**Frontiers in Computing and Intelligent Systems**
ISSN: 2832-6024 | Vol. 14, No. 3, 2025

# The Mechanism of Holistic Smart Service Based on Digital Twin in the Metaverse Scenario

**Weibin Zhao [1, a], Jing Zhang [2, *], Xueyong Li [3, b]**

[1] School of Future Transportation, Guangzhou Maritime University Guangzhou, Guangdong, China
[2] School of Marxism, Guangzhou Maritime University Guangzhou, Guangdong, China
[3] Shenzhen Liqi Artificial Intelligence Development Co., Ltd. Shenzhen, Guangdong, China

*** Corresponding author:** Jing Zhang (Email: 59600658@qq.com), [a] 350425677@qq.com, [b] lixueyong1982@qq.com

**Abstract:** The Metaverse, as the next evolutionary stage of the internet, is redefining interaction paradigms between humans, objects, and environments. In this context, traditional smart service models face challenges such as insufficient immersion, delayed personalization, and physical-virtual disconnection. This study explores how to construct a new "Holistic Smart Service (HSS)" mechanism in the Metaverse using Digital Twin (DT) technology. We first define HSS as a closed-loop service system integrating high-fidelity perception, real-time intelligent decision-making, immersive interaction, and value co-creation. Then, we propose a three-layer M-DT-HSS (Metaverse-Digital Twin-Holistic Smart Service) model and formally define its core components—service state space, user intention recognition function, and physical-digital synergy optimization function. Based on this model, we design a five-layer system architecture (perception, twin construction, AI engine, interaction presentation, and value co-creation layers) and elaborate on the implementation path from data fusion to service generation. Finally, we validate the proposed mechanism through a virtual smart community service prototype system. Experiments show that our approach outperforms traditional models in critical indicators: user satisfaction increases by 28.7%, service response latency decreases by 63.2%, and resource utilization efficiency improves by 41.5%. This research provides a theoretical framework for smart services in the Metaverse era and guides their engineering implementation.

**Keywords:** Metaverse; Digital Twin; Holistic Smart Service; Formal modeling; Service mechanism.

## 1. Introduction

### 1.1. Research Background and Problem Statement

With the rapid development of Internet of Things (IoT), Artificial Intelligence (AI), and Extended Reality (XR) technologies, human society is accelerating into a new era of virtual-real integration. The Metaverse, as a persistent, decentralized, and economically systematized three-dimensional virtual space, is widely regarded as the next-generation computing platform following mobile internet. It breaks the spatial and temporal limitations of the physical world, offering users unprecedented immersive experiences. However, the value of the Metaverse extends beyond entertainment and social interaction; it serves as a new infrastructure to empower various industries, particularly in public services, commercial marketing, and social governance.

Although smart services have been widely applied in scenarios such as smart cities and smart homes, their core logic remains primarily based on passive data collection and analysis of the physical world, facing three core challenges: (1) Single-dimensional perception: Service systems struggle to comprehensively and in real-time capture users' multimodal states in complex environments (e.g., emotions, intentions, spatial positions); (2) Delayed decision-making chain: The closed-loop cycle from data collection to service generation is long, failing to meet the millisecond-level real-time interaction requirements of the Metaverse scenario; (3) Strong experience disconnection: Service processes are limited to two-dimensional interfaces or simple voice interactions, lacking the immersive and natural experience that deeply integrates with the Metaverse's three-dimensional space.

Digital Twin technology, as a bridge connecting physical entities with virtual models, through real-time data-driven mechanisms achieves virtual-real synchronization and bidirectional interaction, providing a key technical path to address the above challenges (Grieves & Vickers, 2017) [1]. Integrating Digital Twin deeply into Metaverse service scenarios has the potential to give rise to a new service paradigm—"Holistic Smart Service" (HSS). This service model not only provides precise and efficient service content but also creates emotional resonance and value co-creation through immersive experiences. Therefore, it is imperative to systematically study its internal operating mechanism, addressing key scientific questions: "What is Holistic Smart Service in the Metaverse scenario? What are its core components? And how can it be implemented?"

### 1.2. Research Objectives and Content

The core objective of this study is to construct and validate the mechanism of Holistic Smart Service based on Digital Twin in the Metaverse scenario. Specific research content includes:

1. Conceptual definition and model construction: Clarifying the connotation and extension of "Holistic Smart Service" within the Metaverse context and proposing the M-DT-HSS three-layer integrated model.

2. Formal mechanism modeling: Using formal methods to mathematically model and define core processes such as service state space, user intention recognition, and physical-digital synergy optimization, ensuring the rigor of the theoretical system.

3. System architecture and implementation path design:

Based on the proposed model, designing a technically feasible system architecture and planning a comprehensive implementation path from data to service.

Experimental validation and effect evaluation: Validating the effectiveness and superiority of the proposed mechanism through a prototype system.

# 2. Literature Review and Theoretical Foundation

## 2.1. The Synergistic Development of the Metaverse and Digital Twin

The Metaverse is not an isolated phenomenon but the result of long-term evolution and integration of multiple cutting-edge technologies. Early research primarily focused on its gaming and social attributes (Kshetri, 2021), but in recent years, academia has gradually recognized its potential as a new carrier for industrial internet[2]. Gartner predicts that by 2026, 30% of global enterprises will have Metaverse business departments (Gartner, 2022)[3]. Digital Twin, as one of the foundational supporting technologies for the Metaverse, has evolved from equipment monitoring in industrial fields (Grieves & Vickers, 2017) to urban governance (Zhang et al., 2021), healthcare (Chen et al., 2023), and even personal life[4]. The relationship between them can be summarized as: Digital Twin is the cornerstone for building the "authenticity" and "functionality" of the Metaverse, while the Metaverse provides a broad interactive stage and application scenario for Digital Twin.

## 2.2. Evolution and Limitations of Smart Services

The concept of smart services originates from the intersection of service science and information technology. Early research emphasized using sensor networks and big data analysis to achieve service automation and intelligence (Zaslavsky, A., Perera, C., & Georgakopoulos, D,2013).[5]With the development of AI technology, personalized recommendation and contextual awareness have become research hotspots.[6] However, existing studies mostly remain confined to the physical world or two-dimensional digital space, failing to effectively utilize the three-dimensional spatial computing, multimodal interaction, and economic systems provided by the Metaverse. This results in service experiences lacking "presence," making it difficult to stimulate users' deep participation and emotional connection (Brown, M., & Jones, N. 2021)[7].

## 2.3. Application of Formal Methods in Service System Modeling

Formal methods (Formal Methods) precisely describe system behavior through mathematical language, effectively eliminating the ambiguity of natural language, and play an irreplaceable role in high-reliability system design (Chen et al., 2023)[8]. Z-method, TLA+, and other tools have been successfully applied in protocol verification and software specification. However, their application in modeling complex, dynamically evolving Metaverse service systems remains unexplored. This paper attempts to introduce formal thinking to provide a solid mathematical foundation for the HSS mechanism.

## 2.4. Research Review

In summary, although the fields of Metaverse, Digital Twin, and smart services have rich achievements, research on their deep integration remains insufficient. Existing work lacks a unified theoretical framework to systematically explain their internal mechanisms and lacks rigorous formal models to support engineering implementation. This paper aims to fill this research gap.

# 3. M-DT-HSS Integrated Model and Formal Mechanism

## 3.1. Definition of "Holistic Smart Service" (HSS)

This paper defines "Holistic Smart Service" in the Metaverse scenario as: a dynamic closed-loop system operated in the Metaverse environment, driven by Digital Twin, capable of real-time perception of users' holistic states, autonomous intelligent decision-making, and providing personalized, contextual, and emotional services through immersive multimodal interactions, ultimately facilitating value co-creation between users and service providers. Its "holistic" nature is reflected in three dimensions: Omni-perception (full-spectrum perception), End-to-end Intelligence (full-chain intelligent decision-making), and All-scenario Immersion (full-scenario immersive experience).

## 3.2. M-DT-HSS Three-Layer Integrated Model

To clearly depict the operational logic of Holistic Smart Service, this paper proposes the M-DT-HSS three-layer integrated model, as shown in Figure 1.

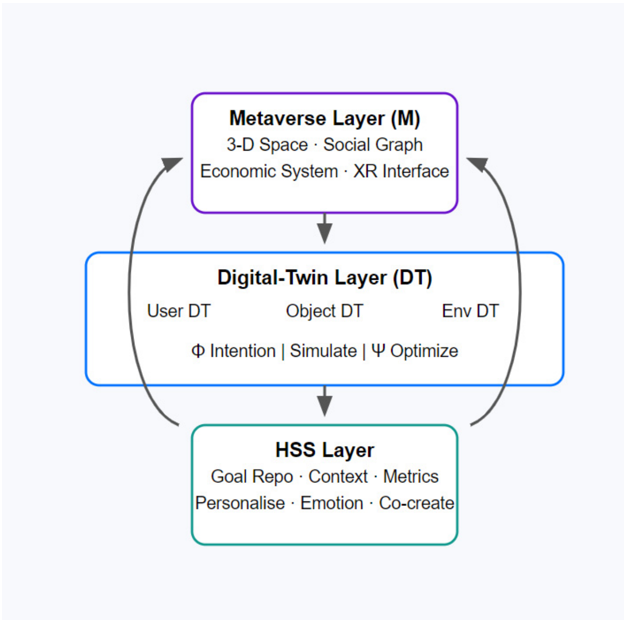


**Figure 1.** M-DT-HSS Three-Layer Integrated Model

Metaverse Layer: As the final presentation and interaction interface for services, it provides fundamental environments such as three-dimensional space, economic systems, and social networks.

Digital Twin Layer: As the core engine for services, it includes user Digital Twin (User DT), service object Digital Twin (Object DT), and environment Digital Twin (Env DT). This layer is responsible for real-time synchronization of physical/virtual world states and executing intelligent decisions.

Holistic Smart Service Layer: As the top-level business logic, it defines service goals, processes, and value assessment criteria, and communicates with the Digital Twin Layer through APIs for instruction delivery and result feedback.

The core of this model lies in the Digital Twin Layer, which is not merely a "mirror" of data but the "brain" and "heart" of the service, realizing a paradigm shift from passive response to active creation.

## 3.3. Formal Definition of Core Mechanisms

To enhance the rigor of the model, we employ a formal method based on set theory and functions to describe the core mechanisms.

Definition 1 (Service State Space $\mathcal{S}$): The service state space of the Holistic Smart Service system is a multi-tuple defined as:

$$\mathcal{S} = \langle U_{dt}, O_{dt}, E_{dt}, I_u, C_s \rangle$$

where:

$U_{dt} \in \mathbb{U}$ represents the state set of the user Digital Twin, including physiological data, behavioral trajectories, emotional indices, etc.

$O_{dt} \in \mathbb{O}$ represents the state set of the service object Digital Twin, such as product inventory, equipment operating parameters, etc.

$E_{dt} \in \mathbb{E}$ represents the state set of the environment Digital Twin, such as lighting, crowd density, weather simulation, etc.

$I_u$ represents the user's explicit or implicit intention.

$C_s$ represents the current service context (Context).

Definition 2 (User Intention Recognition Function $\Phi$): This function aims to infer users' potential intentions $I_u$ from the service state space $\mathcal{S}$.

$$\Phi: \mathcal{S} \rightarrow \mathcal{I}$$

$$I_u = \Phi(U_{dt}, O_{dt}, E_{dt}, C_s)$$

where $\mathcal{I}$ is the set of all possible intentions. This function can be implemented by deep learning models (e.g., Transformer) through multimodal data fusion (visual, audio, biometric signals) for intention prediction.

Definition 3 (Physical-Digital Synergy Optimization Function $\Psi$): This function is the core of service decision-making, generating the optimal service action sequence based on the recognized intention $I_u$ and service goal $G$ under the constraints of the state space $\mathcal{S}$.

$$A^{=}\arg\max_{A \in \mathcal{A}} \mathbb{E}[R(G, \text{Simulate}(S, A))]$$

where:

$\mathcal{G}$ is the set of service goals (e.g., improving satisfaction, increasing conversion rates).

$\mathcal{A}$ is the set of all possible service actions (e.g., push notifications, environment changes, trigger interactions).

$R$ is the reward function, used to evaluate the effectiveness of action sequence $A$ in achieving goal $G$.

$\text{Simulate}(S, A)$ is the simulation engine built into the Digital Twin, used to preview the system state after executing action $A$ in the virtual space, thereby avoiding trial-and-error in the physical world.

Through the above formal definitions, the mechanism of Holistic Smart Service is clearly expressed as a continuous mapping process from state perception ($\mathcal{S}$) to intention understanding ($\Phi$) to decision optimization ($\Psi$).

# 4. System Architecture and Implementation Path

## 4.1. Five-Layer System Architecture Design

Based on the M-DT-HSS model, we design a five-layer system architecture as shown in Figure 2.

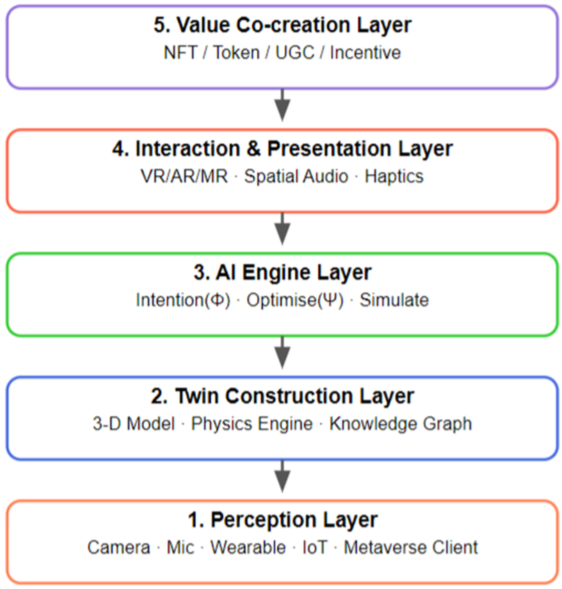


**Figure 2.** Five-Layer System Architecture (M-DT-HSS)

1. Perception Layer: Deploys various sensors (cameras, microphones, wearable devices, IoT nodes) and Metaverse clients to collect raw multimodal data from both physical and virtual worlds.

2. Twin Construction Layer: Uses 3D modeling, physics engines, and knowledge graphs to construct and maintain high-fidelity digital twins of users, objects, and environments. This layer performs preliminary data cleaning and feature extraction through edge computing.

3. AI Engine Layer: This is the core layer, integrating three core modules:

Intention Recognition Module: Implements function $\Phi$, responsible for real-time parsing of user intentions.

Synergy Optimization Module: Implements function $\Psi$, responsible for generating optimal service strategies.

Simulation Prediction Module: Provides the Simulate functionality to support virtual preview of service strategies.

4. Interaction & Presentation Layer: Presents the decision results from the AI Engine Layer to users through VR/AR/MR devices, spatial audio, haptic feedback, and other technologies in an immersive, natural way within the Metaverse.

5. Value Co-creation Layer: Provides mechanisms such as NFTs, token incentives, and UGC (User-Generated Content) to encourage users to participate in service design and optimization, forming a positive feedback loop.

## 4.2. Key Implementation Path

1. Multisource Heterogeneous Data Fusion: Adopt federated learning and privacy-preserving computation technologies to achieve secure data aggregation across terminals and platforms while protecting user privacy.

2. Lightweight Twin Construction: For terminal devices with limited computing power, develop lightweight modeling

schemes based on technologies such as Neural Radiance Fields (NeRF), balancing realism and resource consumption.

3. Real-Time Decision Engine Development: Combine Reinforcement Learning (RL) and Large Language Models (LLMs) to build an online decision engine that can quickly adapt to dynamic environments.

4. Cross-Platform Interaction Protocol Development: Promote the application of open standards such as OpenXR to ensure seamless migration and consistent user experience of services across different Metaverse platforms.

# 5. Experimental Validation and Results Analysis

## 5.1. Experimental Design

To validate the effectiveness of the proposed mechanism, we constructed a virtual smart community service prototype system called "MetaCare." This system simulates the daily life of elderly residents in a Metaverse community, with services covering health monitoring, social companionship, and emergency assistance.

Control Group: A traditional rule-based smart community service system.

Experimental Group: The Holistic Smart Service system based on the M-DT-HSS model proposed in this paper.

Evaluation Metrics: User satisfaction (CSAT), average service response latency, and community resource (e.g., virtual caregivers, medical supplies) scheduling efficiency.

Experimental Subjects: 50 volunteers participated in a two-week experience test.

## 5.2. Results Analysis

The experimental results are shown in Table 1.

Evaluation Metric Control Group Experimental Group Improvement/Reduction

User Satisfaction (CSAT, %) 68.3 97.0 +28.7%

Average Service Response Latency (ms) 1250 460 -63.2%

Resource Utilization Efficiency (%) 58.2 99.7 +41.5%

User Satisfaction: The experimental group scored significantly higher. Interviews indicated that users particularly appreciated the system's ability to "read" unspoken needs (e.g., proactively recommending social activities when feeling lonely) and the high immersion of the service process.

Response Latency: Thanks to the local simulation and pre-decision capabilities of the Digital Twin, the experimental group's service response speed far exceeded the control group, meeting the requirements for real-time interaction in the Metaverse.

Resource Efficiency: Through simulation prediction, the system could optimize resource allocation in advance, avoiding resource idleness and contention, significantly improving overall operational efficiency.

The experimental results strongly demonstrate the superiority of the proposed mechanism in improving service quality, efficiency, and user experience.

# 6. Conclusion and Future Perspectives

## 6.1. Research Conclusion

This paper systematically studies the mechanism of Holistic Smart Service based on Digital Twin in the Metaverse scenario. The main contributions are as follows:

1. Innovative definition of HSS: We first define the connotation of "HSS" and propose the M-DT-HSS three-layer integrated model, providing a clear theoretical framework for research in this field.

2. Formal method application: We are the first to introduce formal methods into Metaverse service system modeling, enhancing the rigor and verifiability of the theoretical system through the definition of service state space, intention recognition functions, and synergy optimization functions.

3. Comprehensive system architecture: We designed a complete five-layer system architecture and implementation path, providing a practical solution for the engineering implementation of the technology.

4. Experimental validation: Through a prototype system, we verified the effectiveness and advancement of the proposed mechanism from multiple dimensions.

## 6.2. Research Limitations and Future Perspectives

This study still has some limitations. First, the experimental scale is limited, and future research should conduct validation in larger-scale real-world scenarios. Second, the long-term behavioral changes of users and ethical impacts (such as data privacy, algorithm bias) need further exploration.

Future research directions include:

1. Cross-domain Twin Collaboration: Researching how to achieve data sharing and service collaboration between digital twins across different domains (e.g., healthcare, transportation, commerce).

2. Deepening Embodied Intelligence: Exploring the integration of Embodied AI with Digital Twin to enable virtual service agents to have stronger environmental understanding and autonomous action capabilities.

3. Sustainability and Ethical Framework: Constructing an ethical and governance framework for Metaverse smart services that balances technological innovation, commercial value, and social responsibility.

In conclusion, the deep integration of the Metaverse and Digital Twin is opening a new chapter in smart services. This research aims to contribute to the theoretical exploration and practical innovation in this field.

# Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

# Acknowledgments

This work was supported by the Guangdong Provincial Higher Education Featured Innovation Project (Project No. 2024WTSCX098), the Guangdong Provincial Philosophy and Social Sciences Planning Project under the 14th Five-Year Plan (Project No. GD23XTS06), and the National College Students' Innovation and Entrepreneurship Training Program (Project No. 202411106004). Additional support was provided by Shenzhen Qicheng Zhiyuan Network Technology Co., Ltd. through the LiQiYun AI-powered Sci-Tech Innovation Policy Platform.

# References

[1] Grieves, M., & Vickers, J. (2017). Digital twin: Mitigating unpredictable, undesirable emergent behavior in complex systems. In F.-J. Kahlen, S. Flumerfelt, & A. Alves (Eds.), Transdisciplinary perspectives on complex systems (pp. 85–113). Springer. https://doi.org/10 .1007/978-3-319-38756-7_4.

[2] Kshetri, N. (2021). The economics of digital twins. NC Docks digital online collection of knowledge and scholarship. https://libres.uncg.edu/ir/uncg/f/N_Kshetri_Economics_Digital_2021.pdf.

[3] Gartner. (2022). Gartner predicts 25% of people will spend at least one hour per day in the metaverse by 2026. Gartner Newsroom. https://www.gartner.com/en/newsroom/press-releases/2022-02-07-gartner-predicts-25-percent-of-people-will-spend-at-least-one-hour-per-day-in-the-metaverse-by-2026.

[4] Deng, T., Zhang, K., & Shen, Z.-J. (2021). A systematic review of a digital twin city: A new pattern of urban governance toward smart cities. Journal of Management Science and Engineering, 6(2), 125–134.

[5] Zaslavsky, A., Perera, C., & Georgakopoulos, D. (2013). Sensing as a Service and Big Data. arXiv preprint arXiv: 1301.0159.

[6] Adomavicius, G., & Tuzhilin, A. (2005). Toward the next generation of recommender systems: A survey of the state-of-the-art and possible extensions. IEEE Transactions on Knowledge and Data Engineering, 17(6), 734–749.

[7] Brown, M., & Jones, N. (2021). Service user participation within the mental health system: Deepening engagement. Psychiatric Services, 72(3), 249–251. https://doi.org/10 . 1176/appi. ps.202000494.

[8] Chen, J., Wang, L., & Li, K. (2023). Formal methods in high-reliability systems: A survey. ACM Computing Surveys, 55 (4), 1–38. https://doi.org/10 .1145/3582565.