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A three-dimensional robust ridge estimation positioning method for UWB in a complex environment

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Abstract

The Ultra-Wide Bandwidth (UWB) signal has received much attention due to its penetrability and high positioning accuracy with the increasing demand for indoor positioning, in which Global Positioning System (GPS) signal is challenging. In practice, there are two main problems with indoor 3D positioning based on UWB. One is that the quality of Time Difference of Arrival (TDOA) measurements varies in different observation environments. Namely, the time delay generated by Non-Line-of-Sight (NLOS) causes an enormous deviation from the real distance and cannot be well distinguished from the measurement reducing the accuracy of positioning. The other problem is that the height estimates, which are calculated using the conventional least square method, are extremely unstable due to the limitation of the Base Station (BS) layout. To address these problems, this paper presents Robust Ridge Estimation (RRE) for UWB positioning. Firstly, NLOS errors are detected, and the weights of each measurement are automatically adjusted in accordance with their quality, which is represented by the residuals between the estimated measurements and real observations. Then, the ridge estimation algorithm is applied iteratively for position estimation based on a robust estimation framework, which updates the weight of the measurements at each iteration. This approach transforms unbiased estimation to biased estimation by adding constraints that minimize the weighted quadratic sum of some parameters. As a result, the impact of NLOS can be reduced. The experimental result shows an improvement of RMSE in positioning with 45.71% when compared with ridge estimation in an NLOS/Line-of-Sight (LOS) mixed environment and an increase of robustness to NLOS with 56.11%.

Keywords: Time Difference of Arrival (TDOA); NLOS detection; Ultra-Wide Bandwidth (UWB); Robust estimation; Ridge estimation

1. Introduction

With the development of Global Navigation Satellite System (GNSS) and internet technology as well as mobile communication technology, it has wide applications in navigation, positioning and geodesy (e.g., Jin et al., 2004, 2009 and 2011; Wu et al. (2010); Jin and Najibi, 2014), while location services have become one of the fastest growing domains (e.g. Deng et al., 2014). Location information is a significant constituent of the big data required by space research, containing more than just the location. It plays an important role as supplement of GNSS in space information obtaining (e.g. Arun et al., 2016). According to the statistics, more than 80% of human activities occur in indoor environments. So, indoor location information is a crucial part of research studies and can create great value and improve efficiency in many applications, such as warehouse management, prisoner supervision and integration with other navigation information (e.g. Li et al., 2016). Moreover, UWB system can also extraordinarily contribute to the mission in large space station or the mission of landing other planets. However, satellite navigation systems, such as GPS and BeiDou (Jin et al., 2007, 2016

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and 2017), cannot work properly or provide users with satisfactory positioning services in those GPS-denied environments, such as underground parking, city canyons and outer space. In the search for a substitute for satellites signals, UWB technology has attracted considerable attention and become a hot topic in this area due to its properties of strong penetrability, high time resolution and perfect security. In recent years, a huge number of classic UWB positioning algorithms have been proposed, like the CHAN algorithm and Taylor expansion algorithm (e.g. Monica and Ferrari, 2015). Most of these algorithms available in literature seem to work in very controlled environments (e.g. Örner Çetin et al., 2012) and focus on two-dimensional positioning, although three-dimensional positioning may provide more useful information for indoor applications. But under NLOS conditions, these methods would be adversely impacted and loss in the positioning precision (e.g. Zampella et al., 2014). Thus, a more effective, stable and robust three-dimensional positioning method should be developed.

NLOS delay-time errors, which result from the blocking of direct paths and the influence of metal objects, have been considered one of culprits in location estimation failure (e.g. Deng et al., 2013). The investigation illustrates that a high positioning accuracy can be achieved (e.g. Jourdan et al., 2008) in ideal indoor environments where only LOS propagation exists or NLOS error between the mobile station (MS) and all BSs can be eliminated. However, in a real indoor environment in which the direct paths from MS and BSs are always blocked by walls, furniture, or many other appliances, the signal measurements usually include massive errors caused by excess reflection paths. Worse still, this kind of errors cannot be exactly modelled or eliminated, since they are varied in different environments. Therefore, the key is to find a method to identify NLOS measurements in all observations and to minimize the impact of NLOS errors as much as possible.

There are two main traditional approaches. The first one (e.g. Wann and Hsueh, 2008; Wu et al., 2007) is to derive a statistical model for the distribution of time of delay in a specific environment through a large amount of experimental data and utilize the statistical parameters of random variables to represent the real NLOS time of delay, which will be deducted from the measurements before location estimation. Although the positioning accuracy may be improved, the location error must still exist because this approach does not distinguish and identify LOS from all LOS-NLOS mixed measurements and even dispose them as the same method as NLOS, which instead decreases the precision of LOS measurements and has an adverse impact on location estimation. The other approach is to assign different weights to each measurement in accordance with its possibility of being NLOS. The Residual Weighting Algorithm (Rwgh) attempts to selectively remove NLOS-corrupted measurements by examining the residuals between estimated measurements and real observations (e.g. Chen, 1999). The estimated location of the MS is determined by using different groups of measurements, and the measurements number of which is greater than the minimum required for 3-dimensional positioning. The sum of all residuals of a specific BS, which is incorporated in every possible set of measurements to perform MS location estimation once, is a good indicator of how much certainty we have in the measurement generated from this BS: the higher the value is, the lower the weight we will assign to that measurement. Hence, we can rely on a group of good measurements and avoid the NLOS corrupted observations for localization. However, the complexity of Rwgh is rather high, which results in higher computational costs.

In general, both of these two approaches are negative, which ignore the characteristics of the signal itself and thus cannot eliminate NLOS time of delay error at the root. An NLOS detection method taking into account signal energy was proposed (e.g. Al-jazzar and Caffery, 2005). Based on this idea, some scholars proposed a more positive method that considered both a single signal arrival time and the received energy (e.g. Wu et al., 2008). The principle of this algorithm is to model energy loss by comparing signal energies of different paths. The NLOS error estimation can be formulated and further used to compensate the original range measurements using the energy-loss model. However, NLOS/LOS identification methods that rely on signal energy are proved to be susceptible to environmental noises, and the static positioning accuracy of these kinds of methods is low (e.g. Xiao et al., 2010). The state-of-the-art NLOS error detection and correction technique is proposed (e.g. Guvenc et al., 2007; Mucchi and Marcocci, 2007). Based on the multipath channel statistical parameter, the kurtosis, NLOS errors can be well modelled by log-normal random variables. Then, a joint likelihood ratio test is developed for LOS/NLOS detection. The technique can not only effectively distinguish NLOS from LOS and NLOS mixed conditions but also can evaluate the quality of different signal conditions. The only flaw of this method is its heavy dependency on signal channel characteristics, which makes it impracticable. Some researchers treat the location estimation problem as a geometric optimization procedure and consider the geometric constraints between measurements, which corrects the location estimate formed from the biased range measurement using a sequence of range constraints (e.g. Yu and Guo, 2008; Gifford et al., 2010). By using range observations, several positioning circles can be drawn, and the optimum MS estimate should be in the overlap of all circles. However, this method can be hardly expanded into three-dimensional space. In addition, without the statistical characteristics of NLOS errors, positioning error is proportional to the NLOS error.

After NLOS identification and correction, the preprocessed TDOA data can be used for location estimation. Currently, there are many three-dimensional positioning methods based on pseudo-distances in various applications, especially in the area of GNSS positioning. The basic positioning principles of UWB and GNSS are the same: the