required for dynamic measurement of a moving WMR using LBMS are unknown.

We propose a method that compensates the position of a moving WMR measured by LBMS, which makes use of the dynamic measurement error (DME) calculated from four different time intervals.

We report that this compensation method yields satisfactory results in terms of accuracy and repeatability after various simulations and experiments. The purpose of this study is to develop a method for achieving high accuracy during dynamic measurements, which should almost equal static measurement accuracy.

We clarify the specifications required for dynamic measurement of LBMS in order to realize highly accurate trajectory tracking control of a moving WMR.

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Symbols

- $A(x_A, y_A)$: Position of beacon A
 $B(x_B, y_B)$: Position of beacon B
 CW: Clockwise laser beam
 CCW: Counterclockwise laser beam
 L_{INT} : Interval of laser beacons A and B
 $R_{ab}(x_{ab}, y_{ab})$: Actual position of WMR
 $R_m(x_m, y_m)$: Measured position of WMR
 $R_f(x_f, y_f)$: Fixed position of WMR after compensation
 $R_{fe}(x_{fe}, y_{fe})$: Difference between R_{ab} and R_f
 $R_s(x_s, y_s)$: Measured position of WMR before compensation
 $R_{se}(x_{se}, y_{se})$: Difference between R_{ab} and R_s
 r_{pa} : Resolving power of laser beacon measurement system
 t_{A1} : Incident time interval of CW-CCW of laser beacon A
 t_{B1} : Incident time interval of CW-CCW of laser beacon B
 t_{A2} : Incident time interval of CCW-CW of laser beacon A
 t_{B2} : Incident time interval of CCW-CW of laser beacon B
 t_{*11} : Incident time interval of CW-CCW in R_1 (Constant)
 t_{*21} : Incident time interval of CCW-CW in R_1 (Constant)
 t_{*12} : Incident time interval of CW-CCW in R_2 (Constant)
 t_{*22} : Incident time interval of CCW-CW in R_2 (Constant)
 t_{*1m} : Incident time interval of CW-CCW which are moving R_2 from R_1
 t_{*2m} : Incident time interval of CCW-CW which are moving R_2 from R_1
 Δt_* : Incident time difference of the laser beam per turn
 Δt_{*1} : Incident time difference that occurs between CW-CCW
 Δt_{*2} : Incident time difference that occurs between CCW-CW
 T_{SL} : Sampling time of laser beacon (rotational cycle time)
 V : speed of WMR
 θ_A : Angle between AB and AR
 θ_{AR} : Relative angle between θ_A and θ_R
 θ_{ARC} : True angle of θ_{AR}
 θ_B : Angle between AB and BR
 θ_R : Directional angle of WMR
 θ_{RC} : True directional angle of WMR

Subscript* shows "A" in the case of beacon A and "B" in the case of beacon B.

$\Delta\theta_A$: Angle difference of θ_A

$\Delta\theta_{Re}$: Measurement error of directional angle of WMR

2. Measurement Principle and Specifications for the Laser Beacon Measurement System

2.1 Measurement principle of LBMS

Two beacons placed on A and B are arranged with constant distance interval L_{INT} as shown in Fig. 1. Two laser beams are scanned from a laser beacon: one is turning clockwise (CW), the other is turning counterclockwise (CCW).

LBMS uses four laser beams to measure the position of a WMR. Consequently, the receiver and the interface that receive four laser beams are loaded into the WMR and two photodiodes are vertically arranged in double file and symmetrically on either side of a shelter board located at receiver center.

Each photodiode corresponds each of the laser beacons (A and B). An analog pulse is sent to the interface when the laser beam is incident to the photodiode. The incidence time intervals of the CW and CCW laser beams are changed into the number of count pulses at this interface. The number of count pulses is transmitted to the computer with an RS232C circuit.

Angles θ_A and θ_B between the two laser beacon positions are shown in Fig. 1 and these angles are calculated from Eq. (1) using four incidence time intervals t_{A1} , t_{A2} (beacon A) and t_{B1} , t_{B2} (beacon B).

$$\left. \begin{aligned} \theta_A &= -\frac{t_{A2}\pi}{(t_{A1} + t_{A2})} \\ \theta_B &= \frac{t_{B1}\pi}{(t_{B1} + t_{B2})} \end{aligned} \right\} [\text{rad}] \quad (1)$$

As shown in Fig. 1, t_{A1} , t_{B1} are the incidence time intervals corresponding to the interval of CW-CCW and t_{A2} , t_{B2} are the incidence time intervals corresponding to the interval of CCW-CW. If θ_A is negative, it

Fig. 1 Relative position of the laser beacon measurement system to the WMR and the incident time intervals

exists in the 4th quadrant in Fig. 1. Using θ_A , θ_B and the length of L_{INT} , the length of BR_m is calculated as follows.

$$BR_m = \frac{\sin(\pi/2 + \theta_A)}{\sin(-\theta_A + \theta_B)} L_{INT} [\text{mm}] \quad (2)$$

We obtain $R_m(x_m, y_m)$ of the WMR using $B(x_B, y_B)$ (the position of beacon B), referring to Eq.(2).

$$\begin{aligned} x_m &= x_B + BR_m \cos \theta_B \\ y_m &= y_B + BR_m \sin \theta_B \end{aligned} \quad (3)$$

2.2 Specifications of LBMS

The specifications of LBMS are shown in Table 1. The length of L_{INT} changes the precision and accuracy of the measured position. In the case of $L_{INT}=8[\text{m}]$, we identified static measurement accuracy and precision of LBMS that received official approval, with transit which has a precision of $10''$. After official approval, it was noted that position accuracy is below a maximum of $2[\text{mm}]$ and position precision is below a maximum of $0.5[\text{mm}]$ in the standard deviation.

3. Compensation Method for DME

3.1 Dynamic measurement error (DME)

To measure accurately the position of a moving WMR using this system, it is necessary to receive four laser beams at the same position. However this is impossible, because there is a time lag between the incidence times of the four lasers. Therefore, it is difficult to accurately measure the position of the moving WMR leading to dynamic measurement error (DME).

When the WMR is moving from points R_1 to R_2 at a directional angle $\theta_R[\text{rad}]$ and speed $V[\text{mm/s}]$ during rotational cycle time $T_{SL}[\text{s}]$ of the laser beam as shown in Fig. 2, we explain the DME using the following three cases.

Case(1) When the WMR stops at R_1

Case(2) When the WMR is moving from R_1 to R_2

Case(3) When the WMR stops at R_2

The incidence time chart of the laser beam for each of the above-mentioned each cases is shown in Fig. 3.

When the WMR is moving from R_1 to R_2 as shown in Fig. 2, the starting point for the time axis in Fig. 3 is CCW incidence time in case(1). All thick vertical lines are incidence times in case(1). The thin lines before and behind the thick lines are incidence times in case(2) and case(3).

The incidence time intervals in case(1) and case(3) are always constant because the WMR stops. However incidence time intervals t_{A1m} and t_{A2m} in case(2) change slightly compared with those in case(1) since the WMR is moving. This incidence time difference results in DME. When the WMR begins moving from R_1 after the CCW laser beam incidence,

Table 1 Main specifications of laser beacon measurement system (LBMS)

Measurement Sampling Time T_{SL}	0.1[s]
Beacon Revolution	600[rpm]
Resolving Power r_{pa}	0.00045[deg]=1.62[']
Measurement Area	About 50[m]×50[m]
Reproducibility	< 2[']
Angle Accuracy	< 30[']

Fig. 2 Relationship between angle difference $\Delta\theta_A$ and incidence time differences Δt_{A1} , Δt_{A2}

Fig. 3 Incidence time chart

the incidence time of the CW laser beam is gotten faster Δt_{A2} . The time when the CCW laser beam is incident again is delay $\Delta t_A (= \Delta t_{A1} + \Delta t_{A2})$ in comparison with case(2).

In case(3), the incidence time of the CCW laser beam is delay Δt_A in comparison with case(1) and the incidence time of the next CW laser beam becomes shorter Δt_A . On the other hand, the incidence time of the next CCW laser beam becomes later Δt_A .

In order to measure the position of the moving WMR accurately, the incidence time intervals in case(3) are obtained when the WMR reaches R_2 . The value of Δt_A is determined by recognizing the conduct of the WMR (directional angle θ_R and speed V) while the laser beam rotates by $360[\text{deg}]$. This Δt_A causes the DME.

Fig. 4 Relationship between relative angle of laser beams, directional angle θ_R of the WMR, angle difference $\Delta\theta_A$ and speed v of the WMR

Next, we discuss incidence time difference Δt_A , Δt_B per turn of the laser beam. First, a way of determining the incidence time difference Δt_A is explained. Δt_A occurs while the laser beam of beacon A rotates by 360[deg]. Directional angle θ_R and speed V of the WMR are assumed to be constant during a sampling time with respect to the following Eqs. (4) - (6), since the sampling time is very short.

Also, the estimated position data can be measured at every sampling time using an inner world sensor (an encoder) that was installed in the WMR.

Equations (4) - (6) are used to solve Δt_A and Δt_B . The incidence time difference Δt_A is written using $\Delta\theta_A$ and T_{SL} as shown in Eq. (4).

$$\Delta t_A = \frac{T_{SL}}{2\pi} \Delta\theta_A \quad (4)$$

The angle difference $\Delta\theta_A$ is shown in Eq. (5). $\Delta\theta_A$ is proportional to the element that is perpendicular to the laser beam with speed V of the WMR as shown in Fig. 4. Incidentally, if the DME is sufficiently small compared with the length of AR , AR can be calculated using WMR's measurement position before compensation.

$$\Delta\theta_A = \tan^{-1} \frac{VT_{SL} \sin \theta_{AR}}{|AR|} \text{ [rad]} \quad (5)$$

If sampling time T_{SL} is 0.1[s], it does not interfere even if directional angle θ_R and speed V are constant. When angle θ_A which was previously measured is used, θ_{AR} shown in Fig. (4) is obtained.

$$\theta_{AR} = \theta_R - \theta_A \text{ [rad]} \quad (6)$$

The incidence time difference Δt_B caused by beacon B is obtained in the same way. Results of Eqs. (4) to (6) are derived from Eqs. (4.b) and (4.c).

$$\begin{aligned} \Delta t_A &= \frac{T_{SL}}{2\pi} \Delta\theta_A \\ &= \frac{T_{SL}}{2\pi} \tan^{-1} \frac{VT_{SL} \sin \theta_{AR}}{|AR|} \text{ [rad]} \end{aligned} \quad (4.b)$$

$$\begin{aligned} \Delta t_B &= \frac{T_{SL}}{2\pi} \Delta\theta_B \\ &= \frac{T_{SL}}{2\pi} \tan^{-1} \frac{VT_{SL} \sin \theta_{BR}}{|BR|} \text{ [rad]} \end{aligned} \quad (4.c)$$

3.2 Compensation method for the DME

The compensation method calculates t_{A12} , t_{A22} from t_{A1m} , t_{A2m} and Δt_A , Δt_{A1} , Δt_{A2} are obtained while WMR is moving as shown in Fig. 3. Each of the incidence time intervals are derived from Fig. 3 as follows.

$$\Delta t_A = \Delta t_{A1} + \Delta t_{A2} \quad (7)$$

$$t_{A1m} - \Delta t_{A2} = t_{A12} - \Delta t_A \quad (8)$$

$$t_{A2m} + \Delta t_{A2} = t_{A22} + 2\Delta t_A \quad (9)$$

Moreover, Δt_{A1} , Δt_{A2} are deduced using t_{A1m} , t_{A2m} and Eq. (6).

$$\begin{cases} \Delta t_{A1} = \frac{t_{A1m}}{T_{SL}} \cdot \frac{T_{SL}}{2\pi} \Delta\theta_A \\ \Delta t_{A2} = \frac{t_{A2m}}{T_{SL}} \cdot \frac{T_{SL}}{2\pi} \Delta\theta_A \end{cases} \quad (10)$$

From Eq. (10), $\Delta t_{A1}/\Delta t_{A2}$ is

$$\frac{\Delta t_{A1}}{\Delta t_{A2}} = \frac{t_{A1m}}{t_{A2m}} \quad (11)$$

From Eqs. (7) to (11), t_{A12} , t_{A22} are expressed as

$$t_{A12} = t_{A1m} + \Delta t_{A1} \quad (12)$$

$$t_{A22} = t_{A2m} - \Delta t_A - \Delta t_{A1} \quad (13)$$

Also, t_{B12} , t_{B22} caused by beacon B are obtained.

$$t_{B12} = t_{B1m} + \Delta t_B + \Delta t_{B2} \quad (14)$$

$$t_{B22} = t_{B2m} - \Delta t_{B2} \quad (15)$$

Compensated intervals, t_{A12} , t_{B12} , t_{A22} and t_{B22} are substituted for t_{A1} , t_{B1} , t_{A2} , t_{B2} in Eq. (1) ($t_{A1} \leftarrow t_{A12}$, $t_{B1} \leftarrow t_{B12}$, $t_{A2} \leftarrow t_{A22}$, $t_{B2} \leftarrow t_{B22}$). After compensated angles θ_A , θ_B are obtained, a compensated position is calculated using Eqs. (1) to (3).

3.3 Influence of measurement error of the directional angle

Here, we discuss how the influence of measurement error of the directional angle θ_R affects the incidence time difference Δt_A . The WMR's θ_R is assumed to be the summation of the true directional angle θ_{RC} and measurement error $\Delta\theta_{Re}$, θ_R is expressed as

$$\theta_R = \theta_{RC} + \Delta\theta_{Re} \quad (16)$$

In the same way, using the true angle θ_{ARC} of Eq. (4), θ_{AR} expressed as

$$\theta_{AR} = \theta_{ARC} + \Delta\theta_{Re} \quad (17)$$

Next, we substitute Eq. (17) for Eq. (6) to obtain Δt_A . Using the approximations $\cos \Delta\theta_{Re} \approx 1$ and $\sin \Delta\theta_{Re} \approx \Delta\theta_{Re}$, if $\Delta\theta_{Re} \ll 1$, measurement error $\Delta\theta_{Re}$ is rearranged by substituting Eq. (6) into Eq. (17).

$$\begin{aligned} \Delta t_A &\approx \frac{T_{SL}}{2\pi} \tan^{-1} \\ &\quad \cdot \frac{VT_{SL} (\sin \theta_{ARC} + \Delta\theta_{Re} \cos \theta_{ARC})}{|AR|} \text{ [s]} \end{aligned} \quad (18)$$

From Eq. (18), it is clear that Δt_A is influenced by the term $\Delta\theta_{Re} \cdot \cos \theta_{ARC}$.

Next, we should consider the compensated value about the influence of standard deviation for Δt_A . If θ_{ARC} is $\pi/2$ [rad], the term $\Delta\theta_{Re} \cdot \cos \theta_{ARC}$ becomes 0

and Δt_A reaches its maximum value ($\Delta t_{A \max}$). On the other hand, if $\theta_{\text{ARC}} = 0[\text{rad}]$, $\Delta \theta_{\text{RE}} \cdot \cos \theta_{\text{ARC}}$ reaches its maximum value and Δt_A is about 0.8% of $\Delta t_{A \max}$. Then, the standard deviation of the measurement directional angle is $0.008[\text{rad}]^{(8)}$. Therefore, in the case of using LBMS, the influence of Δt_A can be ignored. The directional angle of the WMR can be measured at $0.008[\text{rad}]$ (standard deviation)⁽⁸⁾.

4. Verification of the Compensation Method

4.1 Verification method

In order to verify the compensation method of the DME, some experiments and simulations of dynamic position measurement with a trial WMR are carried out.

4.1.1 Simulation method The simulation method is based on the following assumptions.

- 1) The WMR is assumed to move without receiving any disturbance at all.
- 2) The movement trajectories are straight and circle as shown in Fig. 5.
- 3) The interval L_{INT} between two laser beacons is 8[m] as shown in Fig. 5.
- 4) The speed of the WMR during movement is constant.

When each laser beam is incident on the receiver, the rotational angle is stored. Then, the relative angle from the rotational angle is calculated when the laser beam spinning the opposite way is incident to the receiver. The incidence time interval is calculated from the relative angle. The measured position $R_s(x_s, y_s)$ before compensation is calculated using Eq. (3). Simultaneously, the measured position $R_f(x_f, y_f)$ after compensation is calculated using Eq. (3), using the results of Eqs. (12) to (15).

By comparing the measured positions before and after the compensation with actual position $R_{ab}(x_{ab}, y_{ab})$,

y_{ab}), DME $R_{fe}(x_{fe}, y_{fe})$ after the compensation and DME $R_{se}(x_{se}, y_{se})$ before the compensation are calculated from Eq. (19). The actual position $R_{ab}(x_{ab}, y_{ab})$ of the WMR is calculated at every sampling time.

$$\left. \begin{aligned} x_{se} &= x_s - x_{ab} \\ y_{se} &= y_s - y_{ab} \\ x_{fe} &= x_f - x_{ab} \\ y_{fe} &= y_f - y_{ab} \end{aligned} \right\} \quad (19)$$

4.1.2 Experimental method The movement trajectory in experiment is a straight line as shown in Fig. 5. Also, L_{INT} is 8[m], which is the same as that in the simulation. The trial WMR shown in Fig. 6 is constructed in such a way that it can move on the restriction trajectory installed on the floor surface. A restriction trajectory is installed with precision of $\pm 0.5[\text{mm}]$ using transit which has a resolving power of $10''$ (the direction of the normal line of trajectory).

The trial WMR uses driving wheels whose periphery is covered with 5 mm thick resin for cleat. Changes in wheel diameter can be prevented by using such a special wheel. Therefore, by using these wheels and the restriction trajectory, the encoder can measure the actual position R_{ab} of the WMR. (The specifications of the encoder are shown in Fig. 5).

The speed of the trial WMR is controlled at a constant value and the wow flutter is $\pm 0.4[\%]$. As a result, the measurement error with respect to actual position becomes $\pm 0.04[\text{mm}]$ from the direction of the trajectory tangent when speed $V = 100[\text{mm/s}]$. In experiments, measurement of speed and actual position R_{ab} by the encoder is carried out every 0.1[s], and the external measurement that uses LBMS is also performed. Moreover, compensation for incidence time interval is made at real time. Measurements of $R_s(x_s, y_s)$ before compensation and of $R_f(x_f, y_f)$ after compensation are made at real time using Eq. (3) and Eqs. (12) to (15). Each DME is finally determined using Eq. (19).

4.2 Simulation and experimental results

4.2.1 Effects of WMR speed on DME From Eq. (5), it is estimated that the DME becomes large if the movement mileage of the WMR becomes longer than the rotational cycle time of the laser beacon. Average values of the DME [mm] after 40 measurements are shown in Table 2 for simulation and experiment (WMR speed $V = 10[\text{mm/s}] - 500[\text{mm/s}]$). It is obvious that the average of x_{se} before compensation is proportional to the speed of the WMR, but the absolute value of the average of x_{fe} after compensation is below 1[mm] for both simulation and experiment. Also, it is unnecessary to apply this compensation below speed $V = 30[\text{mm/s}]$, because the DME before compensation is smaller than the position measurement accuracy of LBMS within this

Fig. 5 Experimental environment

Internal Sensor	Encoder: 500pulse/rev, 2phase (Gear ratio 1:40)
Control Resolving Power for Location	0.0125[mm/bit/samp.]
Internal Measuring Resolving Power	0.0114[mm]

Fig. 6 Trial WMR and specifications for internal measurement

Table 2 Relationship between WMR speed and DME (simulation and experiment)

V [mm/s]	Simulation		Experiment	
	x_{se} [mm]	x_{fe} [mm]	x_{se} [mm]	x_{fe} [mm]
10	-0.66	-0.0086	-1.22	-0.54
20	-1.35	-0.008	-1.65	-0.3
30	-2.02	-0.0049	-1.95	0.079
100	-6.79	0.018	-6.8	-0.012
200	-13.6	0.048	-13.7	0.056
500	-34.6	0.26	-35.8	-0.21

$\theta_R=0$ [rad], $L_{INT}=8$ [m], Start(5000,4000), $r_{pa}=0.00045$ [deg]

experimental range.

4.2.2 Dynamic position measurement accuracy of the laser beacon measurement system Here, we examine the measurement position after compensation on the XY plane to verify precision of dynamic position measurement by LBMS. The compensated position y_{fe} at three different speeds is shown in Fig. 7. In this figure, the transverse axis shows X coordinate

Fig. 7 Dynamic position measurement during movement of the WMR (experiment)

x_f after compensation, and the vertical axis shows the difference y_{fe} between the restriction trajectory and the Y coordinate after compensation.

In case of the speed $V=10$ [mm/s], the result is nearly the same as the static position measurement case.

From Fig. 7, it is clear that the value of Y to X and the change of Y to X show good agreement. In other words, the measurement precision of dynamic position is improved by this compensation method. The results of the experiment can be reproduced well.

This may be due to the influence of floor inclination and flatness mainly. When the restriction trajectory is installed within precision of $\pm 0.5[\text{mm}]$, it is considered that point R of the trial WMR lies on the restriction trajectory. It is assumed that the laser beam receiver leans along the X or Y direction, because the receiver is installed on top of the trial WMR and its position depends on the grounding height of each wheel. If there exists a difference of $1[\text{mm}]$ in the grounding height of the drive wheels on either side, receiver position is shifted by about $1.8[\text{mm}]$ to the Y direction and this affects the measurement value of LBMS. This floor waviness is responsible for the reproducible results obtained experimentally in the Y direction, as shown in Fig. 7.

Using this compensation method, we obtained the improvement of the accuracy about the tangent direction of the trajectory in dynamic measurement.

Moreover, it is not necessary to consider that the measured value of the LBMS hardly influences the DME about the perpendicular direction of the trajectory.

4.2.3 DME before and after compensation

Here, we compare the DME before and after compensation using the straight line and the circle trajectory. We also examine the effect of this compensation method.

The change in DME before and after compensation in the case of straight trajectory is shown in Fig. 8, while that in the case of circle trajectory is shown in Fig. 9.

From the simulation results of straight trajectory, the magnitude of the DME is $14[\text{mm}]$ before compensation; however, it is below $\pm 0.1[\text{mm}]$ after compensation. Also, it is clear that the DME is hardly changed locally because the DME before compensation is only weakly dependent on the measurement time and WMR speed is constant in the straight trajectory.

Next, in the case of circle trajectory in Fig. 9, the magnitude of the DME before compensation always changes with the directional angle of the WMR. However, the DME after compensation is below that of the static position measurement even in the case of circle trajectory.

On the other hand, in the case of straight trajectory, the DME before and after compensation in the experiment ranges from about -2 to $+2[\text{mm}]$ around the mean value of the simulation. The average value (the measurement position accuracy) after compensation of the experimental result becomes $0.06[\text{mm}]$. The effects of this compensation method and this simulation are confirmed from these results.

Fig. 8 Change in DME and the compensation effect (simulation and experiment)

Fig. 9 DME in the case of circle trajectory (simulation)

5. Conclusion

When LBMS is used for dynamic measurement of the WMR, the dynamic measurement error (DME) occurs, because the computer must use previous incidence time intervals to calculate the present position.

We clarified the mechanism involved in generating DME and proposed the compensation method of the DME, which uses information from an internal sensor (the encoder installed in the WMR).

By means of simulation and experiment, we confirmed that the DME could be compensated to a value below that of static measurement.

We showed that dynamic measurement precision which is equivalent to static position measurement precision was obtained by applying this compensation method. Moreover, we verified that this compensation method is effective for measuring the dynamic position of WMR.

Gratitude

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