A Roll Rate Estimation Method using GPS Signals in a Spinning Vehicle

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Abstract

A roll rate estimation method is proposed using the GPS measurement for spinning vehicles such as guided munitions and smart bombs. Before designing the roll rate estimator, the carrier phase and the carrier frequency deviation caused by spinning have been observed. Based on the observation, the spinning frequency is estimated using I and Q value from the correlator. The proposed method is evaluated through computer simulations using a software defined receiver and a GPS IF signal generator.

Keywords: Roll Rate Estimation, smart munitions

1. Introduction

Currently, much work has been performed to increase the range and the accuracy of unguided munitions. To this end, high performance navigation system is required. From 1999's, one of the guided bomb, JDAM (Joint Direct Attack Munitions) developed by Boeing was used over Kosovo, Afghanistan, and Iraq wars and achieved remarkable results [1]. The JDAM series are manufactured by replacing the tail of dumb bomb by the guidance tail kit based on the GPS/INS integration system. The U.S. Naval Surface Warfare Center, Raytheon and TI Systems developed the EX-171 ERGM (Extended Range Guided Munitions). ERGM is a low cost, long range, precision guided munitions that employ a tightly-coupled GPS/INS integration system as the navigation system [2]. The Excalibur 155mm Precision Guided Extended Range Artillery Munitions, also known as the M982 ER DPICM (Extended Range Dual Purpose Improved Conventional Munitions) Projectile, is very effective smart munitions. It provides capability to attack armored vehicles and bunkers etc., out to ranges exceeding current 155mm family of artillery munitions. The munitions will employ Global Positioning System (GPS) - aided inertial guidance and navigation [3].

In applications, such as in JDAM, ERGM and Excalibur, the vehicle to be guided is spinning. In spinning vehicle, INS is very difficult to implement because the scale factor error and the dynamic range lead to large and rapidly increasing attitude error. For example, a munitions spinning at a 3Hz is rotating at 1,080 deg/sec. A scale factor error of 1500ppm[4] will cause an attitude error rate of 1.62deg/sec. The smart munitions employ MEMS IMU for high-shock and cost-effectiveness. These IMU do not have the precision to maintain an accurate attitude estimate at these spinning motions.

This paper proposed a method for estimate the spinning frequency using GPS signals. Before designing the spin estimator, the carrier phase and the carrier frequency deviation caused by the spin have been observed. Based on the observation, the spinning frequency is estimated using accumulation value (I and Q) from the correlator. The proposed method is evaluated through computer simulations using a software receiver and a GPS IF signal generator.

2. Phase variation of GPS signal due to spinning

This paper considers such an application where a spinning vehicle is equipped with GPS receivers for determining its position. Typical examples can be found in military applications, for example, Excalibur and ERGM. Figure 1 shows a simple geometrical relation between a spinning vehicle and a GPS satellite.

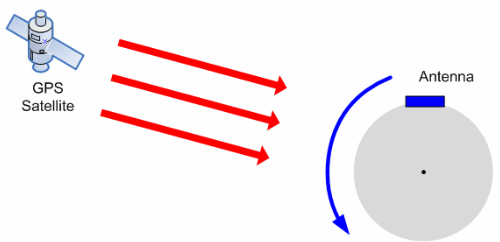


Figure 1. Geometrical relation between a spinning vehicle and a GPS satellite

This paper considers L1 C/A code GPS signal. Then, the received GPS signal can be written as

$$S(t) = AC(t)D(t)\cos(2\pi(f_c + f_d)t + \Delta\phi(t)) + n(t)\,, \tag{1}$$

where A, $C(t)$, $D(t)$, f_c, f_d, $\Delta\phi$ (t) and $n(t)$ denote the signal magnitude, the C/A code, the navigation data ,the carrier frequency, the Doppler frequency due to the relative motion between the vehicle and the GPS satellite, the phase variation caused by the spinning, and the noise, respectively.

The phase variation $\Delta\phi$ can be expressed as

$$\Delta\phi(t) = -2\pi\frac{l(t)}{\lambda} \quad [rad]\,, \tag{2}$$

where λ is the wavelength of L1 carrier and

$$l(t) = r\sin(2\pi f_S t) \tag{3}$$

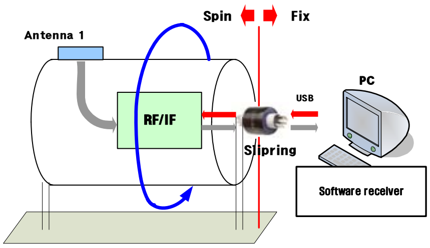
In Equation (3), r is the radius of the spinning vehicle and f_s

is the spinning frequency. It should be noted that the phase variation $\Delta\phi(t)$ can cause the error in the tracking loop larger than expected, even worse can result in failure of signal acquisition if PLL is adopted in GPS receivers. Hence, it is necessary to estimate $\Delta\phi(t)$ and mitigate the effect of spinning on the tracking loop.

Before devising an estimation method for the phase variation, the answer to the following question must be given:

"f_d and $\frac{d}{dt}\Delta\phi(t)$ can be separable?"

The answer to this question is 'yes'. To show this, this paper designs an experimental apparatus shown in Figure 2.



(a) Experimental setup

(b) Picture of experimental apparatus
Figure 2. An Experimental Apparatus

Using the experimental apparatus shown in figure 2, the overall Doppler frequency of the received GPS signal was measured. Figure 3 shows the Doppler frequency measured in the GPS receiver of which RF part is equipped in the spinning vehicle. The spinning frequency was 1Hz. From Figure 3, it can be seen that the Doppler shift caused by the relative motion between the spinning vehicle and the GPS satellite varies much shower than the Doppler component caused by the spinning. This observation tells us that f_d and $\frac{d}{dt}\Delta\phi(t)$ can be separable using appropriate filtering.

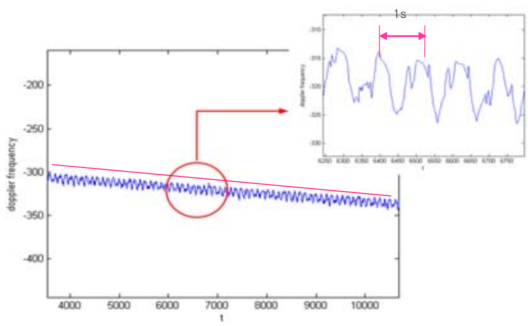


Figure 3. The overall Doppler shift

3. An estimation scheme the spinning frequency

As explained, a phase modulation occurs in the received signal in spinning vehicles. It induce a phase tracking error in GPS receivers. The spinning frequency can be estimated by the phase demodulation.

Figure 4 shows the structure of the tracking loop in the GPS receiver for estimating the spinning frequency. Figure 5 is the block diagram of the spin frequency estimator.

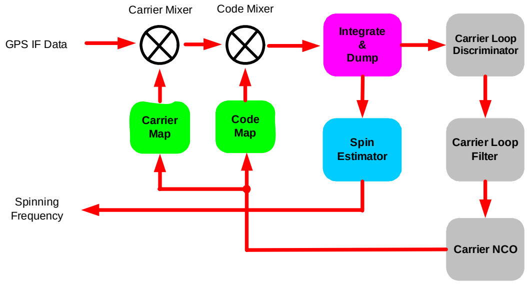


Figure 4. Structure of modified tracking loop

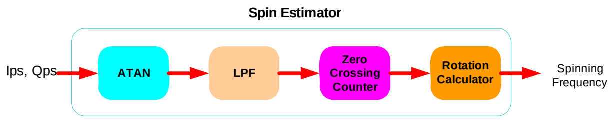


Figure 5. Block diagram of the spin estimator

The I and Q signal of the accumulator are given by

$$S_I(t) = \frac{A}{2}\cos[\Delta\phi(t)] = \frac{A}{2}\cos[a\sin(2\pi f_s t)] + n_I \tag{4}$$

$$S_Q(t) = -\frac{A}{2}\sin[-\Delta\phi(t)] = -\frac{A}{2}\sin[-a\sin(2\pi f_s t)] + n_Q \tag{5}$$

where a is $-\frac{2\pi r}{\lambda}$, n_I and n_Q are the noises after accumulation. The S_I and S_Q will be fed to the spin estimator, where the phase error is calculated by

$$A_s(t) = ATAN2(S_Q, S_I) = a\sin(2\pi f_s t) + n_a \tag{6}$$

The phase error will be passed to a LPF that can effectively remove noise n_a. The cutoff frequency of LPF is set to a maximum spinning frequency expected.

The spinning frequency is estimated using a zero crossing counter which counts the number of samples from previous zero crossing point to current zero crossing point. The condition of zero crossing is defined by

$$A_i < 0 \quad and \quad A_{i-1} > 0 \tag{7}$$

where A_i is the current output of LPF and A_{i-1} is the previous output of LPF. Then, the spinning frequency is calculated by

$$\frac{1}{count\ value} \times f_{isample} \tag{8}$$

where $f_{ismaple}$ is the inverse of the integration time.

4. Validation of the proposed method

In order to validate the proposed method, computer simulations were carried out. GPS IF signal generator was utilized for generating the phase modulation signal. The spinning frequency was estimated using the proposed method. Figure 6 shows test setup for simulation.

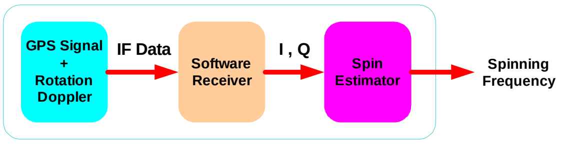


Figure 6. Test setup for simulation

4.1 Generation of GPS signal

The GPS IF signal generator is designed to generate GPS IF signal including adjustable spinning Doppler. Figure 7 shows the structure of GPS IF signal generator.

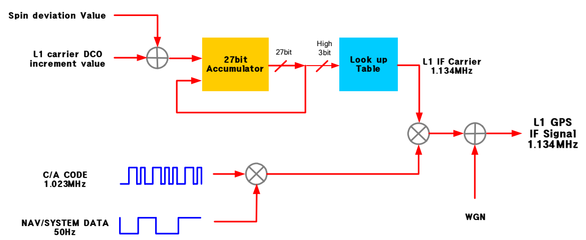


Figure 7. Structure of GPS IF signal generator

In Figure 7, L1 carrier DCO increment value is the phase of the carrier, and the carrier frequency would be changed according to its amplitude. L1 carrier DCO increment value is set as

$$L1\ carrier\ \ DCO\ increment\ value = \frac{f_c + f_d}{f_{sample}} \times 2^{27} \qquad (9)$$

where f_c is the carrier frequency of IF frequency, f_d is Doppler frequency that is caused by the relative motion of the satellite with respect to the user, $f_{sampling}$ is the sampling frequency of the test setup. The Doppler caused by spinning given by

$$rotation\quad doppler = -\frac{2\pi f_s r}{\lambda} \times \frac{\cos(2\pi f_s t)}{f_{sample}} \times 2^{27} \qquad (10)$$

where f_s is the spinning frequency. The test setup generates GPS IF signals under the condition of 1Hz, 2Hz, and 3Hz spinning frequency. The power spectrum of the generated GPS IF signal is shown in Figure 8.

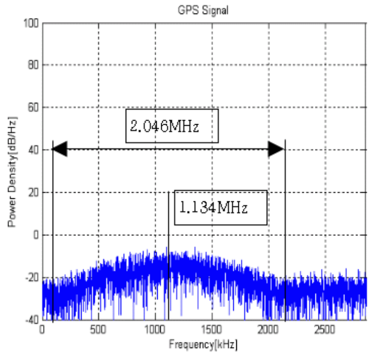


Figure 8. Power spectrum of the generated GPS IF signal

4.2 Estimation of the spinning frequency

The estimation of the spinning frequency was carried out using I, Q value of the software receiver. Figure 9 shows the I^2+ Q^2 as the signal power.

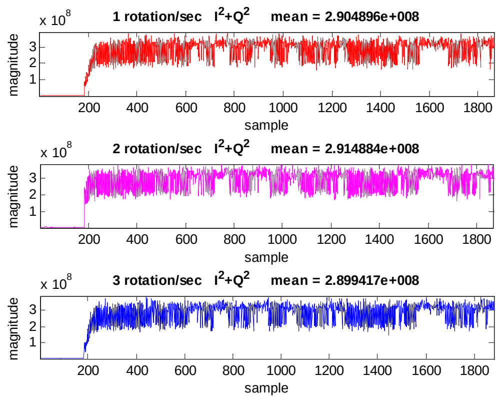


Figure 9. Received signal power

Figure 10 shows output of the output of ATAN block.

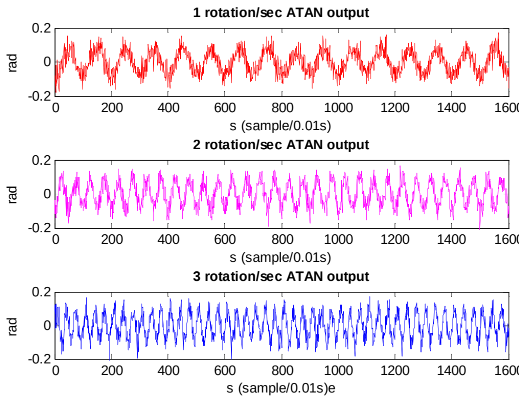


Figure 10. The output of ATAN block

The output of ATAN block is filtered by LPF. Figure 11 shows the filtered output.

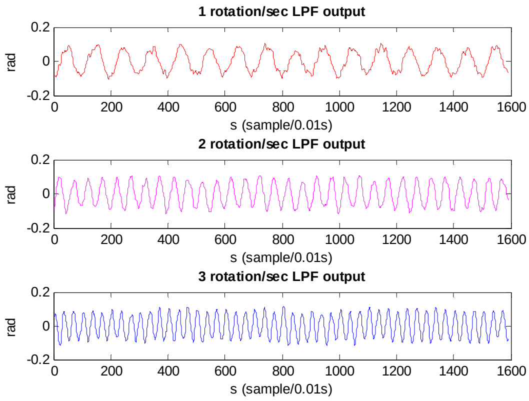


Figure 11. The output of LPF

Figure 12 shows the estimation result of the spinning frequency using the zero counter.

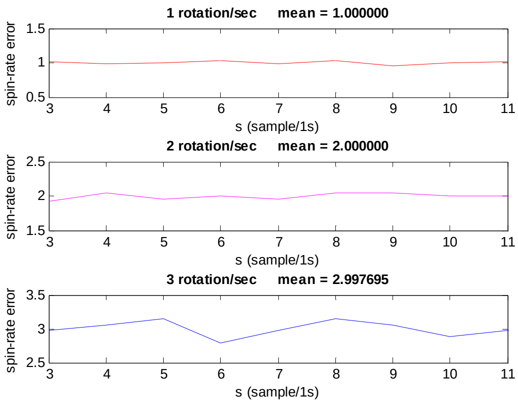


Figure 12. Estimated spinning frequency

The mean value of the estimation error is 0, 0 and 0.0023Hz for 1Hz, 2Hz and 3Hz spinning. From this, it can be concluded that the proposed estimation scheme works well.

5. Concluding remarks

This paper proposed a method for estimating the spinning frequency. Before designing the estimator, the carrier phase and the carrier frequency deviation caused by spinning have been observed. Based on the observation, it can be seen that the phase variation can be separated from the Doppler due to the relative motion of the satellite with respect to the vehicle. The performance of the proposed method was evaluated through computer simulations using a software receiver and a GPS IF signal generator.

As a further work, the performance of the designed estimation method will be evaluated with real signals using a spinning equipment.

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