Journal of Electronic Research and Application, 2026, Volume 10, Issue 6
http://ojs.bbwpublisher.com/index.php/JERA
Online ISSN: 2208-3510
Print ISSN: 2208-3502

Exploration of Digital Twin-Driven Heterogeneous Terminal Linkage and Intelligent Control Technology in the Internet of Things

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Abstract: Digital twin technology provides a new theoretical path for solving the difficulties of heterogeneous terminal interconnection and low control efficiency in the Internet of Things. Starting from the endogenous logic of empowering IoT terminals with digital twins, this article analyzes the mirror mapping and closed-loop interaction mechanism between physical entities and virtual models, achieving a paradigm leap from data synchronization to semantic collaboration. On this basis, a digital twin collaboration architecture for heterogeneous terminal linkage was constructed, and core issues such as unified twin model construction, virtual real dynamic association maintenance, twin inter collaboration triggering, and cross protocol communication decoupling were discussed. Then focus on the key technologies of intelligent management and control based on digital twins, including real-time data stream processing and edge computing integration, terminal state autonomous awareness and exception diagnosis, policy adaptive generation under the centralized-decentralized hybrid architecture, and the management and control evolution path from rule-driven to target-driven. The research provides a systematic theoretical framework for intelligent linkage and efficient control of large-scale heterogeneous IoT terminals.

Keywords: Digital twin; Internet of things; Heterogeneous terminals; Intelligent control

Online publication: Jul 23, 2026

1. Introduction

With the rapid expansion of the Internet of Things, the significant differences in communication protocols, data models, and computing capabilities among massive heterogeneous terminals have led to difficulties in terminal interconnection and complex unified control. Traditional rule-based or centralized gateway-based methods are increasingly exposed to limitations in terms of dynamism, scalability, and semantic interoperability. Digital twin technology, with its ability to establish precise mapping, real-time interaction, and closed-loop optimization between physical entities and virtual spaces, provides a new theoretical perspective for solving the linkage and control problems of heterogeneous terminals in the Internet of Things

[1]. This article aims to systematically explore the technological path of digital twin-driven heterogeneous terminal linkage and intelligent control in the Internet of Things. Firstly, analyze the interconnection limitations and control difficulties of heterogeneous terminals in the Internet of Things, and reveal the endogenous logic of digital twin empowerment; Furthermore, a digital twin collaboration architecture for heterogeneous terminal linkage is proposed, exploring the construction of a unified twin model, virtual real dynamic mapping, and the mechanism of collaboration between twin entities; Subsequently, focus on key technologies such as real-time oriented data stream processing, autonomous state perception, policy adaptive generation under hybrid architecture, and evolution from rule driven to goal driven; Finally, summarize the core values and future directions of digital twins in this field.

2. Digital twins empower the endogenous logic of IoT terminals

2.1. Internet of things heterogeneous terminal interconnection limitations and control challenges

In the Internet of Things, terminal devices are highly heterogeneous in terms of communication protocols, formats, computing power, and membership domains, which limits their interconnectivity and unified control. Some vendors use private interfaces and closed data models to sense, execute, and edge nodes, and these terminals share no standard semantic interoperability between terminals and high levels of information silos. While traditional gateway or middleware solutions can partly solve protocol conversion problems, they have problems like poor scalability, insufficient real-time response, and rigid control logic when the terminal size grows, and cross-domain collaboration requests become large [2]. At the same time, the uncertainty of terminal status, unpredictability of connections, and the low computing power of limited nodes also complicate the conflict between centralized control and distributed deployment. The contradiction is exemplified by the centralized control node's inability to understand the dynamic change of millions of terminals in real time, and distributed terminals lack enough computing and communication resources to achieve independent collaboration. In addition, the terminals belonging to different domains have limited security and data sovereignty requirements, and cannot share the state information directly with each other. Linking them to other domains often requires manual handover or pre-set interfaces and much less response efficiency. Additionally, existing control systems often rely on static configuration or fixed rule chains. When tasks or environmental conditions change, the linkage logic needs to be updated without any ability to adapt to unknown scenarios. These limitations not only limit the growth of IoT systems from data collection to collaboration linkage, but also limit the feasibility of implementing intelligent scheduling and closed-loop control for complex tasks. There is a need for a technology architecture that can uniformly describe heterogeneous terminals at the semantic level and dynamically coordinate virtual and real behaviors.

2.2. Mirror mapping and closed-loop interaction mechanism of digital twins

Digital twins create virtual images of physical terminals with high-quality semantic models for each type or group of IoT terminals, including their characteristics, behaviors, interfaces, and state space, which ensures that underlying physics and protocols are heterogeneous. With this, dynamic matching between virtual and real is preserved via bidirectional data flows: the physical terminal uploads observation information to drive the twin to run, while the twin may add control instructions to reverse the physical object. The key link in the closed-loop interaction mechanism is a feedback loop: the twin simulates and predicts the end behavior and writes deviation or optimization instructions back to the physical end and performs continuous execution of perception decisions [3]. This does not rely on a common communication standard, but instead maps the cross-terminal by the intermediate semantic layer of the twin model, building a basis for linkage control in heterogeneous environments.

2.3. Driving paradigm leap from data synchronization to semantic collaboration

Traditional IoT control is based on data synchronization: terminal status reporting and issuing instructions. There is no common understanding of information meaning between terminals, and collaborative behavior often requires fixed rules. Digital twins have led this control to a new paradigm that moves the definition of control from data synchronization to semantic collaboration. In such a paradigm, twins are not only containers of data but also nodes of semantic interaction: each terminal twin describes its capabilities, needs, and constraints within a common ontology model, and different twins negotiate and decompose the tasks via the same semantic space, thus automatically forming linkage logic [4]. Semantic collaboration enables the system to infer cross-terminal meanings and intent without pre-defined point-to-point links (e.g., automatically detecting causal relationships between temperature anomalies and ventilation equipment by twins and inducing linkage). This leads to the reduction of heterogeneous integration, and makes the IoT systems able to adapt and restructure themselves in a basic fashion–from "transmitting" data to "understanding semantics", to "collaborating action".

3. Digital twin collaborative architecture in heterogeneous terminal linkage

3.1. Method for constructing a unified twin model for multi-source heterogeneous terminals

A unified twin model is the final step to eliminate heterogeneity among IoT terminals. Instead of iterating each protocol separately, this method builds an extensible meta model in which terminals are divided into four basic entities: attributes, services, events, and constraints. Attributes describe static features and state changes in the terminal, services describe their actions in an executable fashion, events describe the trigger conditions for state changes, and limitations reveal operating limits and limitations [5]. A twin can be compiled with consistent expression form using meta model instantiation and semantic annotation for each manufacturer and type of terminals. The construction of the model can be applied for both upstream data-driven automatic learning and explicit downstream manual protocols for known and unknown terminals. A unified model may also be used for cross-terminal relationships modeling, such as spatial inclusion, time collaboration, functional complementarity, etc. This model can explicitly model the relationship with a structured knowledge support for linkage execution.

3.2. Dynamic correlation and behavior consistency maintenance under virtual real mapping

The binding of physical terminals to twins is not static, but is dynamic over time and operation. In order to be behaviorally consistent, the twin model must be able to observe real-time state change, parameter shift, mode-switching, and correct representation bias of the virtual terminal. The dynamic association mechanism is implemented with light heartbeat, differential synchronization, and event-triggered updates (high-frequency updates for fast state changes, refreshing for stable attributes to balance accuracy and communication cost [6]).

If the difference between reality and virtuality is greater than a set value, the system automatically triggers alignment, such as state adjustment, model reparameterization, or inference compensation. The correlation of several twins will also be dynamically updated with connection topology, task roles, or environment context changes of the physical terminal. A dynamic correlation and behavioral consistency will not be satisfied by a dynamic linkage decision that deviates from physical reality.

3.3. Operating mechanism of the terminal linkage triggered by twin collaboration

Twin bodies map physical terminals separately and coordinate actual terminals by jointly computing them. Their functioning can be summarized as follows: perception, negotiation, arbitration, and execution;

(1) Each twin produces linkage requirements according to local states and external events, e.g., temperature twin threshold violations;

(2) The twin performs semantic negotiation in the collaborative space, decoupling the linkage logic with task objectives, terminal capabilities, and load, and selecting what terminals should perform which operations;

(3) By using a distributed consensus or a lightweight auction for obtaining lower bottlenecks at the center [7].

(4) A set of linked instructions is formed in the arbitration process, and decision-making conflicts and resource conflicts are resolved; and

(5) The instruction is sent to the physical terminal for execution by the downstream channel.

Throughout the process, Twin acts as a decoupled layer between the decision maker and the physical object, allowing a physical terminal to complete complex collaborative tasks without communicating directly.

3.4. Twin intermediaries and communication decoupling paths in cross-protocol interactions

Heterogeneous terminals in the Internet of Things rely on different protocols, and if the terminals are directly linked, then they will be highly complex and difficult to maintain. Twin intermediaries provide an efficient communication decoupling pathway: all terminals do not need to communicate with their twin bodies, and twin bodies communicate in a unified digital space. The physical terminal reports its native protocol to the twin, which translates the data into standard semantic messages and publishes them to the co-buses bus. The target twin that needs to be linked subscribes to relevant messages, makes a decision, and provides instructions in a format that the target terminal is able to understand [8]. This architecture makes the cross-protocol conversion from the physical network layer to the twin service layer highly efficient and reduces its reliance on gateways. Twin mediators provide dynamic registration and hot plugging of protocol adapters, allowing terminals of new protocol types to be integrated in the linkage system without resorting to the modification of existing systems, to achieve highly decoupled and scalable communication paths.

4. Key technologies for intelligent control based on digital twins

4.1. Real-time oriented twin data stream processing and edge computing integration

The twin data delivered by the IoT terminals are high-frequency, multi-source, heterogeneous, and centralized, which cannot be processed in real-time. Connect twin data stream processing and edge computing along a vital line. Edge nodes are deployed close to the end and perform light inference tasks such as data cleaning, feature extraction, and local twin models. Only upload high-value or cross-domain collaborative data to the cloud. By lowering some of the twin power to the edge, the system can complete state updates and linkage decisions in milliseconds, and thus, at low end-to-end latency [9]. The fusion has data sharing and joint data sharing between edge nodes, and no single node overload occurs. Twin data stream processor of edge cloud collaboration not only achieves real-tactical response in emergency linkage applications, but also is able to utilize cloud computing power to achieve global optimization and long-term model evolution, which complement each other in time and space.

4.2. Twin model-driven terminal state autonomous perception and anomaly diagnosis

The traditional IoT terminal state perception relies on preset levels of control or simple rules, so complex or hidden abnormal behaviors can be detected. The twin model-driven autonomous perception detects anomalies by comparing the deviation of the physical terminal and the prediction of the twin. The two models not only maintain static parameters of the terminal, but also learn its dynamic laws during normal operation, such as timing dependence, operating condition dependence, and device coupling [10]. When a significant residual between the real-time stream and the predicted values for the twin model is found, the system automatically identifies whether the state is not broken or the performance is not. Based on the distribution of residuals across other dimensions, the presence of anomalies can be identified–sensor drift, actuator failure, or communication interference. This diagnostic is not required by labeling fault samples, or belongs to the unsupervised or self-supervised model. It can adapt to different fault modes and very few samples of the Internet of Things, and significantly helps to improve terminal control in challenging environments.

4.3. Adaptive generation of control strategies under a centralized-decentralized hybrid architecture

IoT management faces a high single-point risk in centralized architecture and low global coordination for decentralized architecture. The centralized-decentralized hybrid architecture provided by digital twins provides an ideal balance: The global twin provides a global view, centered around the cloud or central node, and handles cross-domain strategy formulation, global resource optimization, and long-term goal decomposition; the local twin automatically implements local control at the edge and can respond quickly to changes in state and linkage requirements in the domain [11]. The control strategy is not fixed, but can be generated by adapting to network conditions, task priority, and end-to-end availability. Dynamic changes are made when the local decision is being challenged, and the global goal is being negotiated via twins. The hybrid architecture also supports elastic scaling of control granularity, preferred in centralized coordination where the communication is good, and automatically switches to decentralized autonomous mode during network shutdown or emergencies, and thus, the system can maintain a stable control status with respect to large-scale faults and dynamic environments.

4.4. Evolution of terminal collaborative control from rule-driven to goal-driven

Traditionally, IoT control systems adopt a rule-driven model, which automatically pre-enforces the "if then" logic to trigger the final actions. This mode cannot cope with unexpected situations, and a massive number of rule combinations leads to a very high maintenance cost [12]. Digital twin technology is leading control models towards goal-driven approaches. In a goal-driven case, we no longer focus on the particular operation steps, but only on the high-level goals of users or higher-level tasks (e.g., "reduce energy consumption and comfort"). Twin clusters automatically learn the linkage solutions to reach the goals by semantic knowledge of terminal capabilities and environment perception. The evolution has been guided by the twin model that can support target decomposition, scheme search, and effect estimation, and can be optimized by lightweight programming or reinforcement learning for decision optimization. Since shifting from rules to goals, the system has become flexible, with fewer humans, and also implements a flexible control model for large-scale, long-term, and dynamic IoT applications.

5. Conclusion

Digital twins can overcome heterogeneous terminals and control issues in the Internet of Things by building semantic mirrors and collaborative interactions. From designing a twin model, maintaining virtual and real dynamic associations, the link and communication distance between twins, real-time data stream processing, autonomous anomaly detection, and target-driven control evolution, digital twins advance the intelligent control of the Internet of Things from synchronization to collaboration to a feasible theory for adaptive link and efficient control of large-scale heterogeneous terminals.

Disclosure statement

The author declares no conflict of interest.

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