JPNT 6(4), 135-140 (2017)
https://doi.org/10.11003/JPNT.2017.6.4.135

JPNT Journal of Positioning, Navigation, and Timing

Roll Angle Estimation of a Rotating Vehicle in a Weak GPS Signal Environment Using Signal Merging Algorithm

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ABSTRACT

This paper proposes a signal merging algorithm to increase the signal-to-noise ratio (SNR) of a GPS correlator output to estimate the roll angle of a rotating vehicle in a weak GPS signal environment. Rotation Locked Loop (RLL) algorithm is used to estimate a roll angle using the characteristics that the power of the GPS signal measured at the receiver of a rotating vehicle varies periodically. First, delay times are calculated to synchronize GPS signals using satellites' and receiver's positions and the rotation frequency of a vehicle, and then correlator outputs are delayed in time and merged with each other, resulting in the increase of an SNR in a correlator output. Finally, simulations are conducted and the performance of the proposed algorithm is validated.

Keywords: GPS, roll angle estimation

1. INTRODUCTION

Global Positioning System (GPS) has been widely utilized in military and private sectors since it can provide accurate position, velocity, and timing information anywhere throughout the world (Kaplan & Hegarty 2006). In recent years, studies on using GPS signals at rotating vehicles have been steadily conducted. In particular, studies on estimating the roll angle of rotating vehicles whose trajectory is relatively smooth and predictable, such as spinning shells, and then integrating this with inertial navigation system have been conducted (Doty 2001, Doty & McGraw 2003, Doty et al. 2004, Kim et al. 2012, Choi 2015).

Doty (2001), Doty & McGraw (2003), and Doty et al. (2004) proposed an algorithm of GPS roll angle determination that estimated the roll angle of a rotating vehicle, and applied the algorithm to perform navigation by integrating the estimated roll angle with accelerometer outputs. Kim et al. (2012) proposed a method that estimated a roll angle using an exclusive-OR logic at a rotating vehicle and calculated the Doppler frequency induced by rotation using the estimated roll angle to compensate the tracking loop of the receiver. Choi (2015) proposed an algorithm of Rotation Locked Loop (RLL) that estimated the roll angle of a rotating vehicle, and performed detailed analysis on the RLL algorithm under various conditions. However, the aforementioned proposed methods did not sufficiently consider the environments where GPS signals are weak such that large roll angle estimation error occurs and thereby roll angle tracking is lost.

Thus, this study proposed a method to increase a signal-to-noise ratio (SNR) by merging multiple correlator outputs in a weak GPS signal environment. This paper is organized as follows. In Section 2, the RLL algorithm, which was used to estimate a roll angle in this study, is introduced, and a method to increase an SNR by merging multiple correlator outputs is proposed. In Section 3, the performances of the proposed algorithm are compared through simulations, and error analysis is performed. Lastly, in Section 4, conclusions are presented, along with suggestions for future study.

Received Sep 01, 2017 **Revised** Sep 06, 2017 **Accepted** Sep 08, 2017
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http://www.ipnt.or.kr Print ISSN: 2288-8187 Online ISSN: 2289-0866

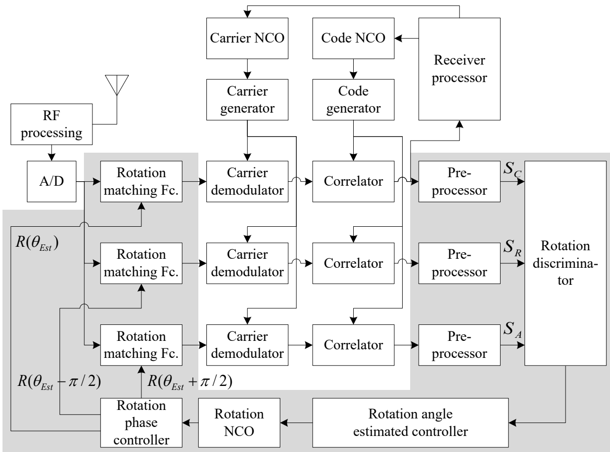

Fig. 1. RLL roll angle estimation algorithm (Choi 2015).

2. ROLL ANGLE ESTIMATION USING SIGNAL MERGING ALGORITHM

In this study, the RLL-based roll angle estimation algorithm proposed by Choi (2015) was employed as a method to estimate the roll angle of a rotating vehicle. The RLL algorithm estimates a roll angle using the change in signal intensity inputted to the antenna via vehicle's rotation. Fig. 1 shows the structure of the GPS receiver which estimate a roll angle. It consists of general GPS receiver structure to which the RLL structure marked with shade is added. The rotation discriminator depicted in the right side calculates a roll angle error, which is a difference between actual vehicle's roll angle and currently-estimated roll angle, using one-cycle integrated centered (S_C), retarded (S_R), and advanced (S_A) correlator outputs. The rotation angle estimated controller and rotation NCO (numerically controlled oscillator) tracks the roll angle (θ_{Est}) of a vehicle by generating a control input using the roll angle error. The rotation phase controller generates 90° retarded (θ_{Est}-$\pi/2$) and advanced (θ_{Est}+$\pi/2$) phase based on the estimated roll angle (θ_{Est}). Function $R(\theta)$ generates a square pulse, which is "1" where the internal parameter θ is in the sections of -90° to +90°, and "0" in the other sections, and the rotation matching function passes the A/D converted GPS signals into the next step based on the square pulse generated by $R(\theta)$. Next, correlator outputs are generated using three signals (centered, retarded, and advanced), which are then passed through the pre-processor, thereby generating one-cycle integrated centered (S_C), retarded (S_R), and advanced (S_A) correlator outputs. This method has the same structure with the delay locked loop (DLL) used in general GPS receivers (Kaplan & Hegarty 2006).

The RLL algorithm estimates a roll angle using changes in received signal via antenna's beam pattern by vehicle's rotation. Thus, there has to be a difference in signal intensity between a section where signals are received and a section where signals are not received. However, this difference in signal intensity is small in an environment where GPS signals are weak, thereby making the error of the rotation discriminator large and finally resulting in losing the roll angle tracking.

In this regard, this study proposed a method to increase the SNR of a correlator output by merging multiple satellite signals. The SNR of a correlator output can be increased by time-synchronizing and merging correlator outputs from different satellites as it receives multiple satellite signals simultaneously. It used the characteristic that when assuming that the noise characteristics of the correlator outputs follow the normal distribution and are independent with each other, signal power becomes N^2 times by merging the N correlator outputs and noise power becomes N times thereby making SNR N times. On the assumption that the position and attitude (pitch and heading angles) of a vehicle are known, a satellite's position is converted into azimuth and elevation angle based on the vehicle's position, followed by calculating the difference with the attitude angle of the vehicle, thereby obtaining a difference in rotation angle between the vehicle and satellite. For shells, their accurate initial position and attitude can be received through a fire control equipment before launch and their movement is quite similar with the already known path after launching. Using this information, thus, the vehicle's position and pitch and heading angles can be obtained. For the satellite's position, satellite orbit information can be received through the fire control equipment prior to launch or can be obtained by decoding GPS signals in real time. Delay times (t_d) for merging multiple correlator outputs can be calculated using the rotation frequency (f) of a vehicle in addition to the previously calculated rotation angle differences.

Assuming that satellite's and receiver's positions in the Earth-Centered, Earth-Fixed (ECEF) coordinate system are $\boldsymbol{S}$ and $\boldsymbol{P}$, and receiver's latitude and longitude are ϕ and λ, transformation matrix C_e^g that transforms the ECEF coordinate system into local geodetic coordinate system that is represented with North-East-Down (NED) is presented in Eq. (1) (Rogers 2003).

$$C_e^g = \begin{bmatrix} -\sin\phi\cos\lambda & -\sin\phi\sin\lambda & \cos\phi \\ -\sin\lambda & \cos\lambda & 0 \\ -\cos\phi\cos\lambda & -\cos\phi\sin\lambda & -\sin\phi \end{bmatrix} \quad (1)$$

Here, a process to calculate azimuth (Az) and elevation

(El) angles of the satellite at the receiver's position is presented in Eqs. (2-6).

$$\boldsymbol{R} = \boldsymbol{S} - \boldsymbol{P} \tag{2}$$

$$\boldsymbol{u_e} = \boldsymbol{R}/||\boldsymbol{R}|| \tag{3}$$

$$\boldsymbol{u_g} = C_e^g \boldsymbol{u_e} \tag{4}$$

$$Az = \tan^{-1}\left(\frac{u_g(2)}{u_g(1)}\right) \tag{5}$$

$$El = \tan^{-1}\left(\frac{u_g(3)}{\sqrt{u_g^2(1) + u_g^2(2)}}\right) \tag{6}$$

where $\boldsymbol{R}$ refers to a relative position between the receiver and satellite, $\boldsymbol{u}_e$ refers to a unit vector directed from the receiver toward the satellite represented with ECEF, and $\boldsymbol{u}_g$ refers to a variable of $\boldsymbol{u}_e$ represented with NED at the receiver's position.

Assuming that the pitch angle of a vehicle is 0° and the heading angle is ψ_p on the basis of due north, the rotation angle of the satellite relative to the vehicle can be calculated via Eq. (7).

$$\phi_{SV} = \left(\frac{\pi}{2} - El\right)\sin\left(Az - \psi_p\right) \tag{7}$$

Given that the rotation frequency of a vehicle is f, a delay time for synchronizing multiple satellite signals can be calculated by Eq. (8), which represents a time to take for the vehicle to rotate by the rotation angle (ϕ_{SV}).

$$t_d = \frac{\phi_{SV}}{2\pi}\frac{1}{f} \tag{8}$$

In Eq. (8), the rotation frequency of the vehicle cannot be practically known. Thus, a predicted value of rotation frequency is used. The initial rotation frequency of a vehicle is needed to employ the signal merging algorithm, and several methods of acquiring it is proposed by Choi (2015). The performance of the signal merging algorithm is relatively insensitive to an error of rotation frequency, and low cost angular sensors with large error range can be used if needed. Once the RLL algorithm is converged, then the rotation frequency in addition to the roll angle are generated as the output of the algorithm, which can be used again in the time delay calculation in the signal merging algorithm.

Fig. 2 shows the block diagram of the aforementioned signal merging algorithm, whose operation is explained as follows: Using N satellites' and a receiver's position, and the predicted value ($\hat{f}$) of the vehicle's rotation frequency, delay times are calculated using Eq. (8) in the calculate t_{d1}–t_{dN} blocks, and then the correlator outputs with regard to the N satellites are delayed in time at the delay blocks, which are then added each other in the sum (Σ) block and divided by the number of satellites (÷N block) to generate the merged correlator output. Here, the correlator output as the input of the delay block represents the one generated at general GPS receiver.

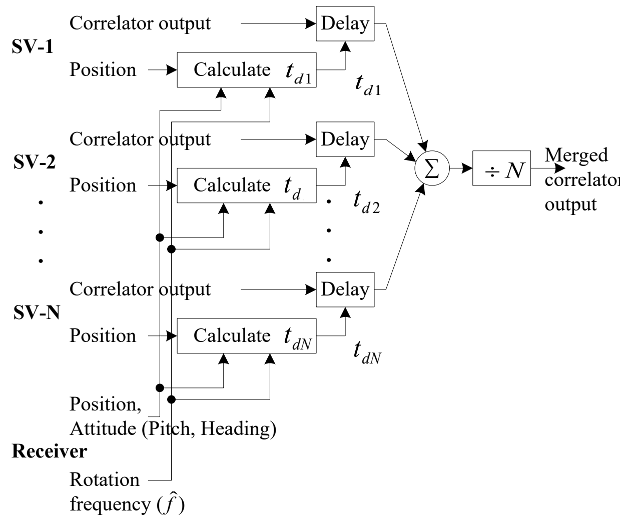

Fig. 2. GPS signal merging algorithm.

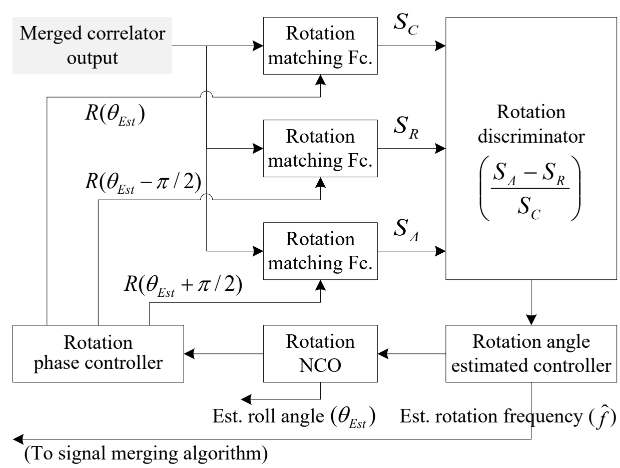

Fig. 3. RLL algorithm using merged correlator output.

Fig. 3 shows the modified RLL algorithm which uses the merged correlator output of the signal merging algorithm shown in Fig. 2. The RLL algorithm in Fig. 1 is partly modified, and the internal blocks have the same functions as those in the blocks in Fig. 1. Note that the structure of the receiver is simplified by using the merged correlator output rather than A/D output signal as the input of the rotation matching function. The rotation frequency estimate ($\hat{f}$)

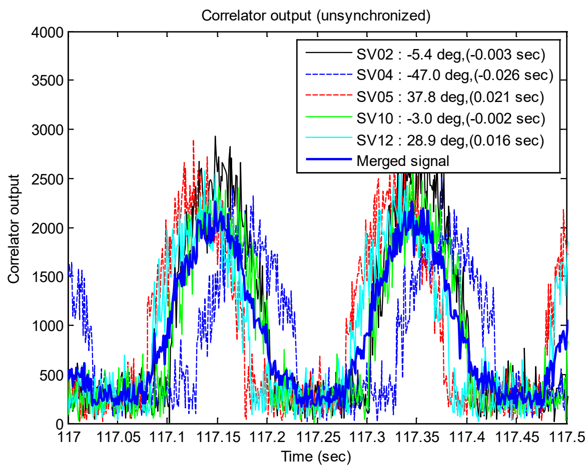

Fig. 4. Correlator output (before time sync).

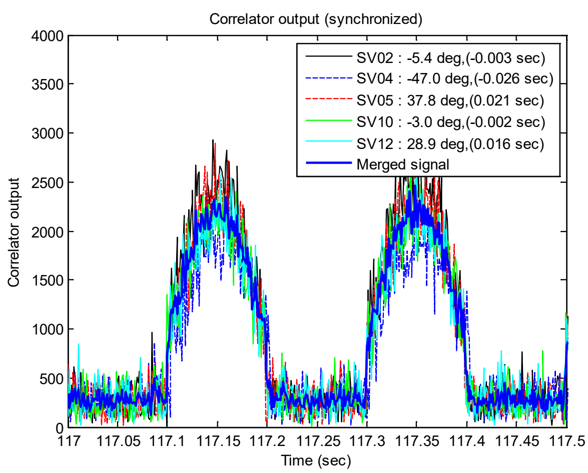

Fig. 5. Correlator output (after time sync).

and roll angle estimate (θ_{Est}) are generated as the outputs of the rotation angle estimated controller and rotation NCO, respectively. In particular, the rotation frequency estimate ($\hat{f}$) generated as the output of the RLL algorithm here is used to calculate the delay time for signal merging as it is inputted to the signal merging algorithm in Fig. 2.

3. SIMULATION AND THE RESULTS

In this study, two simulations were conducted: verification of "improvements on SNR due to the signal merging algorithm" and "reduction in RLL phase jitter in the roll angle estimation algorithm".

First, SPIRENT simulator was used to verify the performance of the signal merging algorithm. An antenna with beam width of 180° was assumed to be mounted, and GPS signals received from 10 satellites from the vehicle that

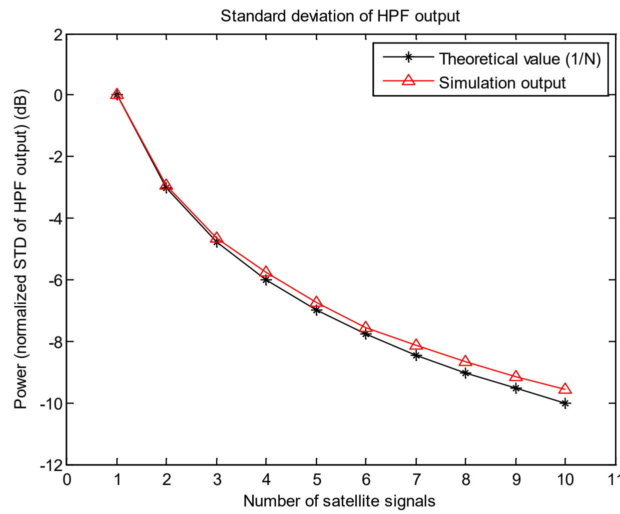

Fig. 6. Noise power by the number of merged signal.

was rotating at 5 Hz were collected. The navigation data were decoded using the collected signals, then followed by acquiring the positions of the satellites and receiver to calculate the rotation angles of the satellites with regard to the receiver. Afterward, delay times with regard to 5 Hz were calculated to perform the time synchronization of the correlator outputs. Figs. 4 and 5 show the correlator outputs of five satellite signals to increase readability out of 10 satellite signals in total. Each of the figures shows the results before and after the time synchronization. The legends in Figs. 4 and 5 represent the calculated results of Eqs. (7) and (8), respectively. They refer to the rotation angle (ϕ_{SV}) of the satellite relative to the receiver and delay time (t_d) for merging based on the zenith of the receiver. As shown in Fig. 5, the correlator outputs with regard to each of the satellite signals are synchronized in time. Fig. 6 shows the relative noise power by decibel according to the number of merged satellite signals based on the noise power from single satellite. The figure shows that when N signals are merged, it is very close to a theoretical noise power of $1/N$.

Second, the RLL phase jitter according to the number of merged signals was obtained after generating 12 satellite signals whose intensity was weak to check the effect of the number of merged signal on the RLL phase jitter. The signal intensity of the SPIRENT simulator data used in the above was strong at 45 to 50 dB-Hz, which was difficult to observe the effect of the merging algorithm due to the tiny phase jitter. Thus, weak intensity signals were generated using software GPS signal generator, which was developed by the Control System Lab. in Chungnam National University for the purpose of generating satellite signals at rotating vehicles. It supports multi-antenna, and generates satellite signals with the input of vehicle's rotation frequency, the

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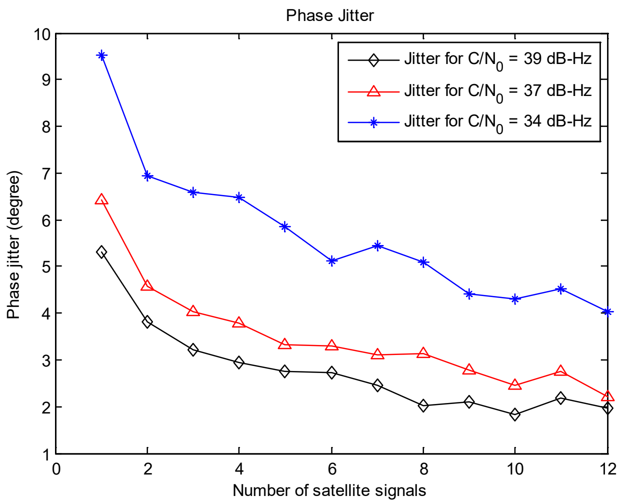

Fig. 7. Phase jitter by the number of merged signal.

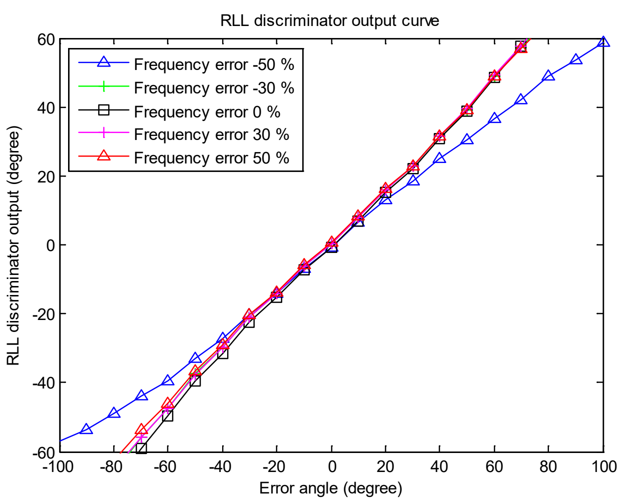

Fig. 8. RLL discriminator output curve w.r.t the rotation frequency error.

number of antennas, satellite orbit information, and satellite signal intensity. Fig. 7 shows the size of RLL phase jitter according to the number of merged signals, in which phase jitters are represented when the intensity of satellite signal is 39 dB-Hz, 37 dB-Hz, and 34 dB-Hz, respectively. The figure verifies the decreasing trend of phase jitter according to the number of merged signals.

Lastly, the effect of the rotation frequency error on the merged correlator output was analyzed. The largest cause of error in time delay calculation for merging algorithm was due to the error in the estimated rotation frequency. In this respect, Fig. 8 depicts the output of the rotation discriminator when the error of rotation frequency is -50 ~ 50% using the same SPIRENT simulator output used in the above. Although the response of the rotation discriminator was slightly degraded at sections whose error angle (horizontal axis) was more than 30° when the rotation frequency error was -50%, other sections showed little effect on the rotation discriminator output.

4. CONCLUSION

This paper proposed a method to increase an SNR by merging multiple correlator outputs to estimate the roll angle of a rotating vehicle in weak GPS signal environments. The output of the SPIRENT simulator was used to verify the performance of the proposed algorithm. The performance result confirmed that signal noise was reduced when the signal merging algorithm was employed. In addition, it was verified that RLL phase jitter was decreased due to signal merging in a weak GPS signal environment, using signals generated by the software GPS signal generator. The insensitivity of the merged correlator output to the rotation frequency error was also verified through the error analysis. However, the proposed merging algorithm requires prior information of approximate attitude (pitch and heading angle) of a vehicle, which is a drawback.

For the future study, the roll angle of a rotating vehicle that moves along the ballistic trajectory such as rotating shell will be estimated using the proposed method in this study, and the performance will be analyzed. The performance of the proposed algorithm will be verified through outdoor tests in environments where actual GPS signals are received.

ACKNOWLEDGMENTS

This work has been supported by the National GNSS Research Center program of Defense Acquisition Program Administration and Agency for Defense Development.

REFERENCES

Choi, H. H. 2015, Roll Angle Estimation Technique Based RLL Using Satellite Navigation Signal, PhD Thesis, Chungnam National University, Korea

Doty, J. H. 2001, Advanced Spinning-Vehicle Navigation - A New Technique in Navigation on Munitions, Proceedings of the ION 57th Annual Meeting, June 11-13 2001, Albuquerque, NM, pp.745-754

Doty, J. H., Anderson, D. A., & Bybee, T. D. 2004, A Demonstration of Advanced Spinning-Vehicle Navigation, Proceedings of the ION NTM 2004, Jan. 26-28 2004, The Catamaran Resort Hotel San Diego, CA, pp.573-584

Doty, J. H. & McGraw, G. A. 2003, Spinning-Vehicle Navigation Using Apparent Modulation of Navigation Signals, US Patent 6520448 B1

Kaplan, E. D. & Hegarty, C. J. 2006, Understanding GPS: Principles and Applications, 2nd ed. (Boston: Artech House, Inc.), pp.1-20, pp.153-183

Kim, J. W., Kang, H. W., Hwang, D.-H., & Lee, S. J. 2012, Signal Tracking Method of GNSS Receivers for Spinning Vehicles, International Journal of Control, Automation and Systems, 10, 529-535. https://doi.org/10.1007/s12555-012-0309-5

Rogers, R. M. 2003, Applied Mathematics in Integrated Navigation Systems, 2nd ed. (Reston, Virginia: AIAA, Inc.), p.48

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