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Periodic Bias Compensation Algorithm for Inertial Navigation System

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Abstract : *In this paper, an INS compensation algorithm is proposed using the accelerometer from IMU. First, we denote the basic INS algorithm and show that how to compensate the position error when low cost IMU is used. Second, considering the ship's characteristic and ocean environments, we consider with a drift as a periodic external environment change which is affected with exact position. To develop the compensation algorithm, we use a repetitive method to reduce the external environment changes. Lastly, we verify the proposed algorithm through the experiments, where the acceleration sensor is used to acquire real data.*

Key words : *Auto Sailing System, INS, IMU, Constant Bias, Periodic Bias, Position, Compensation*

1. Introduction

Over the years, there has been a major upsurge of interest in the integration of the global positioning system (GPS) and inertial navigation system (INS) as a cost-effective way of providing accurate and reliable navigation aid for civil and military vehicles (ships, aircrafts, land vehicles, and etc)(Britting 1971, Chui and Chen 1987, Farrell and Barth 1998, Loebis et.al. 2004). For automatic sailing system in the sea, generally a GPS is very useful for measuring the exact position, because of no obstacle between ship and satellite. But, it suffers a large bound of position error. Also, when a ship is passing the waters dangerous for navigation, a precise automatic sailing system is required. However, measuring precise position requires a high resolution and high price of GPS module.

Generally, the INS includes two modules; alignment module and navigation module. Any errors in either the alignment module or the navigation module will be integrated and will be propagated over time. The performance and the navigation accuracy of the INS are determined by its errors.

To overcome these errors, the phi-angle approach and psi-angle approach(Benson 1975, Bar-Itzhack 1981, 1988) have been proposed. But, they requires a small attitude error. In many cases, the requirement can not be satisfied for low cost inertial measurement whose sensitivity is not enough to measure the earth rate. Thus, the INS error models with small angle assumption can not be satisfied in given accuracy and performance for the navigation system with low cost IMU (Inertial Measurement Unit).

On the other hand, the Kalman filter is the most commonly used for using INS and other navigation data in both INS alignment and navigation modules. But they requires linear process model and observation techniques (Chui and Chen, 1987). An extended-Kalman filter(EKF) is also widely used for non-linear model by using Jacobian matrices. However, it has to use Jacobian matrices and it is difficult for implementation in EKF.

Thus, they still needs to develop the low price IMU for high resolution INS system with auto compensation for the external environment changes.

In this paper, an INS compensation algorithm is proposed using the accelerometer from IMU. First, we denote the basic INS algorithm and show that how to compensate the position error when low cost IMU was used. Second, considering the ship's characteristic and ocean environments, we consider with a drift as a periodic external environment change which is affected with exact position. To develop the compensation algorithm, we use a repetitive method to reduce the external environment changes. Lastly, we verify the proposed algorithm through the simulations, where the acceleration sensor is used to acquire real data. In future, a parameter auto-tuning method for the proposed algorithm considering for gyro sensor will be researched.

2. Basic Theory for IMU

2.1 IMU Principle

Generally, IMU is included a set of three orthogonal installed accelerometers and three orthogonal installed gyros. The standard IMU is shown in Fig. 1. By installing

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these sensors in the vehicle body, this kinds of INS is called strap-down INS. For implementation, the INS should overcome the unbounded growth in the position and the velocity errors due to the integration of inertial measurements that will contain various forms of error.

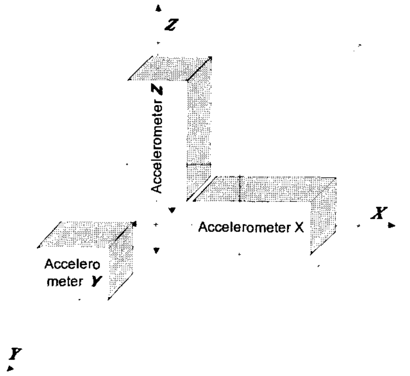

Fig. 1 An IMU installed in a vehicle

An INS consists of two module such as alignment and navigation. From the accelerometers and the gyros, the measured data are input to the INS. By considering the installed the accelerometers and the gyros, the measured data should be converted to base position in INS. By mis-alignment of accelerometers and gyros, the error of alignment will be integrated for obtaining velocity and position, respectively.

In navigation module, it compensates the gravity and non-gravity acceleration sensors, and transforms to the coordinate system. From the transformed data, double-integration calculation will be done for obtaining the velocity and position. In this case, bias factor, integration error, zero setting and other environment changes will be integrated together. Also, the signal of acceleration sensor is passed through the filter and amplifier. When using the amplifier, the acceleration signal contain the infinitesimal drift in steady state. So it makes an immense position error in case that the drift passed by double integral calculation for converting to position.

2.2 Bias Effects and its Characteristics

The bias of accelerometer is generated by its circumstance and it can be divided into two cases: constant bias and periodic bias. The constant bias depends on the circumstance of sensor inside and keeps constant. But the circumstance of sensor outside will be changed with low frequency which is effected by seasonal, day and night, temperature, and atmospheric pressure etc. When using double integration for calculating the distance, these kinds of drifts can make the increasing the position error dramatically.

2.3 Drift Compensation Algorithm

For compensating the constant drift of accelerometer, the following algorithm will be used generally.

Step 1 : Acquire the acceleration sensor values with drift on x, y, and z axes, respectively, and for example, one of them a_y is as follows.

$$\overline{a_y} = a_y + \delta a_y \tag{1}$$

where a_y denotes original acceleration sensor value and δa_ydenotes an accelerometer value with drift on y axis, respectively.

Step 2 : Calculate the velocity using numerical integral method.

$$\overline{v_y}(t+1) = \int_t^{t+1} \overline{a_y}(\tau)d\tau + \overline{v_y}(t) \tag{2}$$

Step 3 : The drift compensate for velocity

$$v_y(t+1) = \overline{v_y}(t+1) + d_v \tag{3}$$

Step 4 : Calculate the position by using numerical integral method.

$$\bar{y}(t+1) = \int_t^{t+1} \overline{v_y}(\tau)d\tau + \bar{y}(t) \tag{4}$$

Step 5 : The drift compensate for position

$$y(t+1) = \bar{y}(t+1) + d_p \tag{5}$$

In the above algorithm, the drift can be compensated by on-line calculation, thus v_y and y can be obtained respectively, where an accumulated position error will be reduced by small sampling time, but computational error will be increased. To obtain design method for the drift compensation gains d_v and d_p, we will show two methods; constant compensation algorithm and periodic compensation algorithm in next chapter, respectively.

3. Design Method for Drift Compensation Gains

3.1 Design Method for Constant Drift Compensation Gains

If the drift of accelerometer included into original signal, then the average drift can be obtained during constant periodic time. So the original signal can be estimated by drift compensation method from the measured signal with drift value.

For this, the accelerometer should be installed in steady state and obtain the accelerometer data during constant periodic time. From these data, the velocity drift d_v and position drift d_p are calculated, respectively. At this time, the accelerometer should be leaved from the external circumstance changes with long experimental time. But, the constant drift compensation algorithm is not useful when the circumstance is changed or the type of accelerometer is changed.

3.2 Design Method for Periodic Drift Compensation Gains

Generally, the external environment circumstance will be changed ordinarily. Almost these kinds of circumstances can be changed on periodic time such as seasonally, day and night, or tide etc. At the same time, the average drift can be obtained during constant periodic time and used this value, when drift included into original signal.

On the other hand, in auto pilot system for ship, the GPS system is used for determining the position, but it also has a considerable position error caused by SA, ionospheric and tropospheric refraction, time errors of satellite and receiver, multi-path error, ephemeris error and so on. For compensation of the GPS signal, sometime they use the IMU. In this case, the sea condition such as tide, wind or sea surface condition etc. can affect a ship's navigation. Under the general assumption, the ship can be moved by sinusoidal wave where tide or wind affects a ship's sailing in periodically. From these conditions, we can make a periodic drift compensation algorithm by following procedure. Fig. 2 show the block diagram for periodic drift compensation.

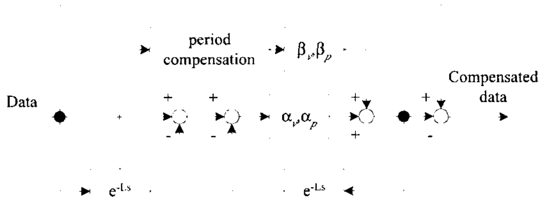

Fig. 2 Block diagram of periodic drift compensation

In Fig. 2, the parameters α_v and α_p denote the velocity and position errors compensation gains and β_v and β_p denote the periodic compensation gains for velocity and position errors, respectively.

<Calculation Procedure of Periodic Compensation Gains>

Step 1 : Calculate the natural frequency and its magnitude for accelerometer circumstance by FFT method.

Step 2 : From the FFT results, decide the dominant frequency L of accelerometer.

Step 3 : Make periodic L data table from decided dominant frequency modes.

Step 4 : Initialization of periodic L data table.

Step 5 : Calculate the velocity drift compensation gain

$$d_v(t+1) = \beta_v(\max(peak) + \min(peak))/2 + \alpha_v(\overline{v}_y(t+1) - \overline{v}_y(t+1-L) - d_v(t)) \quad (6)$$

where max(peak) and min(peak) denote the maximum and minimum value from obtained acceleration sensor data, respectively.

Step 6 : Calculate the position drift compensation gain

$$d_p(t+1) = \beta_p(\max(peak) + \min(peak))/2 + \alpha_p(\overline{y}(t+1) - \overline{y}(t+1-L) - d_p(t)) \quad (7)$$

In the above procedure, the **Step 5** and **6** will be calculated by periodically on the calculation routine. And the calculated values should be saved and used it in next calculation.

4. Experiments and Discussions

4.1 IMU Bias

To calculate the IMU bias, we obtain the accelerometer data from acceleration sensor (CXL10LP3, crossbow technology, inc). The sampling time is adjusted on 0.0114[s] and the data is obtained in steady state for 60[s]. The obtained results with accelerometer bias are given in Fig. 3 - 5, respectively.

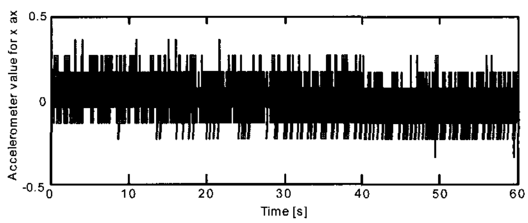

Fig. 3 Accelerometer value for x axis

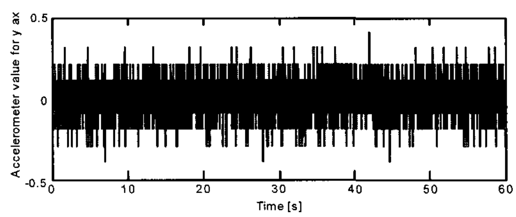

Fig. 4 Accelerometer value for y axis

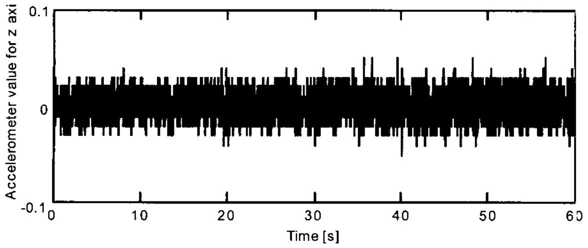

Fig. 5 Accelerometer value for z axis

From the above data, the distance can be calculated by using double integral and its results without bias compensation is shown in Fig. 6.

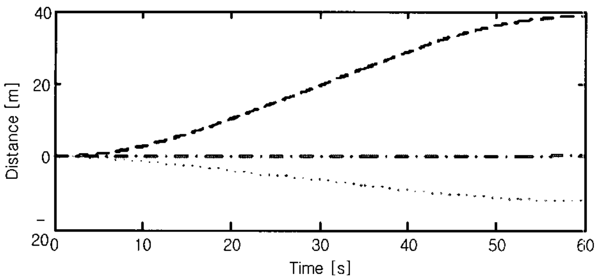

Fig. 6 Distance without bias compensation

In Fig. 6, the dashed line, dotted line and dash-doted line show the distances on x, y, and z axes, respectively. As one of results, we verify that the errors of distance on x and y axes increased dramatically.

Table 1 Calculated bias for 60 [s] on each axes

	x axis	y axis	z axis
Velocity Bias	-8.0148e-017	-7.9307e-017	1.5295e-018
Distance Bias	0.014410	-0.004479	0.000106

4.2 Constant Bias Compensation

By using Table 1, we can compensate the velocity and the distances which are calculated by integral method from Eq. (1) to Eq.(5), respectively. Then the following compensated distance data can be obtained as in Fig. 7.

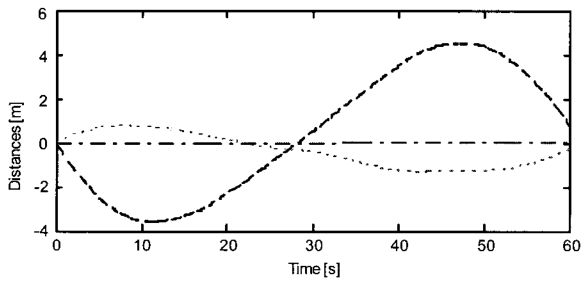

Fig. 7 Distance with constant bias compensation

In Fig. 7, the distance can be reduced from around 40[m] to around 4.2[m] on x axis. From this result, we can verify that the constant bias compensation algorithm effects to the accelerometer bias compensation.

To verify the constant bias compensation, we make an accelerometer test, which is to shake the sensor on x, y, and z axes, respectively. The results are given in Fig. 8 Fig. 10.

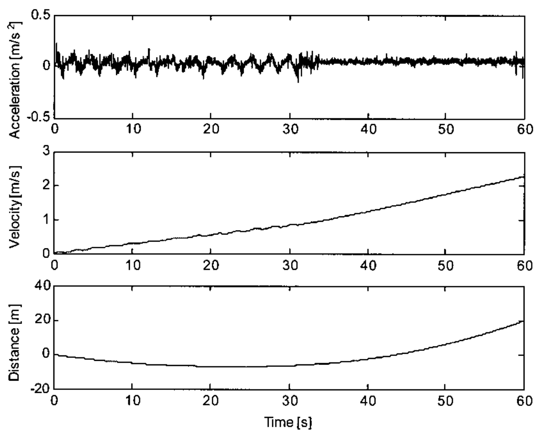

Fig. 8 Constant bias compensated data on x axis

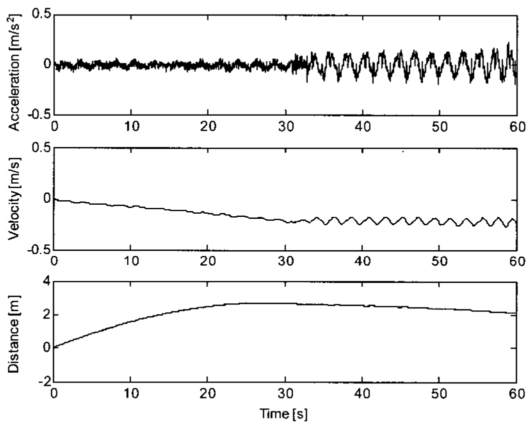

Fig. 9 Constant bias compensated data on y axis

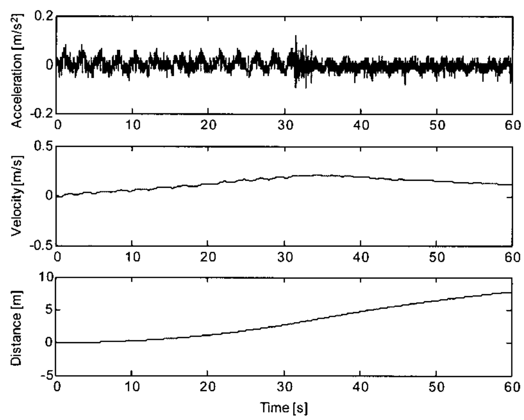

Fig. 10 Constant bias compensated data on z axis

In the above figures, the distances are increased by external environment changes, where distance error on x axis is around 20[m].

4.3 Periodic Bias Compensation

To solve these problem which increase the distance errors, first of all, we verify the environment changes. For this, we are using FFT method to check the main frequency term which effects to the accelerometers. The FFT result is shown in Fig. 11- Fig. 13

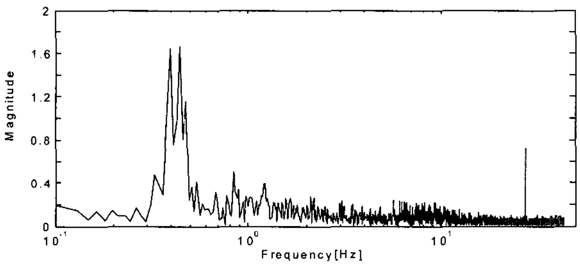

Fig. 11 FFT results on x axis

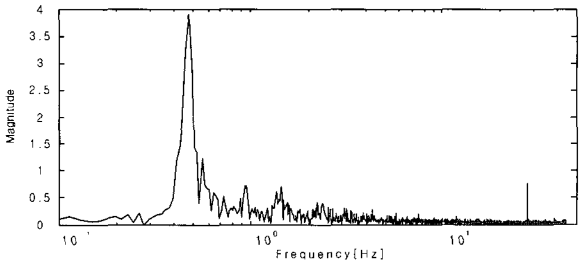

Fig. 12 FFT results on y axis

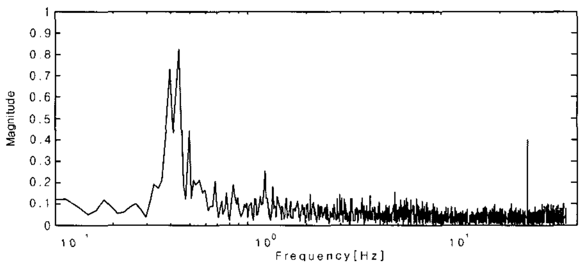

Fig. 13 FFT results on z axis

From the FFT results, we select the main frequency and calculate its period as Table 2

Table 2 FFT results on x, y and z axis

Main frequency [Hz]			Magnitude [dB]			Period [s]		
$x$axis	$y$axis	$z$axis	$x$axis	$y$axis	$z$axis	$x$axis	$y$axis	$z$axis
0.443	0.476	0.443	1.660	3.899	0.823	2.256	2.102	2.256

In simulation for periodic bias compensation, we obtain the parameters by using proposed algorithm where the parameters are calculated by trade-off method as Table.3

Table 3 Parameters for periodic bias compensation

	x axis		y axis		z axis	
	velocity	distance	velocity	distance	velocity	distance
α	0.5	0.5	0.5	0.1	0.5	0.1
β	6.0	2.0	5.0	1.0	5.0	4.0

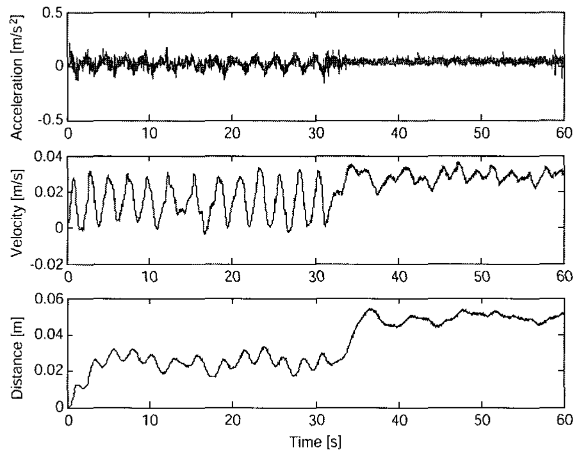

Fig. 14 Periodic bias compensated data on x axis

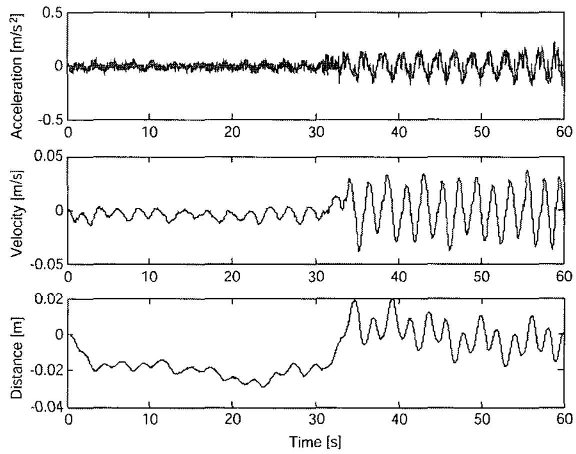

Fig. 15 Periodic bias compensated data on y axis

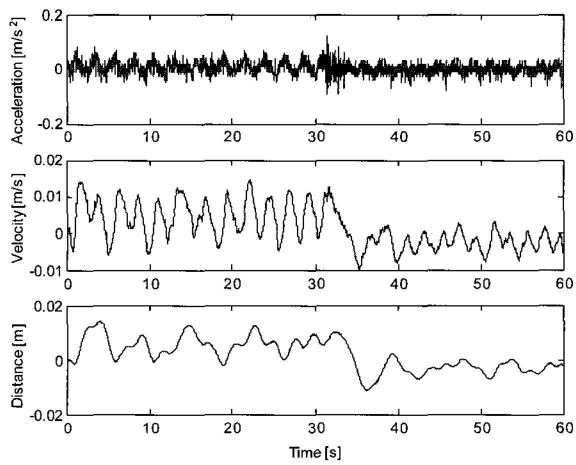

Fig. 16 Periodic bias compensated data on z axis

Using the parameters in Table3 and the periodic compensation algorithm, we can get the results in Fig. 14–Fig. 16, where the same accelerometer's data with those of Fig. 8 and Fig. 10 are used.

By comparison Fig. 8 Fig. 10, the distance can be reduced from around 20[m] to around 0.06[m] on x axis. Also on y axis, the distance reduced from around 3 [m] to around 0.02 [m]. We have same results on z axis, where the distance reduced from around 8[m] to around 0.02[m]. From this result, we verify that the above results show the excellent noise cancellation.

5. Conclusions

In this paper, we have proposed a periodic bias compensation algorithm to reduce the external accelerometer noise or environment change by using repetitive compensation method. First, we have been shown the constant compensation bias algorithm for accelerometer with constant bias, and introduce a design procedure for it. Second, for external environment changes in accelerometer, we proposed a compensation algorithm, where FFT method used for obtaining the magnitude and its frequency using accelerometer data. From the 1st mode of frequency, the periodic of environment change is obtained. For simulation, we make a data memory for periodic data, where a repetitive method is used. In simulation, the constant bias compensation algorithm is applied to verify the constant bias cancellation. In simulation result of constant bias compensation, the algorithm is useful without external environment change, but the position error will be increased in case of environment changes. In simulation of periodic bias compensation, we can verify that the algorithm can cancel the external environment changes in given. The parameter of auto-tuning method for the proposed algorithm will be researched in future. Also we need to consider a compensation algorithm for gyro sensor to make a perfect IMU.

References

[1] C.K. Chui and G. Chen(1987), "*Kalman Filtering with Real-time Applications*", Springer-Verlag, New York.

[2] D. Loebis, R. Sutton, J. Chudley and W. Naeem(2004), "*Adaptive tuning of a Kalman filter via fuzzy logic for an intelligent AUV navigation system*", Control Engineering Practice, Vol. 12, pp.1531-1539.

[3] F.A. Faruqi(2000), "*Non-linear Mathematical Model for Integrated Global Positioning/Inertial Navigation System*", Applied Mathematics and Computation, Vol. 115, pp. 191-212.

[4] F.A. Faruqi, K.J(2000). Turner "*Extended Kalman Filter Synthesis for Integrated Global Positioning/Inertial Navigation System*", Applied Mathematics and Computation, Vol. 115, pp. 213-227.

[5] J. Farrell and M. Barth(1998), "*The Global Positioning System and Inertial Navigation*", McGraw-Hill.

[6] J.F. Wagner and G. Kasties(2004), "*Applying the principle of integrated navigation systems to estimating the motion of large vehicles*", Aerospace Science and Technology, Vol. 8, pp. 155-166.

[7] K.R. Britting(1971), "*Inertial Navigation System Analysis*", Wiley, New York.

[8] X. Kong(2004), "*INS Algorithm using Quaternion Model for Low Cost IMU*", Robotics and Autonomous Systems, Vol. 46, pp. 221-246.

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