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Role, path, and vision of "5G + BDS/GNSS"

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Abstract

Communication, positioning, navigation, and decision-making abilities have evolved into Positioning, Navigation, and Timing (PNT) intelligence during the long process of human migration and hence promoted human evolution. This article defines intelligence and smartness from the perspective of biological intelligence. New requirements as a result of the development of communication, navigation, time service, and decision making are identified in this study. The article points out that there are many radio PNT service methods, such as 5G, the new-generation high-speed communication networks and the low-latency and ubiquitous mobile communication networks as well as Global Navigation Satellite System (GNSS), but the integrated application is especially important in providing technical support for the adjustment and control of the physical world by intelligent sensing, cognition, decision-making, and precise coordination. The fusion of 5G and GNSS [including BeiDou Navigation Satellite System (BDS)] information with the corresponding equipment can be embedded into a machine to make it intelligent. Furthermore, the fused information of 5G and GNSS together with the environment information may extend human perception and physical world control ability in terms of time and space scale. It will help to develop critical information infrastructure in the age of intelligence, which will also extend the definition of artificial intelligence. Additionally, the "5G + BDS/GNSS" fusion path is analyzed explicitly herein in terms of realization methods, information processing, and new application services. On the whole, the application of "5G + BDS/GNSS + satellite-based communication" as a critical infrastructure for land, sea, air, space and network spatiotemporal control rights is proposed.

Keywords: 5G, BDS/GNSS, Ubiquitous network, Natural intelligence, PNT intelligence

Introduction

Based on the use of changing sounds (including human language) and body movements to interact with each other and gain the perception of the outside world, mutual perception and emotional exchanges are signs of human communication intelligence. Walking, migrating and land enclosure and settlement are the positioning, navigation and timing intelligence that humans acquired in the process of evolution for survival. Humans enjoy exploration, and tend to explore new environments (such as outer space), which is determined by their inherent love of discovery. In nature, communication, positioning, navigation, and decision-making are integrated, as it can be seen in the fact that humans indicated position and location by means of call, gesture and language in their early stage of development. The current integration of 5G with positioning and navigation systems, such as BDS and universally compatible other GNSS, abbreviated to "5G + BDS/GNSS," is the most modern integration of communication, navigation, timing and decision-making intelligence.

PNT infrastructure is the basis for research on substance, energy, information, and human movements, as well as the realization of target management and object control. Owing to the development of science and technology and societal progress, the demand for spatiotemporal information has transformed from post-event to real-time and instantaneous, from static to dynamic with high-speed, from rough to precise and comprehensive, from land to marine and air, from regional to wide-area and global, and from earth to deep space and the universe. Currently, the information demand has evolved from physical space to virtual network space, as well as from nature to humans and society (Liu and Gao 2017).

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The application of spatiotemporal information is only restricted by human imagination. Owing to GNSS-based spatiotemporal information service networks, ubiquitous networks and other observation technologies, any perceptual substance or human near-Earth activity can be measured across time ($>1\times10^{-2}$ ns)and space (>1 μm), from land, sea, air, space, indoor, underground, and even the Internet, the virtual space where human activities occur. This is known as "5G + BDS/GNSS," the time and space-based communication fusion that provides the basis for the extension of ubiquitous surveying and mapping and location-based service for mutual enhancement.

The development of mobile communication, from 1G to 4G, was driven by technology. From 1G analog communication to 2G Global System for Mobile Communications (GSM) technology, followed by time division multiple access to 3G code division multiple access technology, and then to 4G Long Term Evolution (LTE) technology, the major developments of communication technology were all driven by technological progress. Although the transition from 4G to 5G is primarily driven by demand, the core technology is still LTE. 5G is a multi-service and multi-technology converged mobile communication network through the evolution and innovation of technology that satisfies the rapid development needs of various services, including extensive data and connections in the future, and improves user experience. Additionally, the critical new technology of 5G is ubiquitous networking, which features multi-system, multi-level, multi-cell, and multi-carrier. There may be particular a demand for cities to develop another mode of networking, since both the population and communication requirements are greater than those in the countryside (You et al. 2014; Zhang et al. 2016).

Role of "5G + BDS/GNSS"

"5G + BDS/GNSS" will become the most important infrastructure as we enter into the age of intelligence. Intelligence and smartness are abilities owned by living things for survival and reproductive development. Animal intelligence is the highest form of natural evolution, and among them human intelligence reaches the highest level. Both biological intelligence and smartness rely on the perception and cognition of the surroundings, subsequent decision making, and actions taken to adapt to the environments based on spatiotemporal information. Therefore, intelligence is defined as abilities to sense changes, to learn, memorize, and form experiences, to develop knowledge and decision-making mindset via reasoning, to achieve precise coordination for time, location and attitude, and to entirely or partly adapt to the outside environment to seek advantages and avoid disadvantages. Based on perceiving external changes in a particular space–time range, smartness enables animals to recognize the rules and mechanisms of the external changes in that range and realize the prediction of the future or unknown changes for seeking benefits and avoiding disadvantages. For example, ants have swarm intelligence, even overtaking that of human beings in some aspects. Furthermore, crows are smart enough to drink water from a lagena by putting stones into the bottle so that the water can come up to its neck. These examples demonstrate the smartness of living things.

The interconnectivity between the new-generation Artificial Intelligence (AI) technology, which is based on big data, stronger computing power as well as optimal algorithms, and various technologies, will help social production and consumption to evolve from industrialization to automation and intelligence. Humans are entering the age of intelligence, which is the inevitable result of technological development and the extension of biological intelligence, human intelligence, and smartness to nature, society, and machine for perception, cognition, management, and control by homo sapiens. The AI being developed aims to explore and provide natural intelligence not only to machines, but also to humans, the society and the environment, e.g., the existing intelligent buildings and upcoming intelligent roads and networks. Next, we will discuss the role, path, and vision of "5G + BDS/GNSS" in a developing intelligence society.

In the age of intelligence, a clear perception of the outside environment based on the ubiquitous perception network with 5G technology is essential. The ubiquitous perception network expands with the essential characteristics of anytime (time), anywhere (space), anything (the inclusion of everything) and omnipresence (ubiquitous intelligence). This implies the realizing of people-to-people, people-to-objects and objects-to-objects on-demand information access, transfer, storage, cognition, management, control, decision making, and other services based on government, industrial and society needs. The current Internet cannot satisfy a higher demand for information control and management. However, the 5G-based perception network, has strong enough environment perception, as well as content perception abilities and intelligence, which can provide ubiquitous, adaptive reaction, on-demand, and customized information services in addition to management and control applications for people, companies and the society.

The concept of information network is expanding from the Internet of Things (IoT) to ubiquitous network. IoT can connect objects as well as objects with people, not including the control of the physical environment. Hence, ubiquitous network aims to realize the perception, collaboration, integration, and control of both virtual and

physical spaces, based on wide-area and global high-precision time and location-based services.

5G is the infrastructure in the intelligent age, featuring high bandwidth, high speed, high capacity, low power consumption, low latency and Internet of everything. It is developed to satisfy the industrial or individual needs of virtual reality, intelligent manufacturing, automated driving in the future. However, spatiotemporal information is not perceptual or adjustable on the network. Although 5G has a millisecond-level latency, there are still some pending issues, such as the inability to realize the remote control of self-driving cars or locate a physical address using a virtual address.

Hence, new infrastructure is necessitated, that is BDS/GNSS. PNT and time itself are biological intelligence born out of natural evolution. "5G + BDS/GNSS" in the intelligence era can enable biological PNT intelligence in machines and environment. The intelligence gained by machines and environment is called AI, which encompasses a broader scope compared with the early interpretation of AI. The ubiquitous surveying and mapping ability based on "5G + BDS/GNSS" provides PNT intelligence to modern technology. It is not only the critical infrastructure for the precise perception of wide area and global time and space events and target information, but also for wide-area and global intelligent cooperative control.

BDS/GNSS is the only global high-precision and high-stability infrastructure providing PNT. Its best advantage is worldwide coverage, which can realize the precise synchronization of global time service and enable the perceptual ability of time and location to 5G and other systems, such as roads, environment, and satellite networks, in wide areas and even worldwide. The high-precision positioning augmentation technology enables the mobile communication network and Internet to locate the instant position of a mobile information packet and its direction and transient flow rate. Additionally, it allows mobile Internet to integrate indoor and outdoor positioning seamlessly to realize the requirement of smart city construction anywhere and anytime (Yin et al. 2018).

BDS/GNSS and 5G enable and enhance each other to generate five abilities of intelligence, namely perception, learning, cognition, decision making, and adjustment and control, and all of them require microsecond or even nanosecond level precision coordination in location and time. Although we can currently utilize the physical time with the support of current communication technologies, it is still not sufficiently precise or reliable. However, adjustment and control can become difficult at some key moments. Precise adjustment and control can be achieved in some factories or workshops, but not in the global aspect. "5G + BDS/GNSS"can be used to solve this problem, based on perception of physical devices with wide areas or global distribution. Hence, functions, such as computing, communication, precise control, remote collaboration, and autonomy, can be performed to extend the human ability to perceive and control the physical world on time and space scales, which is the goal of industrial Internet (also known as Cyber Physical System (CPS)).

Path toward "5G + BDS/GNSS"

To integrate 5G and BDS/GNSS to serve the industry and society, we can follow the rules from easy to difficult, from simple to complicated, and from architecture to application. The suggested steps are outlined as below.

Integration of BDS/GNSS and 5G base stations

The current synchronization of 5G base stations requires approximately several microseconds to 10 μs. End-user latency consumes 1 ms, which is nearly 1000 times higher than 1 μs. The servers of 5G macro and micro base stations, key gateways, routers and cloud service centers in industries may be equipped with self-controllable, multi-band, multi-mode and low-power consumption GNSS boards that are primarily composed of BDS, to provide precise coordinate location and time synchronization. The GNSS boards may provide unified nanosecond-level time and centimeter-level coordinate systems for 5G base stations, gateways, routers, and main servers. Hence, the "5G + BDS/GNSS" system provides good spatiotemporal information services. Moreover, because the BDS/GNSS board is power efficient, which typically consumes only 0.5–2 W of electricity, thus its energy consumption is negligible compared with that of 5G network.

Because the base stations of "5G + BDS/GNSS" is a ground-based augmentation network with high density and high precision, it is a supplement and extension of national terrestrial reference frame based on BDS data that offers precise positioning, timing and time synchronization services for ground users. By reprocessing and correcting BDS signals, millimeter-level location accuracy and nanosecond-level time accuracy can be achieved, and the ability of earthquake monitoring, early warning, and prediction can be improved based on current national seismic monitoring networks and 5G network. The precise modeling of three Dimensional (3D) atmospheric wet components for wide areas, regions, and local areas, can be established by the integrated data of 5G + BDS/GNSS, and the corresponding big data service for the precise prediction of atmospheric precipitable water can be provided. Additionally, it can analyze water content in air at a precise location and time as well as provide an accurate

forecast in fixed quantities, places and times. For example, "9 mm of precipitation tomorrow morning between 8:30 and 9:50 on the roads in Xi'an high-tech park," which is important for the development of Internet of Vehicles (IoV) and intelligent driving. In addition, it can realize a precise regional 3D ionospheric model, regional soil moisture monitoring, and early warning of thunder and lightning positioning. The applications mentioned above in the atmosphere, ionosphere, and soil moisture are remote-sensing applications enabled by the combination of BDS/GNSS and 5G base stations.

5G network serves the role of BDS/GNSS augmentation PNT service

The 5G base station is not only responsible for receiving BDS signals for positioning and timing service, but also for sending navigation information and ranging signals similar to that of BDS (Deng et al. 2017). The signals from the 5G stations can be used for BDS-based precise positioning, as each base station has its own precise and uniform position and time determined by BDS. Supported by 5G stations, many applications related to precise PNT information will emerge, such as smart city construction, management and control, natural resource planning, management and supervision, smart agriculture, precision agriculture, catastrophic insurance, intelligent transport monitoring and risk control.

Application and service in IoV and Intelligent Connected Vehicle (ICV) operation

Based on previous 5G + BDS/GNSS augmented PNT information, "5G + BDS/GNSS"-based IoV can be established. The IoV system includes vehicle road coordination, as well as the timing and location sensing of vehicles based on "5G + BDS/GNSS." With the support of PNT information provided by "5G + BDS/GNSS," the IoV regional cloud service center can be immediately connected to public security traffic management centers, relevant insurance companies, car owner units and relatives, as well as relevant 4S shops. Information service systems based on updates of real-time road condition information and spatiotemporal information are required in high-precision maps and crowdsourcing. Furthermore, the IoV includes an information service system based on the entire process sensing and control of the road after each intelligent and connected vehicle is started. Using the PNT information provided by "5G + BDS/GNSS" and the real time sensing for vehicles and environments, the centimeter-level location control and nanosecond-level time control of IoV and ICV, respectively can be realized.

Industrial Internet/CPS fusion system

Based on "5G + BDS/GNSS," a high-precision PNT service network, routers, gateways, and key servers can be constructed to realize measurable, calculable, traceable, and adjustable high-precision CPS systems. Therefore, intelligence is achieved via the information control of the physical world, which also satisfies the definition of AI by Simon (1995), a Nobel Prize and Turing Award winner. With some technological enhancements, this AI system can be realized with the support of "5G + BDS/GNSS" augmented PNT information.

However, the integration of BDS/GNSS and 5G does not mean putting them together simply like building blocks. There are many problems need to be solved. For example, the unified time system with nanosecond synchronization accuracy based on BDS is one of the key technologies to achieve our expectation. But the truth is that the timing accuracy of normal receivers of GPS/GNSS range from 20 ns to 50 ns, which cannot satisfy the requirements of applications that need stricter synchronization, and is not suitable for the integration of BDS/GNSS and 5G. With the support of national key research and development program of China, we proposed a one-way timing system based on a ground-based augmentation system (Niu et al. 2019). The system estimates real-time high precision satellite clocks using the ground-based augmentation network as the time reference. Moreover, the time reference is transferred to the terminal through real-time Precise Point Positioning (PPP). Finally, the timing receiver synchronizes its local clock to the reference through real-time clock adjustment to realize high precision timing. Based on this, we have developed a high-precision, high-stability BDS/GNSS timing terminal which can achieve sub-nanosecond level accuracy. The terminal uses an Oven Controlled Crystal Oscillator (OCXO) controlled by external voltage to generate basic frequency, and works by the PPP method. It mainly depends on BDS, and is also compatible with other GNSS systems. We compared the 1 Pulse Per Second (PPS) output of the timing receiver with that of the National Time Service Center (Fig. 1).

The sub-nanosecond result could be seen obviously within all the seven days. And Fig. 2 gives the Allan deviations of the frequencies in this system, which can achieve approximately 6×10^{-14} in one day.

With this terminal, we designed a network speed performance test and measured different network delays, from the network connected directly by a cable to the network connected with a router and server. By calculating different data package latencies under different situations, such as when it travels across routers or servers, or when the router/server is undertaking other tasks simultaneously. According to the test, the data package

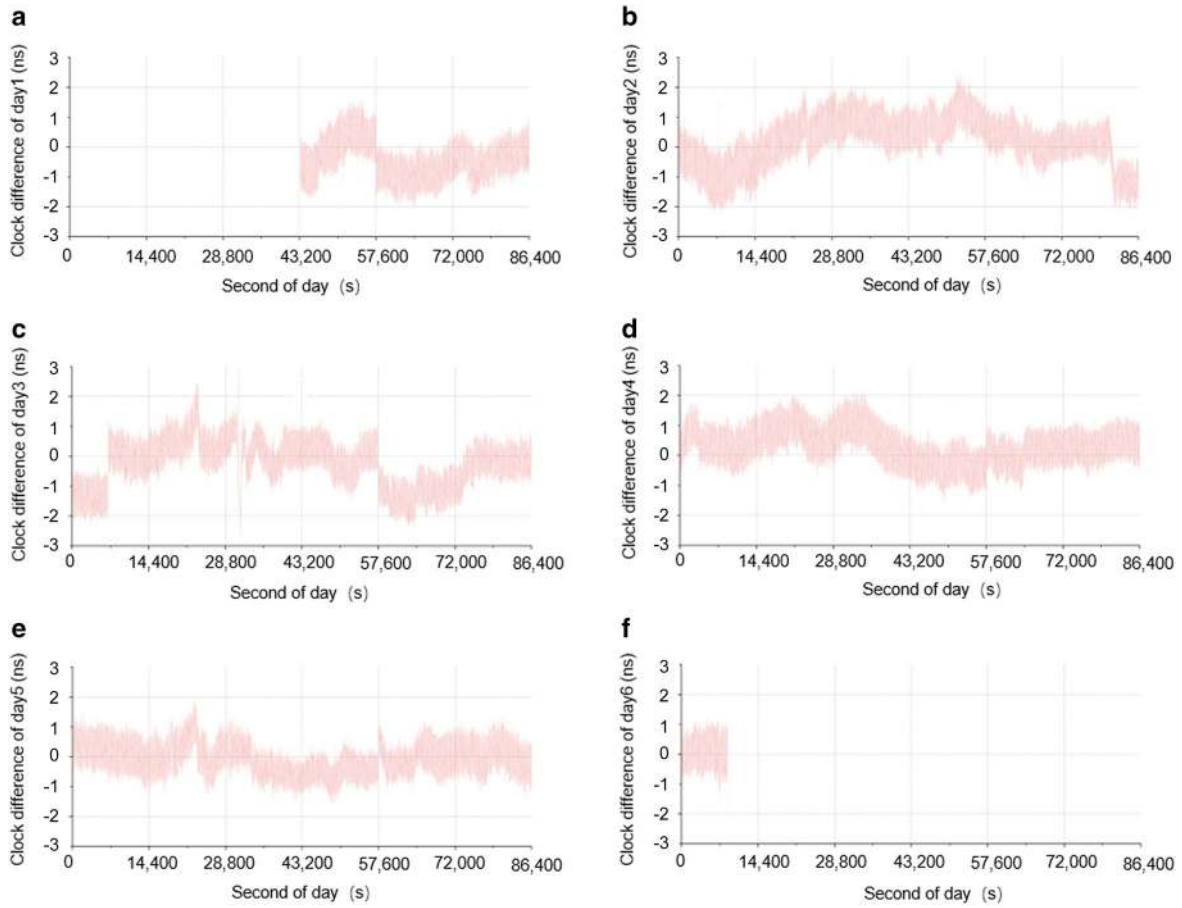

Fig. 1 Daily standard deviations of 1 PPS results

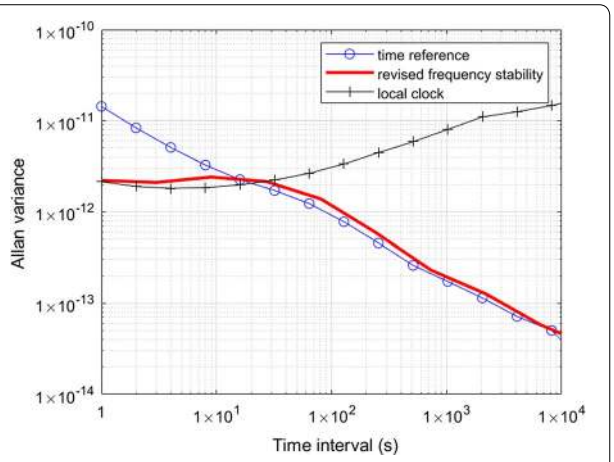

Fig. 2 Frequency stabilities of our timing system

latency differs according to the scene, so the terminal can be used for network anomaly detection or software virus detection.

Therefore, we performed some network security tests. We measured the delay of the packets passing through the network devices (e.g. router) based on the high-precision timing terminal. As shown in the Fig. 3, the delay distribution of the six different routers are different. The hardware and the software program of different routers may cause different delay. Furthermore, the small delay slip of software program can be detected with the high-precision time stamp even if it's changed in instruction-level. This shows that the high-precision timing terminal can be used to detect the changes of network devices (e.g. router), including both the hardware change and software change. The experiment result shows that the time stamp with high-precision BDS terminal can detect delay changes of devices in the network.

Furthermore, the cyclic latency slip can be detected by the high-precision and high-stability BDS time service terminal. This shows that the high-precision and high-stability BDS time service terminal can detect computer hardware and software latency abnormalities as

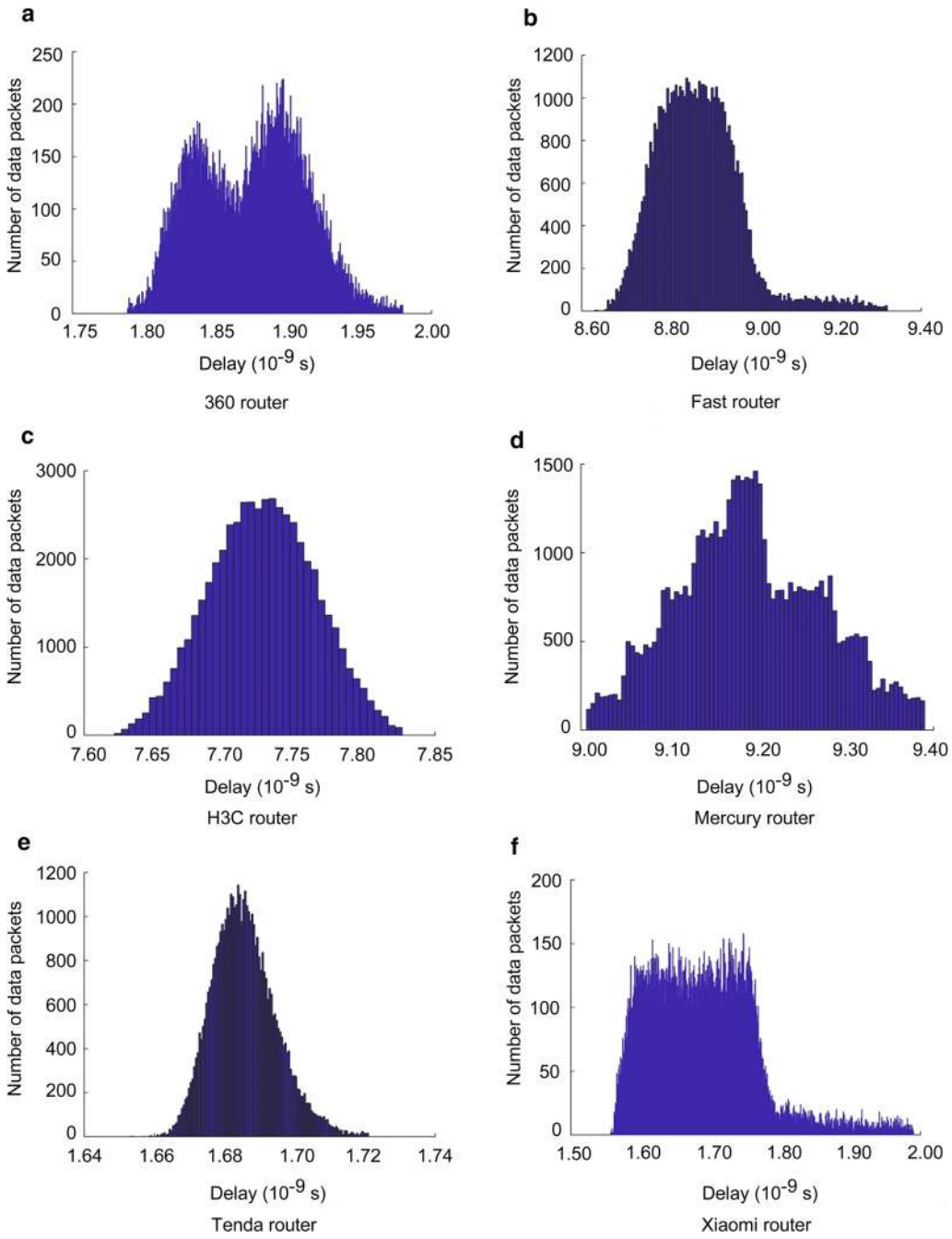

Fig. 3 The delay distribution of the six different routers

computer hardware and software are processing instructions. The process is similar to performing a "CT" scan on both the hardware and software environment to verify if any instruction-level change occurs in the internal processing procedure and precisely calculate which kind of change has happened. The experiments show that the high-precision location stamp, time stamp with high-precision and high-stability BDS terminal can detect instruction-level changes in the internal processing procedures of the tested network devices. These experiments provide a technical basis for future remote control and information security work.

The Internet typically uses random routing protocols for data packages to obtain a faster route to the destination. To solve this uncontrollability of the network, we must first develop a virtual private network (VPN) that is

detectable, calculable, and controllable in the 5G mobile network. Subsequently, we should develop intelligent optimal routing protocols and render local area network data packages measurable, calculable, controllable, traceable, and interceptable in the 5G mobile network. We can then further develop the standards and protocols for remote and intelligent optimal control of wide area network in the 5G mobile network. Finally, we must avail BDS time and location services to help 5G mobile networks realize remote control, multi-task handling, and cooperative sensing control of the industrial Internet.

Realization of indoor/outdoor integrated PNT

This is the most challenging task, as land, sea, space, air, underwater, indoor, and underground should all be connected to the "5G + BDS/GNSS" indoor/outdoor integrated network. Furthermore, the perception, cognition, decision making, controllability, and seamless continuity of space and time should be realized.

Possible applications and vision of "5G + BDS/GNSS"

The application of "5G + BDS/GNSS" means the integration of five data resources: data provided by the BDS, ground-based augmentation system, 5G communication network, "Gaofen" satellite remote sensing, and the Internet, to construct an integrated system. The system should be fundamental, environmental, intelligent, ubiquitous, secure, and controllable for supporting extensive industrial applications, such as IoV, intelligent energy, wireless robot, and drone cloud control. For intelligent energy, the current grid time standards that has remained unchanged since the age of Tomas Edison are out of date. The current phase synchronization precision is 18°, which means that the maximum time gap should be less than 18° (1/20 cycle, which equals to 1 ms); otherwise, it will cause high energy consumption. In the future, "5G + BDS/GNSS" will enable the centimeter-level location and nanosecond-level time control of national grids and realize the nanosecond-level phase synchronization of the input and output voltages of grid devices.

The national security control over land, sea, space, air, and information right can be traced back to the spatiotemporal control rights. It requires precise and reliable spatiotemporal information. "5G + BDS/GNSS + satellite-based communication" is the critical infrastructure to realize the spatiotemporal control rights of land, sea, space, air and information network. The vision of communication-navigation-remote sensing integration, and space-based, ground-based, PNT augmentation integration have been proposed previously (Liu 2018). Among international GNSS orbiting satellite constellations, only BDS with global coverage (BDS-3) satisfies this standard (Yang et al. 2019, 2020).

Conclusion

The rapid fusion of "5G + BDS/GNSS" and a low Earth orbiting (LEO) satellite-based augmentation system with mutual intelligence empowerment will ease the perception, calculation, measurement, and control of the intelligent society. In the process of achieving this goal, there will be a large number of opportunities and more significant challenges. Therefore, more technical issues will need to be addressed, and we must develop transformative technologies to enable a more modernized future.

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Authors' contributions
Liu Jingnan proposed the idea and prepared the main review, whereas Gao Kefu provided evidence for the viewpoints as well as translated and revised the paper. All authors read and approved the final manuscript.

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Availability of data and material
The data presented herein were obtained from laboratory tests and are duly referenced in the text.

Compliance with ethical standards

Competing interests
The authors declare that they have no competing interests.

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