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Jamming Mitigation using an Improved Fuzzy Weighted Least Square Method in Combined GPS and GLONASS Receiver

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ABSTRACT

One of the important concerns in Global Positioning System (GPS) is interference and jamming attack. Different methods have been proposed to mitigate GPS jamming such as antenna array and digital signal filtering. In this paper, the integration of GPS with Russian Global Navigation Satellite System (GLONASS) is utilized to overcome this issue. Increasing the number of visible satellites is a significant benefit of this combined system. We also introduce an improved Fuzzy-Weighted Least-Square (FWLS) method to weight the information according to its transmitter system reliability and satellite properties. The experimental comparison between the proposed method and an improved Wavelet-Packet-Transform (WPT)-based anti-jammer shows that though the accuracy of WPT-based method is more than FWLS method, the FWLS has significantly less computation complexity and more reliability.

1. Introduction

Global Positioning System (GPS) employs Direct Sequence Spread Spectrum (DSSS) for data transmission and thus it has an inherent resistance to intentional (jamming) and non-intentional interferences. However, as the interference power increases, the processing gain of the GPS may be insufficient for interference mitigation. Therefore, it is necessary to apply additional techniques for improving the receiver anti-jamming performance [1,2].

Spatial, adaptive and time-frequency filtering methods are most common techniques for jamming mitigation in GPS receivers [1]. Adaptive antennas can be employed for mitigating of both narrowband and wideband jamming in spatial domain, but they are computationally complex. Also, they impose an extra hardware to the GPS receiver [3].

Adaptive filtering techniques like adaptive notch filters [4], Kalman filter [5], neural-based predictors [6,7], Approximate Conditional Mean (ACM) filter [8] and Augmented State ACM (ASACM) filter [9] can be employed in low-power, low-cost and small-size applications. However, without prior knowledge of the jamming model parameters, they do not have an acceptable anti-jamming performance.

Time-frequency filtering techniques like Short Time Fourier Transform (STFT) based processing [10,11], filter banks [12], Wavelet Transform (WT) [13,14] and subspace processing [15] process the signal in both time and frequency domains, simultaneously. They are well suited for low-cost and low-power applications. They can easily detect and mitigate narrowband jamming from the GPS signal. Among these methods, WT-based methods are more attractive because they use scalable modulated windows and thus they have a flexible resolution in both time and frequency domains. They also solve the signal-cutting problem of STFT and filter banks [14].

Another proposed method to overcome the interference situation is combining GPS receiver with other navigation tools such as other Global Navigation Satellite System (GNSS). Unlike the previous efforts to mitigate the jamming effect on acquisition and tracking parts of GPS receiver, the integrated receiver mitigates jamming in navigation solution part and improves accuracy of positioning. These days, combination of GPS as the most important satellite navigation system with Russian fully operational Global Navigation Satellite System (GLONASS) is one of the popular integrated solution [16,17].

The best-known estimation algorithm for navigation solution is Least Square (LS) that makes the sum of the squares of the errors as small as possible to find the best estimation. Improving the accuracy of LS is an important target which is possible by weighting the high-quality information. This method is known as Weighted Least Square (WLS). For example, Ref. [18] utilizes Carrier-to-Noise density (C/N_0) and elevation angle for weighting and has

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an improvement of 76.89% on the standard deviation value rather than LS method in normal condition.

Selecting an appropriate weighting matrix is an important step in WLS algorithm. A balance among all parameters should exist for finding suitable weights. So, a fuzzy system can be helpful in this situation. The other main step in designing a suitable system is correct defining of rules and membership functions. Ref. [19] reduces the position error to less than 1.5 m using fuzzy system, while it was about 60 m before.

Choosing the best method for jamming mitigation needs to know the differences between different strategies. The aim of this paper is to propose an improved Fuzzy-Weighted Least-Square (FWLS) method for a combining receiver and compare it with a recently published WPT-based method in a GPS-only receiver to show the advantages and disadvantages of each receiver in jamming scenarios. The rest of this paper is organized as follows. In Section 2, the basic principles of the paper are briefly reviewed. The improved WPT-based and proposed FWLS methods are described in Section 3. Then in Section 4, the hardware setup is described. Finally, the experimental results and discussions are reported in Section 5.

2. Basic principles

In this part, basic principles of the paper are reviewed.

2.1. Jamming and interferences

Despite increasing the developments in data collections and navigation solutions in new receivers, the main drawback of the satellite navigation systems are high sensitivity to different interferences including multipath, jamming and spoofing. The effects of interferences on the GNSS receiver are to reduce the Signal to Noise Ratio (SNR) and decrease the availability of satellite information. These will lead to increase the navigation solution error.

GPS signals are transmitted from the satellites orbiting 20,000 km above the earth and can become weaker as they approach the receiver. This weakness makes the signals so sensitive to different interferences. Jammers are the devices deliberately transmit troublemaker signals in the space and as the result, prevent the receivers from determining and reporting the accurate results.

Different strategies have been proposed for GPS jamming mitigation from antenna array to different signal processing method which try to reacquire the jammed information. On the other hand, integration with other navigation tools such as inertial navigation sensors and other satellite-based positioning is the other strategy attracts many researchers. Most of the time, in the second strategy, jamming may also affect the other navigation tool and fail the anti-jamming strategy. So, there is a vital requirement to a data manipulation technique to increase the accuracy with available and even weak information such as weighting higher-quality information [20–22].

Each discussed method has especial pros and cons which can be extracted in theory and also test. Comparison of different methods in this condition can help the manufacturers to find the best according to their required immunity and available resources.

2.2. Wavelet Transform

In the Discrete Wavelet Transform (DWT) a signal is decomposed into low frequency (approximation) and high frequency (detail) parts. Then, the approximation part is decomposed into another low and high frequency parts. Hence, in DWT, frequency localization is sacrificed for time localization at the upper layers. However, in the Wavelet Packet Transform (WPT), the detail parts are also decomposed into approximation and detail parts at each level and thus WPT provides a uniform cover of the signal spectrum at any given scale [14].

In the anti-jamming applications, information of both low and high frequency components are important and thus a higher frequency resolution is needed. So, WPT is more appropriate choice than the DWT. It is described as:

$$\psi^i_{j,k}(t) = 2^{-j/2}\psi^i(2^{-j}t - k) \tag{1}$$

where i is the frequency band parameter. j and k are also the scale and translation parameters, respectively. The wavelet is obtained by:

$$\psi^{2i}(t) = \frac{1}{\sqrt{2}}\sum_{k=-\infty}^{\infty} h(k)\psi^i\left(\frac{t}{2} - k\right) \tag{2}$$

$$\psi^{2i+1}(t) = \frac{1}{\sqrt{2}}\sum_{k=-\infty}^{\infty} g(k)\psi^i\left(\frac{t}{2} - k\right) \tag{3}$$

Wavelets are the scaled and translated versions of a mother wavelet $\psi(t)$. The coefficients $g(k)$ forms a high-pass filter named wavelet filter and $h(k)$ forms a low-pass filter named scale filter. The WP coefficients C of the signal $f(t)$ can be calculated as:

$$C^i_{j,k} = \int_{-\infty}^{\infty} f(t)\psi^i_{j,k}(t)dt \tag{4}$$

Then the WP component of the signal at a certain node can be calculated as:

$$f^i_j(t) = \sum_{k=-\infty}^{\infty} C^i_{j,k}\psi^i_{j,k}(t)dt \tag{5}$$

Original signal can be obtained by summation of all WP components at j^{th} level:

$$f(t) = \sum_{i=1}^{2i} f^i_j(t) \tag{6}$$

2.3. GPS and GLONASS integration

Satellite-based navigation is a tool to determine position, velocity and precise time. Currently, the generic GNSS includes two world-wide operative navigation systems. The first one is U.S. GPS and the other one is Russian GLONASS. GPS and GLONASS integration provides improvements in terms of solution availability and accuracy, but with a needing to an extra observation for introducing an additional unknown, because of GLONASS time offset. Increasing the system immunity to interference and jamming is one of the most important advantages of this combination [23–25].

In the most cases, GPS and GLONASS are the same, but with some differences. These differences are in constellations, signals and references which should be noticed in integrated system design. Another important point discussed by many papers theoretically and practically is the fact that GLONASS performance is not comparable to GPS and sometimes it can make deviation in the integrated receiver solution with low-accurate information [26].

2.4. Weighted Least Square for GPS and GLONASS integration

A major step in positioning using satellite navigation systems is measuring the distance between the satellites and receiver called pseudo-range. By taking into account main errors, the pseudo-range measurement can be defined as: