International Journal of
Geo-Information

MDPI

Article

A Knowledge-Guided Fusion Visualisation Method of Digital Twin Scenes for Mountain Highways

Ranran Tang, Jun Zhu *, Ying Ren, Yongzhe Ding, Jianlin Wu, Yukun Guo and Yakun Xie

Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, Chengdu 610031, China; tangranran@my.swjtu.edu.cn (R.T.); renyingam@my.swjtu.edu.cn (Y.R.); dingyongzhe@my.swjtu.edu.cn (Y.D.); wujianlin@my.swjtu.edu.cn (J.W.); gyk@my.swjtu.edu.cn (Y.G.); yakunxie@my.swjtu.edu.cn (Y.X.)

* Correspondence: zhujun@swjtu.edu.cn

Abstract: Informatization is an important trend in the field of mountain highway management, and the digital twin is an effective way to promote mountain highway information management due to the complex and diverse terrain of mountainous areas, the high complexity of mountainous road scene modeling and low visualisation efficiency. It is challenging to construct the digital twin scenarios efficiently for mountain highways. To solve this problem, this article proposes a knowledge-guided fusion expression method for digital twin scenes of mountain highways. First, we explore the expression features and interrelationships of mountain highway scenes to establish the knowledge graph of mountain highway scenes. Second, by utilizing scene knowledge to construct spatial semantic constraint rules, we achieve efficient fusion modeling of basic geographic scenes and dynamic and static ancillary facilities, thereby reducing the complexity of scene modeling. Finally, a multi-level visualisation publishing scheme is established to improve the efficiency of scene visualisation. On this basis, a prototype system is developed, and case experimental analysis is conducted to validate the research. The results of the experiment indicate that the suggested method can accomplish the fusion modelling of mountain highway scenes through knowledge guidance and semantic constraints. Moreover, the construction time for the model fusion is less than 5.7 ms; meanwhile, the dynamic drawing efficiency of the scene is maintained above 60 FPS. Thus, the construction of twinned scenes can be achieved quickly and efficiently, the effect of replicating reality with virtuality is accomplished, and the informatisation management capacity of mountain highways is enhanced.

Keywords: mountain highway; digital twin scene; knowledge graph; spatial semantic constraint; fusion expression

Citation: Tang, R.; Zhu, J.; Ren, Y.; Ding, Y.; Wu, J.; Guo, Y.; Xie, Y. A Knowledge-Guided Fusion Visualisation Method of Digital Twin Scenes for Mountain Highways. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 424. https://doi.org/10.3390/ijgi12100424

Academic Editors: Wolfgang Kainz and Huayi Wu

Received: 4 July 2023
Revised: 26 September 2023
Accepted: 11 October 2023
Published: 15 October 2023

1. Introduction

Mountain highways are key nodes and hubs projects that connect urban areas with mountainous regions, and realise the interconnection of transportation facilities. They serve as an important channel for expanding human living space, and greatly promote economic development and ensure the safety of social life [1–5]. However, the terrain and landforms in mountainous regions are complex and diverse. Therefore, it is very important to combine modern technology with mountainous highway operation, maintenance and management technology, and create an increasingly intelligent mountain highway management system to improve the level of information management and work efficiency of mountain highways. Digital twin technology is an effective way to achieve the information management of mountain roads [6–10]. Digital twin technology is the mapping of the properties, structure, state, performance and behaviour of real physical entities to the virtual world [11–18]. Digital twin technology also seeks to create a realistic virtual scene of mountain highways with high fidelity and interconnection of all elements, realise the accurate representation of highway operation status and rapid response to road condition information, and better support the information management decision of mountain highways [19–24].

Constructing realistic mountain highway scenes is the key to achieving information-based operation and maintenance management of mountain highways, which helps to improve the efficiency of information perception, precise positioning and management analysis; therefore, achieving the seamless fusion of terrain models and highway models is particularly important [25–32]. Many studies currently focus on the fusion of terrain and features models. The Z-buffer algorithm and floating horizon method [33–36] and the fusion expression of terrain and terrain model is achieved by the geometric embedding method [37–39], obtaining the fusion area triangulation network by using the feature constraint line and the collision detection method between the terrain triangulation network. The fusion of the terrain model and the terrain is achieved by using the local reconstruction of the terrain grid [40–42]. The fusion display of terrain and ground objects is achieved through the construction of a multi-level regular triangulation network, incorporation of a transition area, and implementation of dynamic scheduling for view LOD (Level of Detail) [43–46]. Most of the fusion methods presented above predominantly use feature line constraint fusion for single-scale scenes. These approaches often lead to grid cracks at the junction of feature boundaries and terrain, which fails to achieve the dynamic visualisation demands of multi-level and multi-scale terrain scenes. Although the multi-level regular triangular network fusion partially resolves the cracks in the fusion process, it requires a significant amount of memory and computational resources. Furthermore, most previous research relies on spatial semantic information as a constraint, resulting in an incomplete semantic understanding of the scene and knowledge graph constraints. As a result, it is difficult to apply these approaches to fusion expression for mountainous highways with complex features and correlated information.

This paper aims to study the efficient fusion construction of digital twin scene models for mountain highways and proposes a knowledge-guided digital twin scene fusion expression method for this purpose. The method provides a solution for the issues of poor automation, low modelling efficiency and insufficient scene fusion effects prevalent in the current scene modelling technology regarding digital twin technology demand. Thus, the study efficiently achieves the fusion of mountain highway scenes under knowledge guidance, enables real-time construction and expression of dynamic information in digital twin scenes and provides a base for information management of mountain highways. The remaining sections of this paper are organised as follows. Section 2 outlines the research methodology, which encompasses the overall research concept, development of the mountain road twin scene knowledge graph, knowledge-based mountain road scene fusion modelling and the visualisation publishing process of twin scene. Section 3 comprehensively analyses case studies and delves into the proposed approach. Lastly, Section 4 offers concluding remarks and future research directions.

2. Methods

2.1. Overall Research Idea

The overall framework of the knowledge-guided digital twin scene fusion expression method for mountain highways is shown in Figure 1. First, we explore the characteristics of the objects in the mountain highway scene and the association between them and created a knowledge graph of the mountain highway scene. Second, the knowledge from the scene object library and semantic knowledge source library is utilised as a lead to achieve seamless integration of the road ontology with the underlying geographic scene, using spatial orientation, attributes and topological relationships as constraints. Finally, the digital twin visualisation and publishing framework has been created based on the mountain road scene model. It enables mountain road scene twin modelling through dynamic data access and model-based overlay to facilitate mountain road scene analysis, management and decision-making support.

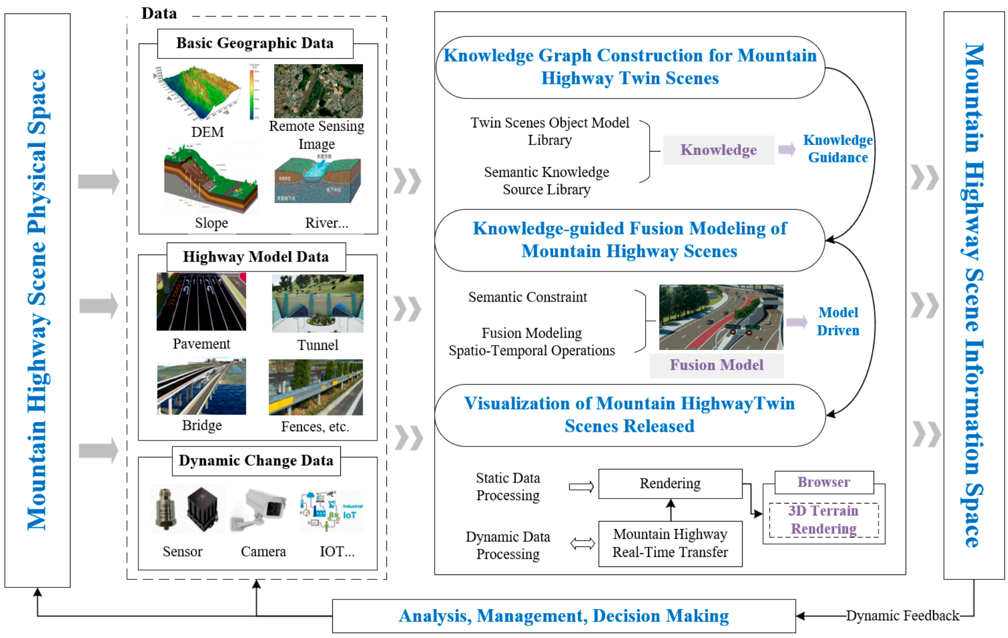


Figure 1. A general framework of the knowledge-guided digital twin scene fusion representation method for mountain highways.

2.2. *Knowledge Graph Construction for Mountain Highway Twin Scenes*

This article adopts a top-down method to construct the knowledge graph. Constructing knowledge graphs using a top-down approach facilitates a comprehensive understanding of the situation to avoid over-construction and information redundancy [47–50]. First, the diversified objects of mountain highway scene and their associated relationships are analysed, based on the data of mountain highway [51–53], basic geographic scene, highway sensor dynamic data and domain-related textual data. Second, according to the content of entities and relationships, the domain ontologies of mountain highways, geographic scenes and the Internet of Things are constructed. Finally, this article establishes a rule set to connect entities from multiple domains to achieve rule-based knowledge fusion across multiple domains. At the same time, the domain ontology of the digital twin scenario for mountain highways is constructed, and the knowledge graph for digital twin scenarios of mountain highways through ontology mapping is established. The knowledge graph construction method is shown in Figure 2.

Given the complex and intertwined relationships among multiple entities in mountain highways, the mountain highway scene is divided into the mountain highway scene itself, basic geographic data and dynamic data from sensors according to data characteristics and attribute information. Subsequently, the twin scene object library for mountain highways is constructed. Among them, the mountain highway scene itself includes road surfaces, bridges, tunnels, crash barriers, drainage systems, risk warning signs, emergency facilities, guardrails, streetlights and signs. The basic geographic ontology includes mountains, slopes, rivers and mountainous buildings. The digital twin ontology includes various sensor data, business data and monitoring videos. Based on this, entity feature extraction, knowledge classification and knowledge format unification are performed. For the parts related to the sensor data in the mountain highway entity, the sensor data is quantified and integrated into the corresponding entity attribute.

In order to build an ontology of mountain highway scenes and a twin knowledge graph of mountain road scenes for better management of mountain road data, a top-down approach is adopted. This approach analyses domain knowledge from literature, standards, rules and experts to clarify the relationships among entities and attributes [54–56]. Based on the knowledge set of mountain highway mapping and sensor data, the relationship extraction is performed. In this step, in order to analyse the susceptibility of accidents on mountain highways and achieve bidirectional feedback of twin data, the focus is on analysing the association relationships between entities in dynamic data scenarios and the various impacts of the represented content on mountain highway scenarios.

At the same time, the dense relationship model in time space is constructed to realise the fast access of dynamic data and achieve the effect of reflecting reality with the virtual. The main contents include the basic geographic scene, mountain highway model and sensor dynamic data. The ontology construction result of the highway digital twin scene is shown in Figure 3.

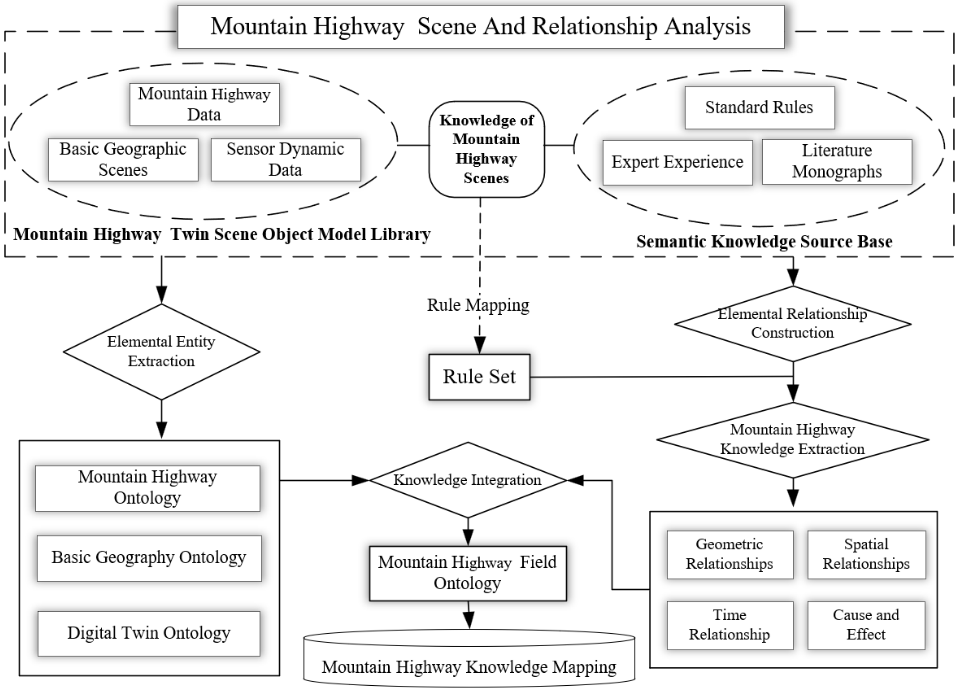


Figure 2. Knowledge graph construction method.

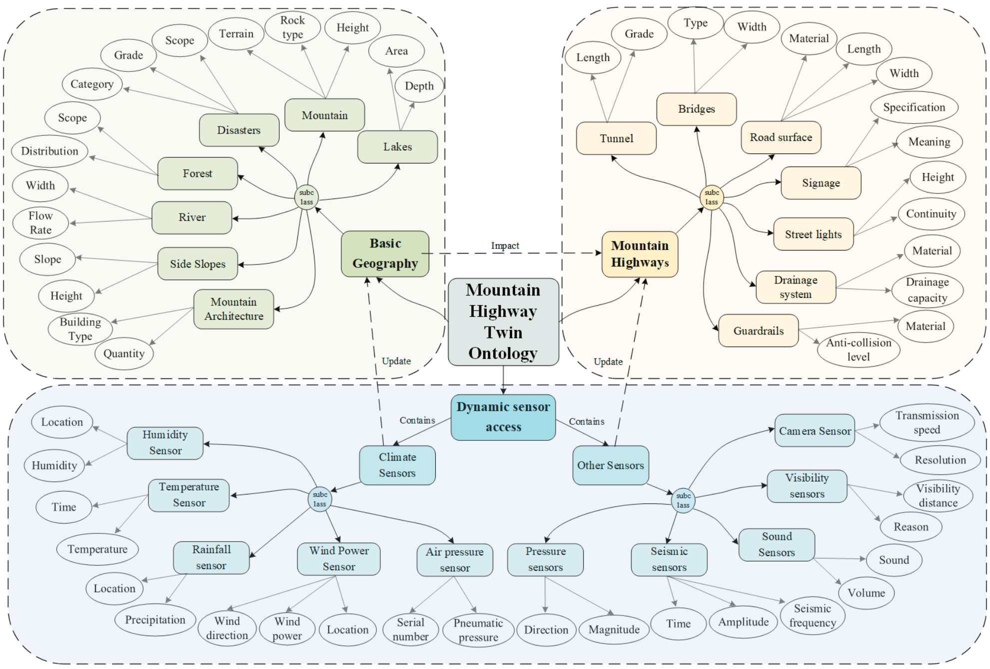


Figure 3. Mountain highway twin ontology graph.

2.3. Knowledge-Guided Fusion Modeling of Mountain Highway Scenes

To achieve the fusion modeling of mountain highways, a real-time fusion modeling method is proposed for mountainous scenes and highway models under spatial semantic constraints. The overall framework for the fusion construction of twin scenes on mountainous highways is shown in Figure 4. First, the access of static and dynamic data provides a basic foundation for the twin scene. Second, semantic constraint rules are constructed on spatial orientation, attribute categories and spatial topology constraints to guide the construction of the entire twin scene. Finally, according to the semantic constraint rules, various scene models are combined, matched and adjusted to achieve the dynamic construction of the digital twin scenario for mountainous highways.

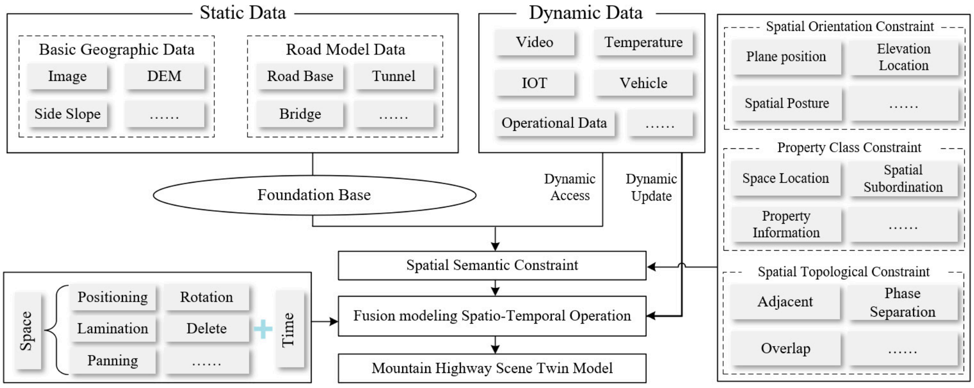


Figure 4. Real-time fusion modeling method for mountainous scenes and highway models.

2.3.1. Spatial Semantic Constraints Rules

Spatial semantic constraint rules are designed to restrict and guide the objects of mountain highway scenes, thereby achieving rapid and accurate construction of three-dimensional scenes. The spatial semantic constraint rules mainly include spatial orientation, attribute categories and spatial topology.

(1) Spatial Orientation constraints

The spatial orientation constraint adopts the spatial coordinate information and three-dimensional attitude information (pitch angle, yaw angle and roll angle) of different physical objects in the highway model. Then, the matching of the spatial position registration and spatial pose between different entity objects can be achieved under a unified geographic reference coordinate system. The yaw angle, pitch angle and roll angle in spatial posture represent rotation around the Z-axis (vertical axis), Y-axis (latitude direction) and X-axis (longitude direction), respectively. The spatial position and spatial attitude are shown in Figure 5.

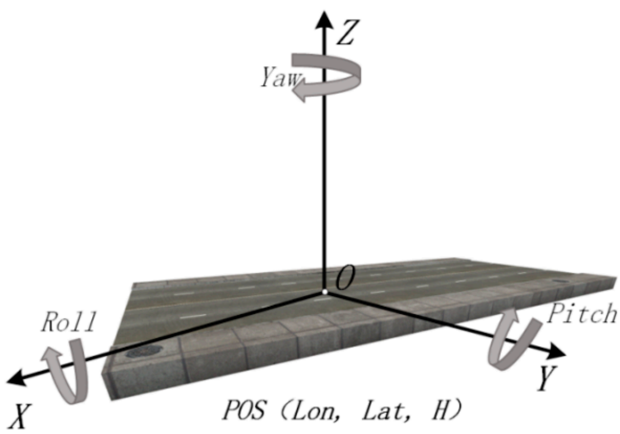


Figure 5. Spatial position and posture.

(2) Attribute Category Constraints

The attribute category constraint mainly includes the spatial location and semantic affiliation of various entities and road ancillary facilities in the highway model. This constraint can be understood as the attributes of each research object, mainly divided into highway component attributes and highway ancillary facility attributes. The attributes, including ID, name, category, location, geometric features and other information, are stored in a text file (Figure 6). The integration and visualisation of data with mountain highway scenes is based on the spatial position and semantic affiliation of each entity object.

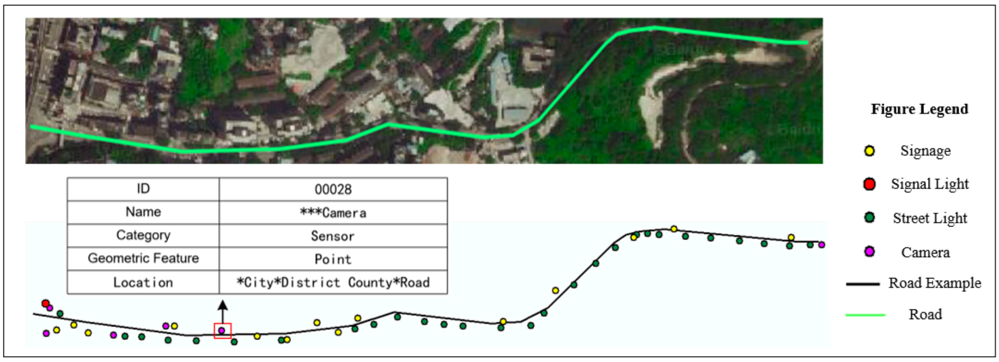


Figure 6. Attribute Information. This example describes the attribute information of this object. The camera, city, district country, and roads here do not have specific names, but are replaced with * symbols, which can represent any name.

(3) Spatial Topological Constraints

3D scene modeling should consider spatial topological relationships such as 3D models and 3D models, 3D models and 2D models, 3D models and one-dimensional models, etc. It should also consider the scene data type for the needs of mountain highway scene construction. This article selects three topological semantics as spatial constraint rules: adjacent, phase separation and overlap.

$$R(A,B) = T(A,B) + E(A,B) + O(A,B) \tag{1}$$

In the formula, R represents the spatial topological relationship between model A and B and T represents the adjacent placement of model A to model B. That is, two models have the same faces but do not intersect internally, such as terrain scene surfaces and highway models. E represents the combination of model A and model B, which, in this article, means a fully contained model, such as terrain scene boundaries that completely include highway model boundaries. O specifies the order of fitting between models, such as the seamless fitting approach of highway models and highway ancillary facilities to the surface of terrain scenes from bottom to top, as shown in Figure 7.

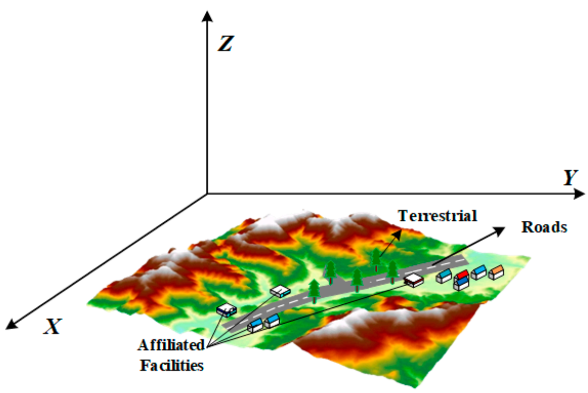


Figure 7. Spatial topological relationships of objects in mountain highway scenes.

2.3.2. Fusion Modeling of Mountain Highway Scenes

(1) Symbolic Modeling of Sensors

To avoid the issue of cognitive differences among users towards different objects, this article conducts symbolic modeling of a series of thematic elements such as sensors. Based on the user's cognitive ability to use colors and symbols in emergency situations and corresponding visualisation needs, this article sets symbols as thematic element information according to different categories. The degree of importance is graded with colors for different levels, which enables users to easily understand the location and importance of dynamic access data in highway digital twin scenes.

(2) Fusion Processing of Terrain and Highway Models

The existing scene fusion modeling methods mainly directly overlay virtual geographic scenes and highway models without any constraint conditions, resulting in an inaccurate representation of the position and spatial relationship between highway models and terrain scenes. To achieve a better fusion of models and 3D terrain scenes, this article adopts spatial semantic constraints to guide the scene construction process. At the same time, fusion modeling operations are conducted using time as the axis to perform spatial operations such as positioning, rotation, fitting and translation of the model.

In addition, due to issues such as data accuracy, quality and different sources of data, the highway model does not match the three-dimensional terrain scene, resulting in the situation of ground objects floating in the air or drilling underground. Based on the 2D data of the road centerline, sensor symbols and the 3D terrain models of different LOD levels, this article uses Formula 2 to compute the real-time 3D coordinates of each data under the response level. Thus, the spatial relationship between feature data (such as highways and sensor symbols) and virtual 3D terrain scenes can be correctly expressed, and the mismatch between features and 3D terrain scenes can be eliminated.

$$Latitude_{level} = f\left(terrainProvider,\ level,\ positions_{(x,y)}\right) \tag{2}$$

In the formula, $Latitude_{level}$ represents the three-dimensional coordinates of corresponding road, sensor symbol and other object data when the 3D terrain tile is at level i. $TerrainProvider$ represents the 3D terrain model. Level represents the corresponding tile level. $Positions_{(x,y)}$ represents the two-dimensional coordinates of geographical objects. The details are described in Equations (3)–(6):

$$Tilex = \frac{(lon + 180^\circ) \times 2^{level+1}}{360^\circ} \tag{3}$$

$$Tilex = \frac{(90^\circ - lat) \times 2^{level}}{180^\circ} \tag{4}$$

$$Rectangle = titleXYToRectangle(Tilex,\ Tiley,\ level) \tag{5}$$

$$Latitude = interpolateHeight(Rectangle,\ lon,\ lat) \tag{6}$$

In the formula, lon and lat represent the longitude and latitude coordinates of a point. $Tilex$ and $Tiley$ represent the tile coordinates of the point. $Rectangle$ represents the geographic scope corresponding to the tile. $Latitude$ represents the elevation value of the point at the given LOD level.

Integrating the above methods, first, the two-dimensional geographic coordinates of the terrain object are converted to the tile coordinates at the corresponding level. Then, based on the global geographical range (-180°~180°, -90°~90°), the number and coordinates of tiles calculate the geographic range corresponding of the tile. Finally, the geographical range corresponding of the tiles is divided into a grid of $h * h$ pixels. Therefore, the corresponding elevation value in the grid can be calculated based on the latitude and longitude coordinates of the point, and then the feature model can be seamlessly integrated with the virtual 3D terrain scene, as shown in Figure 8.

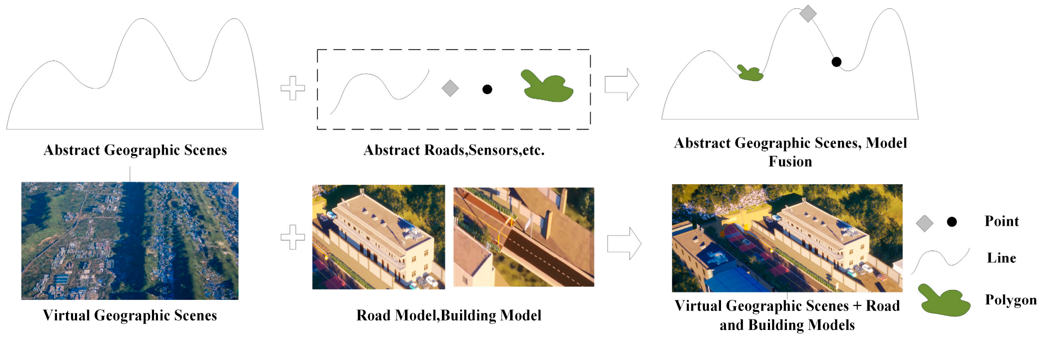


Figure 8. Geographical and terrain scene integration schematic.

2.4. Visualisation of Mountain Highway Twin Scenes

The visualisation and publication of mountain highway twin scenes are divided into two parts: digital twin base scene optimization and visualisation display and digital twin scene visualisation display. The optimization and visualisation display service of the digital twinning infrastructure scene primarily focuses on the visual presentation of the base of mountain highway scenes. Dynamic data access for digital twins involves integrating sensor data and video surveillance related to mountain highway digital twin scenes into the data twin environment. Additionally, users can dynamically access and visualise the integrated data in real-time, which enables the realization of the digital twin for mountain highway scenes. The overall process of visualizing the publication of mountain highway twin scenes is shown in Figure 9.

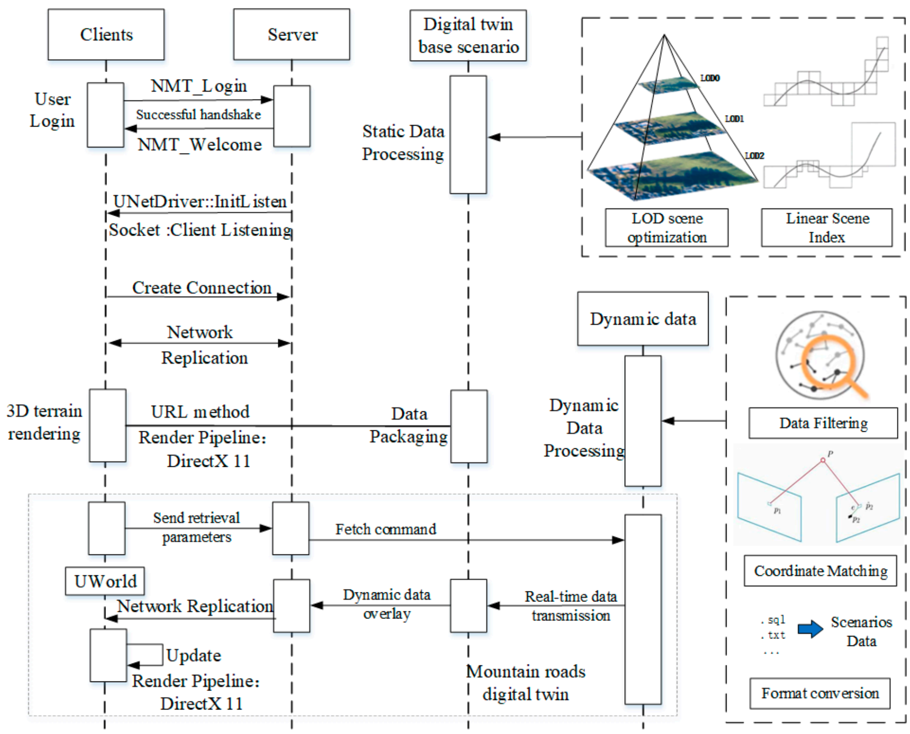


Figure 9. Method for visualising and publishing mountain highway twin scenes.

2.4.1. Digital Twin Base Scenario Optimization and Visual Display

The visualisation of the digital twin base scene is shown in Figure 10. First, the LOD and linear index of the mountain highway model are constructed to support efficient scene drawing. Second, when users perform mountain highway twin interaction operations on the client interface, the main thread is controlled to start or stop requests and transmissions. This meets the interactive needs of users in the digital twin scene of mountain highways. Finally, when the user clicks to enter the client, the system initialises as a whole. The user performs a handshake login between the client and server while logging in. At this point, the main thread is responsible for sending messages to the client UWorld. UNetDriver is responsible for listening to messages from the main thread and communicating with the server, asynchronously requesting twin data and receiving data returned by the server for visual rendering.

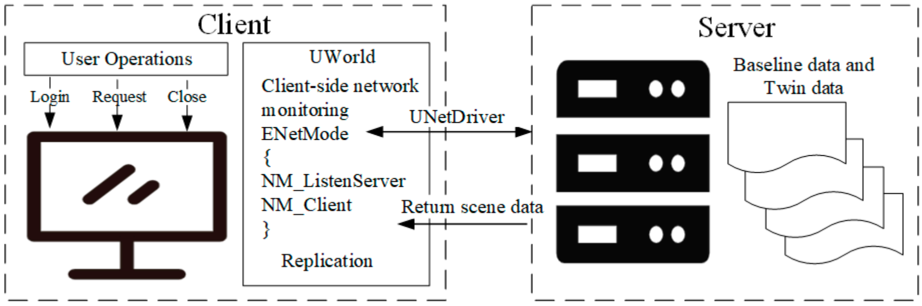


Figure 10. Client-server segment interaction principle.

2.4.2. Digital Twin Dynamic Data Access and Visual Presentation

Due to the different formats and complex structures of data from various mountain highway sensors come in. Therefore, data processing must be performed before accessing the twin scene. First, a rule-based filtering algorithms is applied to the data based on rules defined by the knowledge graph to identify and filter out useless information. Data filtering can significantly reduce data redundancy and decrease the time and cost of data processing and analysis. Second, coordinate matching is also performed to convert corresponding sensor spatial information from world coordinates to computer coordinates in the scene. Additionally, various file formats are converted into easy-to-read files. Finally, Socket is used for data synchronization. The dynamic data is overlaid onto the scene after being processed on the base, and the server-side data is updated in real-time. This process allows the client to view real-time data. Meanwhile, the client uses the UNetDriver::InitListen method to listen for the server's return of computed result data for loading and visualisation rendering, thereby completing the visualisation of the mountain highway twin scene on the client side efficiently.

3. Experiment and Analysis

3.1. Case Study

This article chose the Shapingba (105°16′~105°43′, 29°32′~29°53′) and Jiulongpo Districts (106°14′~106°32′, 29°15′~29°33′) in Chongqing as experimental case study areas to carry out research on knowledge-guided fusion modeling of digital twin scenes for mountain highways. The geographical region is characterised by towering mountain ranges, steep valleys and is crossed by gullies and ravines. The area is mainly mountainous, comprising about 76% of the region's terrain. Hills account for roughly 22%. The remaining 2% is located in the valleys formed by the flowing rivers. The experimental area includes a total length of 16.058 km of national highways, 67.781 km of provincial highways, 34.153 km of county roads. It also consists of 11 bridges and 2 tunnels. This area of mountain highways is typical of the region. The specific case study area is shown in Figure 11.

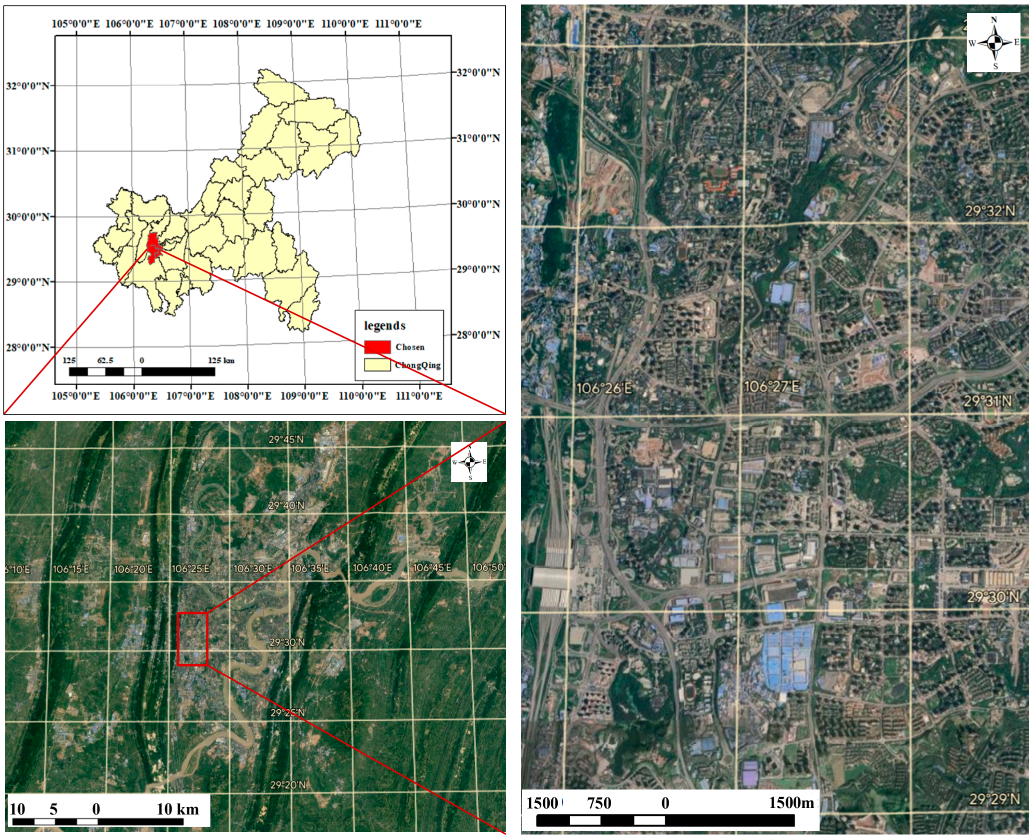


Figure 11. Case area display map.

3.2. Prototype System

3.2.1. Development Environment

This system prototype development environment is configured as shown in the following Table 1:

Table 1. Software and hardware configuration.

	Specifications	Specifications Information
Hardware	CPU Memory Video Cards Video Memory	Inter i7-12700H 16G NVIDIA GTX 3060 6G
Software	PC-based system Software	Windows11 UE4.27 VS2017

3.2.2. System Interface Introduction

(1) Basic Geographic Data

Basic geographic data mainly includes DEM and image data in Shapingba District and Jiulongpo District.

(2) Highway Model Data

Highway model data are mainly the original design data of the highway, including parameters such as starting and ending mileage of each road section according to curve radius, starting and ending mileage. The center line, gradient, road base, bridge, tunnel section start and stop mileage and other parameters are calculated according to existing parameters.

(3) Dynamic Data

Dynamic change data includes information about vehicle location and natural parameters like wind, temperature, moderation and wind direction. It is gathered from sensors on the highway, including those monitoring the road and physical world detection sensors. This data is uploaded in real-time to the management system via network interfaces.

3.2.3. System Interface Introduction

The main interface of the system is shown in Figure 12. The system is based on the UE4 engine. It is mainly used for the management of roads, bridges, tunnels and highway assets. The construction of the digital twin system for mountain highways combines basic geographic data, road model data and dynamic change data of the target area. The road management module includes maintenance section management, real-time road conditions displays and road asset status displays. The bridge management module includes viewing bridges and bridge information displays. The tunnel management module includes viewing tunnels and tunnel information displays. The asset management module includes statistical viewing of highway asset information. At the same time, the system also includes the synchronization of vehicle motion information and road condition information in the digital twin system.

Figure 12. Mountain highway digital twin system results map.

3.3. Case Experiment Analysis

3.3.1. Mountain Highway Integration Modeling

To ensure that the constructed mountain highway scene is standardised and realistic, this article first preprocesses the high-resolution terrain and image data of the case area through coordinate conversion. It creates a height map based on the relationship between terrain grid elevation and grayscale value. Based on the height map, a terrain model is generated in the UE engine, and texture mapping is completed. Then, the scene is fused and modeled through spatial semantic rule constraints. Finally, unified halo rendering is performed in the UE engine. A partial result of the mountain highway twin scene is shown in Figure 13.

From the figure, it can be seen that the spatial orientation constraint in the spatial semantic constraint rules provides a consistent and unified expression for the spatial position and spatial posture of the terrain scene and road scene models. The attribute category constraint ensures the correct expression of roads and their ancillary information in the mountain highway scene. The spatial topology constraint constrains the surface of the terrain, the model of the road and the bottom of other land objects, ensuring that the spatial relations are correctly expressed. The best scale ensures seamless splicing between models through terrain smoothing and extension of the bottom of the highway model.

The efficiency of terrain grid calculation for the road-bridge-tunnel fusion area is key to improving the capability of scene fusion. To validate the efficiency of the proposed method in scene integration, an analysis of the efficiency of terrain grid calculation for the road-bridge-tunnel fusion area is shown in Figure 14, which shows the calculation time of different terrain grids at the tunnel and bridge piers. The case study area spans 100 km and includes 2 tunnel entrances and 11 bridges. From Figure 14, it can be seen that the average time for calculating terrain grids at each tunnel is 5.97 milliseconds, significantly improving the fusion display efficiency.

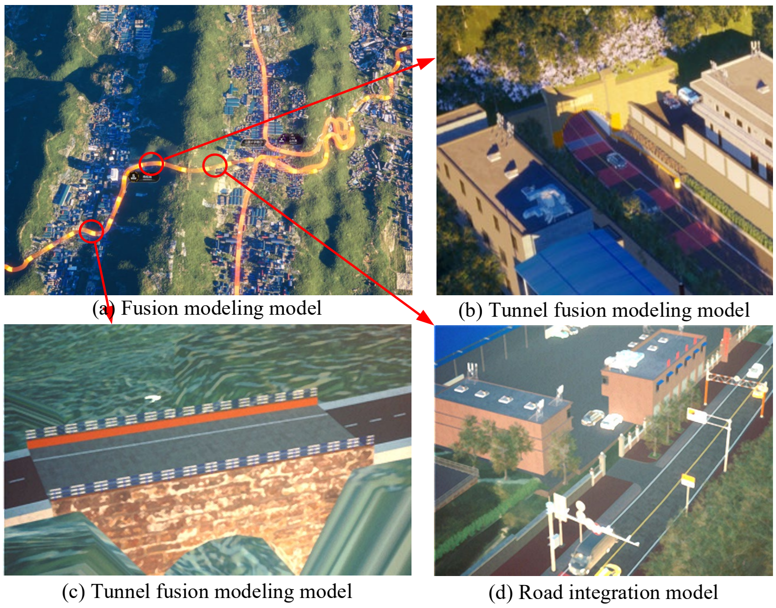


Figure 13. Overall integration model of mountain scenes and road models.

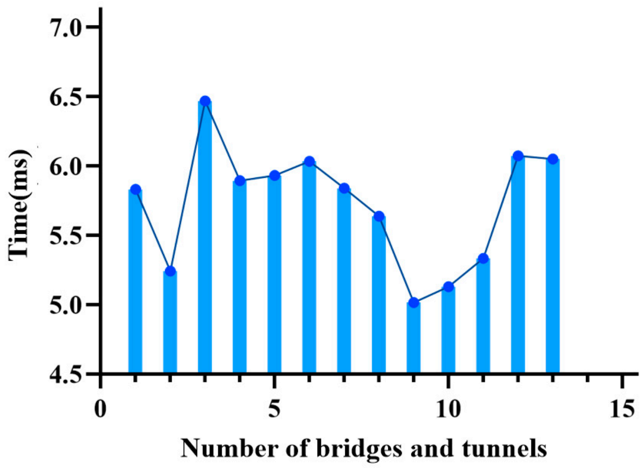


Figure 14. Calculation efficiency of topographic grid at bridge and tunnel.

3.3.2. Dynamic Expression of the Scene

(1) Road Asset Management

In order to better manage the roads in the target area, a scene fusion model is used as the basic foundation, and dynamic data from various sensors are integrated into the scene to update the entity information in the knowledge graph. The updated information is then fed back in real-time to the digital twin system of mountain highways, achieving real-time updates and expression of road asset data. Some expressions of road assets are shown in Figure 15.

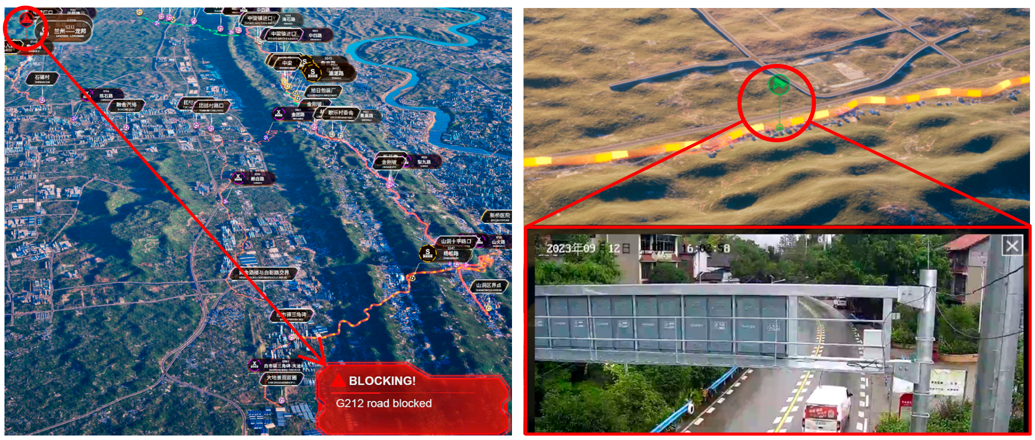
(a) Road asset twins

(b) Camera (c) Roadblocks (d) Signage (e) Signage (f) Road Monument (g) Vehicle speed measurement (h) Crash Barrier

Figure 15. Road asset twins.

(2) Road condition monitoring

Real-time feedback of road traffic flow is incorporated into the mountain highway digital twin system to provide warnings for congested road sections. Video surveillance data can also be accessed to view real-time scenes, as shown in Figure 16.



(**a**) Road blocking alarm (**b**) Road surveillance retrieval.

Figure 16. Road condition monitoring.

(3) Dynamic Monitoring of Vehicle Information

Taking vehicle data as an example, the dynamic access of vehicle status and position information is used to render real-time vehicle model data into the scene. This accurately expresses the operational state of vehicles on the road and tracks the running status of individual road monitoring vehicles, achieving a virtual-to-real effect. By viewing results in different time periods, some of the results are visually displayed, as shown in Figure 17.

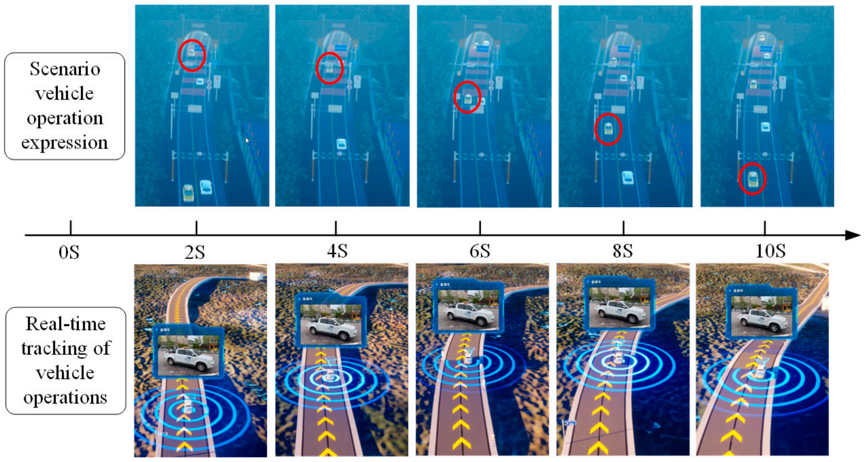


Figure 17. Real-time dynamic representation of the digital twin of the scene.

3.3.3. Scene Rendering Efficiency

The efficiency of scene rendering is directly related to the user experience. If the rendering efficiency is too low, it can cause scene rendering lag, uneven loading and poor user experience. In this paper, a random period of system operation is selected, and the scene rendering efficiency and the number of triangular facets in the scene rendering are recorded to verify the scene rendering efficiency of the proposed method. The experimental results are shown in Figure 18.

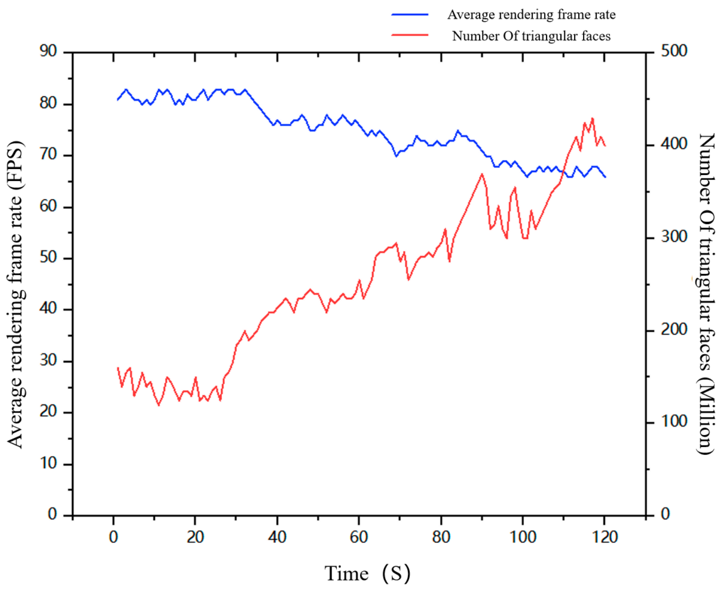


Figure 18. Scene rendering efficiency.

The visual frames perceived by the human eye typically range from 24 to 30 frames per second. When the FPS reaches over 60 frames per second, the difference in subjective perception by the human eye is not significant, and the image seen is relatively smooth. Throughout the entire testing process, the average scene rendering efficiency was 80 FPS. The standard deviation during the testing phase is 5.4, reflecting good stability in scene rendering. The testing results indicate that the method proposed in this article can meet the requirements of real-time visualisation rendering and bidirectional data feedback for digital twin scenes.

During the experimental process, the later data mainly consist of terrain and data sets from various models. Unlike only terrain data, model data such as highways and buildings have more vertices and triangles in the same area, which can lead to a decrease in the rendering frame rate. Based on the Pearson correlation coefficient calculation method, the correlation coefficient between the experimental data frame rate and the number of triangles is −0.93, indicating a negative correlation between the rendering frame rate and the number of triangles. When the number of triangles in the scene is reduced, rendering efficiency improves. Therefore, this study provides a direction for future research on scene rendering optimization, which can significantly reduce scene data while ensuring high-fidelity rendering of important areas, thus improving rendering efficiency.

3.3.4. Comparison of Existing Digital Twin Visualisation Methods

The comparison between this method and existing digital twin visualisation engines in terms of dynamic visualisation effect, visual content richness, rendering efficiency and adaptive ability is shown in Table 2. The comprehensive comparison results indicate that compared with existing methods, this method has obvious advantages, with higher visualisation efficiency, visual effects and richness of content expression.

Table 2. Comparison of digital twin visualisation methods.

Visualisation Engine	Unreal Engine	Unity 3D [57]	Cesium [58]	Supermap [59]
Visual Efficiency	High	High	Medium	Low
Difficulty of Realization	Medium	Medium	Low	Low
Richness of Visual Content	High	High	High	Medium
Adaptive Capability	Medium	High	Medium	Low

4. Discussion

This article attempts to construct a knowledge map and innovate a knowledge-guided fusion representation of a digital twin scene for mountain highways. This section highlights the strengths and limitations of this article's research while proposing suggestions with the hope that future studies will address the challenges raised here.

4.1. Strengths

This article innovatively adopts the method of spatial semantic constraints by constructing knowledge guidance to realise the digital twin scene representation of mountain highways. It aims to provide an intelligent fast modeling method and efficient visual representation. The critical contribution of this article is to propose a knowledge-guided digital twin-scene fusion representation method for mountain highways. The method overcomes the current difficulties of complex scene modeling methods and ineffective visualisation expression to support digital twin scenes in mountainous areas. The specific contributions are shown in two ways. First, a knowledge graph construction method for mountain highway twin scenes is proposed. This method constructs a domain ontology of highway digital twin scenes with the multi-domain association of highways, scenes and IoT to guide scene modeling and visualisation. Second, this study proposes a knowledge-guided fusion modeling approach for mountain highway scenes. The approach is based on the knowledge of highway scenes, the establishment of spatial semantic constraints such as orientation and attributes and topology to construct a visual representation model for the highway scene sensor.

First, this article achieves the efficient fusion expression of digital twin scenes for mountain highways. This article adopts spatial location, topological relationship and attribute relationship as constraints through knowledge guidance to achieve efficient fusion construction of highway ontology and mountain geographical scene. The experimental results show that, from the overall point of view, the mountainous area highway traffic network can be well-modelled and presented to achieve overall control. From a detailed point of view, taking the tunnel mouth as an example, calculating the intersection line between the tunnel mouth and the terrain achieves a high degree of fusion between the tunnel mouth and the terrain. Moreover, from the experimental results, the average fusion construction time of the whole scene is less than 5 ms. The experimental results show that the fusion modeling method proposed in this article can achieve efficient and high-fidelity fusion construction of mountain highway scenes.

Second, real-time visualisation and release of dynamic data are achieved. This article builds a twin scene visualisation method for mountain highways to overlay dynamic data with a base twin scene. Experiments show that the method demonstrated in this article can achieve real-time access and dynamic response of highway monitoring data, including the dynamic expression of highway asset attribute management and traffic conditions. The experimental results indicate that the rendering efficiency of the twin scene is maintained above 60 fps, meeting the requirement for real-time visualisation of the digital twin scene and bi-directional data feedback.

Third, this article presents an example of a digital twin system designed for managing the operation and maintenance of mountain highways. The method proposed in this article was used to develop a digital twin visualisation engine compared with alternative methods. The results demonstrate apparent advantages of the method, including greater visualisation efficiency, richer content, improved adaptability and lower implementation difficulty.

4.2. Limitations

This article focuses on the research carried out on modeling and representation of twin scenarios. The digital twin is a closed-loop process of visualisation display-analysis-diagnosis-decision-making. The experiments in this article only focus on scene visualisation and analysis but fail to fully consider the data release and visualisation of diagnosis and decision-making. Therefore, there is a need to research the release and visualisation of decision-making data.

The fusion modeling approach proposed in this article mainly focuses on aboveground highway facilities, scenes and sensors. This method does not consider subgrade, foundations and geological formations underneath the highway surface. Future research should incorporate integrated fusion modeling above and below ground for more thorough digital twin scene modeling of highways.

4.3. Suggestions

The approach presented in this article is primarily intended for experimentation on PCs and does not consider fusion expression using other augmented visualisation devices. Different visualisation devices have varying demands for model fusion and scene construction efficiency. Therefore, enhancing scene fusion efficiency and realism is essential to satisfy digital twin requirements across diverse augmented visualisations.

The practical implementation of the system is a crucial factor. While the study findings demonstrate the significant potential of the methodology presented in this article for managing information on mountain highways, its actual application in this domain remains uncertain. Most studies are still in the experimental phase, and large-scale applications are lacking to assess performance and usefulness. Implementing these tasks will inevitably pose a challenge, and therefore, further endeavors will be made to apply this research to the practical management of mountain highway operation and maintenance.

5. Conclusions and Future Work

The current methods for modeling complex scenes and visual representation are inadequate for meeting highways' dynamic real-time management requirements. In order to resolve these issues, this article proposes a knowledge-guided fusion visualisation method of digital twin scenes for the mountain highway. The highway scene knowledge forms the foundation for developing a digital twin scene domain ontology incorporating joint highways, environment and IoT sensing to steer the highway scene fusion modeling. The research methodology has been implemented in the management of highways in the districts of Shapingba and Jiulongpo in Chongqing Municipality. The results indicate that the approach results indicate that the approach can achieve scene fusion modeling and dynamic expression, fulfilling the requirements for information operation and maintenance management of mountainous highways.

Following this, two primary tasks require prioritization in addition to the recommendations outlined in the discussion section. First, a digital twin O&M (operation and maintenance) management system for mountain highways must be rigorously developed. Second, research should investigate visually enhanced representations of information descriptions in digital twin scenarios.

Author Contributions: Jun Zhu; Data curation, Ying Ren and Yongzhe Ding; Formal analysis, Yakun Xie; Funding acquisition, Jun Zhu; Methodology, Ranran Tang; Project administration, Jun Zhu; Resources, Ranran Tang; Software, Ranran Tang, Ying Ren, Yongzhe Ding, Jianlin Wu and Yukun Guo; Supervision, Jun Zhu; Visualisation, Ying Ren, Jianlin Wu and Yukun Guo; Writing—original draft, Ranran Tang; Writing—review & editing, Ranran Tang, Jun Zhu and Yakun Xie. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China, grant number [U2034202, 42171397, 42301473]; and Chongqing Science and Technology Project, grant number [GL202209007].

Data Availability Statement: The data that support the findings of this study are available in Available online: https://github.com/Icarusdyz/digital-twin.git (accessed on 1 July 2023).

Acknowledgments: This work was supported by the Chongqing Highway Affairs Center. Meanwhile, we thank the editors and reviewers for their valuable comments.

Conflicts of Interest: The authors declare that they have no known competing financial interest or personal relationships that could have influenced the work reported in this study.

References

1. Courtial, A.; El Ayedi, A.; Touya, G.; Zhang, X. Exploring the potential of deep learning segmentation for mountain roads generalisation. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 338. [CrossRef]
2. Courtial, A.; Touya, G.; Zhang, X. Deriving map images of generalised mountain roads with generative adversarial networks. *Int. J. Geogr. Inf. Sci.* **2023**, *37*, 499–528. [CrossRef]
3. Vega-Zamanillo, Á.; Juli-Gándara, L.; Calzada-Pérez, M.A.; Teijón-López-Zuazo, E. Study on the conservation of bituminous mixes in high mountain roads and coastal zones. *Transp. Res. Procedia* **2021**, *58*, 325–332. [CrossRef]
4. Xia, H.; Liu, Z.; Maria, E.; Xiaotong, L.; Chunxiang, L. Study on city digital twin technologies for sustainable smart city de-sign: A review and bibliometric analysis of geographic information system and building information modeling integration. *Sustain. Cities Soc.* **2022**, *84*, 104009. [CrossRef]
5. Gong, S.; Hua, G. Decision making analysis of traffic accidents on mountain roads in Yunnan province. In Proceedings of the International Conference on Machine Learning for Cyber Security, Nanjing, China, 3–5 March 2023; pp. 228–237. [CrossRef]
6. Sofia, H.; Anas, E.; Faïz, O. Mobile mapping, machine learning and digital Twin for road infrastructure monitoring and maintenance: Case study of mohammed VI bridge in Morocco. In Proceedings of the International Conference of Moroccan Geomatics, Casablanca, Morocco, 11–13 May 2020.
7. Jones, D.; Snider, C.; Nassehi, A.; Yon, J.; Hicks, B. Characterising the Digital Twin: A systematic literature review. *CIRP J. Manuf. Sci. Technol.* **2020**, *29*, 36–52. [CrossRef]
8. Liu, M.; Fang, S.; Dong, H.; Xu, C. Review of digital twin about concepts, technologies, and industrial applications. *J. Manuf. Syst.* **2021**, *58*, 346–361. [CrossRef]
9. Bauer, P.; Stevens, B.; Hazeleger, W. A digital twin of Earth for the green transition. *Nat. Clim. Chang.* **2021**, *11*, 80–83. [CrossRef]
10. Voosen, P. Europe builds 'digital twin' of Earth to hone climate forecasts. *Science* **2020**, *370*, 16–17. [CrossRef]
11. Li, Y.; Zhang, W. Traffic flow digital twin generation for highway scenario based on radar-camera paired fusion. *Sci. Rep.* **2023**, *13*, 642. [CrossRef]
12. Zheng, Y.; Yang, S.; Cheng, H. An application framework of digital twin and its case study. *J. Ambient. Intell. Humaniz. Comput.* **2019**, *10*, 1141–1153. [CrossRef]
13. Tao, F.; Xiao, B.; Qi, Q.; Cheng, J.; Ji, P. Digital twin modeling. *J. Manuf. Syst.* **2022**, *64*, 372–389. [CrossRef]
14. Lu, S.; Fang, C.; Xiao, X. Virtual scene construction of wetlands: A case study of Poyang Lake, China. *Int. J. Geo-Inf.* **2023**, *12*, 49. [CrossRef]
15. Li, W.; Zhu, J.; Dang, P.; Wu, J.; Zhang, J.; Fu, L.; Zhu, Q. Immersive virtual reality as a tool to improve bridge teaching communication. *Expert Syst. Appl.* **2023**, *217*, 119502. [CrossRef]
16. Dang, P.; Zhu, J.; Qiao, X.; Wu, J.; Li, W.; You, J.; Fu, L. How does spatial cognitive style affect indoor fire evacuation way-finding in mobile virtual reality? *Cartogr. Geogr. Inf. Sci.* **2023**, *50*, 272–288. [CrossRef]

17. Dang, P.; Zhu, J.; Pirasteh, S.; Li, W.; You, J.; Xu, B.; Liang, C. A chain navigation grid based on cellular automata for large-scale crowd evacuation in virtual reality. *Int. J. Appl. Earth Obs. Geoinf.* **2021**, *103*, 102507. [CrossRef]
18. Fu, L.; Zhu, J.; Li, W.; Zhu, Q.; Xu, B.; Xie, Y.; Zhang, Y.; Hu, Y.; Lu, J.; Dang, P.; et al. Tunnel vision optimization method for VR flood scenes based on Gaussian blur. *Int. J. Digit. Earth* **2021**, *14*, 821–835. [CrossRef]
19. Semeraro, C.; Lezoche, M.; Panetto, H.; Dassisti, M. Digital twin paradigm: A systematic literature review. *Comput. Ind.* **2021**, *130*, 103469. [CrossRef]
20. Li, L.; Lei, B.; Mao, C. Digital twin in smart manufacturing. *J. Ind. Inf. Integr.* **2022**, *26*, 100289. [CrossRef]
21. Avila, A.M.; Mezić, I. Data-driven analysis and forecasting of highway traffic dynamics. *Nat. Commun.* **2020**, *11*, 2090. [CrossRef]
22. Shahat, E.; Hyun, C.T.; Yeom, C. City digital twin potentials: A review and research agenda. *Sustainability* **2021**, *13*, 3386. [CrossRef]
23. Liao, Z.; Huang, H.; Zhao, Y.; Liu, Y.; Zhang, G. Analysis and Forecast of Traffic Flow between Urban Functional Areas Based on Ride-Hailing Trajectories. *ISPRS Int. J. Geo-Inf.* **2023**, *12*, 144. [CrossRef]
24. Feng, Y.; Ge, N.; Tao, X.; Song, Q.; Xiang, T. Channel Modelling for V2V Highway Scenario Based on Birth and Death Process. *Wirel. Commun. Mob. Comput.* **2022**, *2022*, 3384362. [CrossRef]
25. Li, W.; Zhu, J.; Pirasteh, S.; Zhu, Q.; Fu, L.; Wu, J.; Hu, Y.; Dehbi, Y. Investigations of disaster information representation from a geospatial perspective: Progress, challenges and recommendations. *Trans. GIS* **2022**, *26*, 1376–1398. [CrossRef]
26. Li, W.; Zhu, J.; Fu, L.; Zhu, Q.; Xie, Y.; Hu, Y. An augmented representation method of debris flow scenes to improve public perception. *Int. J. Geogr. Inf. Sci.* **2021**, *35*, 1521–1544. [CrossRef]
27. Zhu, X.; Chen, J.; Gao, F.; Chen, X.; Masek, J.G. An enhanced spatial and temporal adaptive reflectance fusion model for complex heterogeneous regions. *Remote Sens. Environ.* **2010**, *114*, 2610–2623. [CrossRef]
28. Esteban, J.; Starr, A.; Willetts, R.; Hannah, P.; Bryanston-Cross, P. A Review of data fusion models and architectures: Towards engineering guidelines. *Neural Comput. Appl.* **2005**, *14*, 273–281. [CrossRef]
29. Majumder, N.; Hazarika, D.; Gelbukh, A.; Cambria, E.; Poria, S. Multimodal sentiment analysis using hierarchical fusion with context modeling. *Knowl. Based Syst.* **2018**, *161*, 124–133. [CrossRef]
30. Zhang, J.; Zhu, J.; Dang, P.; Wu, J.; Zhou, Y.; Li, W.; Fu, L.; Guo, Y.; You, J. An improved social force model (ISFM)-based crowd evacuation simulation method in virtual reality with a subway fire as a case study. *Int. J. Digit. Earth* **2023**, *16*, 1186–1204. [CrossRef]
31. Wu, J.; Zhu, J.; Zhang, J.; Dang, P.; Li, W.; Guo, Y.; Fu, L.; Lai, J.; You, J.; Xie, Y.; et al. A dynamic holographic modelling method of digital twin scenes for bridge construction. *Int. J. Digit. Earth* **2023**, *16*, 2404–2425. [CrossRef]
32. Dang, P.; Zhu, J.; Zhou, X.; Rao, Y.; You, J.; Wu, J.; Zhang, M.; Li, W. A 3D-Panoramic fusion flood enhanced visualization method for VR. *Environ. Model. Softw.* **2023**, *169*, 105810. [CrossRef]
33. Xie, Y.; Feng, D.; Chen, H.; Lai, Z.; Zhu, J.; Li, C.; Sung, W.B. An Omni-scale Global-Local Aware Network for Shadow Ex-traction in Remote Sensing Imagery. *ISPRS J. Photogramm. Remote Sens.* **2022**, *193*, 29–44. [CrossRef]
34. Bakshi, N.; Shivani, S.; Tiwari, S.; Khurana, M. Optimized Z-Buffer Using Divide and Conquer. In *Innovations in Computational Intelligence and Computer Vision: Proceedings of ICICV*; Springer: Singapore, 2021; Volume 2020, pp. 41–47.
35. Hänel, M.L.; Völkel, J.; Henrich, D. Multi camera placement via Z-buffer rendering for the optimization of the coverage and the visual hull. *arXiv* **2021**, arXiv:2103.11211.
36. Luo, G.; Wang, R.; Wu, H.; Zhao, X.; Huang, X.; Cao, Y.; Liao, C. Fast hidden line removal method for large-scale 3D substa-tion scene model based on Z-buffer algorithm optimization. *J. Graph.* **2021**, *42*, 775.
37. Polis, M.F.; Gifford, S.J.; MckKeown, D.M. Automating the construction of large-scale virtual worlds. *Computer* **1995**, *28*, 57–65. [CrossRef]
38. Papandreou, G.; Zhu, T.; Chen, L.-C.; Gidaris, S.; Tompson, J.; Murphy, K. PersonLab: Person pose Estimation and instance segmentation with a bottom-up, part-based, geometric embedding model. In Proceedings of the European Conference on Computer Vision (ECCV), Munich, Germany, 8–14 September 2018; pp. 282–299. [CrossRef]
39. Wu, H.; Yan, Y.; Ye, Y.; Ng, M.K.; Wu, Q. Geometric knowledge embedding for unsupervised domain adaptation. *Knowl. Based Syst.* **2020**, *191*, 105155. [CrossRef]
40. Chen, B.; Huang, B.; Xu, B. Comparison of spatiotemporal fusion models: A review. *Remote Sens.* **2015**, *7*, 1798–1835. [CrossRef]
41. Zhao, X.; Zhan, P.; Liu, Y. Rapid construction algorithm of 3D urban road network from raster maps. In Proceedings of the International Conference on Virtual Reality and Visualization (ICVRV), Zhengzhou, China, 21–22 October 2017.
42. Solovyev, R.; Wang, W.; Gabruseva, T. Weighted boxes fusion: Ensembling boxes from different object detection models. *Image Vis. Comput.* **2021**, *107*, 104117. [CrossRef]
43. Chen, J.; Liu, T.; Hou, X. Virtual globe-oriented visualization method of multi-scale vector data. *Wuhan Daxue Sxuebao (Xinxi Kexue Ban)/Geomat. Inf. Sci. Wuhan Univ.* **2015**, *40*, 1195–1200.
44. Dinçer, S.G.; Yazar, T. A comparative analysis of the digital re-constructions of muqarnas systems: The case study of Sultanhanı muqarnas in Central Anatolia. *Int. J. Arch. Comput.* **2021**, *19*, 360–385. [CrossRef]
45. Huo, Y.; Yang, A.; Jia, Q.; Chen, Y.; He, B.; Li, J. Efficient visualization of large-scale oblique photogrammetry models in un-real engine. *ISPRS Int. J. Geo-Inf.* **2021**, *10*, 643. [CrossRef]
46. You, J.; Zhu, J.; Li, W.; Guo, Y.; Fu, L.; Dang, P. ROI-constrained visualization of flood scenes to improve perception efficiency. *Int. J. Digit. Earth* **2023**, *16*, 3065–3084. [CrossRef]

47. Tiwari, S.; Al-Aswadi, F.N.; Gaurav, D. Recent trends in knowledge graphs: Theory and practice. *Soft Comput.* **2021**, *25*, 8337–8355. [CrossRef]
48. Zhu, Y.; Wang, X.; Chen, J.; Qiao, S.; Ou, Y.; Yao, Y.; Deng, H.; Chen, H.; Zhang, N. LLMs for Knowledge Graph Construc-tion and Reasoning: Recent Capabilities and Future Opportunities. *arXiv* **2023**, arXiv:2305.13168.
49. Verma, S.; Bhatia, R.; Harit, S.; Batish, S. Scholarly knowledge graphs through structuring scholarly communication: A review. *Complex Intell. Syst.* **2023**, *9*, 1059–1095. [CrossRef] [PubMed]
50. Lai, J.B.; Zhu, J.; Luo, N.Y.; Zhang, Y.; Zuo, L.; Guo, Y.K.; You, J.G. Visual supervision of large-scope heat source factories based on knowledge graph. *Trans. GIS* **2023**, *27*, 408–424. [CrossRef]
51. Lai, J.; Zhu, J.; Chai, J.; Xu, B. Spatial-temporal analysis of industrial heat and productivity in China. *Appl. Geogr.* **2022**, *138*, 102618. [CrossRef]
52. Xie, Y.; Zhu, J.; Lai, J.; Wang, P.; Feng, D.; Cao, Y.; Hussain, T.; Baik, S.W. An enhanced relation-aware global-local attention network for escaping human detection in indoor smoke scenarios. *ISPRS J. Photogramm. Remote Sens.* **2022**, *186*, 140–156. [CrossRef]
53. Xie, Y.; Feng, D.; Shen, X.; Liu, Y.; Zhu, J.; Hussain, T.; Baik, S.W. Clustering feature constraint multiscale attention network for shadow extraction from remote sensing images. *IEEE Trans. Geosci. Remote Sens.* **2022**, *15*, 1–4. [CrossRef]
54. Ryen, V.; Soylu, A.; Roman, D. Building semantic knowledge graphs from (Semi-)structured data: A review. *Futur. Internet* **2022**, *14*, 129. [CrossRef]
55. Issa, S.; Adekunle, O.; Hamdi, F.; Cherfi, S.S.-S.; Dumontier, M.; Zaveri, A. Knowledge Graph Completeness: A Systematic Literature Review. *IEEE Access* **2021**, *9*, 31322–31339. [CrossRef]
56. Guo, Y.; Zhu, J.; You, J.; Pirasteh, S.; Li, W.; Wu, J.; Lai, J.; Dang, P. A dynamic visualization based on conceptual graphs to capture the knowledge for disaster education on floods. *Nat. Hazards* **2023**, *119*, 203–220. [CrossRef]
57. Sun, T.; Cao, Y.; Mao, B. 3D city cadaster data visualization and viewer behavior analysis in virtual reality environment. In Proceedings of the 2020 IEEE/WIC/ACM International Joint Conference on Web Intelligence and Intelligent Agent Technology (WI-IAT), Melbourne, VIC, Australia, 14–17 December 2020.
58. Zhang, Y.; Wang, Y.; Li, M.; Mao, B. Online 3D electricity infrastructure visualization based on cesium framework. In Proceedings of the IEEE/WIC/ACM International Conference on Web Intelligence and Intelligent Agent Technology, Melbourne, VIC, Australia, 14–17 December 2021.
59. Wen, F.K.; Wen, L.G.; Juan, Y.X.; Yang, P.L.; Yu, T.Y. 3D visualization of urban underground pipelines by using Super-Map. In Proceedings of the IOP Conference Series: Earth and Environmental Science, Kuala Lumpur, Malaysia, 24 May 2019.