BeiDou-GPS integrated dual-system with multi-satellites for positioning and navigating farm vehicles

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Abstract: In order to improve the positioning accuracy of self-propelled farm vehicles and to meet the requirements of precision agriculture on the accuracy of machines, a positioning method was proposed based on BeiDou satellite navigation system (BDS) and GPS dual systems with four satellites. The time base and reference coordinates system of BDS and GPS, as well as the transformation between them were discussed in this paper. Two kinds of mathematical models were proposed for the dual-system multi-satellite positioning and dual-system four-satellite positioning. The solution strategies of the proposed model were detailed, and an improved position calculation model of the dual system was developed with modified models. Experimental results demonstrated that the integrated system could enhance the number of visible satellites, expand the scale of the satellite constellation, increase the number of available satellites and improve the positioning accuracy. Besides, the positioning reliability and continuity were also greatly improved.

Keywords: precision agriculture, BDS, GPS, integrated positioning, positioning calculation

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1 Introduction

Satellite positioning system is a system that mainly provides positioning, navigation and timing services (PNT) for users. The reference coordinates system and time system are the basis of satellite positioning system to provide PNT services for users[1-3]. The reference coordinates system provides spatial scales for PNT, and the time system provides the time reference[4]. Different satellite positioning systems use different coordinates and time reference systems as its benchmark[5,6]. Since the number of satellites for each satellite positioning system is limited, and also that the positioning accuracy and the authority for each single system are restricted, the positioning system will face many difficulties if it works independently[7]. Firstly, the positioning accuracy is not high, and it would be easily influenced by constellation structure, geographical location and environmental factors. Secondly, there may exist blind spots because of the limited coverage of each system. Besides, the effective reliability cannot be guaranteed[8], e.g., if a positioning system shuts down suddenly in a particular international situation, it will exert serious impact on those clients using separate systems[9].

BeiDou satellite navigation system (BDS) completed the regional stage deployment on December 27, 2012, which could provide positioning, navigation, time and short message communication service for most parts of Asia Pacific[10,11]. Although the system has worked officially, the system has not been completely built, and the number of satellites is still relatively small. In order to solve the defects of low positioning precision and poor reliability when the BDS works individually, a

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positioning method of integrating BDS and GPS is proposed in this study. Based on the proposed integrated positioning method, satellite constellations of both systems can be used at the same time, which could increase the number of visible satellites, access better satellite geometric structure and reduce the geometric dilution of precision. Accordingly, it guarantees the reliability of positioning accuracy.

2 BDS/GPS Integrated Positioning

The positioning principles of BDS or GPS are basically the same as that of BDS/GPS integrated positioning system, which determine the position of the receiver by using the satellite navigation message propagation time to measure the distance[12-14]. The navigation message contains the information of the satellite, and the receiver can measure the signal propagation time according to the satellite transmission ranging code. The pseudo range between the satellite and the receiver is equal to the single's propagation time multiplied by the speed of light[15]. Therefore, using this pseudo range, the receiver could determine its position. The difference between integrated positioning and separate positioning systems is that the integrated positioning method could receive the navigation message from both systems. However, the coordinate and time reference systems of the two systems are not the same. In order to calculate its accurate position, the coordinate and time reference should be unified[16]. BDS broadcast ephemera employs 2000 Chinese geodetic coordinate which is refereed as CGC2000, and GPS uses WGS-84 coordinate system which are compatible to CGCS2000[17], since the F-value of Ellipsoid flattening of WGS-84 has only millimeter level differences compared to CGCS2000 on the equator. BDS uses BeiDou time (BDT) as the time reference[18], while GPS use GPST as the time reference. The time differences between the receiver clock and that of the two systems must be considered when the observation equation is established. Assuming that the coordinate of receiver is (x_u, y_u, z_u), and the offsets of receiver clock compared to GPS and BDS clock are t_{u1} and t_{u2}, in order to calculate the receiver's location we need five observation equations. The synchronization parameters between BDT and GPST broadcasted by the navigation message of BDS can be taken for mutual conversion[19,20]. It means that a clock offset is eliminated, which will reduce an observation equation for positioning the receiver. Based on the above conditions, the multistory positioning method could be used when the number of visible satellites is larger than or equal to 5 and four satellites positioning method could be used when the number of visible satellites is equal to 4.

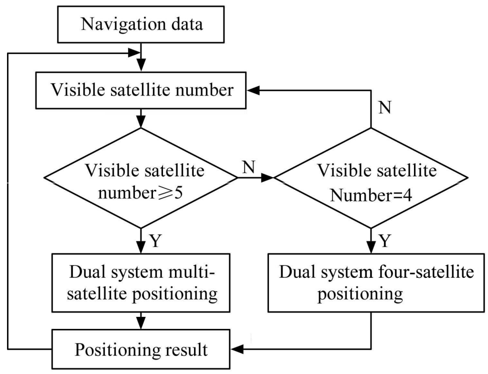

Figure 1 Structure diagram of BDS/GPS Integrated Positioning

3 Dual e-system integrated positioning

3.1 Dual-system of four satellites positioning

The dual system of four satellites positioning method could be used when available number of satellites of the two systems is 4. The following observation equation is set up by these two systems.

$$\begin{cases} p_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} + c \cdot t_{u1} \\ p_j = \sqrt{(x_j - x_u)^2 + (y_j - y_u)^2 + (z_j - z_u)^2} + c \cdot t_{u2} \end{cases} \quad (1)$$

where, p_i is the pseudo range from the receiver to the visible satellites of BDS, m; p_j is the pseudo range from the receiver to the visible satellites of GPS, m; i and j satisfy the relationship i+j=4. Through the observation equations we know that there are five unknown quantities: x_u, y_u, z_u, t_{u1}, t_{u2}, and it is also obvious that there is no definite solution for the four equations with five unknowns. There is a relationship between the system clock and receiver clock in the dual-system as follows.

$$\begin{cases} t_{BDS} = t_R - t_{u1} \\ t_{GPS} = t_R - t_{u2} \end{cases} \quad (2)$$

where, t_{GPS} represents the system time of GPS; t_{BDS} represents the system time of BDS; t_R represents the time of the receiver.

A_{0GPS} and A_{1GPS} are the time parameters of BDT and

GPST which are broadcast in the navigation message of BDS. A_{0GPS} represents the relative clock error of BDT and GPST, and A_{1GPS} represents the relative clock rate of BDT and GPST. The relationship between BDT and GPST is shown in Equation (3):

$$\begin{cases} t_{GPS} = t_{BDS} - t_{BDS-GPS} \\ t_{BDS-GPS} = A_{0GPS} + A_{1GPS} \cdot t_{BDS} \end{cases} \tag{3}$$

From Equations (2) and (3), we can get:

$$t_{BDS-GPS} = t_{u1} - t_{u2} = A_{0GPS} + A_{1GPS} \cdot t_E \tag{4}$$

where, t_E represents the current time of BDS which could be obtained from the navigation message, and the value of t_E is the second part of the period. $\Delta t_{BDS-GPS}$ is the system clock difference between BDS and GPS.

In conclusion, the observation equations of dual-system for satellites positioning can be obtained.

$$\begin{cases} \rho_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} + c \cdot t_{u1} \\ \rho_j = \sqrt{(x_j - x_u)^2 + (y_j - y_u)^2 + (z_j - z_u)^2} + c \cdot t_{u2} \\ t_{u1} - t_{u2} = t_{BDS-GPS} = A_{0GPS} + A_{1GPS} \cdot t_E \end{cases} \tag{5}$$

where, (x_i, y_i, z_i) represents the position of satellite i, and (x_j, y_j, z_j) represents the position of satellite j. ρ_i is the pseudo range between BDS and the receiver; ρ_j is the pseudo range between GPS and the receiver. i and j in the Equation (5) should satisfy the relationship $i+j=4$ in the dual-system of four satellites positioning. The position of receiver can be obtained by two steps: firstly, differentiate Equation (5), and then calculate the coordinate of the receiver by using the least squares method.

3.2 Dual-system of multi-satellite positioning

From the above analysis we can get that the CGCS2000 and WGS84 coordinates are compatible. Therefore, multi satellite positioning method can be employed to calculate the coordinate of the user, when the number of visible satellites receiver location is larger than or equal to 5.

$$\begin{cases} \rho_1 = \sqrt{(x_1 - x_u)^2 + (y_1 - y_u)^2 + (z_1 - z_u)^2} + c \cdot t_{u1} \\ \vdots \\ \rho_i = \sqrt{(x_i - x_u)^2 + (y_i - y_u)^2 + (z_i - z_u)^2} + c \cdot t_{u1} \\ \rho_{i+1} = \sqrt{(x_{i+1} - x_u)^2 + (y_{i+1} - y_u)^2 + (z_{i+1} - z_u)^2} + c \cdot t_{u2} \\ \vdots \\ \rho_n = \sqrt{(x_n - x_u)^2 + (\mathrm{y}_n - \mathrm{y}_u)^2 + (z_n - z_u)^2} + c \cdot t_{u2} \end{cases} \tag{6}$$

where, ρ_1-ρ_i represents the pseudo range between each satellites of GPS and the receiver; ρ_{i+1}-ρ_n represents the pseudo range between each satellites of BDS and the receiver; i represents the number of visible satellites, and n represents the total number of visible satellites of the two systems; (x_i, y_i, z_i) represents the coordinate of satellites; (x_u, y_u, z_u) represents the coordinate of the receiver; c represents light speed.

The equations are liberalized by linear iterative method; then the following equations could be obtained after differentiated.

$$\Delta\rho = \begin{bmatrix} \rho_1 \\ \vdots \\ \rho_i \\ \rho_{i+1} \\ \vdots \\ \rho_n \end{bmatrix}, H = \begin{bmatrix} e_{x1} & e_{y1} & e_{z1} & 1 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ e_{xi} & e_{yi} & e_{zi} & 1 & 0 \\ e_{x(i+1)} & e_{y(i+1)} & e_{z(i+1)} & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ e_{xn} & e_{yn} & e_{zn} & 0 & 1 \end{bmatrix},$$

$$\Delta x = \begin{bmatrix} \Delta x_u \\ \Delta y_u \\ \Delta z_u \\ -\Delta c t_{u1} \\ -\Delta c t_{u2} \end{bmatrix}$$

Using the linear iterative method and then differential to the equations, the Equation (6) can be transformed to the following equation. i.e. $\Delta\rho=H\cdot\Delta x$. $\Delta\rho_i$ represents the difference of the pseudo range and the approximate pseudo range between the visible satellite of i and the receiver in the equations. H is a $n\times5$ matrix which represents the direction cosine of visible satellites to receiver. $(\Delta x_u, \Delta y_u, \Delta z_u)$ represents the deviation of the receiver's real position and approximate position. Δt_{u1}, Δt_{u2} represents the increment of BDT and that of GPST at the current epoch respectively. (e_{xi}, e_{yi}, e_{zi}) represents the direction cosine of the approximate position of receiver and the unit vector of satellite i. The coordinates of the receiver can be calculated by solving the equation using the least square method. At last, the formula of Gauss projection can be used to convert the receiver's coordinate into latitude and longitude.

4 Improved model

4.1 Correction of satellite coordinates

The broadcast ephemeris of BDS and GPS are both using the geodetic coordinate system. Since the spread of satellite navigation message takes some time, the time that the receiver uses to calculate the position is the time when the navigation message is sent, rather than the time when the receiver receives the navigation message. As the earth rotates during the time that the navigation message broadcasts, the coordinate system is also changed. Hence the calculation result of the receiver's position is the position when the navigation message is sent, rather than the current location of the receiver. Consequently, when the receiver calculates its position, it is necessary to point the satellite coordinate at the moment t in the geodetic coordinate system. It takes τ seconds to transmit single from the satellite to receiver, and during this time the earth and the earth coordinate system rotating $\omega_E \cdot \tau$ around z axis, where ω_E represents the earth's rotation in the formula. Therefore, the position of satellite at time τ should be expressed in the earth centered earth fixed coordinate system at time t.

$$M = \begin{bmatrix} \cos\omega_E \cdot \tau & \sin\omega_E \cdot \tau & 0 \\ -\sin\omega_E \cdot \tau & \cos\omega_E \cdot \tau & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot M^S \tag{7}$$

It takes 70-90 ms for signal to transmit from satellite to receiver, and during this time the amount of rotation of the earth is about 7×10^{-6} rad, $\cos\omega_E \cdot \tau \approx 1$ and $\sin\omega_E \cdot \tau \approx \omega_E \cdot \tau$ can be used to simplify the formula. Although the rotation angle looks small, if ignored, it can cause 10-20 m calculation error and corresponding east-west direction position estimation error.

4.2 Weighted evaluation

In the positioning calculation process, since the parameter information that the receiver receives from different satellites are different, we must ensure the quality of each observation when treating the observation equations with least squares adjustment. The satellite elevation angle is the key factor to determine the quality of satellite signals; hence we can construct an weight matrix using the satellite elevation angle as reference to ensure the quality of satellite signals. The range of satellite elevation angle is 0°-90°, and the quality of the single reaches its best status when the satellite elevation angle is 90°. The cut-off elevation angle of BDS is 10°, while the cut-off elevation angle of GPS is 15°. Hence, we set the weight value as 0 when the satellite cut-off elevation angle is less than 15°. The weight is set according to satellite elevation angle as follow:

$$P_i = \begin{cases} 0 & \theta_i \le 15° \\ 2\sin\theta_i & 15° < \theta_i \le 30° \\ 1 & \theta_i > 30° \end{cases} \tag{8}$$

where, θ_i represents the satellite elevation angle, i represents the number of visible satellites. The weight matrix P is composed of the visible satellites:

$$P = diag(P_1, P_2, P_3, \cdots P_i) \tag{9}$$

where, P_i represents the weight value of satellite i. When the visible satellites are sufficient, using the elevation-dependent weighting model to calculate the receiver's position can effectively avoid the error that is caused by the satellite whose signal quality is not good. At the same time, the equation could be simplified by using the weighted method, the unnecessary redundancy calculation could be reduced, part of the system error can be eliminated, and the receiver position calculation time is reduced. In summary, the proposed method improves current methods significantly.

5 Experiments and data analysis

In order to test the feasibility of the proposed algorithm, we implemented the multi-constellation integrated position calculation using MATLAB. The experimental setting was as follows: data were collected from a building roof of the College of Information and Technology of Heilongjiang Bayi Agricultural University on March 9th, 2013, observation time is 24 h, time interval for acquiring data is 1 s. MATLAB was used for data calculation and analysis.

5.1 Number of visible satellites

The number of visible satellites is an important factor for the positioning accuracy of the receiver. For the proposed method, only when the number of the visible satellites is no less than five, and the number of equations is no less than the number of unknowns, then the receiver can complete the position calculation. And also, when the number of visible satellites is kind of large enough (e.g. ≥ 5), the receiver could select good observation satellites to calculate the position, reduce redundant information and make modification, which could improve the positioning accuracy.

By the end of 2012, there were five geostationary orbits (GEO) satellites, four Medium-Earth Orbits (MEO) satellites, and five Inclined Geo Synchronous Orbits (IGSO) satellites in the orbits of BeiDou system. As shown in Figure 2, within the 24 hours collecting data, there are 10 visible satellites of BeiDou system for most of the time, and the worst situation is that 8 satellites are visible. It means that the BeiDou system has been able to provide navigation and positioning services for users independently and stably. The number of visible satellites of negative positioning system equals the sum of that of BDS and GPS, which means that the integrated positioning system has a better satellite constellation geometric strength. In addition, even though some bad signals were removed, integrated positioning system has enough usable satellites. Integrated positioning system could enhance the stability of positioning, reduce unnecessary redundant calculations, and improve the positioning accuracy.

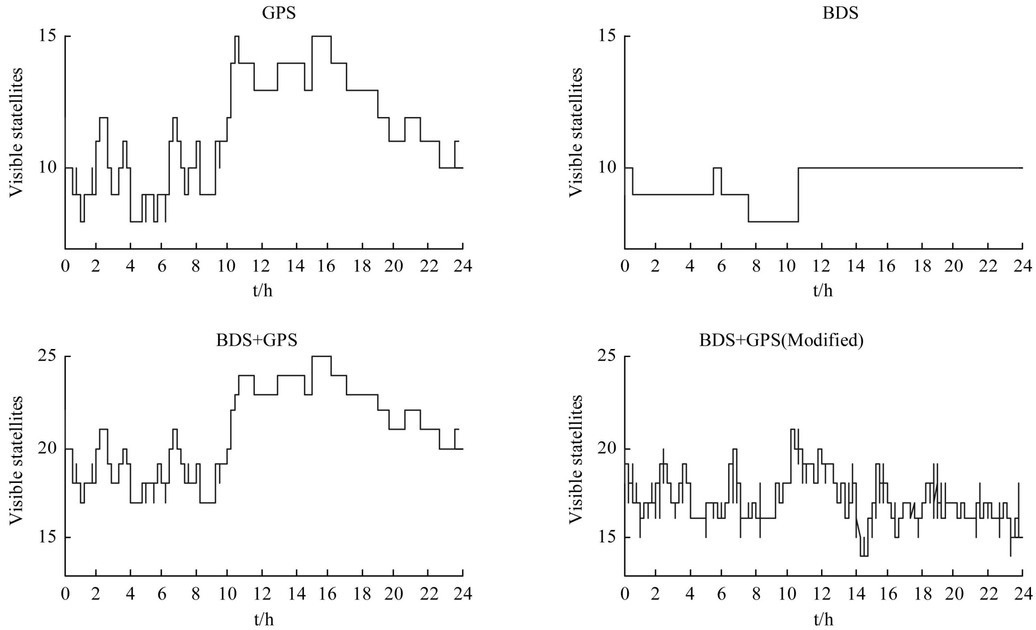

Figure 2 The number of satellites

5.2 Precision factor DOP

The value of DOP is an important factor for the geometric strength of the satellite constellation, which indicates the quality of the space geometry distributions of users and satellites. The value of DOP is smaller, then the geometric strength of the satellite constellation is stronger, and there is higher positioning accuracy. Factors that influence the positioning accuracy include positional dilution of precision (PDOP), horizontal dilution of precision (HDOP), and vertical dilution of precision (VDOP). Figure 3 plots the PDOP value of independent system and integrated system respectively.

As shown in Figure 3, the positioning accuracy of GPS is higher than that of BDS, and the accuracy of integrated positioning system is higher than the two independent systems, which demonstrates that integrated positioning can improve the positioning accuracy.

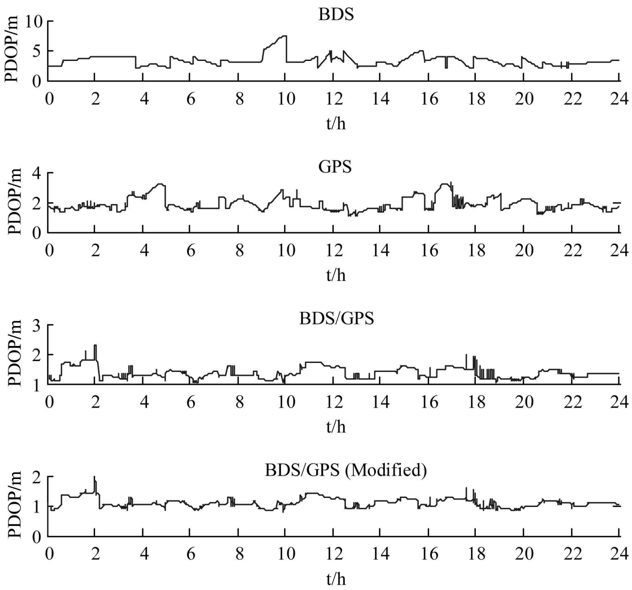

Figure 3 Position accuracy (PDOP)

Table 1 shows the statistics of the average value, the mean square deviation and the maximum deviation of PDOP, HDOP and VDOP of independent systems and integrated system. By comparison it can be concluded that, the result of BDS and GPS multi-constellation guidance positioning system is much better than that of independent systems, which means that the multi-constellation positioning system can provide a more accurate and stable positioning result.

Table 1 Statistics of different positioning accuracy factor

Positioning mode	PDOP			HDOP			VDOP		
	Average/m	RMSE	Maximum deviation/m	Average/m	RMSE	Maximum deviation/m	Average/m	RMSE	Maximum deviation/m
BDS	3.2287	0.8681	7.3	2.0175	0.6993	3.624	2.714	0.768	5.363
GPS	1.8355	0.4477	3.302	0.9114	0.1997	1.823	1.5144	0.4085	2.815
BDS+GPS	1.3504	0.1848	2.272	0.7518	0.0962	1.236	1.1254	0.1729	1.995
BDS+GPS (Modified)	1.1438	0.1672	2.0825	0.7205	0.0847	1.079	1.0519	0.1537	1.785

6 Conclusions

This paper discusses the principle and algorithm of the BDS/GPS navigation system in detail, and provides the BDS/GPS dual-system four-satellite localization method, which solves the problem of failing to locate the position temporarily caused by the shielded satellite signal for regions with complex geography situation. The measured data were processed using MATLAB. It is concluded that the number of visible satellites in dual-system has been maintained at more than 15. Using the method of integrated positioning generated three indicators, named PDOP, HDOP and VDOP, and the average positioning accuracy of these three indicators are respectively 1.3504 m, 0.7518 m and 1.1254 m, which are better than the positioning accuracy of the independent system. Unified time reference and coordinate system of BDS and GPS constellation can effectively reduce the positioning blind spots and increases the available number of satellites. Through the improved positioning model, the geometric configurations of available satellite constellation are improved, and the receiver positioning accuracy is raised and the reliability of the location system is enhanced. The BDS and GPS integrated positioning method for position calculation could reduce the dependence on a separate system of GPS. Integrated positioning and navigation system has wide application prospect in the development of precision agriculture.

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