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Perspective

BlockNet: Beyond reliable spatial Digital Twins to Parallel Metaverse

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THE BIGGER PICTURE The Metaverse is the expansion of Digital Twins in the fields of people and society. Although the Metaverse existed 10 years before the emergence of Digital Twins, it is still in the concept stage, and Digital Twins has been widely used in industries and other fields. We extracted the immutable characteristics of Blockchain and proposed a secure multidimensional data storage solution called BlockNet that can ensure the security of the digital mapping process of the Internet of Things, thereby improving the data reliability of Digital Twins. Additionally, to address some of the challenges faced by multiscale spatial data processing, we proposed a nonmutagenic multidimensional Hash Geocoding method, allowing unique indexing of multidimensional information and avoiding information loss due to data dimensionality reduction while improving the efficiency of information retrieval and facilitating the implementation of the Metaverse through spatial Digital Twins based on these two works.

1 2 3 4 5 **Concept:** Basic principles of a new data science output observed and reported

SUMMARY

The development of Digital Twins has enabled them to be widely applied to various fields represented by intelligent manufacturing. A Metaverse, which is parallel to the physical world, needs mature and secure Digital Twins technology in addition to Parallel Intelligence to enable it to evolve autonomously. We propose that Blockchain combined with other areas does not simultaneously require all of the basic elements. We extract the immutable characteristics of Blockchain and propose a secure multidimensional data storage solution called BlockNet that can ensure the security of the digital mapping process of the Internet of Things, thereby improving the data reliability of Digital Twins. Additionally, to address some of the challenges faced by multiscale spatial data processing, we propose a nonmutagenic multidimensional Hash Geocoding method, allowing unique indexing of multidimensional information and avoiding information loss due to data dimensionality reduction while improving the efficiency of information retrieval and facilitating the implementation of the Metaverse through spatial Digital Twins based on these two studies.

INTRODUCTION

Successful online games generally have a grand and complete view of the world, such as the continent Azeroth in "World of Warcraft." These worldviews are often created through the imagination of game designers, allowing players to control the activities of the roles in a magical continent while confusing some of them regarding whether they are in reality or a game. However, compared with the completely fictional game world, the game "Second Life" provides players with an online social platform where they can engage in activities in the game identical to those in reality, such as conversation, physical interaction, trade, and construction, to create a "real society on the Internet." Thirty years ago, in his science fiction book *Snow Crash*, Neal Stephenson proposed the Metaverse concept. Unlike "Second Life," the Metaverse parallels the physical world and is a virtual world exactly like the physical world, thereby establishing a super-large space that integrates both the physical world and virtual world;[1,2] this can also be understood as a parallel universe created in the virtual world. Technology is a tool that can turn fantasy into reality, and spatial Digital Twins map the attributes of physical entities in multidimensional space to the virtual world.

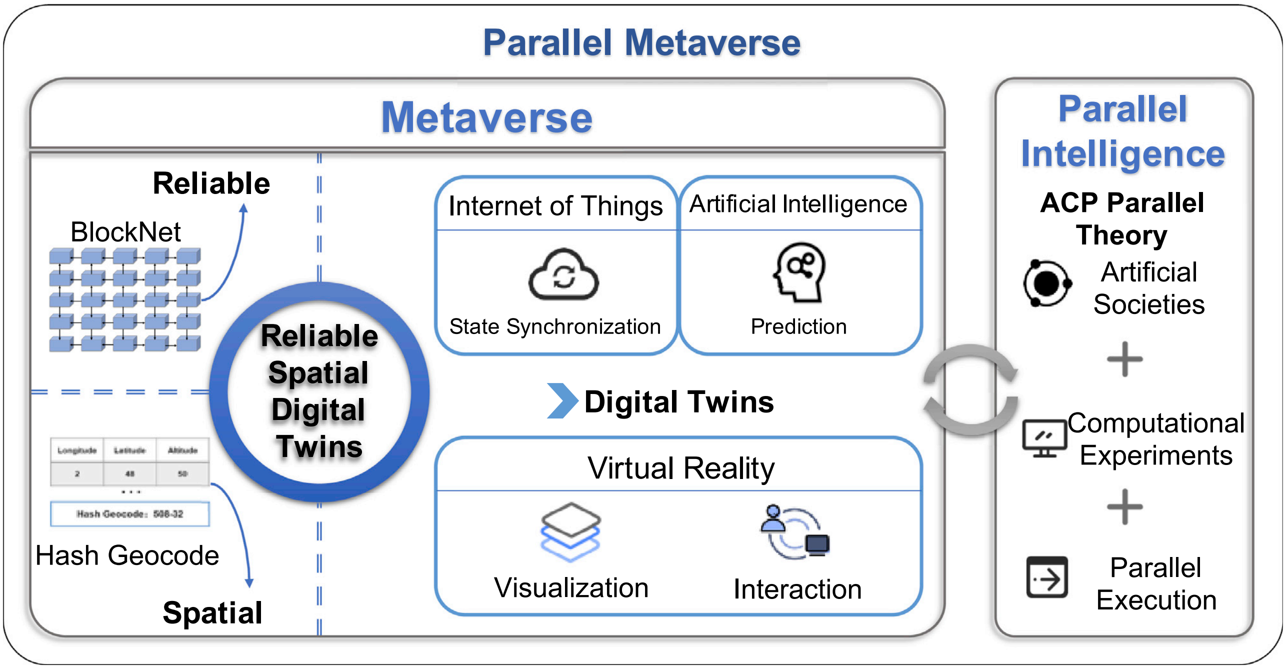

Figure 1. From reliable spatial Digital Twins to Parallel Metaverse
Reliable spatial Digital Twins consisting of BlockNet, Hash Geocoding, and Digital Twins map the attributes of physical entities in multidimensional space to the virtual world. In this process, the visualization and interaction of the virtual world is realized through Virtual Reality, and its dynamism and intelligence are supplemented by the Internet of Things and artificial intelligence to further realize the Parallel Metaverse through Parallel Intelligence.

In this process, the visualization and interaction of the virtual world is realized through Virtual Reality. However, Virtual Reality lacks dynamics and intelligence, so it is necessary to synchronize data such as the status and attributes of physical entities in real time through the Internet of Things and make predictions using artificial intelligence[3] so that Virtual Reality can become the core technical means for realizing the Metaverse and, thus, the leap from technology to art: state-of-the-art. Figure 1 is the structure of a Parallel Metaverse.

Digital Twins technology can be integrated with emerging technologies (e.g., Blockchain)[4,5] to ensure confidence, traceability, compliance, authenticity, quality, and security.[6] In academia, this technology has been applied to power electronic converter diagnosis,[7] parallel society and social contact,[8,9] dynamic capture of robotic information,[10] digital double-edge networks,[11] and other cutting-edge cross-fields. Kapteyn et al. proposed a probabilistic graphical model as a formal mathematical representation of a Digital Twins and its associated physical asset and instantiated this model to enable a structural Digital Twins of an unmanned aerial vehicle.[12] Niederer et al. analyzed the demand for Digital Twins in the industrial, discussed exemplar applications that motivate challenges and opportunities for scaling Digital Twins and that underscore potential barriers to wider adoption of this technology.[13] In an investigation on Digital Twins, we found that the process of spatial data mapping faces great data security risks, so secure multidimensional data storage technology based on spatial data self-organization mapping is a main research direction for the future. Blockchain cannot be tampered with and exhibits collective maintenance and traceability. Spatial data self-organization mapping is a key application scenario of Blockchain technology.[14]

In 2019, Tao and Qi published a comment in *Nature* and proposed that currently, the Digital Twins technique faces various problems such as ununified data types and modeling methods, and proposed the establishment of unified data and model standards for Digital Twins, the development of a common design and development platform suitable for all models, and the creation of a public database with shared data and models;[15] this will be the future trend of development. The proposed spatial data organization method in this investigation enables the secure sharing of spatial data based on Blockchain technology and can be used as an underlying technology to help solve the data-sharing problem of Digital Twins. We designed a completely multidimensional geocoding method to perform unified organization coding for sensing devices and data sources of Digital Twins to ensure data standardization. We also proposed BlockNet, a spatial Digital Twins-oriented security storage mapping model, a universal design and development platform for Digital Twins. Parallel System refers to a common system composed of a certain natural reality system and one or more virtual or ideal artificial systems. This concept is similar to Digital Twins but covers more scenarios and is more intelligent than Digital Twins.[16]

THE CHALLENGE OF MULTISCALE SPATIAL DATA

The parameters that define a space, such as the dimensions, depth, volume, and density, vary profoundly in granularity, allowing spatial sciences to cover a large scope from the macroscopic universe to microscopic molecules while making it difficult to use a general model to build full space states and use a common data structure to store multidimensional full space data.

Because of the complexity and polymorphism of spatial data, it is often difficult to achieve organization storage through modeling; therefore, the development of spatial science generates opportunities as well as challenges for the partitioned and accurate storage of massive data. Currently, our investigation of space is mainly on three scales, i.e., macroscopic (cosmic studies represented by astrophysics and other cosmic sciences), mesoscopic (e.g., Virtual Reality, Geographical Information Systems, urban transportation route planning, applied meteorology), and microscopic (microcosmic studies represented by cytology, genetics, and other fields). Macroscopic visualization is the most obvious representative application of the Metaverse. It collects celestial data in the physical world and uses visualization methods such as Virtual Reality to create a universe simulation system on a computer. Funded in part by NASA, OpenSpace developed in 2015 is interactive data visualization software designed to visualize the entire known universe and portray our ongoing efforts to investigate the cosmos.[17] Today, 6 years later, an international team of researchers has created Uchuu, the largest and most realistic simulation of the universe to date, which covers the 13.8 billion years of the universe's history from the Big Bang to the present, by using ATERUI II, the world's most powerful supercomputer dedicated to astronomy.[18] Previously, we investigated the visual modeling of multiscale spatial data covering the three scales described above, including UnityMol,[19] a visualization platform for three-dimensional molecules, and three-dimensional Earth and smart city visualization based on WebVRGIS.[20] We found that if the micromolecular scale is included in a space research system for studying the Earth space association represented by the virtual world and the three-dimensional Earth, a series of problems arise. For example: (1) intricate detailed spatial location information makes it difficult for the topology-based traditional spatial organization method to partition and index data that are in the transition state between different scale spaces from micro to macro; and (2) massive data at the extreme macro- and microscales and their transition states are impossible to store and retrieve in real time through traditional data organization methods. Therefore, it is necessary to effectively partition the spatial data of the three scales described above to improve data indexing efficiency.

Spatial data partitioning is mainly achieved through dynamic partitioning or static partitioning. The construction of Voronoi diagrams, a representative dynamic partitioning method, has been widely used in the decomposition and description of global data. However, dynamic partitioning algorithms are highly dependent on data characteristics, requiring excessive computational power during the partitioning process and therefore being unsuitable for multiscale partitioning from macro to micro. Therefore, we propose a nonmutagenic multidimensional Hash Geocoding method that facilitates the organized storage of complex and large multidimensional geographic data regarding longitude, latitude, and altitude information and achieves the asymptotic partitioning of geographic data from the macroscale and mesoscale to the microscale. For this purpose, a flexible data structure with an adaptive scale to code length is established for multiple scales to realize data mapping in three parallel spaces: physical space, data space, and virtual space.

In Hash Geocoding, the coding for geographic information is multilevel. For example, geographic information can be partitioned to 16 blocks using 1-bit hexadecimal numbers and 256 blocks using 2-bit hexadecimal numbers. In Hash Geocoding, the number of blocks increases by 16-fold with each addition to the number of bits. The total area of the Earth is approximately 510 million km^2, and when partitioned ten times with Hash Geocoding the accuracy can reach 0.463 m, which means that the accuracy covers ten block layers from coarse to fine. After verification through calculations, we concluded that only 256-bit Hash Geocoding is needed to realize the multiscale division and transition from the microscopic molecular scale to the macroscopic solar system scale. Figure 2 shows the process of Hash Geocoding.

In addition, the process of extracting physical scene information and mapping it to virtual space based on geographic blocks is cross-domain, with possible data-interpretation errors and data-tampering attempts. Moreover, geographic information includes the confidential data of the state, and its security is directly associated with national security; therefore, it is imperative to improve the security of geographic data.

Fan and Zhang use Blockchain to store multidimensional power grid data. However, because the linear block structure has not been fundamentally changed, they cannot provide an effective solution for the secure storage of spatial data.[21] To combine Blockchain with Digital Twins to achieve secure data mapping, we conducted in-depth investigations on the Blockchain consensus algorithm and its coupling with Big Data and the Internet of Things.[22–24] These preliminary studies prompted us to propose the concept of BlockNet based on Blockchain technology, i.e., replacing the chain structure with the network structure to store the hash geocoded spatial information and passing the hash coded block information to the next block for sprawling gene propagation to ultimately achieve the secure storage and mapping of spatial data. However, in previous studies traditional Blockchain was used for storing multidimensional information, which cannot accurately represent the relative position information; this major issue can be effectively solved through BlockNet.

MULTIDIMENSIONAL HASH GEOCODING

By comparing and analyzing the advantages and disadvantages of spatial information data and Hash Geocoding, on the basis of the original Hash Geocoding we include the altitude information and thus implement geocoding with three dimensions (longitude, latitude, and altitude) to make Hash Geocoding more suitable for block-storing multidimensional multilevel spatial data. On this basis, we further use the geocoding method of the Hilbert space-filling curve and propose a three-dimensional Hash Geocoding-based logical distance determination method.

Mainstream Hash Geocoding methods are carried out on a two-dimensional plane, based on the principle that a plane is divided into 16 blocks and that each block can be further divided so that multilevel partitioning is achieved. As shown in Figure 3, during the coding process the longitude and latitude of geographic reality space are converted into binary codes, cross-combined, and then further converted into the corresponding hexadecimal system in four-digit sets. However, this method can allow only single primary key indexing on the information of a two-dimensional plane but cannot represent the altitude or does not allow indexing of the information in the altitude

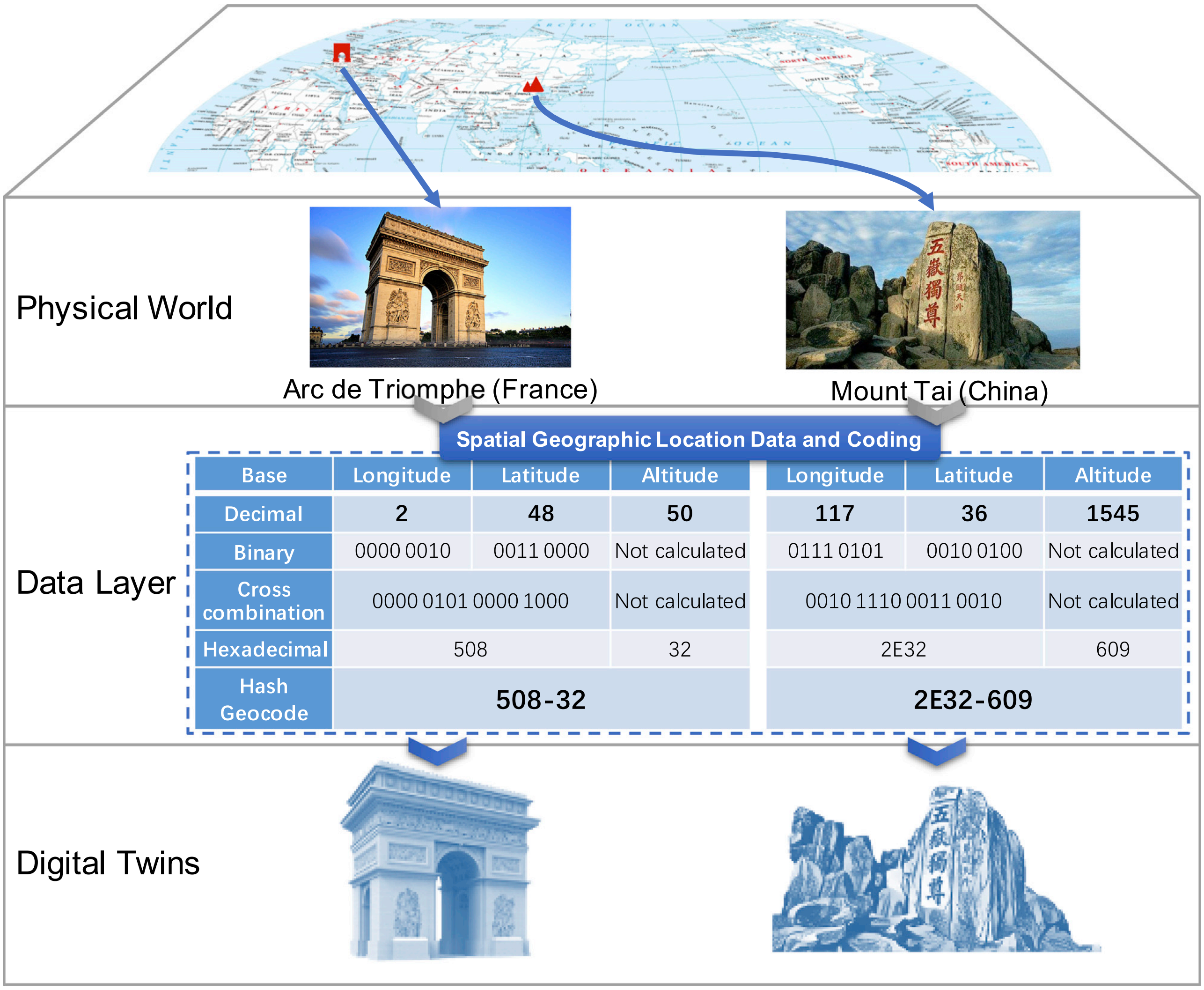

Figure 2. The process of data from the physical world to the data layer to Virtual Reality
In the data mapping process of the three parallel spaces of physical space, data space, and virtual space, the nonmutagenic multidimensional Hash Geocoding method is used in the data layer to store complex and large multidimensional geographic data regarding longitude, latitude, and altitude information and achieves the asymptotic partitioning of geographic data from the macroscale and mesoscale to the microscale.

dimension. In the spatial data organization mapping process, especially the virtual space construction process, indexing multidimensional information is required, so altitude can be a major parameter. To prevent the altitude information from becoming noise data in the calculation of the two-dimensional logical distance owing to directly cross-combining longitude, latitude, and altitude coding, we first cross only n bits of longitude and latitude to form 2n-bit binary coding combinations. After hexadecimal conversion of the combinations to two-dimensional hash geocodes, the altitude parameter is then hexadecimally converted and annexed at the back as a suffix code to form a fixed-length code with the two-dimensional hash geocode.

To achieve the organization mapping of full spatial data, it is necessary to combine BlockNet and Hash Geocoding to realize fine-grained data organization and storage. In Hash Geocoding, the coding of geographic information is coded in multiple levels—for example, using hexadecimal numbers geographic information is partitioned in 16 blocks, and using 2-bit hexadecimal numbers it can be partitioned in 256 blocks. With each additional bit, the number of blocks in Hash Geocoding increases 16-fold. The area of the Earth is approximately 510 million km^2, so performing Hash Geocoding ten times (i.e., 10-bit Hash Geocoding) achieves an accuracy of 0.463 m, which means that ten layers of blocks from coarse to fine are obtained. If Blockchain technology is used on each layer, building the Blockchain network takes a very long time, but if Blockchain technology is used only on the bottom layer, resources are saved while the security of the data is guaranteed.

On this basis, we propose the logical spatial distance determination algorithm, in which the logical distance determination is divided into two cases: (1) when two-dimensional logical distance determination is performed, the plane hash geocode of two nodes is converted to binary exclusive OR (XOR) to obtain the logical distance; (2) when three-dimensional logical

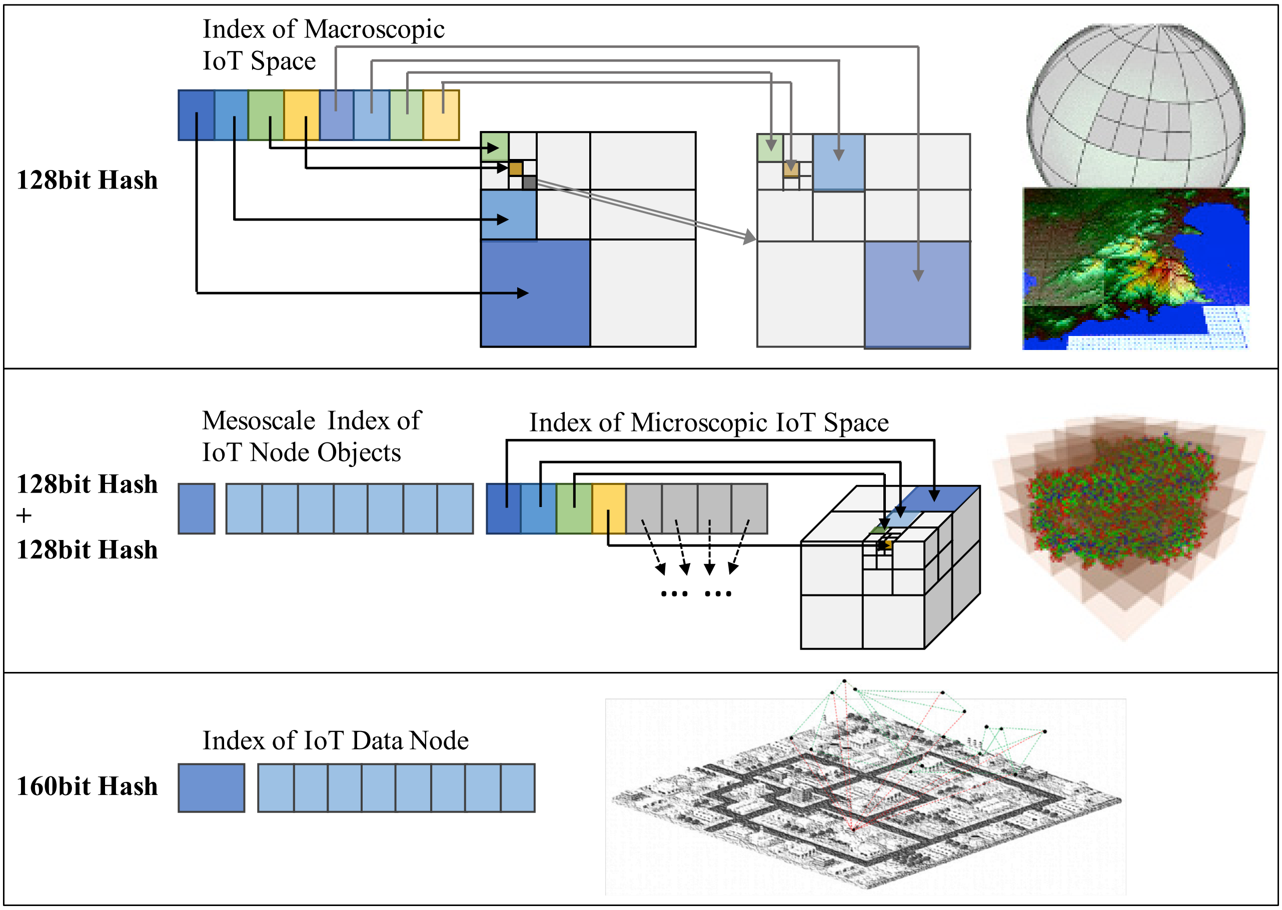

Figure 3. Coupling index structure, assuming n = 32

Mainstream Hash Geocoding methods are carried out on a two-dimensional plane based on the principle that a plane is divided into 16 blocks and that each block can be further divided so that multilevel partitioning is achieved. During the coding process, the longitude and latitude of geographic reality space are converted into binary codes, cross-combined, and then further converted into the corresponding hexadecimal system in four-digit sets.

distance determination is performed, the two-dimensional distance is first obtained by coding the latitude and longitude to perform the XOR operation, after which the altitude distance is obtained by coding the altitude to perform the XOR operation. Finally, the three-dimensional logical distance between the two regions is calculated using the spatial geometric function.

At present, unique coding is performed on industrial equipment using barcodes, QR codes, and Radio-Frequency Identification (RFID) in the identification and resolution technology of the Industrial Internet of Things; this type of coding has also been frequently applied to industrial Digital Twins. However, the application scenarios of the Parallel Metaverse are not limited to industry, and the data necessary to be acquired and coded are similarly not limited to industrial equipment operating data. To ensure the accurate description of physical systems, it is necessary to investigate the mechanism through which the spatial data of the entire scenario influence each other. Three-dimensional Hash Geocoding is an identification and resolution technology as well as an effective way to partition and index these spatial data. Moreover, it can connect the physical space, data space, and virtual space in series and maximally enhance the coupling of the three sets of spatial data, thereby ensuring the reliability of the Parallel Metaverse as well as the accuracy of the prediction results.

Three-dimensional Hash Geocoding partitions the space into multiple cubes and then performs unique coding on each of them. Thus, physical entities in this space are registered to one or several hash geocodes to represent their location information. However, determining their accurate position in space is an issue. We can mix several positioning techniques from microscale to macroscale to perform multiscale asymptotic positioning and use different positioning techniques for different accuracy requirements and different transmission distances: when high-precision positioning is needed, nanosensors are used; with decreasing accuracy requirements or increasing transmission distance, laser length gauges, ultrasonic ranging, Near-Field Communication, RFID, Ultrawideband, Bluetooth, WiFi, Zigbee, Global Positioning System, radio telescopes, and other methods can be employed for asymptotic positioning. In addition, we are investigating the sensing methods for scenarios from the microscale and mesoscale to the macroscale. Because of its flexible nature, Hash Geocoding can represent geographic information of varying accuracies well and adapt to codes of

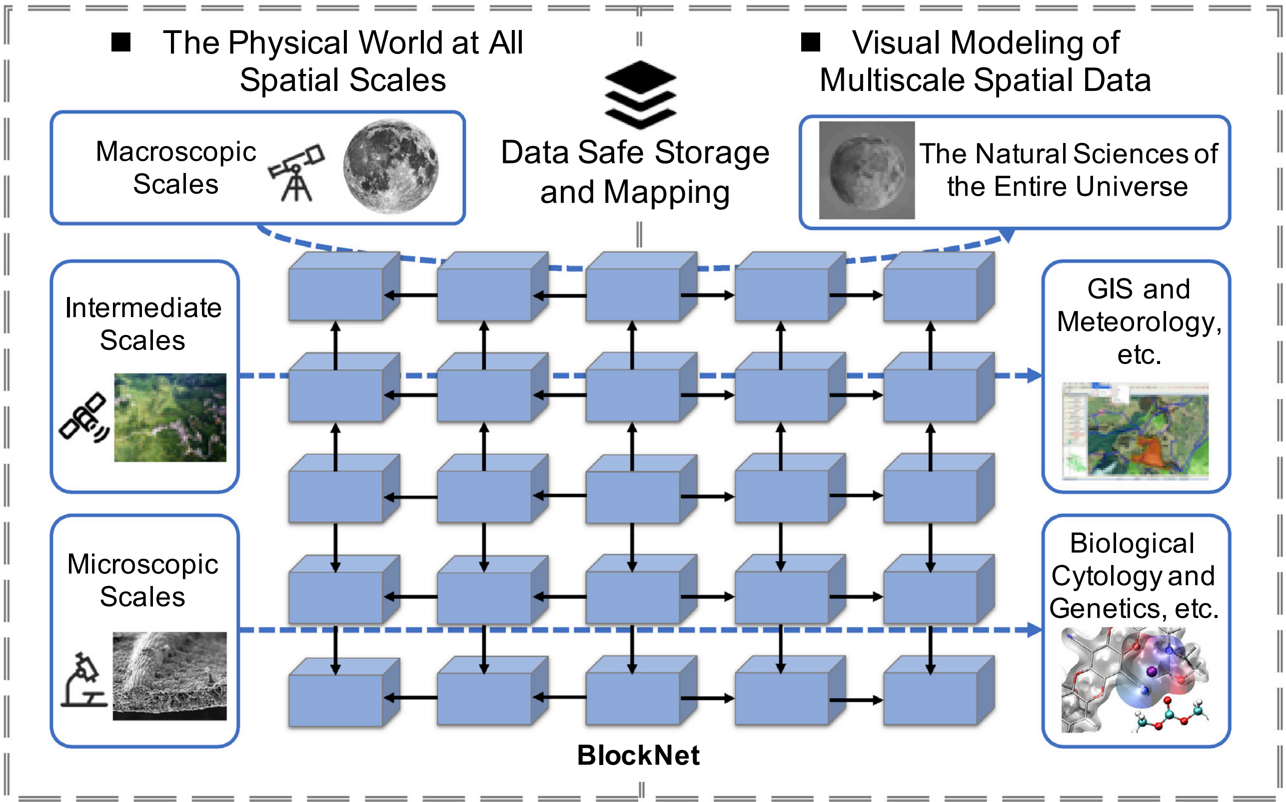

Figure 4. BlockNet safe storage and mapping of data at various spatial scales
BlockNet can realize the safe storage and mapping of data at various spatial scales, including macroscopic (cosmic studies represented by astrophysics and other cosmic sciences), mesoscopic (e.g., Virtual Reality, geographical information systems, urban transportation route planning, applied meteorology) and microscopic (microcosmic studies represented by cytology, genetics, and other fields).

different lengths according to the accuracy of geographic information.

BlockNet

Traditional Blockchain linear storage methods have difficulties in representing multidimensional data, for which we propose a nonstretching, deformable, multidimensional data-oriented block storage method. In the proposed BlockNet storage model, blocks still have the sequential connection relations. Unlike the conventional Blockchain case where each node has only one in-degree and one out-degree, in BlockNet each node has a plurality of in-degrees and out-degrees. After the sprawling gene propagation in the entire BlockNet, the generated BlockNet model is very robust and has stretch resistance, so properties such as nonstretchability and deformability can be obtained in BlockNet. Figure 4 shows multiple application scenarios of BlockNet.

In this model the chain between blocks should be one-way, which requires us to find a block as the starting block for the sprawling gene propagation (because the next block stores the hash value of the current block data, we analogize it to genetic inheritance). The first block that starts the propagation is called the source block. We use the central block as the source block for testing and ultimately design the first-generation propagation rule of BlockNet; i.e., each block propagates toward the direction opposite to the source block, according to which BlockNet also propagates to achieve the net-wide sprawling propagation of two-dimensional data.

Our observation of the constructed model shows that the average in-degree and out-degree values of each block are all 2 because the hash coded data of each block is added to its successor block; the higher the out-degree value a block has, the less likely the block is to be tampered with, and the farther the block is from the central block, the lower the cost of tampering with the data. Two unique types of blocks are observed: the source block in the middle of BlockNet and the edge blocks in four corners. The source block is the genesis block, with no in-degree and an out-degree of 4, and it is the safest block in the entirety of BlockNet; edge blocks have in-degrees but no out-degrees and thus are the easiest to tamper with, with a tampering difficulty of almost 0.

To ensure the data safety of the edge blocks, the hash values of edge block data are packed together and stored in a single block for other blocks to supervise.

To solve the problem of the blocks farther away from the source block having lower block safety, we use multiple blocks at the same time as the source block in the propagation; the shared edge blocks of multiple source blocks can still exhibit the redundant update problem, which we call radial flow cross.

To prevent radial flow cross of two source blocks, if the target block already has the out-degree to the current block during the propagation process, the propagation is stopped, and the node information with an out-degree of 0 is stored in the edge node information block.

In this model, gene propagation is performed outward layer by layer starting from the source block. Therefore, when BlockNet is constructed using the gene propagation algorithm, the safety coefficient can be calculated by counting the rounds of propagation to assess the security of BlockNet.

In the scenario of multisource BlockNet propagation, to prevent radial flow cross the propagation is stopped when the target propagation block has the out-degree to the current block. However, owing to the problem of network latency or computational power limitations, when a source block propagates too fast and thus sprawls faster than the other blocks, it leads to too small an area for the other nodes to propagate in BlockNet, resulting in a low overall safety coefficient, thus impacting the other source blocks in BlockNet.

To achieve high reproduction of physical space data through Virtual Reality space under the premise of guaranteed safety, information updates in BlockNet are indispensable. This situation is, in a sense, impossible to achieve. In the BlockNet model, modifying the data of a certain block is allowed, and the modification itself does not cause the entire net to experience information update.

DISCUSSION

The combination of Blockchain and Digital Twins is applied to the Industrial Internet of Things, Building Information Modeling, intellectual property protection, and other fields. Shuhail et al. applied Digital Twins to Industrial Internet to achieve fault prevention and stored life-cycle data based on Blockchain.[25] Celik et al. recorded the architectural, structural, and MEP (mechanical/electrical/plumbing) information of a building into the Blockchain, respectively, and then integrated it.[26] Li et al. proposed a Digital Twins sharing scheme based on Blockchain to protect the copyright and knowledge of Digital Twins during sharing and took 3D printing as an example to verify and evaluate.[27] Hemdan and Mahmoud proposed a Digital Twins framework based on Blockchain to ensure the security of each transaction during the communication between virtual assets and physical assets.[28] Putz et al. developed a DAPP based on Blockchain, which is applied to the security information management of industrial 4.0 assets by Digital Twins.[29] Bellini et al. improved the credibility of Virtual Reality scenes by using Blockchain as a data-sharing method.[30] Ryskeldiev et al. proposed a point-to-point distribution model based on decentralized Blockchain, which represents virtual space as blocks and stores the whole Metaverse in a JSON array so that it can be easily stored and shared in plain text. However, this also leads to limited information that can be stored and faces information loss when spatial data are reduced to string.[5] Nguyen et al. effectively manage and automate the complex interaction between Metaverse service providers and Metaverse users using smart contracts and designed a new fragmentation scheme to improve the scalability of the underlying Blockchain.[31] These methods ignored the dispersion of scene data in multidimensional space.

Here, we proposed Hash Geocoding for multidimensional data. Furthermore, we proposed a multidimensional logical distance judgment algorithm based on a binary XOR operation to calculate the logical distance between two three-dimensional Hash Geocoding nodes in space, which is significantly more computationally efficient than a Euclidean distance calculation. We propose a construction method whereby a multidimensional BlockNet is used to establish a genetic propagation mechanism and select the source block. Thus, propagation occurs in multiple directions, based on the standard applied to the three-dimensional Hash Geocoding. We also designed and analyzed the relationship between the in-degree and out-degree, as well as the logical distance between the source block and the block safety index. We proposed a multisource block solution whereby BlockNet can effectively eliminate the risk of radial propagation (radial cross-flow and radial impact) in the multicenter block.

The BlockNet data organization model can be widely applied to smart cities, smart security, intelligent manufacturing, and other fields.[32] It is often difficult to incorporate regulation of illegal constructions into the urban planning process. For example, some residents illegally build high-rise structures or expand existing structures to increase their living area and secretly demolish these temporary structures before inspection. This "guerrilla warfare" approach makes regulation very difficult. Hash Geocoding can be used to categorize urban spatial data, and the results can be stored securely on BlockNet. Law enforcement officers can then read the space-time data in BlockNet and use historical reproduction to assess the historical state of a building. The difficulty of regulating illegal buildings is thus reduced. Moreover, spatial Digital Twins are not limited to objects of static data and normal state data and can be used to describe dynamic data, such as people and vehicles, as well as the relationship between physical entities, making it possible to record events in smart cities. For example, when a crime occurs in the city, police can use spatial Digital Twins to reproduce the incident at the scene of the crime. Police can use incident reproduction to visualize the entire crime process, as well as the getaway route and visual renderings of criminals, and can even obtain identity information for use in a criminal investigation, case handling, and evidence collection. There are already many examples of typical Digital Twins applications in the intelligent manufacturing industry represented by predictive maintenance and energy consumption analysis. BlockNet thus ensures the reliability of Digital Twins data, which is a solid "guardrail" to protect the "highway" of data mapping from physical to virtual, to guarantee the safety of the data found in the Parallel Intelligent System. Furthermore, Parallel Intelligence is used to perform a synchronous analysis of the reliable data, thereby profoundly improving the prediction accuracy. When engineers repair equipment malfunctions and address source code bugs, equipment can often be inadvertently back-ordered. The lack of records of the operation process makes the repair process difficult to reproduce. Digital Twins-based malfunction and process reproductions can help improve the repair process and efficiency. Moreover, some experiments can be challenging to repeat because of extremely difficult execution. However, the experiments can be mapped to a virtual space using a spatial Digital Twins, and the BlockNet data organization model can be used to improve the data reliability of these Virtual Reality scenes. Thus, the entire life cycle of equipment entities can be truly reflected.

In future work, we will collect samples from real spatial data for use in constructing Virtual Reality scenes, use the proposed multidimensional Hash Geocoding for high-efficiency indexing of spatial data, and use the Blockchain data organization model as a basic data storage solution to ensure data reliability. In this way, the credibility of simulated Virtual Reality scenes can be improved, and a true mapping from the physical world to the virtual world can be accomplished, thereby realizing a leap from spatial Digital Twins to a Parallel Metaverse.

Jules Verne, "the father of science fiction," once said, "Anything one man can imagine, other men can make real." We may witness the application of BlockNet to spatial Digital Twins, and even a Parallel Metaverse, very soon.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

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