Virtual Scene Construction Driven by Digital Twin: A Case Study of Autonomous Driving Simulation Testing

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ABSTRACT
Digital Twin technology has emerged as a pivotal innovation in contemporary technological development, enabling the creation of virtual models that interact with real-world entities through real-time data. This paper explores the integration of Digital Twin and new media technologies in virtual scene construction, with a particular focus on their applications in autonomous driving simulation testing. By leveraging Unreal Engine's advanced terrain editing tools, dynamic rendering techniques, and high-precision 3D modeling, this study establishes a high-fidelity virtual test environment for autonomous vehicle development. The research highlights key principles such as fidelity, environmental adaptability, and hierarchical scene composition to enhance realism and interactivity. Moreover, the implementation of dynamic weather conditions and modular design principles ensures a flexible and scalable testing platform. This interdisciplinary approach not only improves simulation accuracy but also provides a robust foundation for optimizing autonomous driving algorithms. The findings underscore the significance of Digital Twin technology in advancing intelligent transportation systems and fostering innovation in virtual scene design.

Keywords: *Digital Twin, New media, Scene design, Autonomous driving.*

1. INTRODUCTION

Digital Twin Technology has become a cutting-edge field in today's technological development. By creating virtual models that correspond to the real world, it enables interaction with physical entities through real-time data, providing extensive application possibilities across various industries [1]. Digital Twin not only offers comprehensive support throughout the product lifecycle but also plays a significant role in sectors such as construction, healthcare, transportation, and urban management. Driven by modern technology, the rapid development of new media technologies has made the virtual entity component in Digital Twin systems more accurate and interactive. This is particularly evident in the construction and display of information systems, 3D geometric models, and data intelligence models. These new media technologies not only enhance the immersive experience of the virtual environment but also improve users' ability to perform real-time monitoring and data analysis of virtual entities[2,3].

Among the many fields of Digital Twin technology applications, the construction of simulation scenarios, as a key component, is becoming an essential means for comprehensive monitoring, simulation, and optimization of the real world. Through the creation of virtual environments and real-time interaction, Digital Twin not only provides a highly realistic testing platform but also enables comprehensive monitoring and analysis of the environment, behavior, and system performance[4,5]. When combined with new media technologies, the applications in this field will become even more diverse and rich, particularly in the areas of scene design and interactive experiences, thereby generating significant innovative potential[6].

In the context of integrating digital twin technology with new media technology, the involvement of design disciplines not only enriches the expressive forms of scenario construction but also provides deeper optimization methods for user experience and interaction. As an interdisciplinary research field, design plays a crucial role in the application of digital twin technology, particularly in interface design, user experience optimization, and visual representation.

Design emphasizes a human-centered design approach, enabling digital twin systems to precisely meet user needs when constructing virtual scenarios[7]. For example, in virtual environments, the optimization of interface design and interaction logic enhances system usability, allowing users to intuitively understand and operate digital twin systems. Furthermore, well-structured visual hierarchies, information layering, and user guidance mechanisms significantly improve user immersion and interaction within virtual scenarios. Research in information visualization within design provides innovative possibilities for data representation in digital twin technology. Since digital twin systems rely on real-time data monitoring and analysis, presenting such data in an intuitive, dynamic, and interactive manner becomes key to enhancing user understanding and decision-making efficiency. By integrating design visualization techniques, such as infographics, dynamic data dashboards, and 3D data interaction models, complex multidimensional data can be made more comprehensible, with enhanced feedback mechanisms for users. Design also plays a pivotal role in virtual environment construction and interaction experience enhancement. By leveraging new media technologies, such as immersive experience design, virtual reality (VR), and augmented reality (AR) technologies, design facilitates the creation of virtual environments that align more closely with user cognitive habits in digital twin systems[8]. For instance, in urban planning and architectural management, high-fidelity 3D modeling and spatial interaction design improve the readability and operability of virtual cities, enabling professionals to conduct planning and management more intuitively. The interdisciplinary nature of design allows it to effectively integrate digital twin technology, new media technology, and human-computer interaction techniques, thereby creating innovative and practical solutions across different application domains. For example, in intelligent transportation, smart manufacturing, and digital cultural heritage preservation, design helps digital twin technology achieve aesthetic and functional enhancements, improving user experience and the overall application value of these systems.

Therefore, while this paper explores the integration of digital twin technology and new media technology in scenario design, it also emphasizes the role of design disciplines — particularly how design thinking, information visualization methods, interaction experience optimization, and interdisciplinary integration drive the innovative development of digital twin systems.

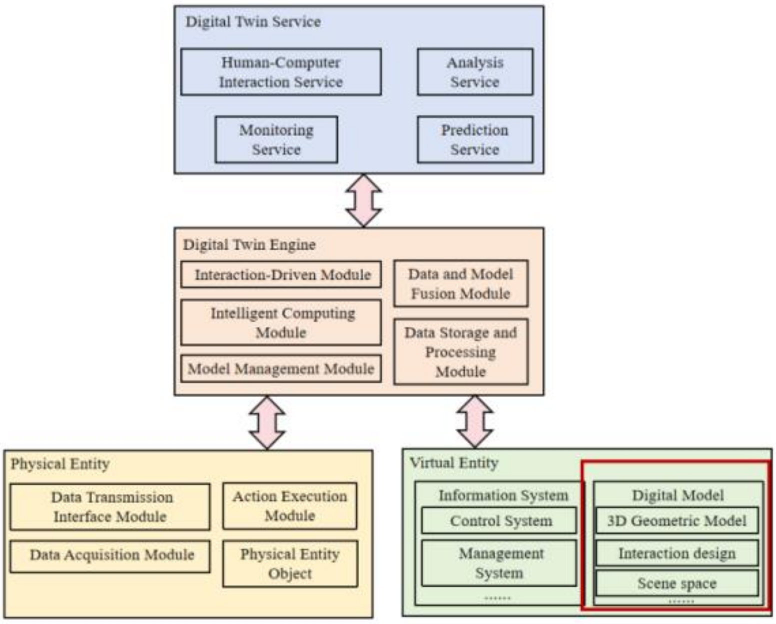

Figure 1 Illustration of the application of a digital twin system, with the highlighted section representing the virtual scenario module.

2. SIMULATION SCENE DESIGN CASE STUDY

2.1 Case Background

This paper focuses on the research of autonomous driving in test field roads, aiming to create simulation scenarios that meet testing requirements and are more aligned with real-world environments.

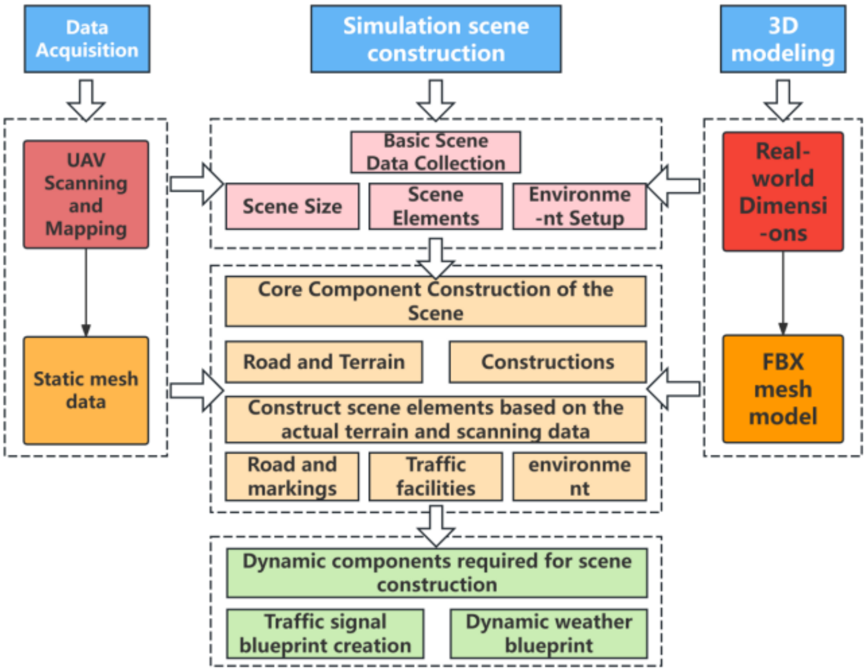

Figure 2 Simulation scenario construction process.

The simulation scenarios developed in this study are generated based on scanned road data. To enhance the realism and complexity of the simulation tests, we fully leverage Unreal Engine's terrain editing tools and dynamic rendering techniques to finely optimize lighting, materials, and environmental effects within the scene. The application of these techniques not only enhances the immersion of the virtual testing environment but also ensures a high-fidelity reproduction of visual details, thereby providing a high-precision and reproducible testing platform. This platform accommodates various complex driving scenarios, offering strong support for the validation and optimization of autonomous driving algorithms while improving the reliability and scientific rigor of simulation experiments. (“Figure 3”, “Figure 4”)

Figure 3 Map scanning results.

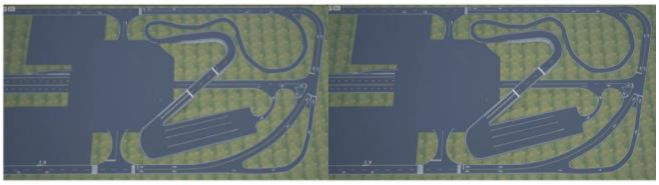

Figure 4 Manual scene construction based on scanning results.

2.2 Scene Construction

In this study, models of buildings, traffic facilities, and other environmental elements were created using professional 3D modeling software with detailed texturing to ensure a high level of visual realism and fine-grained detail representation. During the modeling process, the FBX static mesh (Static Meshes) format was employed, along with the generation and application of essential texture maps, including diffuse maps, normal maps, roughness maps, and ambient occlusion maps. These high-quality models and texture data were subsequently imported into the virtual simulation engine for mesh importation and material scripting, further enhancing scene realism and lighting effects. Throughout this process, the Form and Function Unity design principle was adhered to, ensuring that the appearance of buildings and facilities met aesthetic standards while maintaining structural rationality and interactive attributes, thereby making the virtual scene both visually appealing and functionally practical.

Furthermore, to ensure the accuracy of road structures and the high fidelity of details, we fully utilized Unreal Engine's terrain editing tools and the Spline Pro blueprint tool to edit spline lines, allowing for the precise construction of roads and road markings. These tools not only ensured that the road layout closely resembled real-world conditions but also improved modeling efficiency and operability. In the road modeling process, high-precision map data was used to ensure that the constructed road network was highly aligned with real-world road systems, thereby enhancing the reliability of the simulation environment. This approach reflects the principles of Verisimilitude and Scale Proportion, ensuring that the road's shape, scale, and texture details adhere to real-world proportions while providing clear and distinguishable visual guidance for users, enhancing immersion and user experience.

The modeling of urban roads serves as the core of the entire scene construction process. By creating highly realistic urban road environments, a solid foundation is established for the overall virtual scene, supporting the subsequent addition of environmental elements, dynamic settings, and interactive scenarios. Adhering to the principles of Hierarchical Design and Modular Construction, a bottom-up approach was adopted in the modeling process, with roads forming the primary framework, followed by the gradual addition of traffic facilities, buildings, and environmental details. This structured approach ensures clarity in scene composition, ease of adjustment, and optimization. Additionally, by applying Light and Shadow Shaping and Color Contrast principles, we ensured that roads and their surroundings maintain clarity and distinguishability under various lighting conditions. This contributes to a more realistic simulation environment, providing a high-quality simulation platform for autonomous driving testing, traffic flow simulations, and research on intelligent transportation systems.(“Figure 5”)

Figure 5 Test field scenario built in unreal engine.

The required 3D models and road editing for the scene are meticulously developed by referencing actual high-precision map data, ensuring accurate restoration of real-world location layouts and road structures. This process follows the principle of fidelity and authenticity, where every detail, from road width to lane markings, is precisely recreated to maintain realism. Additionally, the placement of environmental objects, such as buildings, streetlights, and traffic signs, adheres to the scale proportion principle, ensuring that spatial relationships are preserved and the scene remains visually and functionally coherent.

Meanwhile, the scene's primary light source and ambient lighting are continuously refined to enhance depth perception and overall visibility. Using Unreal Engine's Lumen system and Process Volume, exposure, shadows, and filters are carefully adjusted to create a balanced and immersive visual environment. The principle of light and shadow shaping is applied to emphasize contrast and depth, making objects appear more natural under varying lighting conditions. This meticulous lighting design enhances the perception of materials and textures, aligning with real-world atmospheric effects.

A crucial aspect of the simulation is the introduction of special scenarios, such as construction zones and severe weather conditions, to test the robustness of autonomous driving systems. For instance, a dynamic weather system is implemented to simulate conditions like heavy rain, reducing visibility and adding challenges to perception algorithms. This process follows the principle of environmental adaptability, ensuring that the test environment is not only visually convincing but also functionally diverse to assess system performance under different operational constraints.

To achieve real-time weather adjustments and dynamic environmental changes, this study utilizes the Ultra Dynamic Sky (UDS) weather blueprint, which allows for seamless transitions between different weather states. The integration of modular design principles ensures that various environmental factors, such as rain intensity, fog density, and wind effects, can be dynamically controlled without compromising system performance. By leveraging Unreal Engine's real-time rendering capabilities, this approach significantly enhances the complexity and variability of the simulation environment, making it an effective testing platform.

Moreover, the scene design emphasizes hierarchical composition, where foundational elements such as roads and buildings provide a structured framework upon which dynamic elements like traffic flow and weather effects are layered. This structured approach ensures scalability and adaptability, allowing for continuous refinement and expansion of the virtual environment. (“Figure 6”)

Figure 6 Simulation of multiple complex scenarios.

By meticulously replicating real-world maps and traffic signage on a one-to-one scale, the realism of the scene is significantly enhanced. The innovative aspect of this simulation framework lies in the application of Unreal Engine's powerful rendering and dynamic environmental features to create a high-fidelity, interactive urban driving environment. This approach not only elevates the realism and complexity of the test scenarios but also provides strong technical support for the development and validation of autonomous driving systems, ensuring that they can operate safely and efficiently in diverse real-world conditions.

3. CONCLUSION

The integration of digital twin technology and new media technology is driving comprehensive innovations in scenario design. From high-precision virtual environment construction to multi-sensory immersive interactions, the convergence of these technologies is introducing new application perspectives and technological breakthroughs across various industries. Whether in architectural design, urban management, traffic simulation, or emergency response, the synergy between digital twins and new media significantly enhances design accuracy and testing efficiency. In the field of design, this integration fosters deep interaction between virtual and physical spaces, transforming design paradigms from static 2D or 3D representations into real-time, dynamically adjustable intelligent design models. Particularly in intelligent transportation systems and autonomous driving simulation environments, digital twin-based visualization methods optimize road planning, enhance human-machine interaction experiences, and enable forward-looking explorations of future mobility models.

This study demonstrates how the integration of digital twin and new media technologies within an autonomous driving simulation testing system improves testing efficiency, reduces costs, and provides an interactive and immersive testing platform. By incorporating interactive visualization techniques, the testing of autonomous driving systems extends beyond individual environmental parameter adjustments; instead, simulation-based design facilitates the optimization of human-machine collaboration strategies, enhancing test comprehensiveness and practical applicability.

With the continuous advancement of artificial intelligence, cloud computing, and the Internet of Things (IoT), the integration of digital twins and new media technologies will drive transformative innovations in design disciplines, intelligent transportation, and autonomous driving simulation testing. In the future, simulation testing environments will evolve into highly intelligent and adaptive systems, capable of real-time parameter optimization while integrating deep learning algorithms for dynamic adaptation and self-evolution, thereby enhancing testing precision and applicability. In the design domain, the deeper application of digital twin technology will further facilitate the interaction between virtual environments and real-world scenarios, transitioning the design process from static representation to visualized, interactive, and intelligent dynamic systems. Meanwhile, advancements in multi-modal data fusion and enhanced perception technologies will significantly improve immersion and realism in virtual simulations, enriching human-machine interaction experiences and enabling more creative and effective design methodologies.

Ultimately, this trend will accelerate the advancement of autonomous driving technology towards higher safety standards, support smart city development, and drive the evolution of future mobility models. Additionally, it will provide new theoretical and practical perspectives for the discipline of design in the era of intelligent systems, shaping innovative and impactful research directions.

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