Can Digital Twins Enable Autonomous Trains?

Jacopo Maltagliati, Giovanni Denaro
Department of Informatics, Systems, and Communication
University of Milano-Bicocca
Viale Sarca 336, Edificio U14, 20126 Milan, Italy
j.maltagliati@campus.unimib.it, giovanni.denaro@unimib.it

***Index Terms*—Autonomous Railways, Digital Twins, Edge Computing, Distributed Systems, Software Architecture**

I. Introduction

Modern railway systems are becoming increasingly integrated and digitalized. Advances in communication technologies are enabling the migration of subsystems and functions to the cloud. The ultimate goal of railway digitalization projects, such as EU-Rail R2DATO [1], is to achieve unattended train operation (i.e., self-driving) in open railway environments.

This transition introduces inherent challenges. Unlike closed systems (e.g., metropolitan transit), railway networks span vast geographic areas and operate in unpredictable environments. Since coordination centers cannot be located close to the track, operations must rely on a distributed architecture in which trains communicate with centralized services over a wide-area network. Operating autonomously within this architecture requires (i) an up-to-date model of the railway network to perform macroscopic coordination tasks, such as network-wide planning and scheduling, and (ii) the ability of each train to react instantly to obstacles or unforeseen track conditions to ensure collision avoidance.

While the literature provides the mathematical and stochastic models [2] required to support both network-level coordination and train-level autonomy, a software architecture capable of deploying these models across a heterogeneous, high-latency infrastructure is still lacking. The central challenge is to determine where control functions should execute, how operational state information should be distributed, and how communication delays can be mitigated through architectural design.

II. Problem Statement and Technical Challenges

In recent years, significant advancements in autonomous control at the level of individual trains have been made, leading to real-world demonstration systems [3]. However, equipping every train with autonomous control capabilities does not, by itself, enable network-wide coordination or traffic planning, both of which require an up-to-date model of the railway network.

Due to the inherently local nature of onboard sensing, each train has access only to its internal state and to a limited view of the surrounding environment. As a result, no individual train can maintain a complete model of the railway network. In the current infrastructure (i.e., the European Rail Traffic Management System [4]), the railway network representation is managed by regional control centers. Data collected by the trains is periodically relayed to trackside equipment via radio links [5] and subsequently forwarded to control centers through multiple communication layers [6]. This architecture inevitably introduces propagation delays. As a result, the information available to the control centers may not accurately reflect the current state of the railway network.

Moreover, communication delays affect all interactions between trains and centralized services, forcing every control and planning function to operate on delayed information and explicitly account for the latency. This requirement further complicates the allocation of responsibilities across the railway infrastructure, as different functions exhibit different tolerance to communication delays. While operations performed on a longer time scale (e.g., traffic management, routing, and conflict resolution) can generally tolerate limited delays, safety-critical functions (e.g., speed control, braking, and movement authority enforcement) require timely and reliable control actions. As a result, these functions cannot be effectively centralized without introducing unacceptable operational risks.

An effective autonomous railway system must therefore employ a hierarchical control system that balances centralized decision-making, which relies on a global model of the network, and local decision-making, which must react to safety-critical events with minimal latency. Realizing this system requires distributing control responsibilities across the infrastructure while accommodating communication delays.

Digital Twins (DTs) are a promising architectural paradigm for realizing such a distributed control system. DTs have demonstrated their effectiveness in domains such as industrial IoT [7], smart manufacturing [8], autonomous transportation [9], and intelligent infrastructure management [10], where they address challenges related to safety, mobility, infrastructure integration, communication, and long-lived operational assets. Their application to the railway domain, however, remains comparatively underexplored despite its particularly demanding combination of these challenges.

III. Proposed Architecture

We propose an edge-cloud architecture based on a DT for each train, leveraging next-generation cellular networks (i.e., 5G-FRMCS [11]) to enable direct communication between trains (i.e., the edge) and regional control centers (i.e., the

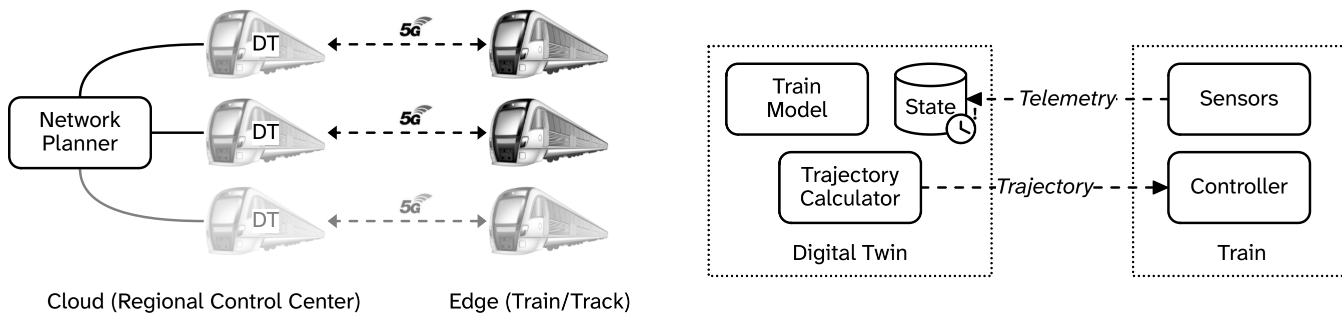

Fig. 1: (Left) Proposed edge-to-cloud architecture. The control centers host the DTs and the network planner, and communicate with trains via 5G-FRMCS. (Right) Interaction between a train and its DT. A behavioral model compensates for communication delays and estimates the train's current state. Reference trajectories are transmitted back to the train through the same interface.

cloud), simplifying the communication infrastructure and reducing end-to-end latency.

The DT periodically synchronizes with telemetry received from the train and combines it with a behavioral model to maintain an estimate of the train's current state. Cloud-hosted applications interact with this state estimate rather than delayed observations, effectively abstracting the effects of network latency. The DT also provides a standardized interface for data and commands, abstracting the underlying communication infrastructure from higher-level control functions. This interface provides a natural integration point for future high-bandwidth onboard sensors. Collectively, the DTs form a distributed model of the railway network that supports scheduling, routing, conflict resolution, and traffic optimization. Leveraging the aforementioned interfaces, these functions can be centralized in the cloud, enabling network-wide planning and route optimization.

To translate routes into control actions, the architecture employs a hierarchical control algorithm originally proposed for platooned metro train operations in [12], comprising a high-level predictive controller that generates reference trajectories and a lower-level controller that tracks these and produces actuator commands. The DT's state estimation and prediction capabilities make it a natural execution environment for the higher layer of the hierarchical controller, which continuously computes reference trajectories over a finite prediction horizon and transmits them to the train. The lower-level controller executes on board the train, where it tracks reference trajectories and produces actuator commands. As it operates directly on the train, it remains responsible for safety-critical control functions and maintains safe operation despite communication delays or temporary network disruptions.

This architecture directly addresses the challenges identified in Section II. Digital Twins provide a unified mechanism for distributed state estimation and delay compensation, enabling cloud-hosted algorithms to operate on a consistent representation of the railway network without being coupled to the characteristics of the underlying communication infrastructure. At the same time, the hierarchical control structure separates network-wide optimization from safety-critical train control, allowing each function to execute at the layer most appropriate to its timing requirements.

IV. Ongoing Work

While the proposed architecture addresses the distribution of control functions and operational state information, several challenges remain before its practical deployment can be fully assessed.

A primary research challenge concerns communication management and delay compensation. The proposed architecture relies on DTs to abstract the characteristics of the underlying communication infrastructure, but achieving this objective requires efficient mechanisms for large-scale synchronization over cellular networks.

A second challenge is the quantitative evaluation of the architectural benefits provided by the DT abstraction. While the proposed framework is designed to reduce the impact of communication delays on control and planning functions, future work should investigate the extent of these improvements in existing railway control algorithms. Realistic simulation environments capable of modeling communication delays and network behavior are required to assess the feasibility of the proposed approach.

Finally, future autonomous train platforms will require additional perception capabilities (e.g., radar, LiDAR, depth cameras) to detect dynamic obstacles at runtime. Future research should investigate how perception-derived information can be incorporated into the architecture while preserving the real-time guarantees required for safe train operation.

V. Conclusions

This paper proposed a Digital Twin-based edge-to-cloud architecture for autonomous railway systems. By combining cloud-hosted DTs with a hierarchical control framework, the proposed approach enables network-level coordination while preserving the low-latency execution required for safety-critical train control.

The architecture addresses the challenges introduced by the distributed nature of railway systems by providing a unified mechanism for state distribution, latency compensation, and control-function partitioning. As a result, it establishes a foundation for future autonomous railway platforms that decouples control algorithms from the underlying communication infrastructure.

References

[1] Europe's Rail Joint Undertaking (EU-Rail), "Flagship Project 2: R2DATO – Digital & Automated up to Autonomous Train Operations." https://rail-research.europa.eu/rail-projects/fp2-r2dato/, 2022. Horizon Europe Grant ID: 101102001. Project duration: 2022–2026.

[2] M. A. Vaquero-Serrano, F. Borrelli, and J. Felez, "A learning model predictive control for virtual coupling in intelligent train control systems," *Computer-Aided Civil and Infrastructure Engineering*, vol. 40, no. 31, pp. 6279–6304, 2025.

[3] J. Schröder, C. G. Alpoim, B. Dickgießer, and V. Knollmann, "Digital s-bahn hamburg – germany's first implementation of ATO over ETCS," *SIGNAL + DRAHT*, vol. 113, no. 7–8, pp. 52–59, 2021.

[4] European Union Agency for Railways (ERA), "ERTMS Scope of the Test Specifications," 2023. Version 4.0.0.

[5] F. Flammini, A. Lazzaro, and N. Mazzocca, "Modeling of railway logics for reverse engineering, verification and refactoring," *International Journal of Safety and Security Engineering*, vol. 1, no. 1, pp. 77–94, 2011.

[6] A. L. Ruscelli, G. Cecchetti, and P. Castoldi, "Cloud networks for ertms railways systems (short paper)," in *2016 5th IEEE International Conference on Cloud Networking (Cloudnet)*, pp. 238–241, 2016.

[7] H. Xu, J. Wu, Q. Pan, X. Guan, and M. Guizani, "A survey on digital twin for industrial internet of things: Applications, technologies and tools," *IEEE Communications Surveys & Tutorials*, vol. 25, no. 4, pp. 2569–2598, 2023.

[8] H. Park, A. Easwaran, and S. Andalam, "Challenges in digital twin development for cyber-physical production systems," in *Cyber Physical Systems. Model-Based Design* (R. Chamberlain, W. Taha, and M. Törngren, eds.), (Cham), pp. 28–48, Springer International Publishing, 2019.

[9] X. Hu, S. Li, T. Huang, B. Tang, R. Huai, and L. Chen, "How simulation helps autonomous driving: A survey of sim2real, digital twins, and parallel intelligence," *IEEE Transactions on Intelligent Vehicles*, vol. 9, no. 1, pp. 593–612, 2024.

[10] Q. Lin, L. Zhang, X. Zhou, J. Chen, and X. Xu, "Software-defined control: New architecture and practices in building automation," *Journal of Building Engineering*, vol. 113, p. 114076, 2025.

[11] Ericsson, "Integrating FRMCS: Enhancing rail communications with 5G technology," white paper, Ericsson, mar 2026.

[12] X. Luo, T. Tang, M. Chai, and H. Liu, "A hierarchical mpc approach for arriving-phase operation of virtually coupled train set," *IEEE Transactions on Intelligent Transportation Systems*, vol. 25, no. 7, pp. 7237–7249, 2024.