BDS/GPS Multi-System Positioning based on Nonlinear Filter Algorithm

Jae Hyok Kong[1] and Xuchu Mao[2]

[1] Shanghai Jiao Tong University

Received: 12 December 2015 Accepted: 4 January 2016 Published: 15 January 2016

Abstract

The Global Navigation Satellite System can provide all-day three-dimensional position and speed information. Currently, only using the single navigation system cannot satisfy the requirements of the system's reliability and integrity. In order to improve the reliability and stability of the satellite navigation system, the positioning method by BDS and GPS navigation system is presented, the measurement model.and the state model are described. Furthermore, Unscented Kalman Filter (UKF) is employed in GPS and BDS conditions, and analysis of single system/multi-systems? positioning has been carried out respectively. The experimental results are compared with the estimation results, which are obtained by the iterative least square method and the extended Kalman filtering (EFK) method. It shows that the proposed method performed high-precise positioning. Especially when the number of satellites is not adequate enough, the proposed method can combine BDS and GPS systems to carry out a higher positioning precision.

Index terms— global navigation satellite system (GNSS), positioning algorithm, unscented kalman filter (UKF), beidou navigation system (BDS).

1 I. INTRODUCTION

ith the development of space information technology, some countries are constructing Global Navigation Satellite System (GNSS). Now, in addition to USA's GPS and Russia's GLONASS, the Europe's Galileo and China's Bei Dou navigation satellite System (BDS) are being built. Japan, India and other countries are also planning to build their own regional navigation satellite systems. Even though it is GPS that is the most developed navigation satellite system and it has many advantages, it also has some disadvantages of system reliability that cannot satisfy the requirements of a single navigation system in the certain situations [1]. Recently, the idea of multinavigation positioning that consists of GPS, GLONASS, Galileo and regional satellite positioning system is gradually getting more interest in the field of satellite navigation. Especially, the combination of GPS and BDS can overcome the deficiency of the single system, and shows better effects on system performance.

The most conventional positioning estimation methods are the iterative least square method (ILS), extended Kalman filter (EKF) and unscented Kalman filter (UKF), etc. ILS can solve three-dimensional positioning only when it receives the signals from at least four satellites. This method is simple, and its computing speed is fast, but it has a large linearization error and a low positioning estimation precision. The EKF can only be accurate for a first order Taylor series. There may be a larger nonlinear error, and it needs to compute the Jacobian matrix, in addition to the calculation being difficult and one of the main sources of error [2]. The UKF represents statistical properties of the system by deterministic sampling and avoids the disadvantage that the EKF must compute the Jacobian matrix. Theory shows that the EKF predicts the means correctly up to the second order of Taylor series and covariances up to fourth order. In contrast, the UKF predicts the means and covariances correctly up to the fourth order [3].

The positioning accuracy of the GNSS, especially the low-price GNSS receiver, cannot always be satisfied. This is because during the positioning process many errors, especially the measurement and satellite position errors, cannot be deleted. Traditional methods can hardly minimize their influence. Filtering algorithm provides an important method to reduce these errors and improve the GNSS positioning precision.

This paper proposes a BDS-GPS system model, using UKF to perform position estimation, and the experimental results illustrate the effectiveness of our proposed method.

Section?lists the general concept of the GNSS positioning. Section? summarizes the general used algorithm for GNSS receiver positioning and introduces the UKF algorithm which will be used in our proposed models for GNSS position estimation. Section? describes the unity of space coordinate system and time system of GPS and BDS. Section? addresses the developed nonlinear model and the filter implementation. Section? includes recent experimental results and provides the comparison of these results from GPS and BDS with ILS, EKF and UKF. Finally, Section? concludes the paper and describes the future developments.

2 II. GNSS Positioning Overview

GNSS is a worldwide, all-weather navigation systems able to provide tridimensional position, velocity, and time synchronization to UTC scale. GNSS considers the earth's center as the reference point, to determine the position of the receiver antenna in the reference coordinate system. Since the positioning operation requires only one receiver, it is called the standalone positioning. The basic principle of the standalone GNSS positioning is that taking the observed distance between GNSS satellite and the user receiver antenna as the benchmark, which is based on the known instantaneous satellites' coordinates, to determine the position of the corresponding user receiver antenna. According to the different positions of the user receiver antennas, GNSS positioning can be divided into dynamic positioning and static positioning.

GNSS positioning is based on the one-way ranging technique: the propagation time to transmit from satellite to user receiver is measured and multiplied by the signal propagation velocity to obtain satellite-touser range. The offset of the receiver clock relative to the system time scale should be estimated to position. The measured range between receiver and satellite is referred to as pseudorange, and can be represented as follows:i i u i R c t ? ? ? = + +**(1)**

where i ? is the i th satellite's pseudorange measurement, i R is the geometric distance receiversatellite, u c t ? is the receiver clock offset (scaled by speed of light c) and i ? contains the residual errors after satellite-based and atmospheric error corrections. Equation (1) holds for both single GNSS (i.e. BDS or GPS only) and u c t ? is referred to the time scale of the considered system. In multi-constellation case, a further unknown, representing the inter-system time offset, must be estimated.

3 III. GNSS Positioning Algorithm

a) Iterative Least Square Method ILS based position estimation is conventionally used by GNSS receiver because of its simplicity and rapidity. The algorithm is based on the pseudorange equation. Since the pseudorange equation contains four unknowns: 3-D coordinates and one clock bias, at least four satellites are received to take 3-D positioning. Since these equations are nonlinear, they need to be linearized using the first order Taylor series approximation. Then a least squares solution is used and the receiver position can be calculated out [4]. This algorithm is simple and easy to implement, but the position estimation accuracy is low and the stability is not strong. b) Unscented Kalman Filtering UKF algorithm is the minimum variance estimation based on UT (Unscented Transform). It was first proposed by Julier et al. [5] in 1995. In the UKF with the deterministic samplings, the state distribution is again approximated by Gaussian Random Variables (GRV), but it is now represented using a minimal set of carefully chosen points. Those points are propagated through the true nonlinear system. Besides the possibility of improvement in precision, the UKF is much easier to implement than EKF. Unlike EKF, the UKF do not require Jacobian evaluations or any partial derivative calculation. Some papers were proposed the new UKF algorithm [6], and used in GPS positioning [7,8,9].When no more than 4 satellites can be received, a precision of data processing can be obtained by considering UKF algorithm's small linearization error. Based on this fact, this paper proposes UKF as the position estimation algorithm for composing GNSS based navigation systems.

First, assume that state and measurement equations of the system are discrete time nonlinear systems:1 (,) ( ) t t t t t t x f x w z h x v + = ? ? = + ? (2)

where t

x is state vector, t z is measurement vector, and t w is zero-mean independent gaussian white noise of which the covariance matrix is Q . t v is zero-mean independent gaussian white noise of the measurement of which the covariance matrix is R.

4 Initialize with

5 [ ]

0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 ?= ?( )( ) ??[0 0] ?( )( ) (, ,) T a a T T a a a a a T x E x P E x x x x x E x x P E x x x x diag P Q R ? ? = ? ? ? ? ? ? = = ? ? ? ? = ? ? = ? ?**(3)**

Calculate the sigma point1 1 1 1 ?= ( ) a a a a t t t t x x L P ? ? ? ? ? ? ? ? ? ± + ? ?**(4)**

Calculate weight coefficient( ) ( ) 2 0 0 ( ) ( ) = ( ) = ( )**(1)**= =1/[2(L+)] i 1, , 2L m c m c i i W L W L W W ? ? ? ? ? ? ? + + + ? + = ?**(5)**

where2 = ( ) 0 1 2 L k L ? ? ? + ? ? ? ?

, in order to control the distribution of the sigma points; =2 ? , in order to introduce the high order information. Time update: Details about the UKF algorithm are described as follows:Year 2016

6 Global Journal of Computer Science and Technology

Volume XVI Issue I Version I ( )G \1 1 2 ( ) \1 , \1 0 2 ( ) \1 , \1 \1 , \1 \1 0 \1 1 2 ( ) \1 , \1 0 =f(,) ??[ ][ ] (,) ?x x w t t t t L m x t t i i t t i L c x x T t t i i t t t t i t t t t i x v t t t t L m t t i i t t i x W P W x x z h z W z ? ? ? ? ? ? ? ? ? ? ? ? ? = ? ? ? ? ? ? ? ? = ? ? ? ? ? ? = = = ? ? = = ? ? ?**(6)**

Measurement update equations: 2 ( ) , \1 \1 , \1 \1 0 2 ( ) , \1 \1 , \1 \1 0 1 \1 \1] 1 ?[ ][ ] ?[ ][ ] ??( ) t tK P K ? ? ? ? ? ? ? ? = ? ? ? ? ? ? ? = ? ? ? ? ? ? ? = ? ? = ? ? = = + ? = ? ? ?**(7)**

where,= v ; = ( ) ( ) ( ) T T a T T T a x T w T v T x x w ? ? ? ? ? ? ? ? ? ? ? ? ? .

a) The unity of the two coordinate systems

The definition of coordinate system of BDS's CGCS2000 is essentially equal to GPS's WGS84. Their reference ellipsoids are very similar, and there mainly exists an extremely small flat rate difference. Flat rate difference between two coordinate systems causes a deviation of 0.105mm in latitude and altitude, and the largest deviation of gravity is b) The unity of the two time systems Since BDS and GPS use atomic time, there is no leap second in both systems. The difference between the two systems is 1356 weeks in whole week and 14 seconds in second. The navigation message of BDS contains the synchronization parameters between BDS and GPS, but its implementation content in the message is unpublished. So we cannot directly realize the full synchronization between the two systems. Instead this problem, we simply add 14 seconds to BDT's time for the rough calculation, and add a variable to represent the different system's time deviation.

V. The Positioning of bds and gps using the ukf Nonlinear Kalman filter can be well applied in the GNSS positioning estimation, because of the characteristics of the Kalman filter in which the current state parameter is updated according to the observed value using the predictive value. The system model consists of the process model and the measurement model.

7 a) Process model

The state includes the receiver position and velocity coordinates in CGCS2000 ECEF coordinate system, and the receiver clock offset which is related to states and the clock drift caused by the Doppler deviation. It also includes the non-white error in each satellite channel. So the overall system state has 10 fundamental states plus one shaping state for each observable channel: is the non-white error in each satellite channel. Because the error in each satellite is independent, it can be modeled as a first-order Gaussian-Markov process.1 2 (, ,, , , , , , , , **, ,…,**

Since there is a deviation in the two systems' times, in order to eliminate positioning error caused by time deviation between BDS and GPS, a variable sys t c t ? should be added.

Considering the above state model, and a generic kinematics model for the receiver coordinates, we obtain the associated system model.1 t t t x F x C w + = ? + ?

The state transition matrix F is given by0 0 A F B ? ? = ? ? ? ?

where A is a 10 10 × time invariant matrix and B is a 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 1T T T A T ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? = ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? (, , ,) B diag ? ? ? = ?

t w is the system driving noise, which is given by 1 2 1 2 = , ,, , , , , , , , , **T t**0 0 D C E ? ? = ? ? ? ?

where, D is a 10 7 × time invariant matrix and E is a n n × diagonal matrix which are given respectively by The correspondent process noise covariance matrix t Q is given by **??** ,){ } 2 2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 XYZ t T t t t sys R ct Q Q Q E w w Q ? ? ? ? ? ? ? ? ? ? ? ? ? ? ? = = ? ? ? ? ? ? ? ? ? ?????? with 2 2 2 (, ,) XYZ X Y Z Q diag ? ? ? ? = ?? ???? ?? ?? ?? 2 2 2 1 2 (,ct c c cn Q diag ? ? ? = ?

where

8 {

} 11 12 21 22t t t Q Q Q E w w Q Q ? ? ? ? ? ? = = ? ? ? ? ? with 2 2 3 0 11 1 2 2 2 12 1 2 2 0 22 1 2 2 2 2 3 2 8 2 2 3 h Q T h T h T Q h T h T h Q T h h T T ? ? ? ? ? ? ? ? ? ? ? = + + = + = + +

where2 -1 2 = =100 2 +1 2 +1 ? ? ? ? ? ? ? ? = ?? 20 19 21 0 1 2 9.4 10 , 1.8 10 , 3.8 10 h h h ? ? ? ? ? ? = × = × = × b) Measurement model

The pseudoranges and Doppler shifts form the measurements set, the measurement equations of the BDS's pseudorange b ? and GPS's pseudorange g ? are as follows.2 2 2 ( ) ( ) ( ) b b it t it b it it b b b t it t it t it b it it r r c t v X X Y Y Z Z c t v ? ? ? ? ? ? = ? + + + = ? + ? + ? + + + 2 2 2 ( ) ( ) ( ) g g jt t jt g jt jt g g g t jt t jt t jt g jt jt r r c t v X X Y Y Z Z c t v ? ? ? ? ? ? = ? + + + = ? + ? + ? + + +

where, , ,t t t X Y Z are the receiver position coordinates, , , b b b it it it X Y Z are the i th BDS satellite's coordinates, , , g g g jt jt jt

X Y Z are the j th GPS satellite's coordinates, it ? is the non-white error in i th satellite channel, and it v is the measurement noise of i th channel.

Doppler shifts give information related to the receiver velocity. Doppler is also used in our formulation, modeling it as: X Y Z ? ? ? are velocity coordinate of i th satellite at time t . So, the system measurement t z for n satellites is given by: n are the number of measured BDS and GPS satellites.2 2 2**2 2 2** ( )( ) ( )( ) ( ) ( ) ( ) ( ) ( ) ( ) ( ) ( )t it t it t it t it it t it t it t it t it t it t t it t it t it X X X X Y Y Y Y D X X Y Y Z Z Z Z Z Z c t R X X Y Y Z Z ? ? ? ? + ? ? = ? + ? + ? ? ? + + + ? + ? + ? ? ? ? ? ? ? ? ?1 2 1 2 1 2 1 2 = , ,, , , , , , , , , **T b**

9 VI. EXPERIMENT AND ANALYSIS

In the experiment, a set of BDS/GPS data collected by the NovAtel OEM-615 receiver is used. The position estimation is performed using the matlab in the PC environment. The raw data are processed using three algorithms: ILS, EKF and UKF.

The position estimation errors (, ,)

x y z are shown in Figures 1-3.

10 Data

The number of visible satellites during the experiment is shown in figure 4. Since the observation environment was good in the outdoor with a clear view of the sky, the number of BDS satellites was stable at 10, GPS satellite numbers changed between 6 and 7. The current BDS satellites are distributed in geostationary orbit (GEO) and inclined geosyn-chronous satellite orbit (IGSO) over China. That's why the BDS satellite number that is received is stable at present stage. The correspondent root mean square errors(RMSE) are compared in table 1-3. It's not difficult to find whether BDS, GPS or BDS/GPS positioning, the result of the UKF has a higher accuracy than that of ILS and EKF. When the number of the visible satellites is large, this method cannot fully represent its superiority. We have eliminated some of the original data so as to simulate the condition of less visible satellites, the case when the numbers of BDS and GPS were in the 2-3 range. In a single system, where there are less than four visible satellites, the positioning cannot be obtained by the conventional method, but a multi-system positioning model is a good way to deal with this situation. The number of visible satellites after part of them have been removed is shown in figure **??**. BDS remained at three, but GPS changed in 2-3.

Figure **??** : The number of visible satellites after remove When the number of satellites is less than four, the single system cannot be calculated; the advantage of multi-system positioning can now be represented. As long as the sum of BDS and GPS satellites is not less than five, the multi-system can be calculated effectively.

In figure 7, we can see that the number of satellites is going down, ILS algorithm's positioning precision is getting worse, and the rapid change in the number of satellites causes unsatisfactory results. Kalman filtering overcomes these difficulties well. Reduction in the number of satellites does not have a significant impact on the positioning result. positioning system, we can adopt the multi-system positioning method. We can get the results by using the ILS algorithm, but the error is too large and it does not meet the requirements of practical application. The Kalman filtering algorithm of the multi-system can still maintain high precision, and it has a huge advantage.

11 VII. CONCLUSION

In this paper, the multi-system position estimation algorithm which uses the UKF algorithm was proposed, which was verified by the real BDS/GPS data. We improved new nonlinear positioning models for the two navigation systems. After analysing the characteristics of BDS and GPS, the unity of time and space of the two systems was considered. We selected the BDT as the time standard, and the CGCS2000 as the coordinate standard. The proposed models can well address the frequent change of the GNSS satellites. The experimental result shows that the performance of the algorithm is better than ILS and EKF algorithms. On the other hand, UKF and EKF algorithms reach higher stability than ILS algorithm. Thus the proposed method also can be used in multi-system position estimation under the bad positioning conditions. In a single system when there are less than four visible satellites, the positioning cannot be obtained by the conventional method.

However, using the proposed nonlinear positioning models, the high precision positioning can be solved as long as the sum of the satellites is no less than five in the dual system. In addition, the positioning accuracy is much higher than the result obtained by the iterative least square algorithm. Future work will include the implement of the other nonlinear filters with the proposed GNSS positioning models. [1] [2]

Figure 1:

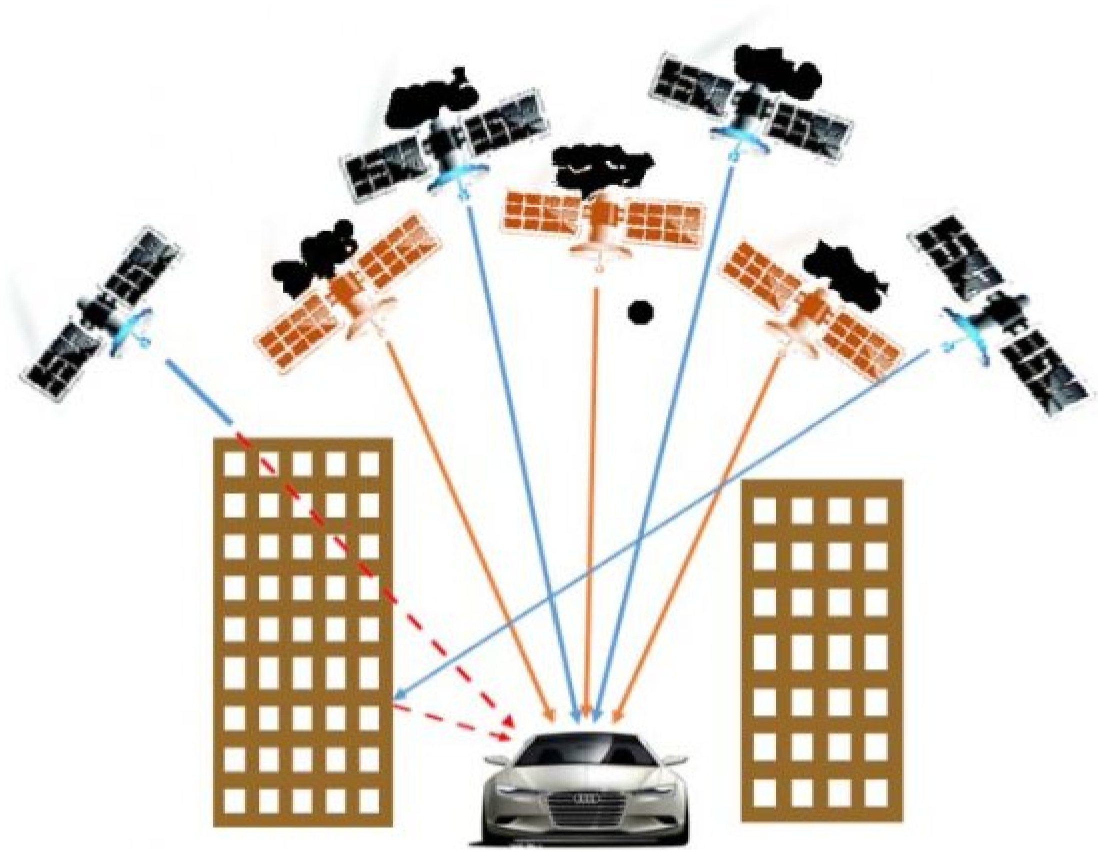

Figure 2:

t x = sys t X X Y Y Z Z c t c t c t t t t t t t t t ? ? ? ? ?

where, (, ,) t t t X Y Z is the receiver's position, (, ,) t t t X Y Z ? ? ? is the receiver velocity, , c t c t t t ? ? ? are the receiver clock offset and the clock drift bias, respectively, offset between the two systems, between the Doppler shift and pseudorange's rate, 1 (, ,...,) 2 t t nt ? ? ?

Figure 3:

1

	RMSE/m			
	X	Y	Z	3D
ILS	3.429	4.487	4.879	7.463
EKF	3.437	4.065	4.770	7.148
UKF	3.438	3.136	3.655	5.917

Figure 4: Table 1 :

2

	RMSE/m			
	X	Y	Z	3D
ILS	3.464	9.086	12.948	16.193
EKF	3.013	8.396	12.743	15.555
UKF 3.031		7.055	11.330	13.687

Table 3 : Position Estimation Error using BDS/GPS's data

	RMSE/m			
	X	Y	Z	3D
ILS	2.979	6.077	10.437	12.439
EKF	2.880	4.681	9.521	10.994
UKF	2.573	4.345	9.308	10.589

Figure 5: Table 2 :

4

	data after removal RMSE/m			
	X	Y	Z	3D
ILS	4.491	8.981	13.240	16.488
EKF	4.425	6.456	13.078	15.241
UKF	3.492	6.371	12.519	14.475

The correspondent root mean square errors of the various methods are compared in

Figure 6: Table 4 :

4

Figure 7: table 4 .

[Cooper and Durrant ()] ‘A Kalman filter Model for GPS navigation of Land Vehicles’. S Cooper , W Durrant . *IEEE Conference on Intelligent Robots and Systems (IR0S’94)*, (Munich, Germany) 1994.

[Julier and Uhlmann ()] ‘A New approach for filtering nonlinear system’. S Julier , J Uhlmann . *Proceeding of the American Control Conference*, (eeding of the American Control Conference) 1995. p. .

[Julier and Uhlmann ()] ‘A new extension of Kalman filter to nonlinear system’. S Julier , J Uhlmann . *The 11th International symp. on Aerospace/Defense Sensing, Simulation and Controls*, 1997. p. .

[Liu and Lu ()] ‘An Adaptive UKF Filtering Algorithm for GPS Position Estimation’. J Liu , M Lu . *WiCom ’09. 5th International Conference*, 2009. 2009. p. . (Wireless Communications, Networking and Mobile Computing)

[Psiaki ()] ‘Batch Algorithm for Global-Positioning-System Attitude Determination and Integer Ambiguity Resolution’. M L Psiaki . *Journal of Guidance, Control, and Dynamics* 2006. 29 (5) p. .

[Wei ()] ‘Chinese geodetic coordinate system 2000 and its comparison with WGS84’. Z Wei . *Journal of Geodesy and Geodynamics* 2008. 28 (5) p. .

[Hewitson and Wang ()] ‘GNSS receiver autonomous integrity monitoring (RAIM) performance analysis’. S Hewitson , J Wang . *GPS Solut* 2006. 10 (3) p. .

[Psiaki ()] ‘Kalman Filtering and Smoothing to Estimate Real-Valued States and Integer Constants’. Mark L Psiaki . *Journal of Guidance, Control, and Dynamics* 2000. 23 (5) p. .

[Perea and Elosegui ()] ‘New state update equation for the unscented Kalman filter’. L Perea , P Elosegui . *Journal of Guidance, Control, and Dynamics* 2008. 31 (5) p. .

[Mao et al. ()] ‘Nonlinear GPS Models for Position Estimate Using Low-cost Receiver’. X Mao , M Wada , H Hashimoto . *The IEEE 6th Intelligent Transportation System Conference*, (Shanghai, China) 2003. p. .

[Antonio et al. ()] ‘Performance assessment of aided Global Navigation Satellite System for land navigation’. A Antonio , G Salvatore , G Ciro . *IET Radar, Sonar and Navigation* 2013. 7 (6) p. .

[Kaplan ()] *Understanding GPS Principles and Applications*, E Kaplan . 2006. Boston: Artech House, Inc. (Second Edition)