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Development of Comprehensive PNT and Resilient PNT

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Abstract: Any single Positioning, Navigation and Timing (PNT) technology has its vulnerability and limits, even the powerful Global Navigation Satellite System (GNSS) is no exception. To provide continuous and reliable PNT information to users, the theory and technique of comprehensive PNT information system and resilient PNT application system have attracted great attention from Chinese scholars. We try to summarize the progress and development of the synthetic PNT system, including the proposal, the modification and the improvement of the comprehensive PNT, as well as the follow-up resilient PNT. The frame of China's comprehensive PNT system consisted of comprehensive PNT infrastructure and comprehensive PNT application system is initially described; the achievements on some main PNT technologies are introduced; the conceptual models of resilient PNT are given; besides, existing researches on resilient function models and stochastic models are summarized according to different user scenarios.

Key words: GNSS; comprehensive PNT; resilient PNT; resilient function model; resilient stochastic model

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1 Introduction

Satellite navigation systems have advantages in high precision, global coverage and real-time service, making it the most widely used Positioning, Navigation and Timing (PNT) technology in the world. However, Global Navigation Satellite System (GNSS) signals are vulnerable to low landing power and poor penetrating, which cannot serve non-exposed spaces or easy to be inferred. With the explosion of the weaknesses of GNSS, it is realized that only relying on GNSS or any single PNT technology may bring potential risks, and a new PNT system needs to be built to guarantee the safety of core PNT users[1]. Published in Nov. 2022, "China's Beidou Navigation Satellite System in the New Era" by the State Council Information Office of the People's Republic of China says that a more extensive, more integrated, and more intelligent comprehensive spatiotemporal system with BDS as the core is going to be created in the coming years[2].

In 2016, the concept of a comprehensive PNT system was proposed, namely a PNT information source frame covering from deep space to deep sea providing seamless PNT information for users in any environment[3]. Correspondingly, the thinking of micro-PNT terminal system and resilient PNT application system were proposed for the resilient application of multiple PNT information[4-5]. Since then, the key technologies in the construction of comprehensive PNT information sources and study on resilient PNT methods and algorithms have became a research highlight in China. With deeper study, an intelligent PNT concept was proposed as a more advanced PNT application mode catering to the requirements of the intelligent society[6-7]. Then, a secure PNT system is formed with comprehensive PNT information sources, resilient

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PNT application mode and intelligent PNT service mode[1]. And also, organized by the Chinese Science Academy associated with the national nature financial community, the Chinese Positioning, Navigation and Timing 2035 Development Strategy was published in May 2023, proposing the leading key technologies in PNT for the coming 10 to 15 years[8].

In the following sections, the frame of comprehensive PNT system consisted of comprehensive PNT infrastructures and comprehensive PNT application system is presented; then, the significant achievements are introduced on the aspects of navigation satellite constellation at Lagrange points, Beidou Global Navigation System (BDS-3), Low Earth Orbit (LEO) Satellite Augmentation System, and various ground-based PNT systems; the resilient PNT concept and its key elements are described, and the study progress on resilient methods and algorithms in underwater scenarios, indoor scenarios and urban scenarios is presented; besides, the future development is comprehensive PNT and resilient PNT is described.

2 Comprehensive PNT System

The concept of comprehensive PNT system describes a PNT information source system without distinguishing the comprehensive PNT infrastructure and the comprehensive application system in the initial description[3-4]. Through a series of discussions, it is realized that the comprehensive PNT system should be divided into comprehensive PNT infrastructure system and comprehensive PNT application system (as shown in Fig.1)[1]. Comprehensive PNT infrastructure system contains all the large artificial PNT information sources covering from deep space to deep sea, and the comprehensive PNT application system is various PNT terminal sensors receiving artificial and natural PNT signals or self-sensing the state of motion of the carriers.

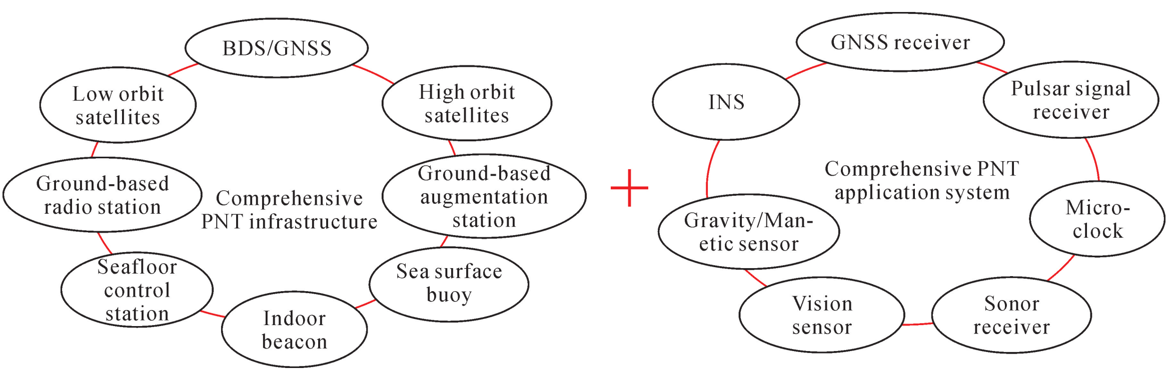

Fig.1 Comprehensive PNT system

As an important part of the national comprehensive PNT system, the comprehensive PNT infrastructure system is a seamless PNT main information source frame which should be designed and constructed based on different PNT information sources. In the exposed space from deep space to the ground, the artificial PNT information source frame includes navigation satellite constellation at Lagrange points connecting the PNT service from ground to deep space; the existing or improved Beidou navigation satellites at high and medium earth orbits, serving for the exposed ground users, ships and low orbit vehicles; the low orbit navigation satellite constellation, augmenting the Beidou navigation system; the ground-based radio stations such as the ground-based radio navigation stations "Changhe", ground-based augmentation stations of BDS/GNSS and mobile base stations, augmenting or compensating satellite navigation systems. In non-exposure spaces, beacons such as WiFi, infrared and radio frequency and Ultra Wide Band are also important PNT information sources. In underwater environments, sea surface buoys and seafloor beacons are all main PNT infrastructures providing PNT information and transmitting time-space data.

Also, the integrated PNT sensors like INS and micro-clock, as well as the natural PNT information sources like matching information (magnetism, gravity and image) and pulsar signals, could be applied as compensation methods in many scenarios. Besides, Scene-Based Augmentation Systems (SceneBAS) for comprehensive PNT should also be included in the comprehensive PNT application system, for example, the geo-graphic scene in three dimensions could be important PNT augmentation information[9].

2.1 Navigation satellite at Lagrange points

The navigation satellite constellation at Lagrange points of the Sun-Earth and the Earth-Moon system is still under demonstration. A feasible thinking on navigation satellite at Lagrange points is making it not only the navigation method for cisluar spaces, but also the navigation relay station from the surface of the earth to deep space. The navigation signal should follow the same structure as Beidou/GNSS signals to realize the compatibility and interoperability with Beidou/GNSS. Besides, the satellites should carry upward and downward antennas directing to the deep space and the earth respectively. The upward antenna is to broadcast navigation signals for deep space users, and the downward antenna is to receive the signal of GNSS to realize the transferring of the space and time datum[1].

2.2 Satellite navigation technology

BDS-3 was accomplished in Jun. 2020, and officially opened service in Jul. 2022. series of creative designs are used such as the hybrid constellation, the whole constellation inter-satellite links, and Asymmetric Constant Envelope-Binary offset Carrier (ACE-BoC) signal modulation mode[10-11]. These creative designs strongly support not only the PNT performance but also six featured services namely Regional Short Message Communication Service (RSMCS), Precise Point Positioning Service via B2b (PPP-B2b) signal, Global Short Message Communication Service (GSMCS), Medium-altitude Earth Orbit Search & Rescue Service (MEOSAR) and Satellite Based Augmentation Service (SBAS).

The performance of BDS-3 is evaluated and assessed by academies and organizations[12-14]. The international GNSS monitoring and assessment (iGMAS) evaluated the performances of BDS-3 signal and the basic PNT service in 2022, and the results showed that each item could fill the requirement of the design index (as shown in Tab. 1). The SBAS service could broadcast GPS/BDS single- and dual-frequency augmentation information through BDS GEO satellites achieving APV-I and the CAT-I precision. The PPP-B2b performance for real-time positioning is about 0.1~0.2 m which is at the same level of PPP with IGS real-time products, and the convergence time is about 20~30 min[12,15-16].

Tab.1 Performance of BDS-3 signal and system service

Signal accuracy	SISRE/m			Orbit/m		Clock/ns			BDGIM/m	
	B1I /B3I			IGSO	MEO	IGSO		MEO	Day	Night
	1.13			1.81	1.24	2.13		1.78	0.89	0.59
System performance	Positioning/m								Timing /ns	PDOP availability
	B1I		B3I		B1C		B2a			
	H	V	H	V	H	V	H	V		
	3.50	5.45	4.66	7.04	2.99	4.22	4.06	7.28	13.01	100%

On the aspect of further development, demonstrations are made on the inter-satellite links and the IGSOs to improve the service performance[1,11]. A space-based autonomous time keeping method was proposed using a Hydrogen maser as the reference clock, and the predicted clock bias is 0.1 ns in 1 h[17]. IGSOs are suggested to increase the inclination angle to support PNT service in polar region, and involve in RSMCS, BDSBAS and PPP-B2b to overcome "South Wall" effect[11].

2.3 Low Earth Orbit (LEO) satellite augmentation system

Low Earth Orbit (LEO) satellite augmented space-based PNT is a research highlight in recent years and progress has been made on both technology development and LEO constellation construction. With stronger received signal power and better special geometry, LEO constellation becomes a key component of comprehensive PNT system[18]. China now has many commercial LEO navigation augmentation constellation projects, such as "Hongyan" constellation, "Hongyun" constellation, and "Centispace"[19]. In Oct. 2022, the Beijing Future Navigation Technology Co., Ltd. launched the S5 and S6 satellites of "Centispace" for the demonstration of the LEO navigation augmentation system (see in http://www.beidou.gov.cn/yw/xwzx/202210/t20221026_24755.html). The whole constellation is planned to be hundreds of satellites and will help to realize rapid kinematic positioning and navigation at the centimeter level. The system is designed to be highly compatible with BDS and users may directly use it through software updates.

The related key technologies on LEO augmentation system have been researched, such as constellation design, broadcast ephemeris design, the combined orbit determination of LEO and GNSS satellites andrapid PPP augmented with LEO, etc.[18,20-22]. A confirmed conclusion is that the PPP accuracy and convergence time could be significantly improved by LEO constellation[19,23-24].

2.4 Ground-based augmentation system

As an important support of BDS, the network ground stations of ground-based augmentation systems have been built across China, with the guidance of the government and efforts from central enterprise and related departments[2]. Until 2020, over 25 000 stations were built or under construction with over 10 000 000 high precision receivers, chips and cards[25]. Also, a series of National Standards were published on the technologies of station construction, communication network, data processing center, broadcasting interface, etc. The system could provide real-time meter-level, decimeter-level, centimeter-level, and post processing millimeter-level positioning augmentation service, which has been applied in many fields such as transportation and electric power industry[26-27].

2.5 Land-based radio navigation system

Land-based radio navigation system at very-low frequency is planned to be updated with the re-awareness of its advantages on better anti-inference. Chinese "Changhe 2" system is still in operation with 6 navigation stations, 3 monitoring stations and 1 control center. The system can serve the South China Sea, East China Sea and North China Sea. More navigation stations are going to be built to expand the coverage of the system, and improve the service accuracy, continuity and integrity through the improvement of signal structure, etc[28-29].

2.6 Ground-based communication base stations

Recently, ground-based communication base stations have been engaged in PNT service. With more than 4.8 million communication base stations and 500 thousand 5G stations, China has the largest 5G network and user group in the world. The positioning pattern integrated with 5G and BDS is developed rapidly and the largest high-precision positioning system based on it is published by China Mobile in Oct. 2020. The system is able to provide sub-meter, centimeter, and millimeter level positioning service through 5G network which has good application prospects in areas like vehicle management, autonomous driving and vehicle-road cooperation[30].

2.7 Seafloor and underwater beacon positioning system

The start of Chinese seafloor PNT infrastructure construction is relatively late and facing many difficulties not only in device development but also the positioning theory and methods. With the support of "Maritime Power Policy", some progress has been made in both device development and seafloor geodetic network establishment[31]. Following the criteria of long-term working ability, and better pressure-resistant, anti-corrosive, anti-dragging and anti-flow, the seafloor geodetic station shelter in deep sea is developed with an overflow structure and a stable foundation bed; the shallow-sea shelter is developed with an overflow-type anti-dragging structure and a penetrating design[32-33]. The seafloor geodetic network is realized by extending and densifying the basic configuration with one master station located in the center of a square, and four auxiliary stations distributed on the four vertexes of the square. Successfully verified the performance of geodetic station devices in shallow sea, long-term seafloor geodetic stations were initially established in the deep-sea area of 3000 m in 2019. The internal positioning accuracy of the seafloor station turned out to be better than 0.05 m, and the navigation accuracy within the geodetic network coverage of 10 km with acoustic/INS/gravity is better than 10 m[32].

3 Resilient PNT Technology

With so many PNT information sources provided by comprehensive PNT infrastructure and nature PNT information, the coming problem for PNT users is how to use multiple information optimally according to the scenario and requirements of the users. The resilient PNT concept was then proposed to provide a PNT application pattern with full use of available information in comprehensive PNT to generate continuous, robust and reliable PNT results[5]. Following up, the connotation and characteristic of resilient PNT is discussed[33-34].

On the aspect of sensor integration, the PNT terminal should resiliently integrate available PNT sensors based on the optimal, available, compatible and interoperable principles; on the aspect of model building, resilient algorithms should be applied to adjust and optimize the basic functional model and stochastic model making them more suitable for the scenario[5].

Resilient model modification should take both functional model and stochastic model into account[5]. The common expression of resilient observation model at time t_k can be given as[5]

$$L_i(t_k)=A_i\hat{X}(t_k)+F_i(\Delta_{t_{k-m},t_{k-m}})+e_i \qquad (1)$$

where, $\hat{X}(t_k)$ is the estimating parameter vector at time t_k; L_i is the observation measured by sensor i; A_i and e_i are the corresponding design matrix and observation random error vector; and $F_i(\Delta_{t_{k-m},\, t_{k-m}})$ is the modification function related with observation error series $\Delta_{t_{k-m},\, t_{k-m}}$ from time t_{k-m} to t_k. If the Extended Kalman Filtering (EKF) algorithm is used, resilient dynamic function model is also needed, whose common expression at time t_k can be given as[5]

$$\bar{X}(t_k)=\Phi_{k,k-1}\hat{X}(t_{k-1})+G_i(\Delta_{\bar{X}t_{k-m},t_{k-m}})+W_i \qquad (2)$$

where, $\bar{X}(t_k)$ is the prediction parameter vector at t_k, $G_i(\Delta_{\bar{X}t_{k-m},\, t_{k-m}})$ is the modification function related with dynamic model error series $\Delta_{t_{k-m},\, t_{k-m}}$ from time t_{k-m} to t_k; and W_i is the processing noise matrix.

Resilient stochastic model is to adjust the stochastic model of observation information and dynamic information according to their uncertainty in parameter estimation. Existing variance component estimation, robust estimation and adaptive estimation are typical resilient stochastic models[35-37], and the common expression for EKF can be used as

$$\hat{X}_k=(\bar{P}_{\bar{X}_k}+A_1^{\mathrm{T}}\bar{P}_1A_1+\cdots+A_r^{\mathrm{T}}\bar{P}_rA_r)^{-1}(\bar{P}_{\bar{X}_k}\bar{X}_k+A_1^{\mathrm{T}}\bar{P}_1L_1+\cdots+A_r^{\mathrm{T}}\bar{P}_rL_r) \qquad (3)$$

where, $\bar{P}_{\bar{X}_k}$ and $\bar{P}_j$ are the adjusted weight matrix of predicted vector and observation vector L_i.

Absolutely, resilient PNT is the development trend of PNT application, and relevant researches have already started based on different application scenarios.

3.1 Resilient PNT application in underwater scenarios

In underwater scenarios, resilient PNT researches are conducted under the PNT information frame mainly consisted of acoustic positioning and INS, and compensated with gravity/magnetic matching, digital compass, digital pressure sensor, etc. To decrease acoustic observation error, a series of resilient methods are employed. The observation mode of circle tracing line aided with cross tracing lines is applied to weaken the influence of some systematic errors[32,38]; the periodic error terms, piece-wise polynomial terms, and random walk terms are added to the observational model for compensating the systematic errors[39-41]. Also, a resilient stochastic model has been built based on robust estimation to control the effect of outliers through decreasing the weight of outlying observations[42]. Experiments are conducted in South China Sea, and the positioning results of deep seafloor datum points show that the Root Mean Square (RMS) of the slant range residuals can be better than a dozen centimeters, and the accuracy of station coordinates in three-dimension can be 0.4 cm with internal coincidence[32].

3.2 Resilient PNT application in urban scenarios

In urban areas, GNSS signals are easy to be sheltered by buildings and interfered by other signals. The cellular net and ground-based navigation stations can be the backup of GNSS, and ground-based GNSS augmentation system, pseudo-satellites and magnetic/image matching can be the compensation. In urban environments, multipath and Non-Line-Of-Sight (NLOS) signals are one of the main errors affecting the final PNT results. To increase the signal reception classification and control the effect of NLOS and multipath on final results, some machine learning methods are applied. Based on the predicted multipath value, adaptive filtering is applied to adjust the weight of the multipath signals[43]. The dynamic update model of the observation weight based on the observation apriori trust and Bayesian maximum likelihood posterior estimation is formed[44]. An INS error compensation model is established based on Gradient Boosting and Decision Tree[45]. On the aspect of multi-source data fusion, a GNSS/INS-integrated system is formed enabling to calibrate INS autonomously based on a robust motion mode self-recognition technique[46]; a GNSS/INS/Odometer-integrated system is formed enabling the real-time calibration and compensation of odometer error based on environment information[47-48].

3.3 Resilient PNT application in indoor/underground scenarios

Indoor and underground PNT systems are mainly relayed on radio frequency positioning technologies such as WiFi, Bluetooth, Ultra Wide Band (UWB) and compensated with autonomous positioning methods such as INS, pseudo-satellites, cellular and magnetic matching. Robust estimation and robust Bayesian estimation are used to control the effect of observation outliers, and covariance component estimation is applied to adjust the contribution of different observations[49-50]. Rich achievements are made in the resilient fusion of radio PNT information like WiFi, Bluetooth, UWB, and pseudolites, and the resilient integration of autonomous navigation method like INS, gravity/magnetic matching[51-52].

4 Development Trends for the Future

For future developments, more efforts should be put into both the construction of comprehensive PNT infrastructure and the study of resilient PNT application mode to form a more consistent, secure and reliable spatiotemporal service system. On the aspects of comprehensive PNT infrastructure construction, the scheme of navigation satellite constellation at Lagrange points needs deeper demonstration; the new generation of BeiDou satellites should be developed with better constellation configuration, more flexible signal modulation mode, and more powerful features; the LEO augmentation constellation should be well planned considering the compatibility with BDS; various land-based PNT stations should be further improved to better augment BDS; underwater PNT has lots of technologies to be solved which is the still relatively backwardness in comprehensive PNT. On the aspects of resilient PNT, more resilient models and algorithms should be built for more complex PNT scenarios, and intelligent methods should be involved to stimulate PNT application mode convert to intelligent PNT.

5 Conclusion

Comprehensive PNT is to provide seamless and redundant information, and resilient PNT is touse the information to provide optimal multi-source PNT application strategies. For users in complex environments with secure PNT requirements, the collaborative utilization of the comprehensive PNT system and the resilient PNT system are of great significance for continuous, robust and reliable PNT services. Chinese scholars pay highly attention to comprehensive PNT infrastructure design and resilient PNT application research, progress and achievements have been made on the construction of comprehensive infrastructures, as well as the theoretical and experimental study of resilient PNT methods.

(1) Comprehensive PNT infrastructure is the prerequisite for resilient PNT applications, and resilient PNT provides important support for comprehensive PNT. Without comprehensive PNT, resilient

PNT is impossible to realize; without resilient PNT, comprehensive PNT is nothing but individual PNT information.

(2) The development schedule of the comprehensive PNT system in different areas is unbalanced, with advancing in satellite-based PNT technology, and relatively falling behind in that of deep space and deep sea.

(3) Initiated by Chinese scholars, the resilient PNT system design and resilient model establishment have become research focuses in the PNT field. Although some achievements have been made, the realization and application of a relatively complete resilient PNT system are still on the way. Also, resilient PNT should be improved to intelligent PNT gradually which is an inevitable trend of the future secure PNT system.

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