Periodic Bias Compensation Algorithm for Inertial Navigation System

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ABSTRACT

In this paper, an INS compensation algorithm for auto sailing system is proposed, where low cost IMU (Inertial Measurement Unit) is used for measuring the accelerometer data. First, we denote the basic INS algorithm with IMU and show that how to compensate the error of position by using low cost IMU. Second, in considering the ship's characteristic and ocean environments, we consider with a factor as a periodic external disturbance which effects to the exact position. To develop the compensation algorithm, we use a repetitive method to reduce the external environment changes. Lastly, we verify the proposed algorithm by using experiments results.

1. Introduction

Over the years, there has been a major upsurge of interest in the integrated global positioning system (GPS) / 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 auto 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, there suffers a large bound of position error. Also, when the ship is passed through in the sea-pollution area, there requires a precise auto sailing system. However, for measuring precise position, also there need a high resolution and high price of GPS module.

Generally, the INS includes two modules; alignment module and navigation module. From these modules, any errors in either the alignment module or the navigation module will be integrated and will propagate 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 proposed. But, there requires a small attitude error. In many case, the requirement can not 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 satisfied in given accurate and performance for the navigation system with low cost IMU.

On the other hand, the Kalman filter is the most commonly used algorithm for fusing INS and other navigation data in both INS alignment and navigation modules. But there requires linear process model and observation techniques (Chui and Chen, 1987). For non-linear model, an extended-Kalman filter(EKF) is also widely used approach where Jacobians method used to make extended model (Chui and Chen, 1987). However, there have to use Jacobians matrices and it is difficult for implementation in EKF.

Thus, there 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 for auto sailing system is proposed, where low cost IMU (Inertial Measurement Unit) is used for measuring the accelerometer data. First, we denote the basic INS algorithm with IMU and show that how to compensate the error of position by using low cost IMU. Second, in considering the ship's characteristic and ocean environments, we consider with a factor as a periodic external disturbance which effects to the exact position. To develop the compensation algorithm, we use a repetitive method to reduce the external environment changes. Lastly, we verify the proposed algorithm by using experiments results.

2. Basic Theory for IMU

2.1 IMU Principle

Generally, *IMU(Inertial Measurement Unit) is assumed* to include a set of three orthogonal installed accelerometers and three orthogonal installed gyros. The standard IMU is shown in Fig. 1. By install these sensors with vehicle body, this kinds of INS is called strap-down INS. For implementation, the INS should overcome to the unbounded growth in the position and the velocity errors due to the integration of inertial measurements that will contain various forms of error.

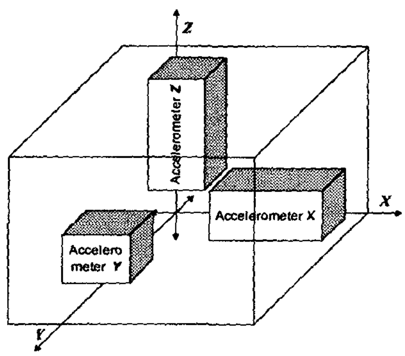

Fig. 1 An IMU installed in a vehicle

Also, two alignment module and navigation module are included in INS. 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, there compensate 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 thought the filter and amplifier. When using the amplifier, the acceleration signal will be includes 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 Drift Effects and its Characteristics

The drift of accelerometer is generated by its circumstance and it can be divided into two cases: constant drift and periodic drift. The constant drift is depended on the circumstance of sensor inside and it kept on constant condition. But the outside circumstance will be changed with low frequency which 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.

Step1: Acquire the acceleration sensor values with drift on x, y, and z axes, respectively.

$$\tilde{a}_v = a_v + \delta a_v \quad (1)$$

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

Step 2: Calculate the velocity by using numerical integral method.

$$\bar{v}_y(t+1) = \int_t^{t+1} \bar{a}_y(\tau)d\tau + \bar{v}_y(t) \tag{2}$$

Step 3: Compensate the drift for velocity

$$v_y(t+1) = \bar{v}_y(t+1) + d_v \tag{3}$$

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

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

Step 5: Compensate the drift of 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, there is used GPS system for detecting the position, but actually there have position error and it depended on the weather condition. For compensation of the GPS signal, sometime there use the IMU. In this case, the sea condition such as tide, wind or sea surface condition etc. can affects to ship's navigation. Under the general assumption, the ship can be moved by sinusoidal wave where tide or wind affects to the 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.

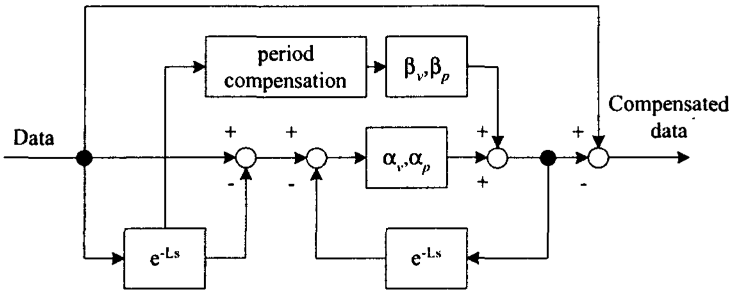

Fig. 2 Block Diagram of Periodic Drift Compensation

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.

< Procedure for Calculation 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

$$d_v(t+1) = \beta_v(\max(peak) + \min(peak))/2 + \alpha_v(\bar{v}_v(t+1) - \bar{v}_v(t+1-L) - d_v(t)) \tag{6}$$

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

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

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 IMU data from circuit board. 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.

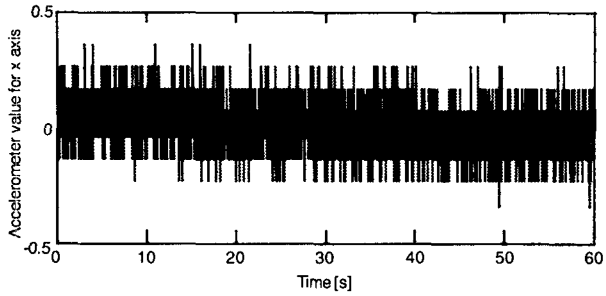

Fig. 3 Accelerometer value for x axis

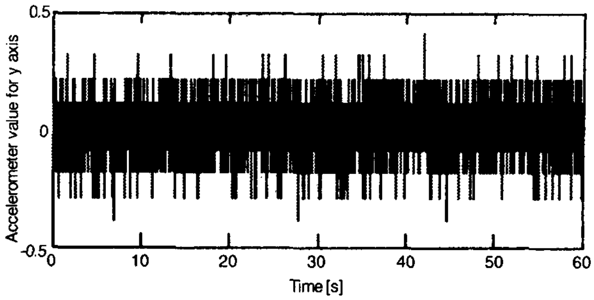

Fig. 4 Accelerometer value for y axis

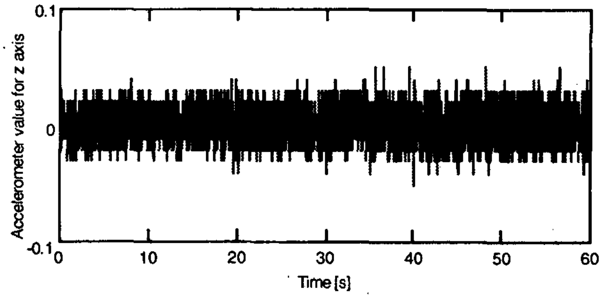

Fig. 5 Accelerometer value for z axis

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

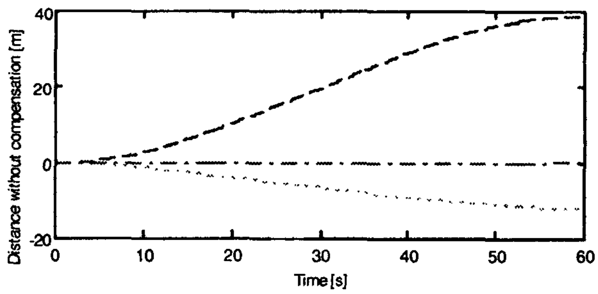

Fig. 6 Distance without bias compensation

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 calculated by integral method from Eq. (1) to Eq.(5), respectively. Then the following compensated distance data can be obtained as in Fig. 7.

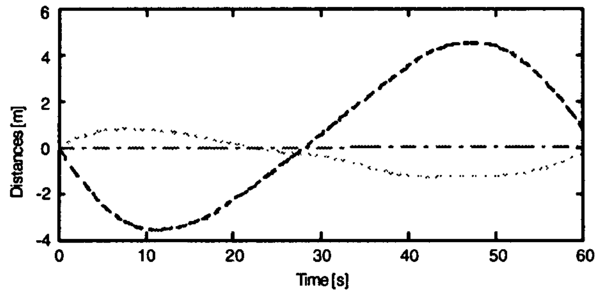

Fig. 7 Distance with constant bias compensation

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.

For verify the constant bias compensation, we make an accelerometer test where the sensor is shaked on x, y, and z axes, respectively. The results are given in Fig. 8 – Fig. 10.

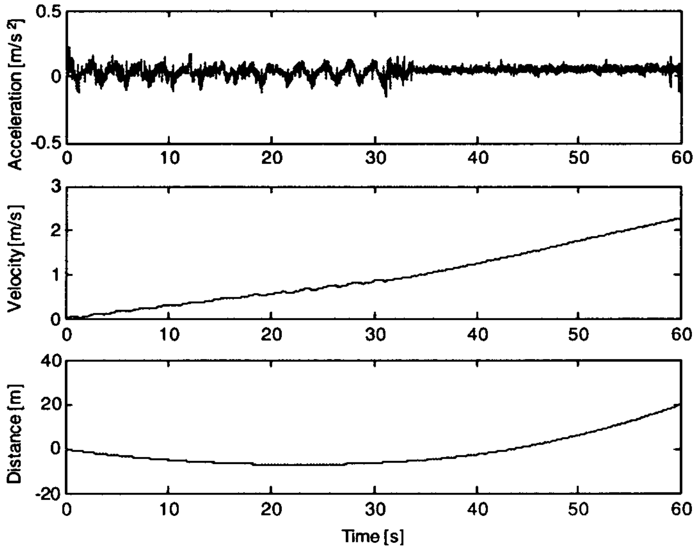

Fig. 8 Constant bias compensated data on x axis

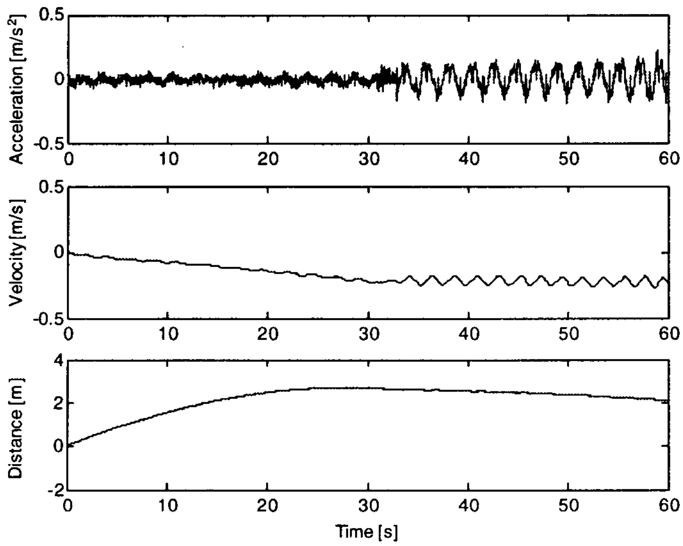

Fig. 9 Constant bias compensated data on y axis

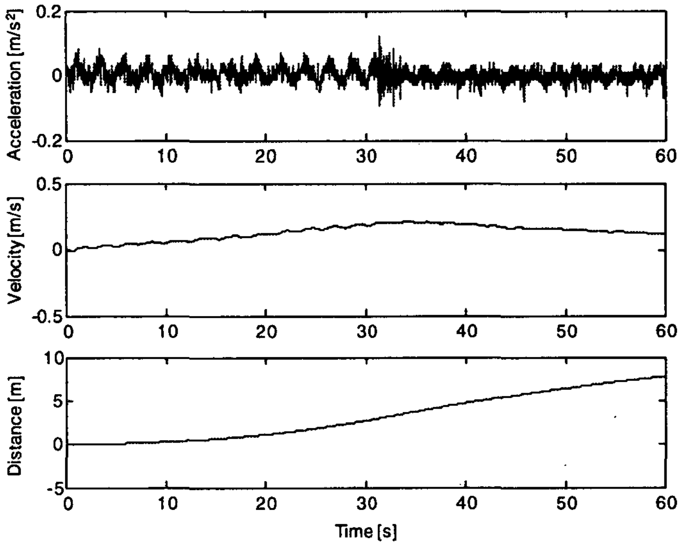

Fig. 10 Constant bias compensated data on z axis

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 using FFT method to check the main frequency term which effects to the accelerometers. The FFT result is shown in Fig. 11

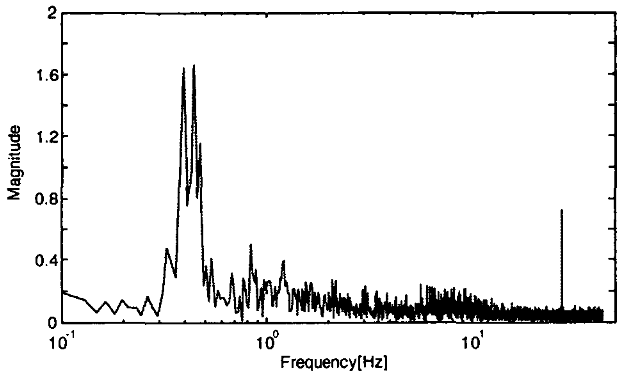

Fig. 11 FFT results on x axis

In Fig. 11, the main frequency mode is 0.4428 [Hz] and its magnitude is 1.6598. From the frequency, the period is calculated as 2.256[s]. In simulation for periodic bias compensation, we define the parameters as Table. 2.

Table 2 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

By using the parameters in Table 2 and the periodic compensation algorithm, we can get the results in Fig. 12-Fig. 14, where the same accelerometer's data with those of Fig. 8 – Fig. 10 are used.

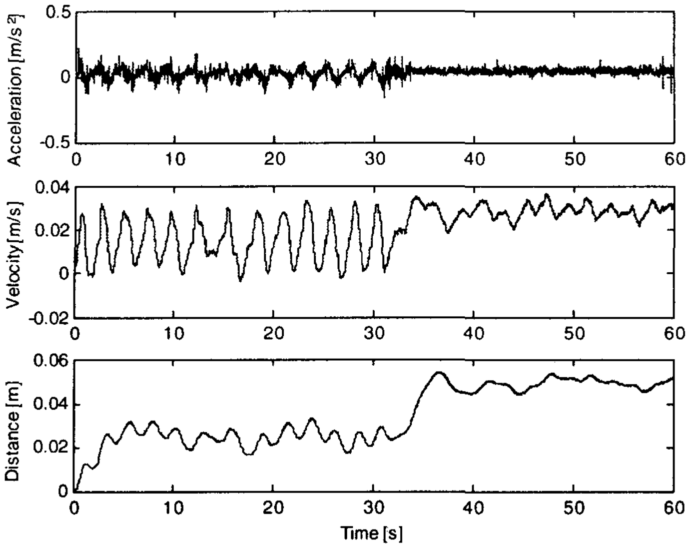

Fig. 12 Periodic bias compensated data on x axis

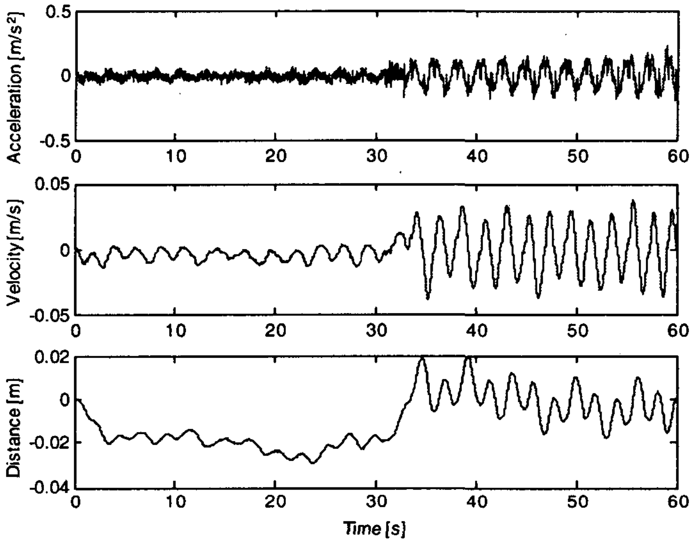

Fig. 13 Periodic bias compensated data on y axis

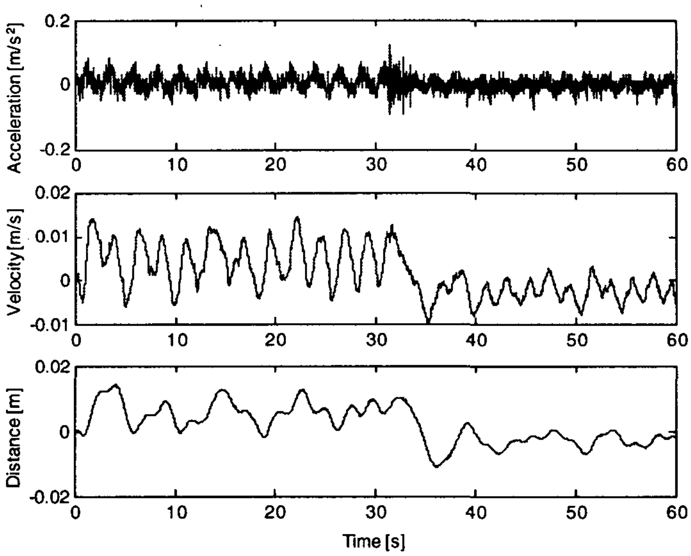

Fig. 14 Periodic bias compensated data on z axis

By comparison Fig. 8 – Fig. 10, 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 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 by using accelerometer data. From the 1^{st} 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 auto-tuning method for the proposed algorithm will be researched in future.

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