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User Requirement Analysis of Resilient PNT System

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Abstract: Firstly, this paper provided a brief introduction to the concepts of Positioning, Navigation and Timing (PNT) and Resilient, and proposed that the fundamental premise for building a resilient PNT system is to identify the diverse needs of users in terms of accuracy, availability, continuity, and other indicators across different typical scenarios. Subsequently, it analyzed user requirements for various scenarios, including aviation routes, maritime navigation, agricultural surveying, train control, vehicle navigation, and emergency response, in different environments such as near-earth, urban, jungle, indoor, and underwater environments. The analysis took into account factors such as the accuracy, availability, continuity, integrity, terminal cost, and form of PNT. Based on this analysis, this paper summarized the user requirements for resilient PNT systems in different scenarios, presenting a comprehensive table of typical user requirements. Furthermore, it suggested that resilient PNT terminals should be cost-effective, compact, low-power, and highly compatible. Finally, the diverse user requirements were summarized and analyzed, providing a research foundation for developing resilient PNT solutions for different typical scenarios, such as near-earth, urban, jungle, indoor, and underwater environments.

1. Introduction

Since the Global Navigation Satellite System (GNSS) provides services, it has been widely used in transportation, agriculture, forestry and fisheries, communication timing, power dispatch, public safety, and other fields [1]. GNSS has provided support for many important infrastructure projects that are closely related to national economy and people's livelihoods, resulting in significant economic and social benefits.

At the same time, GNSS is extremely vulnerable and susceptible to various malicious and unintentional interferences, including blanket jamming, deception jamming, multipath interference, and pulse interference [2]. Therefore, how to improve the resilience and rapid recovery capabilities of PNT services under interference and emergency situations has become a global focus and research hotspot [3].

This paper mainly focuses on user requirements for typical scenarios such as near-earth, urban, indoor, underground, and underwater environments. Based on performance indicators such as accuracy, continuity, availability, and integrity of PNT, as well as factors such as terminal cost, size, power, weight, the most common user requirements are summarized and analyzed. The results can provide a research foundation for developing resilient PNT solutions for typical scenarios.

2. PNT Concept

The GNSS is susceptible to jamming and spoofing [4], and ground-based and satellite-based radio navigation positioning signals are also vulnerable to interference. Furthermore, the penetration performance of all radio signals is poor, making navigation and positioning impossible in underground, underwater, and other obstructed areas. As a result, the integration and fusion of multi-source PNT information sources will become the main direction of future PNT service development, namely the comprehensive PNT service system. Yang Yuanxi, academician of the Chinese Academy of Sciences, defines the national comprehensive PNT system as a PNT service information that is generated based on multiple PNT information sources with different principles, highly integrated by multi-sensor and multi-source data fusion under cloud platform control, and unified in time and space benchmarks, while possessing anti-interference, anti-spoofing, robust, available, continuous, and reliable characteristics [5].

With the construction of the future comprehensive PNT system and breakthroughs in PNT core technologies, the resilient integration of multi-source PNT components, the resilient adjustment of multi-source PNT function models, and the resilient optimization of random models, namely the construction of the resilient PNT service system, will become a research hotspot [6]. Academician Yang Yuanxi defines the resilient PNT system as a PNT information system that is based on comprehensive PNT information, optimized and integrated by multi-source PNT sensors, and generated by means of resilient adjustment of function models and resilient optimization of random models, which is fused to generate PNT information that is adaptable to various complex environments, with high availability, continuity, and reliability [7]. The "Resilient PNT" (RPNT) proposed by Chinese scholars includes the resilient integration of information source, resilient optimization of function models, resilient adjustment of random models, and the resilient fusion methods of multi-source data. Among them, resilient integration is similar to the resilient PNT proposed by the United States, while resilient function models, resilient random models and resilient data fusion are unique to Chinese scholars.

To ensure the security, reliability, and robustness of the PNT system, it is not advisable to heavily rely on the current GNSS as the sole satellite-based PNT information source [8]. Instead, multiple PNT technologies that are mutually interconnected and effectively complementary should be developed on the basis of strengthening the robustness of satellite navigation systems, forming a PNT system with sufficient resilience [9]. The most fundamental prerequisite for constructing a resilient PNT system is to identify the requirements of users in different typical scenarios for indicators such as accuracy, availability, and continuity.

3. User Requirement Analysis

Firstly, the typical business scenarios in different spatial environments were selected for analysis, such as near-earth, sea/ground, urban, jungle/canyon, indoor/underground, and underwater environments. For example, aviation routes and marine navigation were selected for near-earth scenarios, waterborne ship navigation, agricultural surveying, and earthquake monitoring were selected for sea/ground scenarios, railway transportation, vehicle navigation, and safety emergency were selected for urban scenarios, wilderness exploration and forest rescue were selected for jungle/canyon scenarios, shopping malls and underground parking were selected for indoor/underground scenarios, and marine surveying and geological surveying were selected for underwater scenarios. Finally, based on the above research scenarios, the maximum common requirements of users for accuracy, availability, continuity, integrity, alarm time, and coverage range in navigation, positioning, timing, and other aspects in different typical scenarios were summarized, and a summary table of user requirements for typical resilient PNT systems in different scenarios was compiled, as shown in Table 1 to Table 5. (Note: Report on Positioning, Navigation, and Timing (PNT) Backup and Complementary Capabilities to the Global Positioning System (GPS). 2020; 2019 GSA market report issue. European GNSS Agency; 2019 Federal Radio navigation Plan. Department of Defense, Department of Homeland Security, and Department of Transportation. 2019; IMO A. 915(22) REVISED MARITIME POLICY AND REQUIREMENTS FOR A FUTURE GLOBAL NAVIGATION SATELLITE SYSTEM (GNSS); IALA R0129 (R-129) GNSS VULNERABILITY AND MITIGATION MEASURES. 2012; Report on User Needs and Requirements Agriculture. European Global Navigation Satellite Systems Agency. 2019).

Table 1: Summary of user requirements for a typical resilient PNT system in near-ground scenarios

S/N	Scenarios	Scenario requirement	Minimum performance standard indicators that meet the requirements						
			Accuracy (95%)		Availability	Continuity	Integrity	Warning time	Coverage range
			Horizontal	Vertical					
1	Commercial aircraft user scenario level	Maritime	10 or 4nmi	Not applicable	0.99-0.99999	From $1.1x10^{-4}$/hr to $1.1x10^{-8}$/hr	$1.1x10^{-7}$/hr	Not applicable	None
2		Aviation route	2nmi	Not applicable	0.99-0.99999	From $1.1x10^{-4}$/hr to $1.1x10^{-8}$/hr	$1.1x10^{-7}$/hr	5min	
3		Terminal	1nmi	Not applicable	0.99-0.99999	From $1.1x10^{-4}$/hr to $1.1x10^{-8}$/hr	$1.1x10^{-7}$/hr	15s	
4		Non-precision approach	220m	Not applicable	0.99-0.99999	From $1.1x10^{-4}$/hr to $1.1x10^{-8}$/hr	$1.1x10^{-7}$/hr	10s	
5	General aviation monitoring service performance	Aviation route	308m	1nmi	99%~99.999%	1.0×10-5/h	-	300s	Nationwide
6		Termination environment	171m	0.6nmi	99%~99.999%	1.0×10-5/h	-	15s	An area of 20 nautical miles centered on the airport

Table 2: Summary of user requirements for a typical resilient PNT system in sea scenarios

S/N	Scenarios	Scenario requirement	Minimum performance standard indicators that meet the requirements						
			Accuracy (95%)		Availability	Continuity	Integrity	Warning time	Coverage range
			Horizontal	Vertical					
1	Inland waterway stage	Navigation safety	2-5m		99.9%	Task time dependent	10^{-4}	10s	The inland waterway system
2		River engineering and construction ships	0.1-5m		99%		10^{-4}	10s	The inland waterway system
3	Harbour entrance and entry stage	Navigation safety	8-20m		99.7%		10^{-4}	10s	Harbour entrance and approach
4		Resource exploration	1-5m		99%		10^{-4}	10s	Harbour entrance and approach
5		Entry period of engineering construction ships	0.1-5m		99%		10^{-4}	10s	coverage range
6	Offshore stage	Navigation safety	0.25nmi (460m)		99.7%		10^{-4}	30s	Offshore stage
7	Pelagic stage	Navigation safety	A minimum of 2-4nmi(3.7-7.4km); ideal 1-2nmi(1.8-3.7km)		99%		10^{-4}	60s	Repair at least once every 12 hours in 99% cases
8		Resource exploration	10-100m		99%		10^{-4}	60s	Nationwide
9		Search and rescue	0.1-0.25nmi(185-460m)		99%		10^{-4}	60s	National maritime search and rescue area

Table 3: Summary of user requirements for a typical resilient PNT system in ground scenarios

S/N	Scenarios	Scenario requirement	Minimum performance standard indicators that meet the requirements						
			Accuracy (95%)		Availability	Continuity	Integrity	Warning time	Coverage range
			Horizontal	Vertical					
1	Forestry survey	Survey of resources	0.05~10m		99%	Not applicable	0.09~15m	5s~5min	Nationwide/surface coverage
2		Precision application	0.3m		99%		0.6m	5s	Nationwide/surface coverage
3	Seismic/geological monitoring	disaster monitoring	1~10m		Not applicable	Not applicable	2~20m	Not applicable	Nationwide
4	Surveying and mapping	Static survey	0.015m	0.04m	99%	1.1×10^{-4}/hr~1.1×10^{-8}/hr	4hr	30s	Nationwide
5		Dynamic survey	0.04m	0.06m	99%	1.1×10^{-4}/hr~1.1×10^{-8}/hr	Twice for 3min, with an interval of 45min	1s	
6		Waterway measurement	3m	0.15m	99%	1.8×10^{-6}/15 s	1s	1s	
7		Topographic mapping	1~10mm	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable	

Table 4: Summary of user requirements for a typical resilient PNT system in urban scenarios

S/N	Scenarios	Scenario requirement	Minimum performance standard indicators that meet the requirements						
			Accuracy (95%)		Availability	Continuity	Integrity	Warning time	Coverage range
			Horizontal	Vertical					
1	Active train control	Active train control	1.0m		99.9%	Not applicable	2m	6s	Whole line
2		Telecommunication timing	340ns		99.7%		680ns	30s	
3	Highway	Navigation and route guidance	1-20m		>95%	Not applicable	2-20m	5s	Nationwide/ground coverage
4		Dangerous goods tracking	10-20m		99%		10m	5s	
5		Vehicle/trailer tracking	20m		95%		50m	5s	
6	Safety emergency	Public security	0.1-30m		95-99.7%	Whole process	0.2-30m	2-15s	
7		Collision	0.1m		99.9%		0.2m	5s	Nationwide/ground coverage
8		Emergency response	0.1-4m		99.7%		0.2-4m	30s	

Table 5: Summary of user requirements for a typical resilient PNT system in jungle/canyon/indoor/underground/underwater scenarios

Categories	Scenarios	Scenario requirement	Minimum performance standard indicators that meet the requirements						
			Accuracy (95%)		Availability	Continuity	Integrity	Warning time	Coverage range
			Horizontal	Vertical					
Jungle/canyon	Jungle adventure	Jungle adventure	1~5m		95%	Not applicable	2~10m	Not applicable	Nationwide
	Forest rescue	Search and rescue	1~5m		99%		2~10m		
	Wildlife management	Wildlife resource management	0.5~2m		Not applicable		1~4m		
		Wildlife research and tracking	1~10m		Not applicable		2~20m		
Indoor/underground	Underground parking for shopping	Underground parking location	10cm~2m		99%	Not applicable	0.02~4m	5s	Nationwide
		Mall positioning	2m-10m		95%		Not applicable	Not applicable	
	Underground application	Underground land application	0.01~2m		90~99%		0.02~4m	1-15s	
Underwater	Underwater environments	Marine charting	Centimeter level		--	--	--	--	Operation area
		Marine gravity/magnetism	Meter level		90~99%	Not applicable	0.2~10m	1~15s	
		Marine geologic survey	Meter level		90~99%		0.2~10m	1~15s	

4. Terminal User Requirements

In complex environments, a single PNT service system may have the risk of discontinuity, unavailability, or unreliability, and may even completely lose its service capability. It is reasonable to fully utilize multiple sensors to obtain multi-source PNT information, so effective integration of multiple sensors is needed. Resilient integration of multiple sensors refers to the sharing of common components by multiple sensors, and the resilient optimization integration of compatible sensor components, forming a multi-functional PNT service terminal that adapts to various complex environments. In the future, resilient PNT terminals should strive to achieve characteristics such as low cost, compactness, low power consumption, and strong compatibility. In the event of discontinuity, unavailability, or loss of service capability of a single PNT service, it should include miniature devices such as radio navigation, inertial navigation components, and miniature atomic clock components, and have no inter-system bias, meeting interoperability and other characteristics [5].

5. Requirement Analysis Summary

(1) User requirements for positioning accuracy, availability, continuity, integrity, and other indicators vary significantly across different fields and dimensions.

Different applications in various scenarios, such as near-earth, urban, indoor, and jungle environments, exhibit varying degrees of demand for positioning accuracy. While general applications, such as vehicle navigation and marine navigation, do not impose stringent requirements on positioning accuracy, availability, and integrity, precision applications or safety emergencies, such as aviation approach and takeoff, safety collision avoidance, and precision surveying, necessitate high standards for positioning accuracy, availability, continuity, integrity, alarm time, and other indicators, with a strong dependence. Regardless of the application scenario, the higher the requirements, the greater the demands placed on PNT technology and its associated hardware and software equipment.

(2) The need for navigation, positioning, and availability is particularly prominent in closed and obstructed environments, such as indoor, jungle, canyon, and tunnel environments, or in environments where GNSS signals are interfered with or subjected to spoofing attacks.

In remote jungle/canyon areas, underground parking lots, tunnels, bridges, and culverts, navigation signals are subject to interference and obstruction, resulting in weak or even lost signals. In such environments, navigation, positioning, availability, integrity, and coverage range are highly dependent. In scenarios where satellite navigation is unavailable, it is necessary to consider deploying new positioning systems, with high demands on the coverage range and cost of base stations (space segment), as well as the availability, integrity, and stability of the system (service segment).

6. Conclusion

Based on the above analysis, it is evident that the existing basic services of GNSS are unable to meet the ever-evolving user demands. As user requirements continue to increase, industry users are demanding higher performance from navigation services. The current satellite navigation systems are unable to meet user demands in terms of accuracy, integrity, real-time high-precision positioning, and secure timing. Therefore, it is necessary to break through the core PNT technology, achieve resilient integration of multi-source PNT components, resilient adjustment of multi-source PNT function models, resilient optimization of random models, and construct a resilient PNT service system to improve the performance of GNSS in all aspects. This will enable the system to meet the special PNT service requirements of different regions and fields.

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