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Research on Digitalization of Non-Exposed Space

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Abstract

Non-exposed space is defined relative to exposed space, and mostly refers to indoor or semi-indoor scenes, such as urban rail transit, tunnels, coal mines, factories, shopping malls, hospitals, etc. Navigation and location information are closely related to human production and life. No matter in exposed or non-exposed spaces, it is increasingly urgent to obtain location information of mobile terminals quickly and accurately and to provide navigation and location services. Therefore, it is necessary to use the spatial digital technology to complete the three-dimensional visualization modeling of the spatial structure, buildings and facilities of the non-exposed space using a unified spatial coordinate system and BIM technology, so as to realize the spatio-temporal integration of the non-exposed space and the exposed space. Data twinning and structural perspective, complete the smooth transition of business applications in the two spaces, and enhance people's sense of comfort and security in non-exposed spaces. This paper will build the structure of the digitalization of non-exposed spaces, discuss the key technologies, and analyze people's needs for non-exposed spaces..

Keywords: Non-Exposed Space, Space Digitalization, Digital twinning

1.Introduction

People switch between exposed and non-exposed spaces in their daily lives. Therefore, open space and non-exposed space are all about people's living space. With the rapid development of urban construction, underground spaces or non-exposed spaces on the ground, buildings or facilities are becoming more and more complex. In the non-exposed space, accurate positioning signals are difficult to obtain, and the road topology information of the electronic map is very imperfect, which makes the navigation guidance of the navigation electronic map difficult, and the space asset management is not easy to carry out, which makes the work and life in the non-exposed space very inconvenient. The difficulty of the dynamic service of the spatial location of the non-exposed space is like a wall, blocking the rapid expansion of people's extensive production and living activities. Therefore, it is of great significance to study how to "transparent" non-exposed space, break the BIM independent system of building units, form a continuous location service in time and space, and improve the utilization efficiency and effectiveness of non-exposed space.

2.Digitalization of Unexposed Space

The non-exposed space is defined relative to the exposed space. The exposed space is what we often call the open space outside the room, while the exposed space refers to indoor or semi-indoor scenes. To be more precise, the area that can communicate with navigation satellites is regarded as exposed space, and the others are regarded as non-exposed space. The digitalization of non-exposed spaces refers to the use of spatial digital technology to transform the spatial structure, buildings and facilities information of non-exposed spaces into a unified time system, a unified spatial coordinate system, a unified BIM technology, and a unified Internet of Things data. Transmission protocol and unified broadband transmission technology, complete 3D visualization modeling, realize spatiotemporal integration, data twinning, display visualization, and structural perspective of non- exposed space and exposed space, and complete the smooth transition of business applications in the two spaces, to enhance people's sense of comfort and security in non- exposed spaces. Quickly and easily guide people to a safe area in case of special circumstances.

In actual business application scenarios, the three- dimensional space display capability of virtual reality is used, the BIM model is used as the carrier, the real-time operation data of the Internet of Things is integrated, and all kinds of fragmented, scattered and fragmented information data, including non-exposed space The basic structure of the building itself is integrated. Information, fire protection, strong and weak electricity, HVAC, water supply, drainage, sewage, security, energy, facilities and equipment, assets, hidden works, roads, elevators, gathering areas, etc., are further introduced into the daily operation and maintenance management functions of non-exposed spaces , created a virtual reality non-exposed space and equipment operation and maintenance management based on BIM model. At the same time, it also provides the three-dimensional spatial location of traffic, facilities, equipment, and pipelines, quickly locates faults, and shortens the maintenance cycle; intuitive and comprehensive information records are used for the whole process management of building operation and maintenance, creating functions such as statistics, analysis, and data mining. condition.

In people's life scenes, people can know their precise location anytime and anywhere through indoor positioning technology and auxiliary display devices, rely on 3D BIM maps for road navigation and discover surrounding points of interest information, which provides people with comfort in non- exposed spaces. Life, shopping, transportation provide a good foundation.

Specifically, the digitalization of non-exposed spaces means that people can achieve precise positioning and virtual reality environment display through smart terminals at any time and anywhere, and achieve smooth display with exposed spaces. Through the digitalization platform, "Where am I?", "What am I interested in?", "How do I go to my destination?", "How do I escape?", "The space for my assets What is the location and status?", "I want customer service communication" and other functions related to time and space related to the life and work of people and companies, allowing people to experience the same comfort in non- exposed spaces as in exposed spaces.

3.Digitalization for Non-Exposed Spaces

The digitalization system for non-exposed space is shown in Figure 1, it consists of the following seven layers:

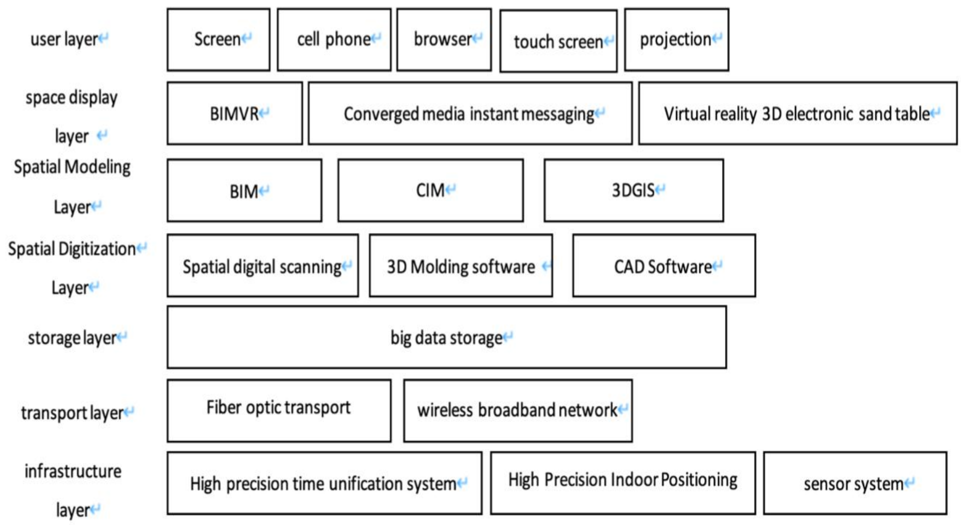

Figure 1. The digitalization system of non-exposed space

● infrastructure layer. The infrastructure layer mainly provides a unified space-time reference platform for the non- exposed space, and at the same time completes the access of various sensors.

● transport layer. The transport layer completes the transmission of data information, including internal data transmission and external data sharing.

● storage layer. The storage layer completes the storage and operation of massive big data.

● Spatial digitization layer. The spatial digitization layer completes the digital processing of non-exposed spaces, and realizes the digitization of spatial entities, environments and resources mainly through spatial digital scanning, CAD architectural software and 3D modeling software.

● Spatial modeling layer. The spatial modeling layer realizes the integration of BIM, CIM and 3DGIS, constructs a twin space that is realistic with the real environment, and quantitatively visualizes the attributes and relationships of various entities in the space.

● Space display layer. The space display layer uses the instant communication of fusion media as a link, and displays the non-exposed space realistically through BIMVR and virtual reality 3D electronic sand table, and completes the human-computer interaction at the same time.

● user layer. The user layer realizes the positioning and environmental display of non-exposed spaces on various smart devices, and at the same time realizes information interaction and special information in the form of acousto- optical prompts.

4.The Significance of Digitalization for Non-Exposed Spaces

With the continuous development of the social economy, people's life and work are carried out in non-exposed spaces for more than 60% of the time every day. The open space has many familiar reference objects to judge its own position and environmental characteristics, which can make people feel a sense of authenticity and security. In the non- exposed space, due to the relatively closed space, there is a lack of surrounding environment that can be referenced and positioned, which often makes people feel nervous and insecure, which can easily lead to loss of direction and cause certain problems for people's work, life and travel. difficulty. In the event of a special situation, how to escape in an emergency is a major problem that needs to be solved in non-exposed spaces. These situations are especially evident in non-exposed spaces such as urban rail transit, tunnels, coal mines, factories, shopping malls, and hospitals.

The establishment of a digitalization platform for non- exposed spaces has the following meanings:

● Show the real physical space harmoniously and con- tinuously with CIM, and solve the "jumping" problem when the space is switched between different systems.

● Realize the seamless connection between outdoor navigation and indoor navigation, and realize the smooth connection of indoor and outdoor path guidance.

● Realize fast and rapid escape guidance in emergency situations, which greatly enhances people's sense of security and improves the success rate of rescue.

● Provide undifferentiated space and time base for the life and work of ordinary users.

● Rapid positioning and traceability of asset management to achieve visual and maintainable asset management.

5.Digitalization Requirements for Non-Exposed Spaces

5.1. Unification of Time

The time of the exposed space and the non-exposed space must be unified and the precision is high enough to ensure the continuity of people's sense of time when switching between the two spaces. For example, the time of the subway system and the time of the public bus system can be unified to ensure people's efficient transfer and travel, so as to achieve the goal of saving time and improving the quality of life.

5.2. Unification of Space Coordinates

At present, due to the difficulty of introducing standard positioning information in non-exposed spaces, independent relative positioning methods are mostly used to build BIM systems, which leads to inconsistencies with the coordinates of exposed spaces, making the built BIM system and the exposed space GIS system unable to fit well. The spatial structure and the road cannot be connected continuously, which brings great inconvenience to people's use of electronic map for orientation identification. Therefore, the spatial coordinate system of the non-exposed space and the spatial coordinate system of the exposed space use the same standard.

5.3. Unification of Positioning Standards

With the development of smart cities and new infrastructure, the need for accurate positioning technology is more urgent. It can be said that non-exposed spatial positioning is the bottleneck that restricts the development of the entire smart city.

From the perspective of the national market application, the non-exposed spatial positioning technology is still in a very early incubation stage, and there are many difficulties:

● Accuracy requirements. The non-exposed space environment is complex and changeable, there are more devices involved in positioning, and people's requirements for positioning accuracy are much higher than those in outdoor areas, especially in some industries involving high- speed mobile device positioning, which have more stringent requirements for accuracy and positioning delay. .

● Construction and deployment are difficult. The non- exposed spatial positioning network needs to be deployed separately at a relatively close distance, and requires a lot of communication and post-construction work. In addition, the privacy structure of the indoor space also greatly increases the workload of the mesh.

● The positioning platform is not unified. Since the non- exposed spatial positioning has just started, the standards are not mature and unified, and the fragmented application scenarios increase the cost of updating dimensions. From a technical point of view, it is not that the current technology cannot solve it, but the cost is too high. In terms of technology, there are many mature non-exposed spatial positioning technologies: 5G, 4G, Bluetooth 4.2, Bluetooth 5.1, Wi-Fi, UWB and vSLAM, as well as RFID, Li-Fi and millimeter-wave base stations that are under discussion. These different positioning methods have different requirements for positioning environment, positioning algorithm, positioning accuracy and positioning communication protocol. Different positioning systems are difficult to interconnect and interoperate, resulting in fragmentation of the positioning system in the exposed space, which cannot be well and complete. It provides common positioning specifications for business scenarios.

5.4. Unification of BIM Data Exchange Standards

Non-exposed spaces rely more on BIM systems for spatial modeling, and form basic electronic maps on the basis of these spatial models. The producers of BIM systems and the publishers of basic electronic maps are often different spatial data producers, resulting in A large number of BIM cannot be used by electronic map manufacturers, nor can it fit well with the building map projection obtained through remote sensing information, resulting in a lot of waste of resources. Therefore, it is necessary to improve the effective use of BIM data by formulating BIM map data exchange standards.

5.5 Unification of Digital Scanning Processing Technology in Non-exposed Space

The spatial digitization of non-exposed spaces is mainly carried out in two ways, one is through the CAD drawing of architectural design, and the other is through the camera +laser point cloud to carry out the spatial dataization. However, different companies use different software systems and different resolutions of spatial data scanning, resulting in inconvenient, unsightly, and uneven accuracy of spatial data- based results in non-exposed spaces, which cannot provide users with a good experience.

6.Digitalization Technology for Non-Exposed Spaces

6.1. Time Synchronization

Countries around the world establish and maintain their own time systems with atomic clocks with excellent performance. GPS time is a time base in the United States, GLONASS is a time base in Russia, and Beijing time is the main time base in my country. The time bases of countries can be compared with each other through Coordinated Universal Time (UTC). The time unification system is composed of a time system center and a number of time distribution centers, and its equipment is composed of radio receivers, atomic frequency standards, standard signal generators and amplification and distribution equipment. The receiver receives the standard time and standard frequency signals broadcast by the National Astronomical

Observatory, so that each time system is synchronized with the standard time and standard frequency. The frequency standard source generates an accurate and stable reference signal, which is sent to the signal and time generator. After frequency division and synthesis, various frequency standard signals, sampling signals, control signals and time codes are formed. Wired cables to user equipment in non-exposed spaces. The distance between the user equipment and the time system center is different, and the time delay of the time system signal reaching each device is also different. When precise synchronization is required, the transmission delay of these signals must be measured and corrected in the data processing process.

Ethernet technology has been widely used in telecom-level networks due to its openness, low price, and ease of use. Ethernet technology is "plug and play", that is, connecting Ethernet terminals to IP networks. You can use the services it provides at any time. However, only a "synchronized" IP network is a true carrier-class network, which can provide guarantee for the multiple-play services that the IP network transmits various real-time services and data services. At present, carrier-class networks have very strict requirements for time synchronization. For a city-wide IP network, the backbone network delay is generally required to be controlled within 1ms. The current Internet time protocol NTP (Network Time Protocol), simple network time Protocols such as Simple Network Time Protocol (SNTP) cannot achieve the required synchronization accuracy or convergence speed. The IEEE 1588 standard is particularly suitable for Ethernet, and can achieve microsecond-level high-precision clock synchronization in a geographically dispersed IP network. The full name of the IEEE1588 standard is "IEEE 1588 Precision Clock Synchronization Protocol for Network Measurement and Control Systems", referred to as PTP (Precision Timing Protocol). The clocks of all nodes are calibrated and synchronized, so that the Ethernet-based distributed system can achieve precise synchronization. The accuracy of synchronization is closely related to timestamp and time information. The pure software solution can achieve the precision of milliseconds, and the combination of software and hardware can achieve the precision of microseconds.

The current version of IEEE 1588 is v2.2, which is mainly used in relatively localized and networked systems. The internal components are relatively stable. The advantage is that the standard is very representative and open. Because of its openness, it is especially suitable for the Ethernet network environment. Compared with other synchronization protocols commonly used in Ethernet TCP/IP networks such as SNTP or NTP, the main difference is that PTP is designed for a more stable and secure network environment, so it is simpler and occupies less network and computing resources. . The NTP protocol is a time synchronization protocol for various independent systems widely dispersed on the Internet. GPS (Satellite-based Global Positioning System) is also aimed at widely dispersed and independent systems. The network structure defined by PTP can achieve high precision, and PTP can achieve precision within microseconds. In addition, the modular design of PTP also makes it easy to adapt to low-end devices.

The precise network synchronization protocol defined by the IEEE1588 standard realizes a high degree of synchronization in the network, so that no special synchronization communication is required when assigning control work, thus achieving the effect of separating the communication time mode from the application program execution time mode. Judging from the current technical level, the best choice for the time system system of non-exposed space is to choose the PTP technology system.

6.2. Positioning Technology

Commonly used positioning methods in non-exposed spaces are: WI-FI positioning, Bluetooth positioning, RFID positioning, ZigBee positioning and ultra-wideband (UWB) technology. The characteristics of these technologies are compared as follows:

As can be seen from the Table 1, UWB technology has obvious advantages:

Table 1. Comparison of Unexposed Spatial Positioning Techniques

Positioning Technology	UWB	Bluetooth	Wi-Fi	ZigBee
IEEE specification	802.15.3a	802.15.1	802.11a/b/g	802.15.4
Maximum signal speed	110Mb/s	1Mb/s	54Mb/s	250Kb/s
Transmission distance range	10m	10m	100m	10-100m
Coding efficiency in ideal environment	97.84	94.41	97.18	76.52
Positioning accuracy	0.1-0.25m	3-5m	3-10m	5-10m
Security	Excellent	Good	Good	/
Penetration	Strong	Weak	Strong	/
Anti-interference	Strong	Weak	Medium Strong	/
Power consumption	Low	Medium low	High	/
Radiation	Low	Medium low	Medium high	/
Locate the farthest distance	200m	10m	30-50m	100/m
construction cost	Medium	High	High	/

● High positioning accuracy

The positioning accuracy of WB is higher and can reach centimeter level. Bandwidth determines the resolution (proportional relationship) of signal distance. The bandwidth of UWB is very wide, which brings an advantage to UWB systems, that is, it can be higher than other traditional systems in distance resolution, and the resolution accuracy is more than 100 times that of traditional systems under certain conditions. The broadband of the UWB pulse signal is in the nanosecond range, and the positioning accuracy is usually less than a few centimeters.

● High security

The transmission power of UWB is low, and the signal can be well concealed in other types of signals and environmental noise. The traditional receiver cannot recognize and receive, and must use the spread spectrum code pulse sequence consistent with the transmitter to perform demodulation. The system has Strong system security.

● Strong system stability and anti-interference ability

From the perspective of radio frequency mechanism, the anti-interference ability of the pulse wave emitted by UWB is stronger than that of continuous electromagnetic waves, and the frequency band of UWB operation is 3GHz-10GHz. Compared with the wireless positioning technology in the 2.4G frequency band, the external interference signal is also much less.

● High transmission rate

Channel capacity is proportional to bandwidth. UWB has wider bandwidth and higher transmission rate, up to 1000Mbps or more.

● Low power consumption

Ultra-wideband radios have RF bandwidths above 1 GHz and require very low average power to transmit. Especially in short-distance communication applications, the transmit power of UWB transmitters is generally lower than 1mW; the lower transmit power can prolong the working time of the system, and the transmit power is low, and the electromagnetic wave radiation to the human body is also small.

● Very wide bandwidth

Have more than 500MHz bandwidth.

● Low cost

The project is simple and cheap.

Therefore, UWB is the first choice for positioning technology in non-exposed spaces.In the future, doing a good job of navigation and positioning into more non-exposed space scenes can effectively promote the all-round construction of the Beidou space-time system and realize the construction of smart cities.

6.3 Spatial Digital Scanning

3D Laser Scanning Technology (3D Laser Scanning Technology) is a high-tech emerging in the mid-1990s and a new breakthrough in surveying and mapping technology after GPS. It uses the principle of laser ranging, by recording the three-dimensional coordinates, reflectivity, texture and other information of a large number of dense points on the surface of the measured object, and quickly reproduces the three-dimensional model of the measured object and various graphic data such as line and surface. Therefore, Also known as “Reality Reproduction Technology”.

3D laser scanning technology is a direct, fast and accurate way to obtain spatial data of objects, which has many advantages. 3D laser scanning technology can provide object point cloud data and structural information, and realize efficient and accurate monitoring of non-exposed spaces from different spatial scales. Terrestrial Laser Scanning (TLS) provides a new efficient and accurate 3D data source. Large- scale acquisition of 3D points. Use TLS to obtain point cloud data, and use corresponding software to extract the basic parameters of the measured object.

At present, the most advanced technology is: using lidar + 3D vision algorithm, combined with Internet 3D rendering technology, to quickly and cost-effectively complete 3D digitization of space, and apply the digitized space model to multiple ports such as PC and mobile. The device is designed with an integrated body, capable of shooting high-definition graphics, accurately collecting point cloud data, with a spatial accuracy of centimeters, fully adapting to a variety of complex indoor environments, and capable of high-precision scanning of indoor and outdoor large space scenes Through the supporting software, digital results of non-exposed spaces can be quickly generated. Its characteristics are as follows:

● With excellent color details, the as-built data can be obtained safely and quickly;

● Provides reliable and realistic visualization, even in extreme light conditions;

● Simplify various measurement tasks by integrating scanning and imaging workflows, even in challenging environments;

● It can be operated by one person, improving on-site efficiency.

Generally, the indicators of large space 3D scanners should not be lower than the following parameters:

● Scanning distance: 0.6-350 meters

● Measurement speed (pts/sec): 2,000/244,000/488,000/976,000

● Ranging error: ±1mm

● Resolution: no less than 165 million pixels, color

● High Dynamic Range (HDR): Exposure 2x, 3x, 5x;

● Parallax: coaxial design, no parallax.

6.4 BIM

BIM is a process of analyzing, simulating, visualizing, constructing drawings, and engineering quantity statistics of buildings in various stages of design, construction, operation and maintenance using the information in the digital model of the building. Therefore, BIM is a process of creating, collecting, managing, and applying information.

The so-called BIM model (or virtual model, digital model), its core is not the model itself (geometric information, visualization information), but the professional information stored in it (architecture, structure, electromechanical, thermal, acoustic, material, price , procurement, specifications, standards, etc.).

The current role of BIM in non-exposed spaces is:

● BIM model maintenance

Refers to the establishment and maintenance of BIM models according to the project construction progress, the use of the BIM platform to summarize all the construction engineering information of each project team, to eliminate the information islands in the project, and to organize and store the obtained information in combination with the 3D model for the whole process of the project. All stakeholders of the project can share it at any time.

● Visual management

The emergence of BIM enables users not only to have 3D visual design tools, what you see is what you get, but more importantly, through the improvement of tools, users can use 3D thinking to complete various changes in the life cycle of buildings. , and also enables owners and end users to truly get rid of the restrictions of technical barriers and know what their investment can get at any time.

● Pipeline synthesis

With the increase in the scale of buildings and the complexity of the functions used, the requirements for the integration of electromechanical pipelines by design companies, construction companies and even owners are becoming more and more intense. Using BIM technology, by building various professional BIM models, users can easily find the collision and conflict in the design in a virtual three- dimensional environment, thereby greatly improving the comprehensive design ability and work efficiency of pipelines. This can not only eliminate collisions and conflicts that may be encountered in the construction process of the project in a timely manner, but also significantly reduce the resulting change application forms, greatly improve the production efficiency of the construction site, and reduce the cost increase and construction delay caused by construction coordination.

● Construction progress simulation

Building construction is a highly dynamic process, and as construction projects continue to expand in scale and complexity, construction project management becomes extremely complex.

By linking BIM with the construction schedule, integrating spatial information and time information into a visual 4D (3D+Time) model, the entire construction process of the building can be reflected intuitively and accurately. 4D construction simulation technology can reasonably formulate construction plans, accurately grasp the construction progress, optimize the use of construction resources and scientifically arrange the site during the project construction process. , reduce costs and improve quality.

● As-built model delivery

A building as a system, when the construction process is completed and ready to be put into use, first needs to be tested and adjusted as necessary to ensure that it can operate as originally designed. In the handover link after the completion of the project, the property management department needs to obtain not only the conventional design drawings and as- built drawings, but also the documents and materials related to operation and maintenance such as the actual equipment status, material installation and usage, etc. that can be correctly reflected.

BIM can organically integrate building spatial information and equipment parameter information, thereby providing a way for owners to obtain complete building global information. Through the association between BIM and the recorded information of the construction process, it is even possible to realize the integration of completion information including hidden engineering data, which not only brings convenience to the subsequent property management, but also can be used for the owner and the owner in the process of future renovation, reconstruction and expansion. The project team provides valid historical information.

● Maintenance plan

During the service life of the building, the building structure facilities (such as walls, floors, roofs, etc.) and equipment facilities (such as equipment, pipes, etc.) need to be continuously maintained. A successful maintenance program will improve building performance, reduce energy consumption and repair costs, and in turn reduce overall maintenance costs.

The BIM model combined with the operation and maintenance management system can give full play to the advantages of spatial positioning and data recording, reasonably formulate maintenance plans, and assign special personnel to special maintenance work, so as to reduce the probability of emergencies during the use of buildings. For some important equipment, the history of maintenance work can also be tracked, so that the applicable status of the equipment can be judged in advance.

● Asset management

An orderly asset management system will effectively improve the management level of building assets or facilities. However, due to the separation of information between building construction and operation, these asset information needs to be entered by a large number of manual operations in the early stage of operation, and data is prone to appear. Entry error.

A large amount of building information contained in BIM can be smoothly imported into the asset management system, which greatly reduces the time and manpower investment in data preparation for system initialization. In addition, since the traditional asset management system itself cannot accurately locate the asset location, the asset tag chip of BIM combined with RFID can also make the location of the asset in the building and related parameter information clear at a glance.

● Space management

Space management is the management of building space in order to save space cost, effectively use space, and provide a good working and living environment for end users. BIM can not only be used to effectively manage resources such as building facilities and assets, but also help management teams to record space usage, handle end-user requests for space changes, analyze existing space usage, allocate building space reasonably, and ensure that space is properly managed. maximum utilization of resources.

● Disaster emergency simulation

Using BIM and corresponding disaster analysis and simulation software, it is possible to simulate the process of disasters before the occurrence of disasters, analyze the causes of disasters, formulate measures to avoid disasters, and emergency plans for evacuation and rescue support after disasters occur.

When a disaster occurs, the BIM model can provide rescuers with complete information about the emergency situation. Combined with the timely acquisition of building and equipment status information through the building automation system, the BIM model can clearly show the location of the emergency situation inside the building and even find the most suitable route to the point of emergency to improve the effectiveness of emergency operations.

The use of BIM determines the accuracy of the details of the BIM model. According to the current BIM standard, the model accuracy should not be lower than LOD300.

The most widely used BIM software today is Revit. Revit can export data models to various intermediate exchange formats. The data in these intermediate formats can be directly imported into 3D GIS software to realize the data integration of non-exposed space and exposed space.

6.5 CIM

City Information Modeling (CIM) is based on technologies such as Building Information Modeling (BIM), Geographic Information System (GIS), Internet of Things (IoT), and integrates urban above-ground and underground, indoor and outdoor, historical status and future multi-dimensional and multi-scale information model data and data. City perception data, to build a three-dimensional digital space urban information organic complex.

In the non-exposed space digitalization technology system, CIM plays the role of smooth data connection and seamless visual operation and display between non-exposed space and exposed space.

The CIM basic platform is a basic platform for establishing three-dimensional digital models of buildings and infrastructures on the basis of urban basic geographic information, expressing and managing three-dimensional urban space, and a basic operating platform for urban planning, construction, management, and operation. It is the basic, critical and physical information infrastructure of smart cities.

In terms of scope, it is an organic combination of GIS data of large scenes + BIM data of small scenes + Internet of Things. Compared with the traditional GIS-based digital city, CIM refines the data granularity to an electromechanical component and a door inside a single city building, and upgrades the traditional static digital city to a perceptible, dynamic online, virtual-real interactive one. A digital twin city provides a data foundation for agile city management and refined governance.

CIM requirements:

● Hasanopenarchitecture

● Strong multi-source data storage and management capabilities

● Excellentmassdatacarryingandschedulingcapabilities

● Excellent 3D rendering engine

● Multidimensional information fusion and visualization

● Good scalability and rich application functions

● Excellent cross-platform and network portability

● Sufficientstabilityandgoodcompatibility

Commonly used CIM software in China are: Tsinghua CityMaker, SuperMap, Terry Skyline, and some platforms that can provide special capabilities.

6.6 BIMVR

BIMVR (Building Information Modeling in Virtual Reality) is a technical means that combines BIM (Building Information Modeling) and VR (Virtual Reality).

VR virtual reality technology is an important direction of simulation technology. It is a collection of simulation technology and computer graphics human-machine interface technology, multimedia technology, sensing technology, network technology and other technologies. It is a challenging cross-technology frontier. disciplines and fields of study. It can bring users the most realistic visual and even tactile experience. Immersion, interactivity and conception are the three major characteristics of virtual reality technology. Users experience various scenes in virtual space through hardware devices, and through Visual, auditory, tactile and other 8 sensory systems for realistic experience.

For BIM technology, it is an inevitable trend to combine various new technical means, whether it is BIM and VR, BIM and big data, BIM and artificial intelligence, and even BIM and block chain may bring extreme benefits to the engineering industry. big development.

Now design and modeling software can make very real BIM building information models before construction, but the current visual 3D model has great limitations, and most of what it brings to users is look and feel. Combining BIM and VR technology allows users not only to see the model, but also to go deep into it and be immersed in it. Through a 1:1 virtual reality environment, they can truly feel in the model. With the development of VR technology, BIMVR can also allow the experiencer to touch this model. The VR immersive experience strengthens the figurative and interactive functions, and greatly improves the BIM application effect, which can make the digitalization of non-exposed spaces reach a higher and better realm.

At present, the commonly used BIMVR software includes Yida VRBIM, Fuzor, Storyboard VR, Smart-Reality and so on.

6.7 Sensors

Collect and transmit the relevant operation and maintenance data of buildings/facility/equipment through the Internet of Things and sensor technology, and display the data collected by the sensor through the BIM visualization feature, so that the collected data is more intuitively reflected in the model, and the data generation can be viewed in real time. position and relative spatial relationship. It is also possible to reprocess the data collected by the sensor through other settings. For example, if a certain threshold is exceeded, the point will flash an alarm to prompt the management to cause an alarm or perform related processing. Combining sensor technology with BIM can realize the linkage between building operation and maintenance data and BIM model, and provide a 3D visualization platform for building operation and maintenance.

Sensors are an indispensable technical means to realize the digitalization of non-exposed spaces.

6.8 Fiber Optic Transport Network

Optical fiber transmission, that is, data and signal transmission using optical fiber as a medium. Optical fibers can not only be used to transmit analog and digital signals, but also meet the needs of video transmission. Optical fiber transmission is generally carried out using optical cables. The data transmission rate of a single optical fiber can reach several Gbps, and the transmission distance can reach tens of kilometers without using repeaters.

There are several advantages to fiber optic transmission. Compared with the rate of 1.54MHZ per second of copper wire, the operating rate of optical fiber network reaches 2.5GB per second. From the bandwidth point of view, the big advantage is that the optical fiber has a large information capacity, which means that a small size cable can be used, and there is no need to update or enhance the signal in the transmission cable in the future. Fiber optic cables have a high resistance to electromagnetic noise such as radios, motors, or other adjacent cables, making them immune to electrical noise. From the perspective of long-term maintenance, the final maintenance cost of the optical cable will be very low. Optical fibers use light pulses to transmit information along optical lines instead of using electrical pulses to transmit information along cables. Optical fiber transmission has the advantages of low attenuation, wide frequency bandwidth, strong anti-interference, high safety performance, small size and light weight, so it has incomparable advantages in long- distance transmission and special environments. Optical fiber as the transmission medium of optical signal has the characteristics of low loss, the frequency band of optical fiber can reach more than 1.0GHz, the bandwidth of general image is only 8MHz, the image of one channel is more than enough to transmit with one core optical fiber, and it is more than enough to transmit voice, control signal or contact signal. more advantageous. The carrier wave in optical fiber transmission is light wave, and light wave is electromagnetic wave with extremely high frequency, which is far higher than the frequency used in radio wave communication, so it is not disturbed. In addition, the glass material used in the optical fiber is non-conductive and will not generate sparks due to circuit breakage, lightning strikes, etc., so it is highly safe and is especially suitable for flammable, explosive and other occasions.

In the non-exposed space, optical fiber transmission will be the core network of the entire information transmission system.

6.9 Big Data Storage

To build a city information model (CIM) and non-exposed space BIM, it is necessary to efficiently load, browse and apply massive CIM/BIM data, aggregate 2D data, BIM models, oblique photography, white model data, and video and other IoT data to achieve historical The visual display of the integration of status quo planning, integration of ground and underground, integration of indoor and outdoor, integration of 2D and 3D, and 3D video integration provides basic functions such as evacuation simulation, progress simulation, virtual roaming, model management and service API, and builds the data brain of smart cities.

Manage all kinds of data, models, drawings and complete digital projects involved in the CIM platform. The database replaces the model as the information carrier, and realizes the aggregation, processing, storage, management, governance and exchange of engineering data in the whole life cycle. Through the application of system software, the tight integration of information, data and business is realized.

The technology used for big data storage is relatively mature at present, and there are many options, which will not be repeated here.

6.10 Converged Media Instant Messaging

A converged media instant communication system that supports text, voice and video, provides early warning, alarm, notification, announcement and other services for applications and people in non-exposed spaces, and terminals can be accessed through UWB or wifi or 5G/4G communication links , to provide quick communication channels for various customer service in non-exposed spaces.

In the non-exposed space, various types of customer service systems are the basic means to ensure the digitalization of the non-exposed space. It creates a virtual open space and enhances the comfort of people in the non-exposed space. The open instant messaging system of convergent media realizes the rapid and extensive transmission of early warning, alarm and real-time video information, and provides various service interfaces to third-party service systems to realize the interaction between systems and ensure the timeliness of customers or maintenance services.

6.11 Virtual Reality 3D Electronic Sand Table

The virtual reality 3D electronic sand table system is based on basic geographic information data, model data, attribute data, and graphic data, and is a system established by various 3D simulation methods. Data is the basis of the entire system. The basic geospatial information database includes the main scale topographic map (DLG), orthophoto map (DOM), raster map data (DRG), digital elevation model (DEM) data, BIM data and other basic geospatial data.

The virtual reality 3D electronic sand table is widely used in urban planning, military exercises, engineering design, agricultural planning, environmental management and other fields, providing convenient and fast measurement functions. Distance measurement, area measurement, height measurement, model distance measurement, etc.

The electronic sand table established by integrating remote sensing, geographic information system and 3D simulation technology has the following functions:

● The terrain information is accurate

Using the national standard topographic map to establish a digital ground model, it can accurately restore the landform form in proportion, and can also accurately restore the building/facility form of the unshielded space.

● Feature representation in detail

Realistically reflect the same surface morphology as the field, and information such as rivers, vegetation, roads, and residential areas is clear at a glance.

● Intuitive performance of ground objects

The color of satellite remote sensing images, through reasonable band combination and time phase selection, can simulate the scene on the spot, as if you were there.

● Easy to browse

In the three-dimensional electronic sand table, you can zoom and roam arbitrarily, simulate flight, and conduct all-round observation and analysis of the target;

● Terrain information retrieval

You can query the geographic coordinates and altitude of any place.

● Terrain analysis and calculation

The calculation of distance, area and volume can be carried out on it, as well as analysis of visibility, section and submergence.

● Simulation

Fire field, explosion, etc. can be simulated at any position above, and route selection and planning can be performed.

● Three-dimensional ground facilities

The building and other infrastructure are displayed in three dimensions.

● Attribute query

Various information can be directly inquired on the three- dimensional electronic sand table.

● Integrated GPS system

Realize tracking and scheduling directly on the three- dimensional electronic sand table.

In short, through the use of virtual reality three-dimensional electronic sand table, the non-exposed space will be completely transparent.

7.Conclusions

By discussing the use of various technologies in non-exposed space to realize its visualization, perceptibility, tactility and immersive experience, this paper makes the transition between non-exposed space and exposed space smooth in time, space and psychology. This paper builds a complete set of digitalization technology system for non-exposed space, and discusses the key technologies.

Non-exposed space is an emerging new field, and it is also the only way for the construction and development of new cities. Make good use of non-exposed space to provide better convenience and services for people's lives, comprehensive use of various technologies, and greater Explore space.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Author Contributions

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Application of BDS in Africa: Current Status, Issues, and Challenges

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Abstract

This paper examines the application of China's BeiDou Navigation Satellite System (BDS) in Africa, analyzing its current status, challenges, and future prospects. As a global navigation satellite system, BDS has achieved global coverage and offers high-precision positioning, navigation, and timing services. Africa, with its rapid urbanization and infrastructural expansion, presents a strategic market for BDS deployment. Under the Belt and Road Initiative, China and African nations have deepened technological collaborations, with BDS playing a pivotal role in sectors such as agriculture, logistics, and public safety. However, BDS adoption in Africa faces hurdles including infrastructural gaps, competition from Western systems like GPS, and technical and market barriers. This paper highlights successful application cases of BDS in Africa, such as in road transport, railway industry, precision agriculture, and international search and rescue. It also identifies key challenges, including the first-mover advantage of European and American navigation companies, political and economic instability in Africa, technical and infrastructure bottlenecks, and difficulties in integrating new technology fields with local industries. The paper proposes strategies to enhance BDS adoption in Africa, such as strengthening policy support, promoting technical training and talent development, and supporting infrastructure development. Future opportunities for BDS in Africa are discussed, particularly in smart agriculture, infrastructure construction, public safety, and emerging industries like smart cities and autonomous driving. The paper concludes that BDS has broad application prospects in Africa and can significantly contribute to Africa's economic and social development through continuous technological innovation and international cooperation.

Keywords: BeiDou Navigation Satellite System (BDS), Africa, Global Navigation Satellite System (GNSS)

1.Introduction

Satellite navigation systems have emerged as indispensable tools for modern infrastructure development, spanning transportation, agriculture, disaster management, and urban governance. As one of the four global navigation satellite systems (GNSS), China's BeiDou Navigation Satellite System (BDS) has achieved global coverage since 2020, offering high-precision positioning, navigation, and timing (PNT) services to over 120 countries. Africa, characterized by rapid urbanization and infrastructural expansion, presents a strategic market for BDS deployment. Under the Belt and Road Initiative (BRI), China and African nations have deepened collaborations in technological innovation, with BDS playing a pivotal role in sectors such as agriculture, logistics, and public safety. However, despite its transformative potential, BDS adoption in Africa faces hurdles ranging from infrastructural gaps to entrenched competition from Western systems like GPS. This paper analyzes the current applications of BDS in Africa, identifies region-specific challenges, and proposes actionable strategies to enhance its adoption.

2.Overview of the BDS

2.1. The Development of BDS

The BeiDou Navigation Satellite System (BDS) is a global satellite navigation system independently developed by China. After years of development, it has become one of the four major global satellite navigation systems. The construction of the BDS can be divided into several stages: the experimental stage of the BeiDou-1 system, the regional coverage stage of the BeiDou-2 system, and the global coverage stage of the BeiDou-3 system. The completion of the BeiDou-3 system marks a breakthrough in China's satellite navigation technology, enabling the BDS to provide global positioning, navigation, and timing services.

The Composition and Working Principle of BDS consists of three main parts: satellites, ground control stations, and user terminals. Satellites are the core of the BDS, providing positioning, navigation, and timing services by emitting signals. The BeiDou-3 system is composed of 24 operational satellites and 3 backup satellites, which are distributed in different orbital planes to ensure global coverage. Ground control stations are responsible for monitoring, controlling, and updating data for satellites to ensure the normal operation of the satellite system. User terminals are the devices that finally receive BDS signals and are widely used in fields such as mobile phones, automobiles, agricultural machinery, and drones, providing precise positioning and navigation services.

2.2. Comparison with Other Satellite Navigation Systems

Compared with other global satellite navigation systems such as the US GPS, Russia's GLONASS, and Europe's Galileo, one of the biggest advantages of the BDS is its innovation in service quality and positioning accuracy. BDS not only provides conventional positioning services but also has a unique "return link" function that can send confirmation messages to people in distress, which is of great importance in the global search and rescue system. Compared with the GPS system, BDS also has stronger anti-jamming capabilities, especially in complex environments such as multipath and urban canyons.

In addition, BDS has also innovated in the scope of services. Its coverage area has expanded from the initial China and surrounding regions to the global level, becoming a choice for global users. In terms of accuracy, BDS can provide sub-meter-level accuracy and provide higher accuracy services for professional users, meeting the needs of different levels of applications.

2.3. The Global Layout of BDS

The completion and commissioning of the BeiDou-3 system have not only enhanced China's influence in the global navigation field but also provided reliable navigation services for countries around the world. At present, the BDS has covered the globe, and under the framework of the Belt and Road Initiative, it has become an important part of China's foreign technological assistance, helping countries along the route to improve infrastructure construction and enhance the technological level of transportation, agriculture, and emergency management. The global layout of the BDS has gradually penetrated emerging markets such as Africa, Southeast Asia, and Latin America. In these regions, especially in Africa, the positioning, navigation, and timing services of the BDS have brought positive impacts to local infrastructure construction and socio-economic development. The cooperation between China and Africa has also provided a good opportunity for the BDS to enter the African market, not only helping African countries solve problems in traffic management, agricultural production, and public safety but also promoting economic cooperation and technological exchanges between China and Africa.With the continuous acceleration of the internationalization of the BDS, more and more countries are choosing to introduce BDS technology, especially in fields such as transportation, agriculture, and mining, the application of the BDS system is continuously expanding. The Chinese government and enterprises are also actively promoting the compatibility and cooperation of the BDS system with other global navigation systems to ensure the competitiveness of the BDS in the global navigation field.

3.Applications of BDS in Africa

3.1. The Demand for Satellite Navigation in Africa

With the rapid advancement of infrastructure construction in Africa, the demand for satellite navigation technology in various countries is increasing. Fields such as transportation, agriculture, and environmental monitoring all rely on high-precision positioning technology to improve work efficiency and safety. For example, large-scale infrastructure projects in Africa often face issues such as insufficient geographical information accuracy, weak traffic management capabilities, and uneven resource allocation. The BDS, with its advantages in providing precise positioning and real-time data updates, can effectively address these issues and provide significant support for the modernization efforts of African countries.

3.2. Feasible Application Cases of BDS in Africa

3.2.1. Road Transport and Vehicle Management

Transportation management is a key area for improving national infrastructure and economic development in Africa. Many countries face issues such as weak traffic management, imprecise transportation scheduling, and significant safety hazards. The introduction of BDS technology has not only improved the real-time monitoring and scheduling management of transport vehicles but also effectively enhanced traffic safety. Taking the cross-border transport monitoring system in South Africa and Zambia as an example, South Africa's BRISK FAST company has adopted high-precision positioning terminals from BDS. By installing BDS vehicle terminals on cross-border transport trucks, real-time positioning, scheduling, and monitoring of transport vehicles have been achieved. These vehicles, traveling long distances between the Democratic Republic of the Congo, Zambia, Botswana, and South Africa, can now obtain real-time data on vehicle location, speed, and status. Through the data transmission system, dynamic monitoring and safety management have been realized. The application of this system has significantly improved transport efficiency and ensured the safety of the transport process. Through the BDS, transport companies can now understand the exact location of each vehicle in real time, schedule them promptly, avoid traffic accidents, and effectively reduce operating costs. Moreover, Zambia's sulfuric acid transport company, Wideway, has also adopted high-precision positioning technology from BDS. By integrating a remote monitoring system, the company can now track in real time the transport vehicles, the status of drivers, and the transportation of hazardous materials, minimizing the risks associated with hazardous material transport. This application not only enhances transport safety but also strengthens management capabilities, especially in cross-border transport, providing important technical support.

3.2.2. Railway Industry Applications

The construction and operation of railways are crucial for the development of African countries, especially in rapidly growing economies where railways serve as vital links for connecting cities, promoting trade, and facilitating transportation. The application of BDS in the railway industry mainly focuses on track measurement, train scheduling, and train operation safety. With the high-precision positioning services provided by the BDS, railway departments can monitor the real-time status of trains, optimize transportation scheduling, and ensure safe operation. Taking the track measurement of China's Beijing-Shenyang High-Speed Railway as an example, the high-precision positioning technology of BDS has played a key role in the measurement of the geometric shape of the railway tracks. In this application, the BDS has helped construction workers to carry out track measurements quickly and accurately, improving construction efficiency and significantly reducing safety risks. In Africa, the BDS has also begun to be applied in some important railway projects, such as the Addis Ababa-Djibouti Railway. The project has adopted the BDS for track measurement, infrastructure monitoring, and train scheduling, successfully enhancing the quality of railway construction and construction safety.

3.2.3. Precision Agriculture Applications

Agriculture is the backbone industry of many African countries, and precision agriculture technology can effectively improve production efficiency and reduce resource waste. In the field of agriculture, the application of BDS technology, especially in agricultural machinery autonomous driving and drone plant protection, has significantly improved agricultural production efficiency.

Taking Mozambique as an example, the country has introduced agricultural machinery autonomous driving systems and drone plant protection systems based on BDS in its large-scale rice cultivation projects. In these projects, agricultural machinery is precisely controlled through the BDS to achieve autonomous driving and accurately complete operations such as plowing, fertilizing, and harvesting. The application of agricultural machinery automation has not only improved the accuracy of operations but also significantly reduced labor costs and increased land utilization. In addition, BeiDou drone plant protection technology has been used for efficient pesticide spraying, which not only improves the efficiency of pesticide application but also reduces environmental pollution and resource waste.

Furthermore, the remote maintenance services of the BDS have also shown great advantages in agricultural machinery management. Through BeiDou and Internet of Things technology, data such as the operating status, fault conditions, and work progress of agricultural machinery can be fed back to the management center in real time, providing precise information for subsequent maintenance and services.

3.2.4. Land Surveying and Infrastructure Construction

Land surveying and infrastructure construction are core components of Africa's rapid development, especially in the process of land management and urban planning in many countries, where precise surveying technology is crucial. BeiDou/GNSS high-precision technology has been widely used in land measurement, urban planning, and infrastructure projects in many African countries, helping to improve surveying accuracy, reduce external interference, and increase work efficiency.

For example, Uganda introduced BeiDou high-precision positioning technology in land surveying and infrastructure construction, which helped the country successfully establish multiple reference stations and improve the efficiency of land management and urban construction. Burkina Faso used BDS to complete rapid terrain surveys when constructing a field hospital, which not only shortened the project time but also significantly increased the speed of hospital construction and contributed to the construction of public health infrastructure.

3.2.5. International Search and Rescue and Public Safety

Some African countries face frequent natural disasters, especially maritime shipping accidents and aviation search and rescue issues. The application of the BeiDou International Search and Rescue System has effectively enhanced the emergency response capabilities in the African region, especially in maritime and aerial rescue operations. Through the precise positioning of the BDS, rescuers can quickly obtain the location information of those in distress, thereby increasing the success rate of search and rescue operations. Since the launch of the BeiDou International Search and Rescue Service in 2020, several African countries have begun to adopt this system. By manually or automatically triggering distress beacons to send alarm signals, the rescue center can accurately locate distressed ships, aircraft, or personnel after receiving the alarm. The application of this system has played a positive role in enhancing the maritime search and rescue capabilities of African countries and can timely mobilize rescue forces in emergencies.

3.2.6 Digital Construction Applications

BDS technology has revolutionized infrastructure development in Africa by enabling real-time quality control and data-driven project management. For instance, in Senegal's Thiès-Touba Highway project, engineers integrated BDS-enabled IoT sensors into construction machinery to monitor asphalt compaction density and temperature in real time. The system utilized BDS positioning to tag each compaction point's coordinates, automatically comparing results against design specifications. Non-compliant segments were flagged for immediate rework, reducing material waste and ensuring uniform roadbed quality. The project also tracked concrete mixer trucks via BDS-GSM terminals, optimizing delivery routes and shortening idle times.

In parallel, China's Shuangliao Highway project demonstrated cross-domain innovation by merging BDS with Building Information Modeling (BIM). GNSS-guided rollers and pavers synchronized with BIM databases, enabling millimeter-level alignment of road layers. Post-construction audits leveraged BDS-recorded trajectory data to verify compliance, achieving integrity for regulatory reviews. Such methodologies offer African nations scalable templates for transparent, corruption-resistant infrastructure governance.

3.2.7. Smart Mining Solutions

BDS addresses Africa's mining sector challenges through full-process digitization, from resource extraction to cross-border logistics. In Mongolia's Tavan Tolgoi coal mine, BDS terminals were deployed to track mining vehicles, crushers, and customs-bound trucks. The system combined geofencing (using BDS/GLONASS dual-mode positioning) with weight sensors to detect unauthorized excavation: if machinery operated outside permitted zones or cargo loads exceeded thresholds, real-time alerts triggered regulatory interventions. Proposed collaborations for Africa include adapting this model to the Congo (DRC)-Zambia copper belt, where BDS could monitor artisanal mining activities and prevent smuggling. Additional pilots in Sudan's gold mines aim to integrate BDS with blockchain for tamper-proof mineral traceability, aligning with OECD due diligence requirements.

3.2.8. Wildlife Conservation

BDS empowers precision ecology management through biometric telemetry collars and habitat mapping. In China's Northeast Tiger and Leopard National Park, the Amur tiger "Wandashan No.1" was fitted with a BDS collar transmitting hourly updates (location, ambient temperature, pulse rate) via BeiDou Short Message Communication (SMC). This data revealed migration patterns, enabling rangers to deter poachers and mitigate human-wildlife conflicts. Notably, the system functioned in deep forest cover where conventional GPS failed.

For Africa, similar collars are proposed for Kenya's elephant corridors and Gabon's forest elephants. BDS-enabled drones could supplement anti-poaching efforts by mapping ivory trafficking routes, while SMC-based alerts would allow real-time coordination between ranger teams across remote reserves.

3.2.9. Smart City Development

BDS underpins Africa's urban digital transformation through high-precision spatiotemporal frameworks. In Deqing County, Zhejiang, BDS fused with 3D city models and AI analytics to optimize traffic light sequencing, reducing rush-hour congestion. Municipal inspectors utilized BDS wearables to geotag potholes and faulty streetlights, streamlining repair workflows. The system also monitored industrial zones for unauthorized emissions, correlating BDS-tracked truck movements with air quality sensor data to identify polluters.

Meanwhile, Chongqing's BDS Common Service Platform demonstrated cross-sector utility, supporting flood prevention via real-time subsidence monitoring of levees and underground pipe networks. Such models are adaptable to African megacities like Lagos or Nairobi, where BDS could enhance flood resilience and informal settlement mapping.

3.2.10. Cross-domain Synergies

The synergistic integration of BDS with IoT, AI, and 5G amplifies its impact across Africa's SDG priorities. For example, Burkina Faso's hospital construction project combined BDS surveying with drone photogrammetry to accelerate site planning—a replicable approach for disaster-relief housing. Similarly, Ethiopia's Grand Renaissance Dam could adopt BDS deformation monitoring to ensure structural integrity amid seismic risks.

Key to scale is localized infrastructure: China's proposal for a Pan-African GNSS Augmentation Network would enable cm-level positioning continent-wide, while joint R&D centers in South Africa and Egypt could tailor solutions for desert agriculture or coastal erosion monitoring.

4.Problems and Challenges Faced by BDS in Africa

4.1. First-Mover Advantage of European and American Navigation Companies

Navigation systems from European and American countries, especially the US GPS and Europe's Galileo, have long dominated the global market. GPS, which began operation in the early 1980s, has undergone decades of technological accumulation and market expansion and has become a globally accepted standard positioning system. Leveraging their early market entry, these European and American brands have established a deep market presence in many countries worldwide, particularly in Africa.

In Africa, many governments and enterprises are accustomed to using the GPS system. The high market influence and internationalization of European and American brands have created significant competitive pressure for the promotion of the BDS. GPS has become the default positioning system for many African government departments and enterprises, leading to a long-term technological dependence. As a result, it is challenging to promote the BDS in the African market, especially when it comes to replacing or being compatible with existing systems.

4.2. Political and Economic Challenges

The instability of the political and economic environment in Africa poses significant challenges to the promotion of BeiDou. Many African countries have experienced long-term political unrest, wars, coups, and other destabilizing factors, resulting in a complex and volatile market environment. Government policies and support often fail to remain consistent over time. In this political climate, Chinese BeiDou companies may face risks associated with government changes and policy shifts. In some countries, the operations of foreign enterprises are particularly susceptible to the influence of the political situation.

Moreover, the significant currency fluctuations and severe devaluation in most African countries directly impact the return on investment for foreign enterprises. The instability of currency values suppresses the purchasing power of many African countries. In some poorer nations and regions, the high cost of BeiDou products and technologies may become a major barrier to their promotion. In such cases, the market expansion of the BDS is often adversely affected by the macroeconomic environment.

4.3. Technical and Infrastructure Bottlenecks

Africa's relatively weak infrastructure, particularly in terms of network and energy, restricts the widespread application of satellite navigation technology. Firstly, many African countries have incomplete internet and communication infrastructure. In remote areas, the lack of full network coverage prevents satellite navigation systems from achieving comprehensive coverage and efficient operation. As a satellite-based high-precision positioning system, BeiDou relies on stable ground networks and communication infrastructure for data transmission and system monitoring.

Secondly, the instability of energy supply is also a significant issue. In many African regions, insufficient or intermittent electricity supply affects the operation of related hardware devices and systems. Without stable power support, the application and data transmission of the BDS cannot be efficiently carried out, further impacting the technology's dissemination and effectiveness.

Furthermore, certain application scenarios of the BDS, such as autonomous driving and intelligent transportation, face technological barriers in Africa despite their high market potential. These emerging technologies typically require robust technical support and a localized industrial base. However, many African countries' underdeveloped technology industries prevent a close integration with BeiDou's advanced technologies. The promotion of technologies like autonomous driving and drones in Africa is still constrained by infrastructure and technological levels.

4.4. Difficulties in Integrating New Technology Fields with Local Industries

The potential for BeiDou applications in emerging technology fields such as autonomous driving, driverless vehicles, and drones is substantial, but the promotion of these technologies in Africa faces significant challenges. Firstly, the level of traffic management and infrastructure in Africa is relatively low, lacking intelligent transportation systems and modern urban planning. The application of autonomous driving technology is confronted with substantial difficulties. In some African countries, poor road conditions, chaotic traffic order, and the absence of basic traffic management facilities further complicate the promotion of autonomous driving technology.

Secondly, drones and driverless technologies have broad application prospects in fields such as agriculture, logistics, and security. However, the low degree of industrialization in African countries and the lack of relevant supporting industries and technical personnel pose significant barriers. These technologies require strong local research and development as well as industrial support. Moreover, they need to be integrated with the existing industrial base in Africa to better meet market demands. However, due to the relatively backward level of science and technology and industrial foundation in Africa, the integration of emerging technologies with local industries faces considerable difficulties.

4.5. Market Competition and Participation

Although the application of BeiDou in Africa is gradually expanding, the scale of BDS enterprises' operations in Africa is relatively small, and their market participation is relatively low. In particular, in the competition for large-scale projects, BDS still faces certain disadvantages. Governments and enterprises in most African countries, especially in important infrastructure construction and high-tech projects, still tend to choose well-established and reputable European and American brands. In addition, European and American enterprises have more complete resources, technology, and service networks in the African market, giving them strong competitiveness.

At present, the operations of Chinese BDS enterprises in Africa are mostly concentrated in small and medium-sized projects and equipment supply. It is difficult for them to participate in large-scale, government-led infrastructure construction. Compared with European and American navigation enterprises, BDS enterprises are relatively weak in international operation, market promotion, and after-sales service. This limits the competitiveness of BDS in the African market.

5.Promotion Experience and Reflections of BDS in Africa

5.1. Promotion Model of Chinese BeiDou Enterprises

Chinese BeiDou enterprises have adopted flexible market promotion strategies during the promotion process in Africa, focusing on cooperation with local enterprises to drive the adaptive application of BeiDou products. Compared to European and American companies, Chinese BeiDou enterprises place greater emphasis on collaborating with local firms when entering the African market. They combine technology transfer with localized development to promote the widespread application of the BDS in Africa.

Firstly, Chinese BeiDou enterprises work with local African government departments, research institutions, and companies to jointly promote the localized application of BDS. Through this cooperative model, BeiDou products can be customized to meet local demands and leverage local resources for market promotion. For example, in key areas such as transportation, agriculture, and infrastructure construction, Chinese BeiDou enterprises have partnered with local African firms to successfully integrate BDS into the specific needs of these industries, achieving product localization and market penetration.

Moreover, cooperation with African enterprises enables BeiDou companies to effectively reduce market promotion costs and accelerate technology dissemination. Local firms have a deeper understanding of the market environment and demands, which helps the BDS better adapt to Africa's unique conditions. For instance, in the agricultural sector, Chinese BeiDou enterprises have introduced drone and agricultural machinery autonomous driving technologies based on BeiDou through cooperation with local agricultural cooperatives, significantly enhancing agricultural production efficiency and precision.

5.2. Successful Cooperation and Market Penetration

To further promote the application of the BeiDou Navigation Satellite System in Africa, BeiDou enterprises and the Chinese government have strengthened technical exchanges and cooperation between China and Africa through regular cooperation forums and exhibitions. These activities not only provide Chinese BeiDou enterprises with opportunities for face-to-face communication with African governments and businesses but also enhance the visibility and influence of BeiDou in the African market by showcasing the advantages and application cases of BDS.

For example, the regularly held China-Africa BeiDou Cooperation Forum has become an important platform for discussion and problem-solving between the two sides. Through such forums, BeiDou enterprises can introduce application cases and successful experiences of the BDS to African countries, demonstrate the great potential of BDS in fields such as transportation, agriculture, and emergency management, and deepen the understanding of the BDS among African nations. These forums and exhibitions not only promote the publicity of BeiDou products but also open up more opportunities for cooperation between China and Africa.

Through these successful cooperation and market penetration activities, BeiDou enterprises can not only establish brand images in the African market but also support local technological development and promote cooperation in multiple fields such as science and technology and economy.

5.3. Strategies to Promote China-Africa Cooperation

To further facilitate the promotion of BeiDou in Africa, both BeiDou enterprises and the Chinese government need to continue to deepen China-Africa cooperation. Firstly, policy support is crucial for the promotion of the BDS in Africa. The Chinese government can assist African countries in better understanding and accepting BDS by providing policy guidance, financial support, and technical assistance. Through cooperation with the governments of various African countries, relevant policies can be formulated to ensure the long-term development of the BDS in Africa.

Secondly, technical training and talent cultivation are also important strategies for promoting the popularization of BDS. China can help African countries train technical personnel related to satellite navigation systems and enhance the capabilities of local enterprises and governments in the application of BDS by dispatching technical experts, holding training courses, and conducting field visits. In addition, establishing BDS research centers and cooperative laboratories in Africa can also help local enterprises better understand the application scenarios of BDS, thereby promoting localized technological innovation.

Infrastructure development is another key factor in promoting the widespread use of BeiDou in Africa. Given that infrastructure in many African regions is relatively weak, especially in terms of network, power supply, and data transmission, the promotion of the BDS relies on the development of these infrastructures. Therefore, BeiDou enterprises can collaborate with African governments and businesses to advance the construction of relevant infrastructure projects, providing a solid foundation for the application of the BDS. For example, building BeiDou reference stations and providing satellite communication technical support are important steps to strengthen BeiDou's market penetration in Africa.

Furthermore, BeiDou enterprises can also promote the application of BDS in more fields through technical cooperation and research projects with African countries. For instance, in emerging technological fields such as precision agriculture, smart cities, and drones, the BDS can be deeply integrated with local technological industries to drive industrial upgrading and technological innovation.

6.Future Development Opportunities

6.1. Growth in Market Demand

6.1.1. Expanding Demand in Smart Agriculture, Infrastructure Construction, and Public Safety

Africa is undergoing rapid urbanization and a demand for agricultural modernization, with significant potential for the application of satellite navigation technology in fields such as smart agriculture, infrastructure construction, and public safety. Amidst global climate change, land degradation, and population growth, the need for efficient agricultural production in Africa is on the rise. Precision agriculture technologies, particularly the application of BeiDou satellite navigation technology, can effectively help farmers increase land use efficiency, reduce resource waste, and boost crop yields. For instance, agricultural machinery equipped with BeiDou can achieve autonomous driving, thereby enhancing plowing efficiency and reducing labor costs.

In terms of infrastructure construction, African countries are actively promoting projects in transportation networks, urban development, power, and water conservancy. BeiDou can provide high-precision surveying and positioning services, offering technical support for infrastructure construction in Africa. In many African countries, especially those with limited resources, the low-cost, high-precision advantages of BeiDou are particularly important. As the demand for infrastructure in Africa continues to grow, BeiDou will face broader market opportunities in the construction of roads, railways, bridges, airports, and other facilities.

Moreover, public safety is another crucial area for BeiDou's future development in Africa. With the increasing complexity of social order, especially in traffic safety, urban management, and emergency response, BeiDou's precise positioning and real-time data transmission capabilities can help enhance the emergency response capabilities of government departments and relevant enterprises, ensuring the safety of people's lives and property. For example, in regions prone to natural disasters, BeiDou can provide rapid and accurate disaster warnings, search and rescue support, and emergency communication services, offering vital technical support for public safety management.

6.1.2. Potential Demand for BDS in Emerging Industries

With the rapid development of emerging industries, especially in the fields of autonomous driving, smart cities, and the Internet of Things, the application of BeiDou will become more extensive and in-depth. Autonomous driving technology, as an important part of future transportation systems, has a huge demand for high-precision, high-reliability satellite navigation systems. BeiDou can not only provide accurate location data for autonomous driving but also share data with other sensors and systems to ensure the safe operation of autonomous vehicles. As African countries gradually invest in intelligent transportation and automation, BeiDou will have more opportunities for application in this field.

Smart cities are an important direction for future urban development, and satellite navigation systems play a vital role in their construction. BeiDou can provide high-precision spatiotemporal data support for cities, used in multiple aspects such as traffic flow management, urban infrastructure monitoring, and energy management. With the acceleration of urbanization in Africa, the construction of smart cities will become an important market demand, and BeiDou will play a significant role in Africa's smart city projects.

6.2. Technological Innovation and International Cooperation

The future development of BeiDou in the African market will rely on technological innovation and international cooperation. First, technological innovation is the core driving force for the wider application of BeiDou in Africa. Through cooperation with research institutions and enterprises in African countries, China can further promote the localization of BDS. For example, by combining the unique geographical environment and application needs of Africa, more products and services that are adapted to the local market can be developed, such as low-cost, easy-to-maintain BeiDou terminal devices designed specifically for the African market.

Driven by technological innovation, BeiDou will see new application forms in multiple fields such as agriculture, transportation, and public safety. For example, by integrating BeiDou with Internet of Things technology, intelligent management solutions can be provided for African agriculture, achieving functions such as intelligent field monitoring, precision irrigation, and remote monitoring. In addition, BeiDou-based intelligent transportation systems and smart city solutions will also offer solutions for the urbanization process in African countries, further enhancing BeiDou's influence in the region.

Second, international cooperation will be key to enhancing BeiDou's influence in the African market. Through cooperation with African national governments, international organizations, and local enterprises, BeiDou can better integrate into Africa's technological ecosystem and economic environment. Cooperative projects under the China-Africa cooperation framework, especially those promoted by the Belt and Road

Initiative, provide broad opportunities for the application of BDS in Africa. Through forms of cooperation such as joint research, technical training, and infrastructure development, BeiDou can help African countries improve their technological levels and promote economic development, while also providing more innovative application cases for the global market.

In the future, BeiDou can also cooperate with other international navigation systems to explore more cross-system application scenarios. For example, interconnectivity with systems such as GPS and Galileo can provide more stable and efficient positioning services for global users, enhancing BeiDou's competitiveness in the international market.

7.Conclusion

7.1. Prospects and Potential of BDS in Africa

The application prospects of the BeiDou Navigation Satellite System in Africa are very broad. With the construction of infrastructure and the rapid economic development in African countries, the market potential of BeiDou will be further unleashed. Africa's demand for high-precision positioning technology is increasing in many fields such as transportation, agriculture, public safety, land surveying, and emergency management. With its high precision, low cost, and global coverage, the BDS can provide solutions for African countries. In the next few years, BeiDou will further penetrate the African market and become an important technological force in promoting Africa's economic and social development.

Especially in the fields of smart agriculture and precision agriculture, with the modernization of agricultural production in Africa, the BDS can improve agricultural production efficiency, reduce costs, and increase farmers' income through automated and intelligent technological support. In addition, with the acceleration of urbanization in African countries, the construction of smart cities and intelligent transportation will bring new market demands, and the BDS will play an important role in these emerging industries.

Moreover, the application of the BDS in the field of public safety, such as disaster early warning, emergency rescue, and disaster relief command systems, will also receive more attention due to the frequent natural disasters in Africa. Through cooperation with the governments of African countries and international organizations, the BDS will play an increasingly important role in Africa's rescue and emergency response fields.

7.2. Implications for Chinese BeiDou Enterprises and Their Globalization Strategy

The application of the BDS in Africa is not only the promotion at the technical level but also a part of the globalization strategy of Chinese BeiDou enterprises. Through successful applications in Africa, BeiDou enterprises can provide strong technical support for other emerging markets around the world and enhance their competitiveness in the international market through cooperation with local enterprises and governments.

Firstly, BeiDou enterprises need to strengthen cooperation with local African enterprises and governments to promote the localization and adaptive application of technology. Cooperation with African countries can not only promote the popularization of BeiDou products but also help enterprises take root in the local market and form long-term cooperative relationships. In addition, actively participating in China-Africa cooperation forums, exhibitions, and other activities, and strengthening the brand promotion and market penetration of BeiDou, will help enhance the international influence of Chinese BeiDou.

Secondly, Chinese BeiDou enterprises should also further strengthen technological innovation to meet the needs of different countries and regions. Continuous innovation in BDS and flexible market strategies will provide strong support for Chinese BeiDou enterprises to stand out in the global market.

7.3. Policy Recommendations and Development Pathways

7.3.1. Strengthening Policy Support

Governments of African countries should increase policy support for satellite navigation technology, especially in key areas such as infrastructure construction and agricultural modernization. The Chinese government can promote the popularization of the BDS in Africa through forms such as technical assistance, policy support, and financial support. At the same time, strengthening cooperation and exchanges between China and Africa in the field of satellite navigation will create a dual effect of policy guidance and market promotion.

7.3.2 Promoting Technical Training and Talent Development

The promotion of the BDS in Africa relies not only on the introduction of hardware equipment but also on the cultivation of local technical personnel. Chinese BeiDou enterprises should cooperate with African universities and research institutions to carry out talent training and technical exchanges in relevant fields. By regularly holding technical training courses and cooperative research projects, African countries can establish a complete technical team to promote the localized application of BDS.

7.3.3 Supporting Infrastructure Development

Given the weak infrastructure construction in some parts of Africa, especially in the fields of network and electricity, BeiDou enterprises can work with African countries to carry out infrastructure projects to provide necessary support for the widespread application of satellite navigation technology. At the same time, African governments are encouraged to incorporate BDS into infrastructure construction to promote its integrated application in more fields.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Author Contributions

The author conducted all research and wrote the manuscript.

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A Comparative Legal Study on the Attribution of Liability for Autonomous Driving Accidents in China and Germany

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Abstract

The rapid advancement of autonomous driving technology has introduced complex challenges in attributing legal responsibility for traffic accidents. Balancing technological innovation with the preservation of social justice has become a pressing concern for both legislators and judicial authorities. This paper conducts a comprehensive analysis of Germany's recent reforms to the Road Traffic Act and the European Union's legislative developments in the Artificial Intelligence Act, focusing on models of accident liability distribution. It further integrates an examination of China's local regulations—particularly those in Shenzhen and Beijing—and relevant provisions from higher-level laws such as the Civil Code. Special attention is given to the logic of liability allocation in Level 3 and above autonomous driving systems, the delineation of driver obligations, the attribution framework for manufacturers, and the issue of algorithmic black-box explainability. The study argues that Germany's layered liability model—centered on the reduction of driver duty of care and the imposition of continuous obligations on manufacturers—along with mechanisms such as mandatory accident data recording, ethical sandboxing, and insurance frameworks, offers a valuable institutional reference for China. It recommends that China develop a unified Autonomous Driving Law to clarify liability attribution across different levels of automation, establish algorithmic governance mechanisms, and define insurance compensation pathways, thereby fostering a governance model that integrates technological rationality with rule-of-law guarantees.

Keywords: autonomous driving; accident liability; layered responsibility model; China-Germany comparison

1.Introduction

As one of the most representative real-world applications of artificial intelligence, autonomous driving technology is rapidly reshaping global transportation ecosystems and the structure of legal systems. According to prevailing international classification standards, autonomous vehicles are categorized into six levels (L0 to L5) based on the degree of intelligence and automation. True autonomous driving typically refers to high-level autonomous systems (Levels 3 to 5), in which the system assumes control over dynamic driving tasks once activated. In contrast, in Levels 0 to 2, the human driver remains the principal decision-maker. Specifically, in Level 3 systems, a fallback driver must be ready to take over when necessary. In Levels 4 and 5, human intervention is no longer required, as the system is responsible for all driving functions—the distinction between the two lies primarily in their respective operational design domains. This paper focuses exclusively on vehicles equipped with Level 3 to Level 5 autonomous driving systems.

As autonomous driving moves from the laboratory into large-scale commercial deployment, existing legal systems face unprecedented challenges in governing emerging technologies. Since 2010, countries and regions including Germany, the European Union, and China have successively promoted the implementation of high-level autonomous driving systems (L3–L5), followed by legislative measures aimed at regulating responsibility attribution and data governance. Notable examples include the Eighth Amendment to Germany's Road Traffic Act (*Straßenverkehrsgesetz*), the draft of the Compulsory Motor Vehicle Insurance Act, the EU's Artificial Intelligence Act, and, in China, the Pilot Program for Intelligent Connected Vehicle Access and Road Use as well as the Shenzhen Special Economic Zone Regulations on Intelligent Connected Vehicles. These legal instruments together form a multi-dimensional regulatory framework encompassing access and testing requirements, liability attribution, data compliance, and ethical oversight. Among these, the issue of accident liability stands out as a central legal challenge in a technologically evolving society, as it involves personal injury compensation, criminal liability, and insurance mechanisms.

Despite significant differences between Germany and China in terms of legal system structures, doctrinal traditions, and technological trajectories, both jurisdictions face common challenges in attributing responsibility for autonomous driving accidents. These include the opacity of algorithmic "black boxes," ambiguous standards regarding driver attentiveness, and manufacturers' limited control over algorithmic behavior.

This paper undertakes a systematic comparative study of China and Germany's legislative approaches, attribution logic, and institutional frameworks, integrating the latest legislative developments and landmark cases. It aims to propose an explanatory and operationally feasible "China model" for regulating liability in autonomous driving.

2.Germany's Legal Framework for Liability Attribution in Autonomous Driving

2.1. Legislative Structure and Ethical Institutional Design

Germany was among the first countries in the world to establish a dedicated legal framework for high-level autonomous driving systems. Its regulatory model reflects a tripartite structure encompassing: (1) national-level legislation; (2) ethical guidance mechanisms; and (3) supporting insurance provisions. This structure operates across three levels—federal legislation, state-level regulatory practice, and European Union law.

At the federal level, the 2017 Eighth Amendment to the Road Traffic Act (Straßenverkehrsgesetz, StVG) is regarded as a legislative milestone in the field of autonomous driving. It formally incorporated SAE Level 3 systems into the legal framework for public road use and recognized the "technical supervisor" (Technisch Verantwortlicher) as the legal driver in certain operational scenarios. This amendment introduced the concept of a “takeover-capable system,” requiring that vehicles must provide drivers with a minimum response window of 10 seconds upon issuance of a takeover request. This reflects the German legislature’s deliberate balance between technical feasibility and human factors engineering. In addition, the amendment mandates event data recording (Pflicht zur Ereignisdatenaufzeichnung) as a legal obligation, thereby establishing a factual basis for subsequent liability attribution and accident reconstruction.

In 2021, the German Federal Ministry of Transport proposed a draft amendment to the Compulsory Motor Vehicle Insurance Act (Pflichtversicherungsgesetz, PflVG), aiming to expand the statutory regime to cover Level 4 and Level 5 autonomous vehicles. Key components of this draft include: (1) Technical Supervisor System (Technischer Aufsichtsperson): For fully autonomous vehicles (L4-L5), the draft introduces a remote supervisory responsibility model. The designated supervisor is tasked with monitoring system status, validating abnormal responses, and managing data preservation. (2) Expansion of Mandatory Insurance Coverage: The draft extends coverage to include personal injuries caused by autonomous system failures and introduces a right of recourse against manufacturers, thereby operationalizing a “pay first, recover later” risk-buffering model. (3) Institutionalization of Ethical Review: Manufacturers are required to submit ethical compliance reports detailing the value judgments embedded in their decision-making algorithms, especially for scenarios involving harm distribution dilemmas such as the classic “trolley problem.”

In addition to national legislation, several German federal states have initiated experimental regulatory projects, most notably the “Ethics Sandbox for Autonomous Driving” (Ethiksandbox Autonomes Fahren). For example, in Rüsselsheim, Hesse, a pilot operational zone for L3 and above systems mandates the installation of Event Data Recorders (EDRs) to capture system-issued takeover prompts, driver reactions, trajectory data, and system interventions. These records must be retained under the supervision of independent regulatory authorities for a minimum of three years. The ethics sandbox also includes algorithmic simulation testing under high-risk scenarios to ensure compliance with Germany’s fundamental constitutional rights.

At the supranational level, the European Union formally adopted the Artificial Intelligence Act in 2023, classifying Level 3 and above autonomous driving systems as “high-risk AI systems.” The regulation establishes a full lifecycle compliance regime encompassing product design, safety validation, risk assessment, algorithmic explainability, and ethical auditing. Manufacturers must submit an Algorithmic Impact Assessment and an Ethical Compliance Report, and they are obligated to continuously update performance metrics and deviation logs during system operation. Periodic audits are to be conducted by independent technical supervisory bodies.

There exists a coordinated governance structure between Germany’s domestic legal framework and EU law: the former supplies implementation-level granularity, while the latter sets overarching compliance ceilings and ethical baselines. For instance, Article 61 of the AI Act mandates that accident-related data must be retained for a minimum of five years, aligning with the German StVG’s requirement of three years for EDR data preservation.

In sum, Germany’s legal framework for autonomous driving is characterized by three core features: the construction of liability logic based on functional system states; the institutional embedding of controllability safeguards; and the reinforcement of bottom-line ethical constraints. Together, these features offer a replicable, reviewable, and legally accountable model for technology-driven traffic governance.

2.2. The Institutional Logic of Germany's Layered Liability System

A central feature of Germany's liability regime for autonomous vehicle accidents is its construction of a "layered attribution framework" that pivots on the level of automation and is delineated by the functional control state. This framework establishes a clear allocation of rights and responsibilities between the human driver and the manufacturer. Rooted in the coordinated application of Section 1a of the Road Traffic Act (Straßenverkehrsgesetz, StVG) and the Product Liability Act (Produkthaftungsgesetz, ProdHaftG), it integrates technological rationality with legal dogmatics, forming a globally instructive paradigm for liability attribution.

2.2.1. Institutional Structure of Layered Attribution: From Duty Reconstruction to Risk Allocation

(1) Drivers: From Comprehensive Duty to "Duty of Alertness"

In Level 3 (L3) systems, Germany dynamically defines the driver's legal obligations based on the system's activation status. During periods when the automated driving system is in primary control, Section 1a of the StVG provides that the human driver is subject only to a limited "duty of alertness" (Aufmerksamkeitspflicht), meaning the driver must be capable of responding within 8–10 seconds following a takeover request—consistent with the boundaries of human factors engineering. Engagement in non-driving activities, such as reading or entertainment, is legally permissible during this time.

This partial exemption from liability is grounded in the notion that once technical control is transferred to the system, requiring the human to maintain continuous monitoring is neither necessary nor feasible (BVerfG, 2023). Nevertheless, the driver must not deliberately evade their obligation to respond. Intentional evasion of a takeover request may trigger criminal liability under Section 315c of the German Criminal Code (StGB) for endangering road traffic safety.

In Level 4 and Level 5 scenarios, German law effectively dismantles the traditional role of the driver. Legally, the individual is no longer regarded as a "driver" but merely as a passenger or user. Unless a human intentionally interferes with the system (e.g., through hacking), they are fully exempt from liability for accidents (cf. Pflichtversicherungsgesetz draft, §5). This legislative posture highlights Germany's foundational attribution principle of Verfügungsprinzip—the notion that "control entails responsibility." When the technical system exercises actual control over risk, humans should not be held accountable for outcomes beyond their control.

(2) Manufacturers: Ongoing Obligations and Strict Liability in Parallel

Manufacturers bear responsibility across the entire product lifecycle—from design, manufacturing, and testing to marketing and over-the-air (OTA) software updates. According to Sections 1 to 3 of the Product Liability Act, manufacturers are strictly liable for damages arising from design defects (Designfehler), failures or delays in software updates (Updatevers*ä*umnis), or unrecognized algorithmic decision errors (Entscheidungsfehler durch KI). This liability holds regardless of fault, reflecting the legislator's intention to internalize systemic risk within the party best positioned to foresee, monitor, and rectify technological errors.

2.2.2. Shortcomings of the Institutional Design

(1) Ambiguity at the Liability Threshold Between Levels 3 and 4

The European Commission's report COM (2020) 64 final highlights persistent ambiguity in responsibility allocation during control transitions in automated driving systems, particularly between Level 3 and Level 4. When an accident occurs due to either a delayed takeover request by the system or a failure of the human driver to respond in time, it remains unclear whether liability should rest with the manufacturer, the software developer, or the human operator. This indeterminacy at the moment of functional shift continues to challenge the legal clarity of the layered attribution model.

(2) Challenges in Allocating Liability Across Cross-Border Supply Chains

Autonomous vehicles rely heavily on complex international supply chains, where components such as sensors, software, and hardware may be sourced from different suppliers and integrated by the original equipment manufacturer (OEM). However, current legal instruments do not clearly define the extent of joint and several liability among secondary suppliers and the OEM. This legal gap complicates the attribution of responsibility when a system failure involves multiple actors across jurisdictions.

To sum up, while Germany's layered liability system for autonomous driving offers a structured and technologically informed framework, it is not without flaws. Critical analysis is essential when adopting or adapting this model, particularly with regard to its current limitations in transitional liability thresholds and transnational supply chain governance. Policymakers should aim to mitigate these weaknesses through more precise legislative definitions and internationally harmonized liability protocols.

2.3. Technical Safeguard Mechanisms: Data Recording, Ethical Review, and Compulsory Insurance Schemes

The effectiveness of Germany's liability framework for autonomous driving accidents lies not only in the legislative delineation of legal responsibilities but also in its robust technical verifiability mechanisms and ethical justification procedures. This institutional "intermediate layer" bridges the gap between factual conduct and legal liability, forming an evidentiary chain essential for attributing fault in complex automated driving scenarios.

(1) Accident Data Recording and Traceability Mechanism

Since 2017, German law has mandated that all Level 3 (L3) and above autonomous driving systems be equipped with Event Data Recorders (EDRs), which capture critical operational parameters before and after an incident. According to Section 63a of the German Road Traffic Act (Straßenverkehrsgesetz, StVG) and Article 61 of the Artificial Intelligence Act (AI Act), EDRs must utilize tamper-proof storage media to ensure data integrity and must be capable of recording key data such as speed, steering angle, brake/throttle input, and system status for at least 30 seconds prior to the incident. Additionally, these devices must support remote access and authorized retrieval by judicial authorities.

To mitigate the risk of "evidentiary asymmetry" caused by manufacturers' control over data, Germany has adopted a "third-party custody + blockchain timestamping" model, wherein a neutral regulatory agency is entrusted with the storage of original data. This framework effectively addresses the issue of unverifiable "black-box algorithms" and provides a robust evidentiary foundation for causal attribution in accident investigations.

(2) Innovative Coordination within the Insurance Regime

Traditional insurance systems face limitations in the autonomous driving context due to difficulties in accurately assessing the probability of algorithmic failure. To address this, Germany has introduced a "mandatory supplementary insurance + manufacturer recourse" scheme. Under this system, all vehicles equipped with L3 and above automation must be covered by a dedicated autonomous driving liability insurance. In the event of an accident, the insurer directly compensates the victim. The insurer retains the right of recourse (Regressrecht) against the manufacturer for any losses attributable to system defects, thereby enabling risk redistribution.

Furthermore, commercial insurers such as Allianz have begun offering specialized products like "software update liability insurance," which covers accidents resulting from remote algorithmic updates. This insurance regime simultaneously enhances the efficiency of victim compensation and functions as a civil law buffer mechanism in cases where the allocation of substantive liability remains unclear. It thereby reduces reliance on criminal prosecution and exemplifies a modern model of "insurance-law" synergistic risk governance.

(3) Ethical Review Mechanism and Normative Justification

In response to ethical dilemmas arising in edge-case scenarios—such as algorithmic decisions on harm distribution (e.g., trolley problem)—Germany has not delegated ethical responsibility solely to market forces. Instead, it has institutionalized an "ethical review mechanism" through a combination of policy guidance and legal formalization.

The Federal Ethics Commission on Automated Driving (Ethik-Kommission für automatisiertes Fahren) issued the "Ethical Guidelines for Automated and Connected Vehicle Traffic" in 2017, establishing 20 foundational ethical principles, such as "protection of human life as paramount" and "prohibition against discrimination in prioritizing victims based on age, gender, etc." When applying for regulatory approval, manufacturers are required to submit an "ethical compliance statement," specifying whether their decision-making algorithms align with these principles—particularly in scenarios involving suboptimal outcomes. Courts may refer to these ethical guidelines when assessing whether a manufacturer has committed gross negligence, thereby evaluating whether the algorithmic behavior was predictable and fell within ethically permissible boundaries.

In a nutshell, Germany's tripartite framework—comprising verifiable data mechanisms, insurance-based risk buffers, and ethically grounded legitimacy—has established a comprehensive system of technical and normative safeguards. This framework not only enhances the practicability of causal attribution in autonomous driving incidents but also supports a restrained application of civil and criminal liability in line with the principles of proportional governance.

3. China's Practice and Challenges in Determining Liability for Autonomous Driving

3.1. Legislative Developments and Local-Level Exploration

In contrast to Germany's top-down, structurally complete legal framework for autonomous driving, China remains in the process of building a top-level national design, with local legislation leading pilot explorations. At present, China's legislative progress is characterized by a dual structure: "central-level policy guidance and foundational legislative exploration + breakthroughs through local regulatory pilots." Significant disparities exist in how responsibilities are assigned across different levels of vehicle automation, how technical standards are established, and how liability mechanisms are constructed. Moreover, "soft law" has proliferated, while "hard law" has progressed relatively slowly.

(1) Central-Level Policies and Regulatory Landscape

To date, China has not yet enacted a unified Autonomous Driving Law or any national legislation with binding legal force specifically addressing liability for autonomous vehicles. The current regulatory system primarily relies on normative documents issued by ministries and other state agencies.

In 2023, the Ministry of Industry and Information Technology (MIIT), along with four other ministries, issued the Notice on the Pilot Program for the Admission and Road Operation of Intelligent Connected Vehicles, which, for the first time at the national level, officially recognized the legality of on-road operation for Level 3 and above systems. The notice also proposed "the gradual establishment of an institutional framework covering aspects such as product certification, data governance, safety assurance, and liability assignment." This is regarded as a significant step toward the development of binding "hard law" regulations.

The Draft Revision of the Road Traffic Safety Law (2023, for public comment) explicitly proposed "exploring the establishment of a liability determination mechanism for road traffic accidents involving autonomous vehicles." However, it has yet to delineate clear legal boundaries between duties of care, product liability, and driver obligations. Most notably, the core issue of how liability is to be allocated when an autonomous system is engaged remains undefined.

Guidance documents issued by the Ministry of Transport and other departments—such as the Guidelines for Testing and Pilot Applications of Vehicle-Road Collaborative Systems and the Trial Guidelines for the Safe Operation of Autonomous Vehicle Transportation Services (Draft for Comment, 2022)—set out numerous standards for testing safety, operational protocols, and data recording requirements. However, these are primarily "soft law" instruments lacking mandatory legal force.

In summary, China's central-level framework remains in a transitional phase from "policy advocacy" to "legislative preparation." A comprehensive and enforceable legal system addressing the unique risks posed by autonomous driving—particularly with respect to liability attribution—has yet to take shape.

(2) Pilot Pathways in Local Legislation

As a pragmatic response to the legislative vacuum at the central level—and in response to the practical need for localized implementation of autonomous driving technologies—several Chinese local governments have proactively promoted regionally effective regulatory ordinances and have attempted to establish frameworks for liability allocation.

The Shenzhen Regulations on the Administration of Intelligent Connected Vehicles (2022) marked the first local legislative effort to distinguish between "human liability" and "vehicle liability," and to explicitly allocate responsibility based on levels of vehicle automation. The core rule provides: for "intelligent connected vehicles with a driver" (primarily referring to Level 3–4), if an accident occurs and the vehicle is found to be at fault, the driver bears liability for compensation; for "fully autonomous vehicles operating without a driver" (Level 5), if an accident occurs, the vehicle owner or manager shall bear liability; in cases involving vehicle defects, the liable party may seek recourse from the manufacturer or seller after providing compensation. This framework offers a preliminary model for liability attribution.

The Draft Regulations on Autonomous Vehicles in Beijing (2024, for public comment) attempted to differentiate liability according to whether the autonomous system was "activated" or "not activated." Although this distinction was eventually removed from the final draft, it reflected ongoing local explorations into categorizing liability based on system status.

Other jurisdictions, such as Shanghai's Pudong New Area and Wuhan's draft regulations, have adopted a model similar to Shenzhen's—where the affiliated enterprise assumes primary liability for accidents involving unmanned vehicles, with a right to recover damages from upstream entities. In contrast, regions such as Hangzhou and Jiangsu have merely stipulated that existing traffic liability rules apply or have provided only general principles.

However, these local legislative efforts exhibit several critical limitations and areas of contention:

First, many normative documents either ambiguously define or overlook the concept of "functional status." While most local legislation attempts to distinguish the basis of liability, there remains a lack of clear, unified, and operational criteria for dividing responsibility in scenarios involving the transition between "system-dominant operation" and "driver takeover" in L3 systems—especially in the case of takeover failure.

Second, the imposition of driver attention obligations is contested. For Level 3–4 vehicles, local regulations commonly require drivers to maintain readiness to take over control at any time. This effectively imposes a continuous and heightened duty of vigilance, which contrasts sharply with jurisdictions such as Germany, where L3 conditions tend to impose only a "limited obligation" (requiring a response only when prompted by the system). Such requirements may unduly burden drivers, contradict the technological design intent, and dampen public willingness to adopt autonomous vehicles

Third, the order and scope of manufacturer liability remain unclear. In several local frameworks, vehicle owners or managers are designated as the primary liable parties in the event of an accident, with manufacturers and sellers bearing secondary liability only upon proof of product defects. This approach has been criticized for conflating "human liability" (for traffic accidents) with "vehicle liability" (for product defects), effectively forcing blameless owners or managers to "take the fall" for potential manufacturing faults. Such misalignment runs counter to principles of product liability law and may inhibit technological innovation and consumer confidence. Furthermore, local regulations often lack or offer only weak provisions regarding manufacturers' continuing obligations—such as software updates, data security, and the retention and accessibility of critical data (e.g., black box records)—thereby creating breaks in the liability chain and impairing traceability.

Fourth, the roles and responsibilities of system designers, data providers, and other stakeholders remain unaddressed. Existing local legislation generally fails to clarify the liability of software developers involved in autonomous driving systems, and neglects to account for potentially at-fault third parties such as equipment providers and network service operators.

Fifth, regional discrepancies may lead to judicial inconsistency. Variations in liability rules across cities can result in divergent adjudications for similar types of accidents, undermining nationwide legal consistency and predictability.

(3) Institutional Assessment and Preliminary Comparison with Germany

A comparison of the legislative approaches of China and Germany reveals that Germany has adopted a "central-legislation-first, systematized construction" model. The 2017 amendment to the Road Traffic Act explicitly stipulated that vehicle, regardless of their level of automation (particularly L3–L4), must not operate independently of human drivers. It also mandated the installation of operational monitoring devices to record real-time driver interventions and system operations, thereby providing critical technical evidence for liability determination. The 2021 Autonomous Driving Act further refined the regulatory framework for specific L4 operational scenarios. The core legislative strategy lies in establishing clear technical standards and recording requirements to enable precise ex post differentiation between human and machine responsibility, with a tendency to shift the liability burden toward manufacturers during system-controlled operation.

In contrast, China's current model more closely resembles a pragmatic combination of "ongoing top-level central design + decentralized local pilot experimentation". Local legislatures have taken proactive steps to fill the regulatory void, particularly by exploring foundational distinctions between human and vehicle liability—as seen in Shenzhen and Pudong. This model facilitates the rapid implementation of technological applications and the accumulation of practical experience.

However, these local regulatory schemes still face major shortcomings in several key respects: precisely defining driver attention obligations under L3 system functional states; clearly delineating the boundary between human and vehicle liability; scientifically establishing the order and scope of manufacturers' product liability; and instituting a mandatory, unified data recording mechanism. These deficiencies contribute to ambiguous lines of responsibility and place excessive burdens on drivers—posing fundamental challenges to the development of a coherent liability framework.

3.2. Attribution Dilemmas: Algorithmic Black Boxes, Misallocated Liability, and Insurance Lag

Despite China's significant progress in the policy promotion and technical deployment of intelligent connected vehicles in recent years, the legal determination of liability following accidents continues to encounter numerous institutional bottlenecks and theoretical challenges. These challenges primarily manifest in the form of misaligned and overly abstract legal norms, ambiguity in the identification of responsible parties and boundaries of liability, lack of technical verifiability due to algorithmic opacity (the "black box" problem), and the delayed evolution of insurance mechanisms.

(1) Misalignment of Legal Application and Over-Abstract Norms

Currently, the primary legal basis for determining liability in accidents involving autonomous vehicles in China rests on Article 1218 of the Civil Code, which governs "liability for highly dangerous activities" and traditionally applies to inherently hazardous operations such as rail transit and aviation. However, extending this provision to intelligent vehicles overlooks the hybrid structure of shared human–machine control in autonomous driving systems. This generates two key problems: on the one hand, accidents involving L3-level systems often cannot be easily attributed to either driver error or manufacturer fault alone, yet there exists no transitional attribution mechanism to address such hybrid scenarios; on the other hand, due to the fact that the Product Quality Law and Tort Liability Law have not yet been updated to reflect the specificities of autonomous vehicle technology, courts lack clear, applicable legal standards, resulting in high uncertainty in fact-finding and liability allocation.

A 2024 case in Chongqing exemplifies this dilemma: an L2.9-level vehicle (functionally close to L3) produced by a domestic automaker was involved in an auto-parking collision in an underground garage, causing minor injury to a pedestrian. The court was unable to determine whether the driver was in a state of expected or actual control at the time of the incident (i.e., whether the system issued a takeover request and whether the driver negligently failed to respond). The vehicle's user manual did not clearly delineate the respective liability implications of "partial takeover" versus "fully automated" scenarios. Ultimately, the court ruled that the driver and the manufacturer should share liability at a 3:7 ratio—an outcome that sparked significant controversy. This case highlights the formidable difficulties faced in China when attempting to adjudicate hybrid-responsibility scenarios involving L3 systems, especially in the absence of mechanisms akin to Germany's mandatory operation monitoring recorders or finely tailored legal guidance.

(2) The Algorithmic Black Box Effect and the Lack of Data Verifiability Intensify the Difficulty of Establishing Causation

Accidents involving autonomous vehicles frequently stem from issues such as misidentification by perception systems, errors in path planning logic, or latency following over-the-air (OTA) software updates. These technical triggers originate from complex algorithmic decision-making processes—commonly referred to as the "black box"—which are highly data-dependent and difficult to reconstruct using traditional chains of evidence This gives rise to a dual dilemma:

On one hand, drivers or users face substantial evidentiary challenges. Lacking access to the system's internal decision logic or real-time operational data, they are often unable to prove that the accident resulted from a system defect rather than their own improper operation. On the other hand, while manufacturers do possess such data, China currently lacks a nationally unified and mandatory standard for data recording, as well as any legal obligation to disclose accident-related data. As a result, manufacturers may refuse to provide complete datasets by invoking trade secret protections, or the data that is recorded may be incomplete or non-standardized, ultimately obstructing the attribution process and making it difficult to determine the true cause of an incident.

Although some courts in China have attempted to mitigate this evidentiary imbalance by applying the principle of “reversed burden of proof,” this approach lacks national legal codification and consistent procedural standards. In the criminal law context, excessive reliance on reversed burden principles risks violating the presumption of innocence and triggering conflicts in legal application. In contrast, Germany’s requirement for mandatory installation of operational monitoring devices and the imposition of strict data retention obligations serve as essential technical safeguards to counteract the algorithmic black box problem and to establish an objective chain of evidence. This remains a significantly underdeveloped aspect of China’s current regulatory framework.

(3) Ambiguity in Identifying Responsible Parties and Institutional Gaps: Mismatches and Priority Disputes Among Multiple Actors

Autonomous driving systems involve a complex web of stakeholders, including original equipment manufacturers (OEMs), hardware and software suppliers, algorithm developers, and data service providers. The traditional binary liability structure—comprising “product liability vs. user fault”—is inadequate to address the intertwined responsibilities of these diverse entities. Take, for example, an accident involving an automated parking system: it could be attributed to sensor calibration errors by the supplier, faults in the path-planning algorithm, system integration flaws by the OEM, or mismanagement of OTA updates.

However, the current legal framework does not clearly delineate the scope of obligations for each party, nor does it establish a transparent mechanism for transferring liability along the responsibility chain. As a result, manufacturers may evade responsibility, users may be left uncertain about whom to sue, and courts face significant challenges in determining fault.

(4) Lagging Insurance Mechanisms and the Absence of Effective Risk Transfer Structures

China has yet to establish a comprehensive and mandatory insurance regime specifically tailored to autonomous driving. The existing insurance framework faces several critical deficiencies:

First, the premium system lacks transparency and standardized criteria. For vehicles equipped with Level 3 or higher systems, insurance underwriting varies considerably across regions and companies, with risk assessments and pricing mechanisms lacking scientific rigor.

Second, the current insurance offerings are not well-suited to the distinctive risks posed by autonomous vehicles. Most automobile insurance products are still designed around conventional human-driven models and fail to include specialized liability endorsements that would cover non-human-triggered accidents arising from technical system failures—such as algorithmic errors, cybersecurity breaches, or systemic malfunctions. Germany’s efforts to adapt compulsory liability insurance to autonomous driving risks within a regulatory framework provide a useful model for China.

Third, insurance compensation often hinges on lengthy judicial determinations. Given the ambiguity and complexity surrounding liability attribution, insurers frequently require final court judgments before disbursing claims. This undermines the prompt relief function of insurance, raising both the difficulty and time cost for victims seeking compensation.

Fourth, there is a lack of robust product liability insurance tailored for manufacturers. Currently, there are no mandatory or enhanced insurance requirements that would adequately cover the substantial compensation risks faced by producers. This gap limits the effective distribution of liability and may disincentivize innovation or fair risk-taking in the industry.

3.3. Criminal Liability Controversies: System Control and the Principle of Penal Restraint

(1) Divergence Between Risk Allocation Philosophy and the Role of Criminal Law

Germany's liability framework for autonomous driving adheres to a "technology-relieves-burden" orientation, embedding the responsibility system within a broader framework of techno-ethics. The core principle asserts that when an autonomous system is operating effectively, the burden and liability on human drivers should be reduced accordingly. In 2021, the German Federal Ministry of Transport issued the Ethical Guidelines for Automated and Connected Vehicle Traffic, articulating key principles such as the "primacy of human dignity" and "minimization of harm." Based on these tenets, criminal liability is deliberately relegated to the background. The preferred mechanisms for handling most autonomous vehicle accidents involve administrative penalties, product recalls, and insurance compensation, with criminal prosecution limited to rare cases where there is clearly demonstrable intent or gross negligence by a human actor. This approach is intended to prevent premature or excessive criminal intervention that could stifle technological innovation.

In contrast, China continues to exhibit a strong evidentiary presumption model in its risk allocation logic, often rooted in a "proof-first" mentality. Local regulations commonly impose a duty on human drivers to "remain ready for takeover at all times," effectively reverting to a conventional driver-centric liability model. This overlooks the ergonomic and cognitive limitations of human response capabilities when the system is in control. At the national level, there is a lack of clear guidance on the principle of penal restraint. For example, local legislation such as the Shenzhen Regulations typically requires that drivers of L3-level vehicles maintain constant readiness to retake control. In practice, this perpetuates—or even intensifies—the high attentiveness obligations typical of manual driving, even during periods when the system is autonomously operating.

This legal stance fails to acknowledge the engineering constraints associated with human takeover responses (e.g., reasonable reaction time upon system handover requests), and implicitly shifts partial preemptive liability for system-induced accidents—regardless of technical faults—onto the human driver. This markedly increases the risk of criminal liability for negligence (such as in cases involving traffic-related injuries or fatalities), particularly when the accident results in serious harm.

(2) Institutional Comparison in the Dimension of Responsibility Construction

Germany's approach to liability delineation in the context of autonomous driving is characterized by a clear hierarchical structure and robust technological support. It adopts a dual-tier framework of "limited obligations for system users + strict liability for manufacturers." Under this model, users of L3 systems are only subject to a duty of vigilance (Aufmerksamkeitspflicht); once the system issues a takeover request, a minimum reaction time of 10 seconds is presumed reasonable—corresponding to ergonomic limits of human response. During periods of normal autonomous operation, the driver bears no obligation to continuously monitor the driving environment. In contrast, manufacturers are held strictly liable for a continuum of technical obligations throughout the entire lifecycle, including algorithm design, system testing, and subsequent over-the-air (OTA) software updates.

By comparison, China's current legal framework exhibits ambiguity in responsibility stratification and lacks sufficient technical verification mechanisms. The prevailing regulations have yet to adopt a layered liability model. Many regional policies treat "takeover ability" as a static precondition for liability, rather than dynamically allocating responsibilities based on real-time system functional status. This not only overburdens human drivers but also leads to the externalization of manufacturer liability, resulting in regulatory asymmetry.

(3) Divergences in Causation Mechanisms and Attribution of Negligent Acts

In the criminal law domain, Germany requires a dual evidentiary threshold for establishing negligence in autonomous vehicle accidents: subjective foreseeability and an objective causal chain. A key institutional mechanism supporting this requirement is the “black box + third-party data custody” regime. Event Data Recorders (EDRs) must capture at least 30 seconds of operational data before and after an incident, and this data must be held by a neutral entity to ensure reliability and impartiality throughout judicial proceedings.

In contrast, Chinese legal practice often grants manufacturers unilateral control over operational data, with no mandatory disclosure or custodianship system in place. Even when courts apply the principle of reversal of the burden of proof, the lack of verifiable and independently preserved data frequently hampers the construction of a complete causal chain, thereby undermining the effective adjudication of both civil and criminal cases.

Some also argue that in scenarios involving so-called “algorithmic complicity,” the absence of a supporting framework for technical verifiability renders even well-articulated criminal statutes ineffective in practice. Without such safeguards, legal attribution risks becoming merely symbolic rather than substantively enforceable.

(4) Comparative Coordination of Ethical Norms and Insurance Mechanisms

Germany emphasizes an integrated approach that combines ex ante ethical institutionalization with responsibility-mitigation mechanisms. Ethical considerations—such as the preconfigured decision logic in “trolley problem” scenarios and the principle of minimizing harm—are embedded in legislative processes and industrial standards. Manufacturers are required to account for and explicitly disclose these ethical parameters in the design and approval of autonomous systems.

Simultaneously, Germany places the insurance regime at the core of its protective infrastructure. A tailored insurance framework serves as the principal mechanism for risk allocation and liability mitigation. Mandatory “supplemental liability insurance” has been introduced for L3–L5 vehicles, covering compensation risks arising from system malfunctions. Moreover, at the federal level, a jointly administered compensation guarantee fund—established by manufacturers, insurers, and other stakeholders—is mandated to ensure victim compensation in situations involving technical complexity, ambiguous liability, or manufacturer insolvency.

In contrast, China currently lacks a unified set of ethical guidelines for autonomous driving. Ethical review remains largely confined to the realm of academic research and has yet to be institutionalized within administrative regulatory systems. On the insurance front, although a few pilot cities have explored “dedicated autonomous driving insurance” products, the rate of market penetration remains extremely low. Consequently, insurance fails to fulfill its intended roles of providing immediate relief and functioning as a risk buffer.

In summary, China and Germany diverge significantly in their approaches to the attribution of liability in autonomous driving, particularly in the criminal domain. Germany adopts a “normative ethics first–institutional support–criminal law as a last resort” model, while China tends to follow a “pragmatism first–regulatory lag–criminal law as a primary instrument” trajectory.

4. Suggestions for improving China's system

4.1. Establishing a Hierarchical Liability Attribution System with Chinese Characteristics

In light of the difficulties in attributing legal responsibility in autonomous driving accidents, China urgently needs to develop a legislatively grounded, dynamically adaptive, hierarchical attribution model. This system should rationally allocate duties and liabilities among drivers, system developers, and manufacturers. Drawing on Germany's stratified logic of "functional state + user conduct + technical responsibility of manufacturers," a three-dimensional institutional framework should be developed.

(1) Introducing "System Activation Status" as the Point of Departure for Liability Determination

Legal attribution in autonomous driving should differentiate among levels of automation (SAE L1–L5) and the distribution of control under various operational states. For instance, in the operational phase of L3 systems—which typically support complex functionalities such as adaptive cruise control and automated lane changing—the determination of a driver's duty of care should hinge upon whether the system had issued a takeover request.

China could incorporate a provision on "system-dominant control state" in its forthcoming Autonomous Driving Law or in revisions to the Road Traffic Safety Law. This provision should clarify that for vehicles at or below L3 level operating in autonomous mode, drivers only bear a duty to respond to takeover requests. In parallel, a "transition window" mechanism—similar to Germany's 10-second takeover buffer—should be established to define a liability shift period after a takeover request has been issued.

(2) Establishing the Driver's "Duty of Alertness" and "Trust Protection" Mechanism

China may also draw on the German StVG Section 1a to define the scope of driver obligations for L3/L4 systems. Under stable autonomous operation, drivers should not bear a continuous monitoring obligation and may engage in non-driving activities. Once a takeover request is issued, the driver must respond within a reasonable reaction time. If the request was not issued in a timely manner due to a system design flaw, primary liability should be presumptively assigned to the manufacturer, and the driver should benefit from a "trust-based exemption."

This approach would not only alleviate the cognitive burden on drivers but also incentivize manufacturers to improve the interpretability and reliability of human–machine interaction during handover phases.

(3) Institutionalizing the Manufacturer's "Continuous Lifecycle Duty"

With regard to manufacturers' liability, China should legislate responsibilities that span the entire lifecycle—covering technical design, data retention, OTA (over-the-air) updates, and user education. Drawing on Article 9 of the EU AI Act on transparency obligations, manufacturers should be mandated to disclose system decision logic and safety threshold parameters. Additionally, an "algorithm failure observation period" (Zeitfenster) could be introduced, during which the manufacturer retains primary responsibility for system performance after deployment of a new version.

Furthermore, China could promote the establishment of independent third-party algorithm review institutions, which would be responsible for system testing, validation, and arbitration in accident-related disputes. By legally formalizing the manufacturer's continuous liability, such measures would enhance their risk identification capacity and prevent gaps in accountability.

4.2. Strengthening Technical Regulation and Supporting Institutional Mechanisms

In establishing a liability attribution system for autonomous driving, the development of a supporting technical regulatory framework and institutional infrastructure is particularly critical. The inherent uncertainty of technology, the opacity of algorithms, and the imbalance in data control render traditional civil and criminal legal frameworks insufficient for effective governance in the modern transportation system. Therefore, China should focus on building coordinated mechanisms in the following three areas.

(1) Establishing Unified Standards for "Data Retention and Retrieval"

Germany has established standardized obligations for Event Data Recorders (EDRs) through Article 28 of the Compulsory Insurance Act and its proposed amendments. These provisions require manufacturers to record key operational parameters of the vehicle from 30 seconds before to 15 seconds after an incident, with tamper-proof mechanisms and third-party custody.

China can draw on this approach by promoting the mandatory installation of nationally standardized EDR devices in autonomous vehicles. These devices should record data on speed, acceleration, sensor status, and takeover requests, among others. Additionally, the establishment of a centralized "Accident Data Sharing Platform" should be pursued to ensure that courts have legal access to critical evidence. To further enhance data integrity, blockchain technology could be introduced to provide timestamp verification and tamper-proof archiving of accident data, thereby ensuring its credibility in legal proceedings.

(2) Establishing a System for "Algorithm Filing and Explainability Assessment"

As China advances the commercialization of autonomous vehicles at SAE Level 3 and above, it could reference Articles 13 and 25 of the EU Artificial Intelligence Act, which provide regulatory guidelines for high-risk AI systems. A mandatory pre-registration and explainability review mechanism should be established, requiring manufacturers to submit an "Algorithm Operation Report" detailing decision-making boundaries, emergency response logic, and risk prediction models. Moreover, third-party professional institutions could be enlisted to conduct "ethical sandbox" testing to ensure that the algorithm demonstrates consistency and ethical acceptability in situations involving complex decision-making conflicts.

(3) Advancing Judicial Reform through "Technological Empowerment"

Ultimately, the attribution of liability is determined within the judicial system. To improve the judiciary's capacity to handle technical disputes, a dedicated "Technical Expert Pool for AI-related Accidents" should be established. This pool would consist of algorithm engineers, traffic modeling experts, and other interdisciplinary specialists to support judges in technical adjudication.

Furthermore, a coordinated adjudication mechanism that integrates "Technology, Ethics, and Law" should be explored. This would involve the joint participation of technical review bodies, ethics evaluation committees, and judicial authorities in pre-trial assessments and accident classification, thereby enhancing the legitimacy and accuracy of legal determinations in autonomous driving cases.

4.3. Innovating Insurance and Social Compensation Mechanisms

In the context of autonomous driving accidents, traditional civil compensation and insurance mechanisms are increasingly constrained by institutional bottlenecks such as difficulties in liability attribution and delays in indemnification. Drawing on Germany's dual-track model of "insurance relief + social co-sharing," China should explore an insurance structure and compensation mechanism more compatible with the autonomous driving context, thereby externalizing and socially adjusting the inherent technological risks.

(1) Developing a Dual Mechanism of "Liability Add-On Insurance" and an "Accident Compensation Fund"

Under the current German model, all autonomous vehicles are required to purchase liability add-on insurance, which covers accident risks arising from algorithmic failures, system misjudgments, and similar causes. In addition, major manufacturers and insurance companies cooperate to establish a "Technical Fault Liability Sharing Fund," which compensates for accidents that pose societal risks but cannot be easily attributed to a specific liable party.

China could adopt a similar approach through the following measures: First, vehicles equipped with Level 3 and above autonomous systems should be mandated to carry liability add-on insurance, with premium rates dynamically adjusted based on vehicle model, usage frequency, and algorithmic stability. Second, the government could encourage the formation of industry alliances among leading automakers, AI vendors, and insurance institutions, which would jointly establish an "Autonomous Driving Liability Compensation Fund." This fund would prioritize compensation for victims in cases involving attribution difficulties or algorithmic opacity. Following disbursement, the fund would retain the legal right to seek recourse against manufacturers or responsible parties to ensure institutional fairness.

(2) Establishing a "Social Compensation System for Intelligent Transportation"

In cases where liability cannot be clearly determined, Germany's Traffic Damage Compensation Act mandates that the state establish a social compensation fund. This fund provides compensation in scenarios involving neutral technology-induced accidents, unforeseeable risk events, cases of cumulative causation where no party is significantly at fault, or where a responsible party cannot be identified despite evident system failure.

China could integrate a similar system into a revised Road Traffic Safety Law or a newly enacted Special Law on Intelligent Transportation Compensation. A "Special Compensation Fund for Intelligent Transportation" could be established using a combination of central government appropriations and supplementary levies from vehicle manufacturers. An administrative arbitration mechanism, coupled with expert evaluations, could be used to assess the degree of liability attribution. In cases where liability cannot be reasonably established, the fund would provide full or partial compensation. Furthermore, procedural rules could grant the fund exemption from traditional burdens of proof, thereby avoiding lengthy litigation and enabling timely relief for victims.

In summary, while building a legislative and liability attribution framework for autonomous driving, China must also simultaneously develop supporting platforms in data governance, algorithmic oversight, insurance mechanisms, and judicial capacity. Such a "proactive institutional design + technological underpinning" model will not only enhance the scientific basis for liability attribution but also provide a practical foundation for modern legal governance.

5. Conclusion and Future Outlook

The large-scale deployment of autonomous driving technologies is profoundly challenging the traditional human-centered legal framework of traffic regulation. Through a systematic comparison of the liability regimes for autonomous vehicle accidents in China and Germany, this article reveals the fundamental differences between the two countries in terms of liability allocation philosophy, technical support mechanisms, and legal application logic. Based on this comparison, it proposes institutional reform paths tailored to China's national context.

Germany has developed a mature system characterized by technological burden reduction, layered liability distribution, and criminal law restraint. In this model, the duty of L3-level drivers is narrowly defined as "takeover response," while manufacturers bear full-lifecycle responsibilities. The system relies on mandatory Event Data Recorder (EDR) standards and a dual-track compensation framework—comprising insurance and public funds—to redistribute risk. Criminal liability is strictly limited to verifiable cases of gross human negligence.

By contrast, China still faces the challenges of liability misallocation, insufficient technical infrastructure, and ineffective attribution mechanisms. Local legislation often imposes excessive vigilance obligations on drivers, while the responsibility ranking for manufacturers remains underdeveloped. Furthermore, the lack of nationwide data standards, ethical review protocols, and dedicated insurance products creates a systemic vacuum. In addition, criminal liability in China often hinges on incomplete evidentiary chains, resulting in practical dilemmas during legal adjudication.

In response to these challenges, this paper proposes a three-tier path for localized institutional optimization. First, in ex ante prevention, China should establish algorithm registration protocols, enforce a national EDR mandate, and implement ethical sandboxing mechanisms. Second, in attribution during the incident, the regime should prioritize product liability for manufacturers during system-dominant periods and clarify the driver's reasonable response duties during takeover phases. Third, in ex post compensation, China may adopt a dual-layer relief mechanism inspired by the German model—combining liability add-on insurance with a national compensation fund.

Moreover, China should explore a paradigm shift toward interdisciplinary collaborative governance, transforming the legal framework from conduct-based attribution to algorithmic risk governance. This requires deep integration between legal theory and engineering practice to construct verifiable adjudication standards. Meanwhile, the principle of criminal law modesty must be upheld to prevent overgeneralized attribution from stifling innovation.

In conclusion, as algorithms increasingly assume the role of decision-makers in traffic systems, the law must move beyond merely adapting existing rules. It must instead undertake a structural transformation toward co-governance through technological and institutional rationality. China must urgently build a forward-looking and globally compatible liability regime for autonomous driving, anchored in shared risk, social compensation, and restrained criminalization, to guide technological development in an ethical and responsible direction.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Author Contributions

The author conducted all research and wrote the manuscript.

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The Impact of Resource Nationalism on Africa’s Critical-Minerals Policy

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Abstract

The accelerated global transition toward low-carbon energy systems has greatly amplified demand for critical minerals such as lithium, cobalt, nickel and rare-earth elements, drawing unprecedented attention to Africa’s abundant reserves. Intensifying geopolitical rivalry has prompted many states to recalibrate mineral policies in pursuit of supply-chain security. Against this backdrop, an observable resurgence of resource nationalism has driven African governments to tighten control over minerals and increase domestic revenue. Employing case-study and policy-analysis approach, this article traces the conceptual evolution of resource nationalism and interrogates its contemporary manifestations across selected African jurisdictions. It systematically examines fiscal instruments, legislative revisions and cooperative frameworks adopted by leading producer countries. The findings indicate that today’s African resource nationalism departs from earlier waves of wholesale nationalization: policymakers now seek a delicate equilibrium amid great-power competition, deploy price-responsive and finely calibrated interventions, and forge transnational partnerships among states with convergent interests. The analysis also identifies persistent vulnerabilities—political turnover, security threats, technological deficits and escalating ESG compliance costs—that could undermine policy efficacy. This study aims to explore the characteristics and impacts of key mineral policies in African countries under the influence of resource nationalism, providing references for transnational capital to identify policy risks and for African countries to optimize resource governance, thereby contributing to the fairness and sustainable development of the global critical mineral supply chain.

Keywords: resource nationalism, critical minerals, Africa, fiscal instruments, legislative reform, international cooperation

1.Introduction

The global energy system is moving rapidly toward decarbonization, and clean-energy technologies—such as electric vehicles, battery storage, and wind-solar power—depend heavily on lithium, nickel, cobalt, rare-earth elements and other critical minerals. These minerals are indispensable inputs for many energy applications, and demand for them is rising sharply as the energy transition accelerates. At the same time, the surge in green and digital technologies has prompted governments to tighten export controls on critical minerals to safeguard their economic security. Critical minerals have therefore become strategic assets at the intersection of energy security and industrial competition, and their supply security and price dynamics are now under intense international scrutiny. Africa holds roughly 30 percent of the world's known mineral reserves—including large deposits essential for solar power, electric vehicles, and storage systems—and meeting future demand will require output of lithium, graphite, cobalt, and other minerals to grow by nearly 500 percent by 2050, making African resources indispensable.

While this resource endowment offers development opportunities, African countries also face significant debt burdens and fiscal pressures. Several governments have financed infrastructure by pledging oil or critical minerals as collateral, thereby increasing their debt load. Moreover, the global race for mineral supply has placed Africa at the center of great-power rivalry. Thus, the continent confronts a dual challenge: seizing market opportunities in green technology while managing external debt stress and geopolitical competition.

Against this backdrop, the present study asks three interrelated questions: Is resource nationalism re-emerging in Africa? If so, what forms does it take and what new characteristics does it display? How has it reshaped African strategies for critical minerals? In recent years, resource-rich states such as Tanzania, the Democratic Republic of the Congo, Mali, Burkina Faso, and Niger have revised mining laws to tighten control over exploration and exports—signaling a concerted effort to capture greater economic returns. A systematic examination of this trend and its developmental trajectories is therefore warranted.

This article argues that African resource nationalism rests on a dual foundation and is driven by dual motives. First, it represents a response to long-standing structural inequalities: resource-rich countries have historically exported raw materials while capturing little downstream value, perpetuating dependency and poverty; resource nationalism is, in part, a reaction against this legacy. Second, it serves as a practical instrument by which African states seek greater resource sovereignty, bargaining power, and revenue in an era of U.S.—China technological competition and supply-chain reconfiguration.

Unlike earlier waves characterized by blanket nationalization or blanket export bans, the current phase employs more nuanced policy tools, pursues more diverse objectives, and follows hybrid pathways. Some governments now classify certain deposits as "critical" or "strategic" minerals and accord them preferential policy treatment. Tanzania's draft 2024 Mining Act, for example, would authorize the government to designate minerals as critical or strategic according to economic and geopolitical considerations. Policy goals extend beyond higher tax rates or equity grabs to include domestic processing, technology transfer, environmental protection, and community development. Instruments are correspondingly varied, ranging from tariff adjustments and sovereign wealth funds to joint ventures and multilateral development projects. In short, contemporary African resource nationalism, while still driven by the quest for greater economic sovereignty, has become more diversified and systematized.

To address the research questions, the study combines case studies with policy analysis and is organized as follows: (1) Africa's position in global critical-mineral supply chains; (2) the evolution of resource nationalism; and (3) the impact of resource nationalism on African critical-mineral policies. Drawing on academic literature, policy documents, and data from international organizations, the article offers a comprehensive assessment of the latest developments in African resource nationalism.

2.Africa’s Critical Minerals

The accelerating shift toward a low-carbon global energy system has elevated critical minerals to unprecedented strategic importance and is set to drive a steep rise in future demand. Cobalt, lithium, nickel, graphite, rare-earth elements and copper are indispensable inputs for renewable-energy infrastructure, electric vehicles (EVs), stationary storage and smart-grid technologies. According to the International Energy Agency (IEA), in its Net-Zero Emissions (NZE) scenario copper demand is projected to grow by 50 percent by 2040, largely because of the rapid roll-out of EV batteries and grid-scale storage. Demand for nickel, cobalt and rare-earth elements is expected to double, while graphite demand could quadruple. By 2040 the demand for lithium may rise eight-fold, underscoring its pivotal role in advanced batteries. Overall, the share of clean-energy technologies in total mineral demand is expanding sharply.

The global value chain for critical minerals is organized into upstream, midstream and downstream segments. Upstream activities focus on exploration and extraction. Geological surveys and smart-mining techniques are used to confirm reserves and recover ores efficiently. These operations are concentrated in resource-rich countries and demand large capital outlays as well as advanced technical capabilities. Midstream processing and refining involve highly complex technologies. Smelting, concentrate decomposition and purification raise material purity and generate higher-value products such as rare-earth permanent magnets, while operators must also meet strict environmental and energy-efficiency requirements. Downstream applications are highly diversified, feeding into renewable-energy systems, high-end manufacturing, information technology and defence industries.

Africa occupies a pivotal position in global critical-mineral supply. United Nations Conference on Trade and Development (UNCTAD) data indicate that the continent hosts roughly 30 percent of the world’s known reserves, including 55 percent of cobalt, 47.65 percent of manganese, 21.6 percent of natural graphite, 5.9 percent of copper, 5.6 percent of nickel, 1 percent of lithium and 0.6 percent of iron ore. Table 1 summarizes the main reserve shares and leading producer countries.

Table 1. Global reserves of critical minerals in Africa and representative producing countries.

Mineral	Africa’s Share of Global Reserves	Principal Producing Countries	Key Uses
Cobalt	~55 %	Democratic Republic of the Congo	EV batteries, aerospace alloys, electronics
Manganese	~47.65 %	South Africa, Gabon	Battery cathodes, alloy steels
Lithium	~1 %	Zimbabwe (hard-rock), Namibia	EV batteries, stationary storage
Nickel	~5.6 %	South Africa, Madagascar	EV batteries (especially NMC and Ni-rich chemistry), stainless steel
Platinum-group metals (PGMs)	~92 %	South Africa, Zimbabwe	Auto catalysts, hydrogen fuel cells, electronic components

Beyond direct energy applications, these materials underpin high-end sectors such as metallurgy, aerospace and telecommunications. The continent’s abundance and diversity of critical minerals therefore make it an indispensable link in the supply chains that enable the global energy transition and advanced manufacturing.

3.The Rise of Resource Nationalism

3.1.Definition of Resource Nationalism

The term “resource nationalism” originally coined in Western scholarship, has been interpreted in various ways. Mares (2010) frames it as a strategy whereby governments shape the rules for exploration, production, transport, and distribution of energy resources to maximize national interests. Ian Bremmer emphasizes the transfer of resource control from foreign firms to state-owned enterprises, highlighting the nationalization dimension. Ma Ye (2014) stresses the state’s lawful jurisdiction over natural resources and its use of administrative, legislative, and market interventions to serve political and developmental goals. Zhang Jianxin (2014) views resource nationalism as a policy orientation that strengthens state sovereignty over resources, regulates their outflow, and enhances their strategic value. Synthesizing earlier scholarship, this paper defines resource nationalism around three core tenets: (1) the resource-holding state’s legitimate claim to permanent sovereignty over its natural endowment; (2) the use of administrative, legislative, and economic instruments to strengthen state control, thereby advancing political goals, economic development, and national welfare; and (3) a nationalist ethos that resources should primarily benefit the domestic populace, rather than foreign powers or multinational enterprises.

3.2.Historical Trajectory of Resource Nationalism

The Age of Discovery in the fifteenth century ended the relative isolation of continents, and European capitalist expansion created a colonial order based on the extraction of precious metals and other commodities. This exploitative pattern laid the ideological groundwork for later nationalist movements. After the Second World War, the collapse of the colonial system spurred newly independent states to assert resource sovereignty, marking the modern emergence of resource nationalism.

The first major wave, from the early twentieth century to the 1950s, coincided with decolonization. Newly independent governments reclaimed resource control through outright nationalization, epitomized by Mexico’s 1938 oil nationalization under President Lázaro Cárdenas, which became a symbol of both industrialization and national pride.

A second wave unfolded in the 1960s and 1970s. The founding of the Organization of the Petroleum Exporting Countries (OPEC) in 1960 signaled collective efforts by developing countries to influence pricing. During the 1973 Arab–Israeli War, OPEC’s production cuts triggered a four-fold oil-price surge. The United Nations’ 1966 Resolution on Permanent Sovereignty over Natural Resources provided legal support, and more than thirty states nationalized mining industries, entrenching the principle of inalienable resource sovereignty.

A third wave began in the twenty-first century and seeks a balance between attracting foreign capital and safeguarding sovereignty. The commodity supercycle[1] from 2003 to 2014 stimulated the enhancement of bargaining power in resource-rich countries, while the strategic value of critical energy transition minerals such as lithium and cobalt has driven a policy shift toward more calibrated regulation. For instance, Indonesia’s 2014 Mining Law banned nickel ore exports, forcing investors to build domestic smelters and propelling the country to the world’s second-largest stainless-steel producer. Chile’s 2022 floating royalty on copper links the tax rate to market prices, securing fiscal revenue without the political cost of outright nationalization.

Most recently, the COVID-19 pandemic, renewed geopolitical tension, and intensified great-power rivalry have amplified supply-chain uncertainties. A new iteration of resource nationalism has emerged in many producing states, aiming to enhance bargaining power and generate greater economic returns. Policy instru-

1 A commodity supercycle refers to a phenomenon in which commodity prices experience a prolonged upward trend under specific economic conditions.

ments now combine traditional nationalization with supply-chain controls, environmental claims, and digital-governance tools, signaling an expanded and more nuanced repertoire of state intervention in the critical minerals sector.

3.3.The Recent Rise of Resource Nationalism in Africa: Causes and Manifestations

Globally, practices of resource nationalism vary worldwide. However, in Africa, this phenomenon is particularly pronounced and exhibits unique regional characteristics shaped by historical context. Africa is a continent exceptionally rich in natural resources, possessing world-leading reserves ranging from traditional minerals like gold and diamonds to critical minerals such as lithium and uranium. Yet, historically, African nations have often played a passive role in the global resource market. Resource development has predominantly been driven by foreign corporations and governments. While resource sovereignty formally resides with the state or region, the technologies for extraction, capital, and market access have long been monopolized by foreign entities, frequently sidelining local interests.

Confronted with this reality, a strong wave of resource nationalism has emerged across Africa. Unlike the resource nationalism observed in Latin America and the Asia-Pacific, which often prioritizes economic benefit maximization, Africa's version represents more than an economic policy choice. It constitutes a response to historical resource plunder and unequal exchange. Essentially, the current rise of resource nationalism in Africa stems from the convergence of three driving forces—historical burdens, the energy transition, and geopolitical maneuvering.

Firstly, fiscal pressures have intensified African states' focus on revenue generation from critical minerals. The combined impact of the COVID-19 pandemic and rising global interest rates has significantly increased debt repayment burdens, leaving many nations on the continent facing debt distress. The African Development Bank projects an annual financing gap exceeding USD 400 billion for structural transformation by 2030, representing nearly 14% of the continent's projected GDP. Concurrently, as international commodity prices enter a downturn, the foreign exchange earnings and fiscal revenues of several resource-dependent African economies are experiencing structural decline. Traditional revenue bases, reliant on bulk commodities like oil and copper, have contracted markedly, rapidly exposing public finance shortfalls. Consequently, African governments are increasingly concentrating on the critical minerals sector—which offers a degree of existing industrial infrastructure and higher anticipated returns—to secure near-term fiscal revenue growth and bolster national sovereignty.

Secondly, against the backdrop of intensifying global demand within the clean energy supply chain, African nations are acutely aware of the strategic leverage inherent in their mineral resources. Zimbabwe exemplifies this trend by banning the export of raw lithium and enforcing domestic process, demonstrating its strategic choice to achieve upward movement within the global value chain. At the international level, African countries are leveraging their voice within global climate governance platforms, such as the UN Climate Change Conferences, to advocate for a reassessment of historical emissions accountability. They are demanding more equitable mechanisms for resource dividend distribution and advanced low-carbon technology support.

Finally, within the global geopolitical landscape, the spillover effects of major power competition significantly influence the formulation and implementation of critical minerals policies in Africa. African states strive to maintain maximum policy independence regarding critical minerals to counter external competitive pressures and safeguard their resource sovereignty. This policy orientation is closely linked to the intense competition among major powers—including the US, China, and the EU—over green transition minerals like cobalt, lithium, and manganese. The EU's Critical Raw Materials Act explicitly sets a target of diversifying strategic raw material supply chains by 2030 to mitigate dependency risks on single sources. The US, through its Inflation Reduction Act, imposes stringent controls on the sourcing of battery minerals, aiming to build resource supply chains aligned with its strategic interests. Concurrently, China, leveraging its technological advantages and global market share in critical mineral processing, continues to optimize its investment footprint in green mineral resources. This multi-polar competition incentivizes African nations to place greater emphasis on strategic autonomy in their critical minerals policy making.

4.The Impact of Resource Nationalism on Critical Minerals Policy in Africa

4.1.Geopolitical Competition and the Restructuring of Global Supply Chains

Currently, nations are actively pursuing strategic initiatives to secure critical mineral resources. The United States has established the exclusionary “Mineral Security Partnership” alliance framework. Concurrently, the Critical Minerals Task Force under the Atlantic Council identifies the 2025 African Critical Minerals Corridor Investment as a strategic pillar of U.S. governmental policy, with one potential corridor spanning between Dakar and Lagos. Furthermore, the U.S. administration plans to leverage the U.S. International Development Finance Corporation in 2025 to enhance its engagement in U.S.-Africa critical mineral cooperation.

China’s accumulated foreign direct investment stock in Africa reached $42.11 billion by 2023, with the mining sector constituting 21.7% ($9.16 billion) - the second largest investment sector after construction. Strategic resource allocation prioritizes copper, cobalt, lithium and other clean-energy-critical minerals, primarily concentrated in resource-endowed jurisdictions including Democratic Republic of Congo, Zambia, and Zimbabwe. Concurrently, both parties are advancing critical mineral cooperation through the Forum on China-Africa Cooperation (FOCAC) institutional framework. The European Union, leveraging its Critical Raw Materials Act, emphasizes domestic processing capacity enhancement. Through memorandum of understanding with Democratic Republic of Congo, Zambia, Angola and others, coupled with its Global Gateway initiative, the EU promotes critical mineral value chain development in Africa via infrastructure development and mineral resource exploitation partnerships.

Hydrocarbon-rich states including Saudi Arabia and the United Arab Emirates are intensifying investments in critical mineral supply chains to diversify their economic portfolios and establish footholds in this emerging sector. Saudi Arabia has been actively pursuing international partnerships through mining-focused memorandum of understanding with multiple states including Democratic Republic of Congo, Egypt, Russia, the United States, and Morocco. The UAE is consolidating its strategic position through a $1.9 billion mining partnership in Democratic Republic of Congo and agreements with copper-rich Zambia. Qatar is concurrently entering this domain, having concluded mining accords with Nigeria while emphasizing the strategic significance of critical mineral cooperation in bilateral discussions with the United States.

Within the global supply chain, resource-rich African nations predominantly remain confined to the initial mining segment. Mining operations still rely heavily on open-pit and artisanal methods. This reliance, coupled with insufficient mechanization, leads to high resource wastage rates. Furthermore, a recent global surplus in critical mineral production capacity has driven down mineral prices. In response, some resource-rich countries have implemented export restrictions to strengthen their pricing power.

Moving to the mineral refining stage, China dominates global processing capacity, holding 50-70% of the share for lithium and cobalt refining, and up to 90% for rare earth elements. This establishes a significant scale advantage for China. Although the EU’s Critical Raw Materials Act sets a target of processing 40% of its consumption domestically by 2030, current levels remain low. Despite possessing substantial mineral resources, African nations largely lack the technical capacity for critical mineral refining. For instance, most cobalt mined in the Democratic Republic of Congo is shipped to China for processing.

The downstream segment of the supply chain, involving high-value-added products like new energy goods, aerospace components, and military equipment, is primarily monopolized by technologically advanced nations or corporations. African participation at this stage is minimal. Notably, current overcapacity in new energy battery production (a major consumer of critical minerals) exerts indirect downward pressure on upstream mineral prices through reduced demand.

4.2.African Key Mineral Policies under Resource Nationalism

According to the theory proposed by Bremmer and Johnston (2009), resource nationalism can be divided into four types: Revolutionary, Economic, Legacy, and Soft. Revolutionary resource nationalism refers to reallocating resource control by forcibly reclaiming assets or tearing up contracts under the opportunity of political and social change. Economic resource nationalism manifests as maximizing fiscal rent values through measures such as taxation, windfall taxes, and equity increases when resource prices are high. Legacy resource nationalism means continuing the state-controlled resource model inherited from the colonial or Cold War periods. Soft (or partnership-type) resource nationalism refers to governments improving national revenue through higher environmental or localization requirements, progressive taxation, or joint venture models.

Historically, all four types of resource nationalism have appeared in African countries. The following table is drawn based on this classification and combined with the performance of key mineral policies adopted by African countries:

Table 2. A Typology of Resource Nationalism with Corresponding African Case

Type	Defining Features	Representative Examples
Revolutionary	Resource control is radically restructured through political upheaval, often accompanied by ideological mobilization.	(1) Zimbabwe (2007) adopted the Indigenisation and Economic Empowerment Act, requiring foreign mining firms to transfer majority equity to Black Zimbabwean entities, triggering divestment and contract renegotiations. (2) Niger (2024): the military government cancelled French firm Orano's licence at the Somair uranium mine, suspended uranium exports and signalled plans to bring in new strategic partners.
Economic	Fiscal instruments are used during price booms to maximize state revenue while avoiding outright nationalization.	Zambia: the mining code links copper-royalty rates to international prices; higher prices automatically raise the royalty, capturing windfall rents.
Legacy	Colonial or Cold-War era state-control structures are retained with minimal reform.	Nigeria (1971) created the Nigerian National Petroleum Corporation, which still dominates the country's oil industry as the primary vehicle of state control.
Soft	State take is increased gradually through ESG standards, local-content rules and joint-venture mandates rather than confrontational measures.	Democratic Republic of the Congo: the state set up Enterprise Générale du Cobalt to act as sole buyer of artisanal cobalt and introduced environmental, labour and traceability standards[2].

2 This project has faced public criticism over allegations of ineffective implementation.

The current wave of resource nationalism in Africa differs from past pursuits of nationalization. It instead seeks to maintain balance amid great-power games by leveraging the current political landscape, fine-tune regulations by closely tracking international key mineral market prices, and establish international key mineral partnerships by uniting with African and other countries sharing similar interests. The following analysis of African countries' key mineral strategies will be conducted from three dimensions: fiscal policies, legislation, and international collaboration.

4.2.1 Fiscal Policies

Under the logic of resource nationalism, African countries tend to increase mineral revenues by enhancing fiscal extraction, commonly through measures such as raising mineral royalties, imposing windfall taxes, and restricting raw ore exports. The Democratic Republic of Congo revised its mining code in 2018, increasing royalties for copper and gold from 2% and 2.5% to 3.5%, respectively, and allowing cobalt mining fees to rise to 10% during periods of high demand. Mali's 2024 mining code increased royalty rates for gold mines from approximately 6% to 10.5%. Additionally, countries like Nigeria and Zimbabwe have banned exports of unprocessed raw ore to promote mineral processing and value addition. For instance,

Nigeria prohibited raw ore exports in 2022 to "end the plunder of raw materials" and encourage local smelting and manufacturing development, and Namibia banned exports of unprocessed lithium ore in 2023. According to the International Monetary Fund(IMF), most African mining fiscal systems consist of royalties, corporate income taxes, and state equity dividends. The rationale behind this approach is to redirect resource revenues through taxes and rents to offset fiscal deficits caused by social infrastructure investments and the impact of the pandemic.

However, excessively high tax burdens can have a "crowding-out effect." For example, after Zambia introduced new mining taxes in 2019, declining copper production led to reduced investment, prompting the government to consider restructuring its tax system. Mali's new law drew strong criticism from mining companies, with a gold mining executive warning, "Excessive taxation will harm investment, and mining companies may choose to shift investments elsewhere."

Overall, African countries are seizing opportunities arising from surging mineral demand driven by the global energy transition. The International Energy Agency(IEA) predicts that by 2040, Africa's key mineral production could attract approximately $50 billion in investment, providing a foundation for increased mining fiscal revenue. African countries must strike a balance between enhancing revenue and attracting foreign investment to address uncertainties from international market price fluctuations and great-power competitions.

4.2.2 Legislation

To institutionalize resource nationalism, African countries have actively strengthened control over mineral resources through legislation. In recent years, more than 30 countries have revised their mining laws to increase government and local community participation. This "resource nationalism" often manifests in various forms, such as reclaiming mines, revoking licenses, raising taxes, and legal reforms. For instance, in 2017, Tanzania significantly amended its mining regulations, granting the government the power to renegotiate contracts deemed "unreasonable" by parliament, expanding state equity in mining projects, and increasing mineral royalties.

Furthermore, many countries have also introduced the concept of "strategic minerals" to establish legal priorities. Kenya's Mining Act stipulates that the state has pre-emptive purchasing rights for strategic minerals (such as precious metals and rare earths) designated by presidential proclamation. Zimbabwe's 2023 fiscal bill lists 10 strategic minerals (including diamonds, rare earths, lithium, and copper), which the president can announce or adjust at any time through official gazettes. These institutionalized measures can ensure that key mineral development meets national strategic needs.

Local content requirements are another legislative tool. Mali's 2023 Local Content Act and implementing rules require that at least 35% of foreign subcontractors and suppliers working for mining companies must be domestically owned, aiming to increase local businesses' and laborers' share in the mining value chain. South Africa's Mining Charter mandates that mining right holders transfer at least 26% (with gradual increases in targets) of equity to historically disadvantaged citizens to promote Black Economic Empowerment.

In summary, African countries have integrated resource nationalism into institutional frameworks through legal revisions, mining charters, and local content policies, requiring foreign enterprises to share more profits and assume social responsibilities, thereby strengthening state control over the mining sector from a legal perspective.

4.2.3 International Collaboration

Against the backdrop of global energy transition and great-power competition, African countries are seeking to enhance their bargaining power through international cooperation to avoid new forms of "resource colonialism."

As for multilateral cooperation, the African Union's African Mining Vision (AMV), adopted in 2009, proposes a framework for "transparent, fair, and optimal mineral development," emphasizing the integration of mining into broader development policies to achieve localized mineral benefits and sustainable use. African union, the Mining Development Centre for Sub-Saharan Africa and other mechanisms provide regional coordination platforms for countries to share experiences in resource policies and advance regulatory reforms. Some studies suggest that African countries could emulate OPEC by coordinating key mineral strategies through alliances. For example, it is proposed that Africa could leverage the negotiation power of the African Continental Free Trade Area to sign favorable trade agreements with China, the U.S., and the EU in exchange for infrastructure, technology transfer, and security guarantees.

As for bilateral cooperation, Africa is reshaping mineral cooperation models with major economies. The EU has emphasized a "raw materials partnership" with Africa in its Critical Raw Materials Act and signed cooperation memorandum with countries like Rwanda, Namibia, and the DRC to advance sustainable supply chains and trade facilitation. The U.S. is actively seeking cooperation with African key mineral states. The Center for Strategic and International Studies has noted that U.S.-DRC cooperation should strengthen mining investment and legal reforms to balance China's influence gained through "infrastructure-for-mining-rights" models. China has long obtained African minerals through infrastructure projects, with Chinese enterprises exchanging copper and cobalt mining rights for constructing roads, hospitals, and other facilities.

Overall, through AU initiatives and negotiations with international partners, African countries aim to transform their mineral resource advantages into returns in technology, capital, and security, thereby preventing themselves from falling into a passive position as mere resource exporters.

4.3.Risks Facing Africa's Critical Minerals Policies Under Resource Nationalism

4.3.1 Frequent Regime Changes

Frequent political instability in many African states undermines the continuity of resource policies. Recent years have witnessed multiple military coups in West Africa and the Sahel region, countries heavily reliant on resource exports. Regime transitions often precipitate resource nationalization or contract re-negotiations. For instance, following the 2021 coup, Mali's military junta retroactively revoked tax exemptions in the mining sector and increased the state's mandatory project equity stake from 10% to 30%, seeking to recover nearly USD 700 million in alleged unpaid mining taxes. That same year, Guinea's new authorities significantly raised resource extraction tax rates (particularly for iron ore), Niger revoked mining licenses held by several French and Canadian companies, and Burkina Faso nationalized two major gold mines, confiscating foreign corporate assets. These cases demonstrate a recurring pattern where new regimes seek to boost fiscal revenues by altering mining contracts, raising taxes, or resorting to nationalization. However, this approach significantly heightens uncertainty and investment risk for foreign capital. The institutional instability caused by frequent power transitions impedes African nations' ability to formulate stable, long-term resource development strategies and makes future policy directions difficult for external actors to predict.

4.3.2 Terrorism and Security Threats

Terrorism and violent conflict pose direct threats to resource exploitation in Africa. In West Africa and the Sahel, activities by Islamist extremist groups severely compromise security around mining sites and critical infrastructure. Under the dire insecurity caused by terrorist attacks in countries like Burkina Faso, at least seven mining companies have suspended operations, contributing to a noticeable decline in the country's 2023 gold output. While Mali's major mines are concentrated in the relatively safer south, terrorist attacks have targeted the capital, Bamako, impacting personnel safety. More critically, the spread of Sahelian terrorism towards coastal nations raises concerns that countries like Benin, Côte d'Ivoire, and Ghana also face heightened risks. This trend would inevitably increase operational costs for mining projects in these nations. These examples underscore how terrorism amplifies uncertainty in mining investment and operations; deteriorating security conditions can force project suspensions or withdrawals.

4.3.3 Insufficient Mining Technology and Capacity Gaps

Africa's widespread lack of advanced mining technology and specialized human capital constrains the depth and profitability of resource development. A severe skills shortage pervades the continent's mining sector, significantly hindering private investment and the development of new projects. Inadequate infrastructure and supporting services compound these challenges; unreliable power supply and underdeveloped transportation and communication networks in many resource-rich countries inflate development costs. Concurrently, insufficient investment by universities and training institutions in fields like geology, metallurgy, and mining engineering has resulted in critical shortages of professionals in chemistry, metallurgy, and engineering, gaps difficult to bridge in the short term. Consequently, even when governments enact policies promoting mineral value addition, implementation often falters. Zimbabwe's mandate for domestic lithium refining exemplifies this issue; lacking adequate smelting capacity, local firms can only process lithium ore into coarse concentrates for export, remaining within the raw material export paradigm and failing to capture the intended value addition. These technological and capacity deficiencies trap African nations in low-value-added segments of the resource chain, hindering economic gains and industrial upgrading.

4.3.4 Weak Pricing Power and Uneven Bargaining Leverage

Significant variations in resource endowments among African countries translate into differentiated bargaining power based on specific mineral demand. For example, lithium iron phosphate and high-nickel batteries require lithium and cobalt respectively, meaning future choices in battery technology within the electric vehicle sector will largely dictate demand trends for these critical minerals. Crucially, however, most African nations possess minimal pricing power in global markets. The overwhelming bulk of resource exports remains in raw material form due to a lack of processing capacity, preventing Africa from capturing the higher profits associated with downstream industries. Consequently, African exporters are largely price-takers, unable to influence price movements. When international commodity prices experience sharp volatility, resource-dependent African economies and public finances suffer disproportionately, highlighting the structural vulnerability stemming from weak pricing power.

4.3.5 ESG and Western Market Compliance Pressures

Increasingly stringent global investor and market demands for adherence to Environmental, Social, and Governance (ESG) standards impose additional costs and pressures on African resource enterprises. Western nations and institutions increasingly mandate that resource projects meet sustainability benchmarks, failing which they struggle to secure financing or market access. For example, the EU's Conflict Minerals Regulation (in effect since 2021) prohibits tin, tantalum, tungsten, and gold entering the EU market from financing armed conflict or utilizing forced labor. Similarly, Section 1502 of the US Dodd-Frank Act requires US-listed companies to disclose the use of conflict minerals in their supply chains. Such regulations compel African nations to strengthen supply chain due diligence and transparency, increasing operational costs and administrative burdens. Some analyses suggest that Europe's exceptionally stringent ESG thresholds effectively raise the barrier for mining investment, potentially disadvantaging European firms. Other actors, such as China and Gulf states, offering more flexible partnership models, may thus become more attractive. In essence, ESG compliance pressures force African resource policies to simultaneously address environmental protection and social responsibility; failure to do so risks financing difficulties and restricted market access.

5.Conclusions

This study demonstrates that the convergence of the new energy transition and great power competition has positioned resource nationalism as a pivotal factor driving the evolution of critical mineral policies in Africa. Crucially, contemporary resource nationalism does not signify a simple return to traditional, comprehensive nationalization. Instead, African states increasingly employ fiscal, legislative, and international cooperation instruments to maximize national benefits from their resource endowments.

Specifically, while fiscal tools boost tax revenue, they often generate negative repercussions for foreign investment due to policy uncertainty and governance capacity constraints. Legislative innovations aim to boost local participation and capture higher value-added segments of the production chain, yet their implementation faces significant limitations stemming from technological and infrastructure gaps. International cooperation offers potential pathways to bridge financing and technological deficits, but it encounters dual constraints——stringent ESG compliance barriers and the spillover effects of geopolitical security dynamics.

These findings indicate that the ability of resource nationalism to translate into sustainable development momentum critically depends on whether African nations can effectively channel short-term fiscal gains into long-term investments in human capital, technological advancement, and regional cooperation. This research contributes to the study of global critical minerals governance by systematically exploring the influence of resource nationalism. The contributions of this study lie in exploring the impact of resource nationalism on global critical mineral governance, while also providing an intellectual foundation for transnational capital to navigate Africa's mining policy risks and fostering collaborative frameworks for mutual benefit.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Author Contributions

The author conducted all research and wrote the manuscript.

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Iranian Science Diplomacy: Management Systems, Strategic Policies, and Sino-Iranian Collaboration

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Abstract

This study analyzes Iran's science diplomacy amidst intricate geopolitical dynamics, focusing on its institutional mechanisms, strategic priorities, and collaborative potentials. Iran's unique governance model—characterized by multi-sectoral coordination under government leadership—has bolstered advancements in energy, defense, and agriculture, laying a foundation for its science diplomacy. Strategically, Iran adopts a diversified approach, fostering regional and global partnerships to enhance technological synergies in energy, information technology, and biotechnology, particularly with Russia, China, and India. However, challenges such as international sanctions, regional instability, and domestic R&D limitations impede progress. Notably, Sino-Iranian collaboration, rooted in historical ties and the Belt and Road Initiative, has expanded from traditional sectors (e.g., agriculture) to cutting-edge fields like AI and renewable energy. While complementarity and dynamic growth characterize this partnership, obstacles remain, including geopolitical tensions, technical standard disparities, and cultural barriers. This research underscores Iran's resilience in leveraging science diplomacy to navigate global challenges and highlights the transformative potential of Sino-Iranian cooperation in advancing regional innovation ecosystems. Findings offer theoretical insights and practical guidance for deepening bilateral ties, enhancing global technological influence, and promoting sustainable development in the Middle East and beyond.

Keywords: Iran, Science diplomacy, China - Iran science diplomacy

1.Introduction

In an era defined by globalization and rapid technological advancements, science diplomacy has emerged as a pivotal instrument for nations seeking to enhance competitiveness and project soft power. As a cornerstone of international relations, it bridges scientific collaboration with geopolitical strategy, enabling states to address global challenges while advancing national interests. Iran, a nation with profound geopolitical significance, abundant natural resources, and a rich cultural heritage, occupies a unique position in this landscape. Its pursuit of science diplomacy is shaped by a confluence of factors: its role as a pivotal Middle Eastern actor, its complex relationship with Western powers, and its ambition to carve out a niche in the global technology ecosystem. This study interrogates the efficacy of Iran's science diplomacy through a dual lens—analyzing its institutional frameworks and strategic partnerships—while spotlighting the implications for Sino-Iranian collaboration.

Recent shifts in the geopolitical landscape and technological paradigms have compelled Iran to recalibrate its science diplomacy strategy. The enduring nuclear imbroglio, characterized by protracted tensions with Western nations, has imposed dual constraints and incentives. On one hand, punitive sanctions have stymied access to cutting-edge technologies and multinational R&D networks. On the other, they have catalyzed indigenous innovation and strategic alliances with non-Western partners. These dynamics raise contentious questions: Can Iran leverage its scientific prowess to circumvent geopolitical isolation? To what extent do partnerships with countries like China and Russia mitigate the impacts of sanctions? Such debates underscore the need for nuanced analysis of Iran's evolving approach to science diplomacy.

Against this backdrop, Sino-Iranian collaboration under the Belt and Road Initiative (BRI) presents both opportunities and challenges. While infrastructure and energy projects have flourished, deeper technological synergies in areas like AI, biotechnology, and renewable energy remain nascent. Critics highlight asymmetries in technical standards, divergent regulatory frameworks, and lingering geopolitical risks. Yet proponents argue that shared interests in regional stability and economic diversification could drive unprecedented cooperation. This study adopts a mixed-methods approach, integrating qualitative policy analysis with quantitative assessments of bilateral R&D investments, to elucidate pathways for enhancing Sino-Iranian scientific partnerships. By unpacking these complexities, the research aims to furnish actionable insights for policymakers and scholars invested in fostering resilient global innovation networks.

2.The Science and Technology Management System of Iran

2.1. Management System

Iran's science and technology management system exhibits a "government-led, multi-sector coordinated, and academia-supported" composite structure. At the strategic level, the Presidential Office coordinates resource allocation across 14 ministries (including Defense, Education, and Industry) through the Highest Scientific Committee, adopting a "triple-helix" decision-making model: the Supreme Leader's Office exercises final authority via the "Expert Commission" to approve national science and technology development plans;[1] the Ministry of Science, Research, and Technology (MSRT) acts as the core executive body, overseeing project approvals, resource distribution, and innovation ecosystem cultivation (e.g., fostering 2,900 knowledge-intensive enterprises post-2010 Knowledge Company Support Law); and universities/research institutes form an innovation matrix. Prestigious institutions like Tehran University (ranking 17th globally in publications) excel in engineering (H-index 182) and nanomaterials (ESI top 1%),[2] while the Atomic Energy Organization operates three national laboratories for nuclear R&D. Despite sanctions, Iran maintained a 44% government science budget share in 2017 (with 28% allocated to basic research),[3] channeling

72% of competitive research funds to five leading universities through performance-based evaluations. This system drove a 420% decade-long growth in materials science publications.[4] Yet challenges persist: R&D intensity languishes at 0.92% (2016), international co-authorship remains low (21%), and high-tech equipment localization hovers below 40% due to import restrictions. Recent breakthroughs include indigenous satellite launches and joint ventures like the EU-funded Clean Energy Research Center, yet systemic bottlenecks underscore the uphill climb toward a knowledge-driven economy.

2.2. Operational Mechanism

Iran's science and technology (S&T) R&D framework exhibits a diversified operational mechanism, integrating government funding, private-sector participation, and international collaboration.

The government acts as a strategic guide through funding mechanisms like the National Science Foundation, which finances critical research in alignment with national priorities. Strategic sectors such as energy, defense, and agriculture receive targeted investments. For example, in the energy sector, state-funded projects focus on advancing petroleum exploration technologies, natural gas extraction innovations, and renewable energy development. These initiatives aim to enhance Iran's technological self-reliance and global competitiveness in energy markets.

The private sector is emerging as a key driver in applied technology R&D. As Iran's economy evolves, businesses increasingly collaborate with universities and research institutes to commercialize innovations. A notable example is the partnership between Iranian automotive manufacturers and research entities to co-develop advanced vehicle production technologies. Such collaborations enable institutions to provide cutting-edge solutions—such as energy-efficient engines or smart manufacturing systems—while enterprises apply these technologies to improve product performance and market value, thereby bridging the gap between academic research and industrial application.

Internationally, Iran actively participates in global R&D networks. Collaborative projects span climate change studies, medical research, and agri-tech innovation, with Iranian scientists contributing expertise while absorbing advanced methodologies. These partnerships not only facilitate knowledge exchange and technology transfer but also elevate Iran's visibility in global scientific discourse. By leveraging international collaborations, Iran reinforces its technological sovereignty while positioning itself as a contributor to solving global challenges.

2.3.Key Science and Technology Fields for Development

Iran has strategically prioritized energy, defense, and agriculture as core sectors aligned with national imperatives and resource endowments. In the energy domain, Iran's abundant oil and gas reserves drive innovations in exploration and extraction technologies. State-funded projects focus on enhancing petroleum geophysical survey accuracy, optimizing drilling efficiency, and reducing costs. Concurrently, Iran is advancing renewable energy infrastructure, particularly solar power systems with improved photovoltaic cell efficiency and wind farms designed to harness the country's untapped wind potential. These efforts reflect a dual approach to energy security—leveraging hydrocarbon wealth while transitioning toward sustainable alternatives.

Parallel to energy advancements, Iran has prioritized defense innovation as a cornerstone of national security. Indigenous development of long-range ballistic missiles, such as the Sejil series, demonstrates technological self-reliance, with these systems featuring extended ranges, precision targeting, and advanced penetration capabilities.[5] The Shahed drone series further underscores military progress, combining reconnaissance and combat functions for border surveillance and tactical operations. Complementing these efforts, investments in military communication networks and radar systems enhance defense informatization, ensuring real-time situational awareness and operational coordination.

Agricultural resilience remains critical to Iran's food security, particularly amid arid climatic conditions. Breakthroughs in water-efficient irrigation technologies—such as drip and sprinkler systems—maximize resource utilization in drought-prone regions. Concurrently, R&D in drought-resistant crops, including high-yield wheat varieties, mitigates reliance on imports. These innovations, exemplified by engineered wheat strains thriving under water-scarce conditions, reinforce domestic agricultural productivity and stabilize national food supply chains.

By integrating resource advantages with targeted technological investments, Iran cultivates synergies across its priority sectors. However, challenges such as sanctions-induced technology embargoes and climate vulnerabilities persist, necessitating adaptive strategies to sustain long-term growth.

3.Iran's Science and Technology Diplomacy and Sino-Iranian Scientific and Technological Cooperation

3.1. Iran's Science and Technology Diplomacy Policies

Iran's science and technology (S&T) diplomacy revolves around its Vision Plan for Science and Technology Development, aiming to break through external technological blockades and enhance domestic innovation capabilities through diversified international cooperation. Domestically, Iran prioritizes regional S&T collaboration via bilateral and multilateral agreements, focusing on energy, agriculture, and disaster management. For instance, leveraging its position as the world's second-largest natural gas reserve holder, Iran has engaged in bilateral energy technology partnerships with Russia and Qatar, such as optimizing shale gas extraction in the South Pars gas field. This initiative synergizes Iranian geological expertise with imported advanced drilling technologies. Additionally, Iran has sought to strengthen its global standing in clean energy through participation in international projects (e.g., UNDP-supported solar power initiatives) while exporting computational simulation technologies to research networks.

In agriculture, Iran has developed salt-tolerant rice varieties that are now cultivated across Uzbekistan's Aral Sea basin, complemented by precision farming tools imported from Turkey. These efforts form part of a regional "technology reciprocity" model. To address shared environmental risks, Iran's Regional Emergency Response Network (RERN)—collaborating with Pakistan, Afghanistan, and Iraq—deploys AI-driven early-warning systems and satellite imagery to mitigate earthquake and flood impacts.

3.2.Iran's Science and Technology Diplomacy Strategies

Iran has established energy, information technology, and biotechnology as the three pillar areas of its science and technology diplomacy, forming a strategic framework of "demand-driven, complementary strengths, and multilateral linkage." In the energy field, relying on its status as the country with the world's largest natural gas reserves, it takes the lead in establishing the OPEC+ technology alliance, and conducts research and development cooperation on shale gas extraction technology with countries such as Russia and Saudi Arabia. Through the "Iran-China Agreement on Peaceful Use of Nuclear Energy Cooperation," it deepens strategic cooperation in fields such as uranium enrichment technology and nuclear power plant operation and maintenance. In the information technology field, it constructs a "two-way opening to the east and west" pattern, launches the cross-border data security project of the "Digital Silk Road" with the European Union, exports encryption algorithm patents to China, and at the same time introduces artificial intelligence algorithm teams from India. At the biotechnology level, it takes the lead in establishing the Islamic countries' crop gene bank, jointly builds a drought-resistant wheat joint laboratory with Pakistan, and introduces Israeli drip irrigation technology to improve the saline-alkali land along the Persian Gulf.

It is worth noting that Iran has established bilateral or multilateral science and technology cooperation committees to hold regular meetings to formulate cooperation plans and coordinate project implementation. For example, since the establishment of the China-Iran Joint Committee for Science and Technology Cooperation in 2016, it has promoted the implementation of 12 joint research projects between the two sides in fields such as nanotechnology and aerospace technology.[6] This institutionalized cooperation model is not only reflected at the inter-governmental level but also active at the private level. The "Silk Road Innovation Port" established relying on the Isfahan Science and Technology Park has attracted the settlement of scientific research institutions from more than 20 countries, forming a full-chain cooperation ecosystem covering technology research and development and achievement transformation.

In terms of cooperation methods, Iran focuses on the combination of technology introduction and independent innovation. Typical cases include the jointly developed BN - 800 fast neutron reactor with Russia. This project has broken through the closed - cycle nuclear fuel technology, increasing the utilization rate of uranium resources to over 90%. It participated in the "Mediterranean Blue Economy" special project of the EU's Horizon program and developed a seawater desalination coupled with photovoltaic power generation system, providing an innovative solution for water resource utilization in arid regions. In addition, through the framework of the Food and Agriculture Organization of the United Nations, Iran implemented the "Green Corridor" program to promote the breeding of stress - resistant crop varieties in the five Central Asian countries. The drought - resistant wheat variety "Isfahan - 1" has been planted in Kazakhstan on an area of more than 100,000 hectares.

From the perspective of resource endowment, Iran's oil revenue supports an annual research and development investment of over $1.5 billion, and the number of nanomaterial patents ranks first in the Middle East. As the rotating chair country of the Organization of Islamic Cooperation, the "Halal Biotechnology Standard" led by Iran has been adopted by 57 member states, laying an institutional foundation for its technology export in the field of biotechnology. It is worth noting that through its control over the Strait of Hormuz, Iran embeds the issue of energy transportation security in science and technology cooperation negotiations. In the bilateral agreement with Japan, it clearly includes the technology for protecting the maritime energy corridor in the cooperation agenda.

However, Iran's science and technology diplomacy faces multiple constraints. Long - term international sanctions have made its dependence on semiconductor manufacturing equipment imports as high as 92%. Restrictions on the procurement of high - end lithography machines directly affect the research and development progress of nanotechnology. The volatile regional situation has increased the uncertainty of technical cooperation. The conflict in Yemen has led to the suspension of the joint solar energy research and development project with Saudi Arabia, causing the Middle East technology transfer index to decline by 17 percentage points. What is more severe is the insufficient investment in scientific research. In 2022, the proportion of Iran's scientific research funds in GDP was only 0.82%, far lower than the global average of 1.7%. The problem of aging infrastructure is particularly prominent in key fields such as nuclear energy and aerospace.

3.3.Overview of Sino-Iranian Scientific and Technological Cooperation

The history of scientific and technological cooperation between China and Iran is long-standing. In the early days, it mainly focused on agricultural technical assistance. China helped Iran build agricultural demonstration centers and promoted advanced planting technologies.[7] Over time, the scope of cooperation has continuously expanded. In the energy sector, the two sides have carried out close cooperation in oil exploration, refinery construction, and other fields. In recent years, cooperation in emerging fields such as information technology and new energy has gradually increased, with joint participation in international information technology projects and exploration of new energy cooperation models. China and Iran regularly hold science and technology cooperation meetings, such as the Joint Committee on Science and Technology Cooperation, which provides a policy guidance and project matching platform for bilateral scientific and technological cooperation.

The scientific and technological cooperation between China and Iran is highly complementary. China has advanced technologies in infrastructure, information technology, and new energy, while Iran has advantages in energy resources and some traditional industrial technologies.[8] The two sides achieve resource sharing through cooperation. The areas of cooperation continue to extend from traditional fields to emerging fields, showing dynamic development characteristics. Moreover, both sides attach importance to long-term stable development and have established multi-level cooperation mechanisms to ensure the smooth implementation of cooperation projects.

Driven by the Belt and Road Initiative, the cooperation needs between China and Iran in infrastructure-related science and technology fields, such as intelligent transportation and green buildings, are continuously growing.[9] The global increase in demand for new energy has also provided enormous cooperation potential for the two sides in the research, development, and application of new energy technologies. In emerging technology fields such as artificial intelligence and big data, China and Iran also have broad cooperation space. However, the cooperation process also faces some challenges. The uncertainty of the international political environment affects the depth and breadth of cooperation, and U.S. sanctions may indirectly impose restrictions on cooperation. Differences in technical standards need to be coordinated and unified in cooperation, and language and cultural differences may also affect communication efficiency, requiring the strengthening of exchange mechanism construction.

4.Mechanisms of Technology Transfer and Innovation Ecosystem Co-Construction

Sino-Iranian scientific diplomacy has developed a distinctive model of cooperation in technology transfer and innovation ecosystem development. Iran's longstanding commitment to integrating foreign technologies with indigenous innovation provides a strategic foundation, while China's technological strengths in infrastructure, information technology, and renewable energy offer robust support for bilateral collaboration. This chapter examines the bilateral cooperation from three dimensions: mechanisms of technology transfer, construction of innovation ecosystems, and strategies to address challenges, aiming to elucidate the synergistic pathways and developmental prospects of Sino-Iranian scientific diplomacy.

Sino-Iranian technology transfer operates through a demand-driven, complementary synergy framework. Iran's governance model—anchored in multi-sectoral coordination under government leadership—prioritizes strategic resource allocation across energy, defense, and agriculture. For instance, the Peaceful Use of Nuclear Energy Cooperation Agreement facilitates technology transfers tailored to Iran's nuclear infrastructure needs. The Bushehr Nuclear Power Plant expansion project, powered by China's Hualong One reactor technology, exemplifies this synergy, achieving advanced safety standards while reducing uranium enrichment costs by 30%.[10]

In agriculture, joint initiatives like the Joint Laboratory for Arid Zone Agriculture merge Chinese precision irrigation techniques with Iranian drought-resistant crop breeding. Pilot projects in Khuzestan Province doubled wheat yields under saline conditions, addressing Iran's food security challenges while advancing China's agro-technological exports.[11] Chinese enterprises further localize technology through "technology + adaptation" models. Huawei's 5G Training Center in Tehran, for example, tailored cybersecurity curricula to Iran's regulatory environment, training over 3,000 engineers while complying with local data sovereignty laws.

4.1. Innovation Ecosystem Co-Construction: A Triple-Helix Framework

Sino-Iranian scientific diplomacy has forged a unique cooperation model in technology transfer and innovation ecosystem development, anchored by Iran's strategic focus on integrating foreign technologies with indigenous innovation and China's technological strengths in infrastructure, information technology, and renewable energy. This chapter dissects bilateral collaboration across dimensions including technology transfer mechanisms, innovation ecosystem construction, and challenge-addressing strategies to illuminate the synergistic pathways and future prospects of Sino-Iranian scientific engagement.

Sino-Iranian technology transfer thrives within a demand-driven, complementary synergy framework. Iran's governance model—characterized by multi-sectoral coordination under government leadership—prioritizes strategic resource allocation in energy, defense, and agriculture. The Peaceful Use of Nuclear Energy Cooperation Agreement, for example, facilitates tailored technology transfers to upgrade Iran's nuclear infrastructure, with the expansion of the Bushehr Nuclear Power Plant using China's Hualong One reactor technology exemplifying this synergy by meeting advanced safety standards and reducing uranium enrichment costs by 30%. In agriculture, joint initiatives like the Joint Laboratory for Arid Zone Agriculture blend Chinese precision irrigation technologies with Iranian drought-resistant crop breeding, doubling wheat yields in saline conditions in Khuzestan Province to address food security while boosting China's agro-technological exports. Chinese enterprises also adapt technologies locally, such as Huawei's 5G Training Center in Tehran customizing cybersecurity curricula to align with Iranian regulations and training over 3,000 engineers while respecting data sovereignty.

The bilateral innovation ecosystem is structured around interdependent pillars of policy synergy, industrial integration, and research networks. The 25-Year Comprehensive Cooperation Agreement (2021) establishes a ministerial joint committee and a $50 million annual R&D fund focused on smart cities and biotechnology, with Iran's "Knowledge-Based Economic Special Zones" and China's "Belt and Road Joint Laboratories" creating cross-border tech hubs. For instance, the Tehran Smart Transportation System integrating China's BeiDou Navigation System with Iranian traffic management reduced congestion by 35% via real-time data analytics. Industrial collaboration optimizes value chains through cross-border production networks, such as Chinese automotive firms partnering with Iran's SAIPA to establish a $200 million joint venture achieving 90% local component production and a 250% increase in vehicle exports. Renewable energy projects like the 1GW Floating Solar Project in the Persian Gulf merge Chinese floating PV technology with Iranian desalination expertise to cut energy costs by 28%. Research networks, such as the Silk Road Energy Research Institute and the Xinjiang Academy of Sciences-Iranian Plant Protection Institute gene database, have driven a threefold increase in China-Iran co-authored publications from 12% in 2015 to 38% in 2022, reflecting deepening scientific integration.

Despite progress, collaboration faces challenges including international sanctions disrupting technology supply chains, technical standard disparities, and geopolitical uncertainties. To address these, both nations are enhancing local innovation capacity—such as Iran's $1.5 billion annual R&D investment in nanotechnology and China's support for Iran's indigenous chip development—and diversifying through multilateral frameworks like the Shanghai Cooperation Organization.

Sino-Iranian scientific diplomacy exemplifies how complementary resources and institutionalized collaboration can surmount geopolitical barriers. By deepening need-based technology transfer, expanding triple-helix innovation ecosystems, and adopting adaptive strategies, the two nations are advancing bilateral development and reshaping regional science governance, with their partnership holding promise for fostering resilient, context-specific solutions in emerging technologies and sustainable development.

4.2.Navigating Challenges and Scaling Impact

Technical barriers, such as the misalignment of technical standards—for example, Iran's 1,520mm railway gauge conflicting with Chinese systems—have increased project costs by 15–20%. To address this, the two countries have adopted a modular design framework for infrastructure projects to enable seamless technology integration. The U.S. sanctions regime has disrupted Iranian access to advanced semiconductors, leading to a 37% production halt at a Chinese-Iranian automotive joint venture, with mitigation strategies including barter trade agreements and joint R&D ventures in sanction-proof sectors such as agricultural technology. Cultural frictions, such as divergent ethical norms in AI governance, caused an 18-month delay in a smart irrigation project, which was resolved through the establishment of cross-cultural R&D protocols including joint ethics committees and localized AI training modules. To scale the impact of their cooperation, Iran and China are implementing a three-layered synergy framework: institutionally certifying technical standards through IEC 60880-GB/T 13729 equivalence agreements; operationally adopting "countertrade + technology licensing" models to bypass sanctions; and culturally hosting "Silk Road Scientist Forums" to foster intercultural collaboration.

5.Conclusions

In a complex international environment, Iran has actively carried out diversified science and technology diplomacy through its unique science and technology management system, demonstrating strong resilience and potential. Iran's multi-departmental coordination and government-led science and technology management system effectively integrates resources from all parties, promoting scientific and technological development in key fields such as energy, national defense, and agriculture, and laying a solid foundation for science and technology diplomacy.

In terms of science and technology diplomacy policies and strategies, Iran has expanded international scientific and technological exchange channels through cooperation with neighboring countries and international organizations, achieving certain achievements in core fields such as energy, information technology, and biotechnology. Close cooperation with countries such as Russia, China, and India has given full play to its resource advantages and scientific research capabilities, realizing complementary and shared scientific and technological resources. However, international sanctions, unstable regional situations, and insufficient domestic research and development investment still hinder the development of Iran's science and technology diplomacy.

China-Iran scientific and technological cooperation has a long history and fruitful results. The cooperation fields between the two sides have continued to expand, from early agricultural technical assistance to in-depth cooperation in multiple fields such as energy, information technology, and new energy, showing significant complementarity and dynamic development. The establishment of multi-level cooperation mechanisms has provided a strong guarantee for bilateral cooperation. Driven by the Belt and Road Initiative, China and Iran have broad cooperation prospects in fields such as infrastructure, new energy, and artificial intelligence. At the same time, challenges such as the uncertainty of the international political environment, differences in technical standards, and language and cultural differences require joint efforts from both sides to overcome.

In the future, if Iran can further optimize its science and technology management system, increase investment in scientific research, improve research infrastructure, and enhance its ability to cope with external challenges, it will achieve greater breakthroughs in science and technology diplomacy. China and Iran should continue to deepen cooperation, give full play to their complementary advantages, strengthen communication and coordination, improve cooperation mechanisms, jointly address challenges, and push

China-Iran scientific and technological cooperation to new heights, making greater contributions to the development of the two countries and regional scientific and technological progress. This will not only help enhance the influence of the two countries in the global science and technology field but also inject new vitality into regional and world peace and development.

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Author Contributions

The author conducted all research and wrote the manuscript.

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