Cognitive Digital Twins in Smart Cities for Emergency Response

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Abstract

By integrating cognitive functionalities with real-time data, a Cognitive Digital Twin (CDT) offers a new way to manage emergency response operations. For instance, by leveraging drones, trucks, and smart lockers, a CDT can support rapid, accurate, and sustainable delivery of supplies during an emergency. This project investigates CDT architecture design and realization.

CDT Differences and Advantages

Unlike conventional digital twins, CDTs not only mirror physical systems but also actively analyze, predict, and optimize operations to make smart decisions. Figure 1 provides a comparison of core functionality.

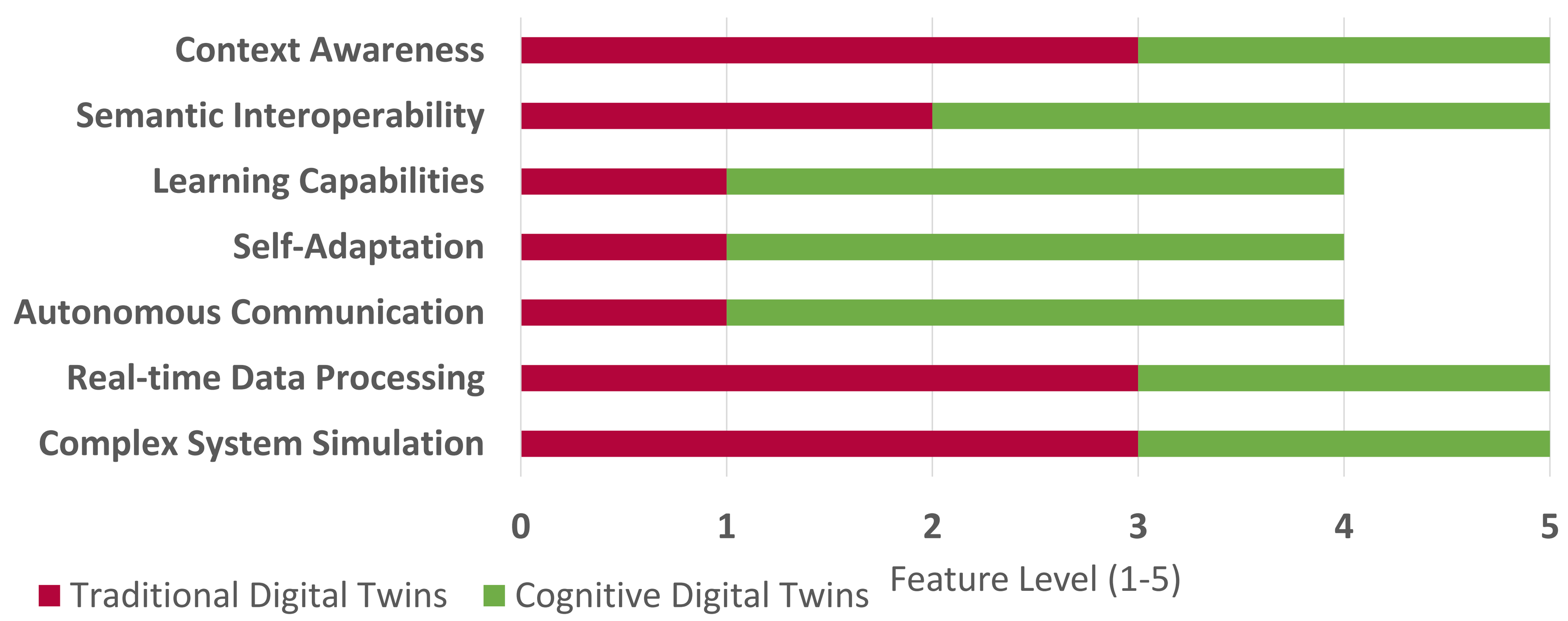

Figure 1: Comparison between Cognitive Digital Twins and Traditional Digital Twins

Key Features of a CDT

- **Continuous real-time data processing**
- **Cognitive capability through integrated AI**
- **Interactive and dynamic decision making**

Research Motivations

Most prior works focus on individual components of an envisioned CDT rather than a comprehensive, semantically-integrated framework. This project looks to build a holistic framework for CDT design that can ultimately be implemented across complex multi-modal networks.

Methodology

Our methodology is based on a six-layer visual mapping architecture for a CDT. This framework considers the flow of heterogeneous data streams across a series of key functionalities that a CDT must provide. It is envisioned for the context of emergency response and supply management (Figure 2).

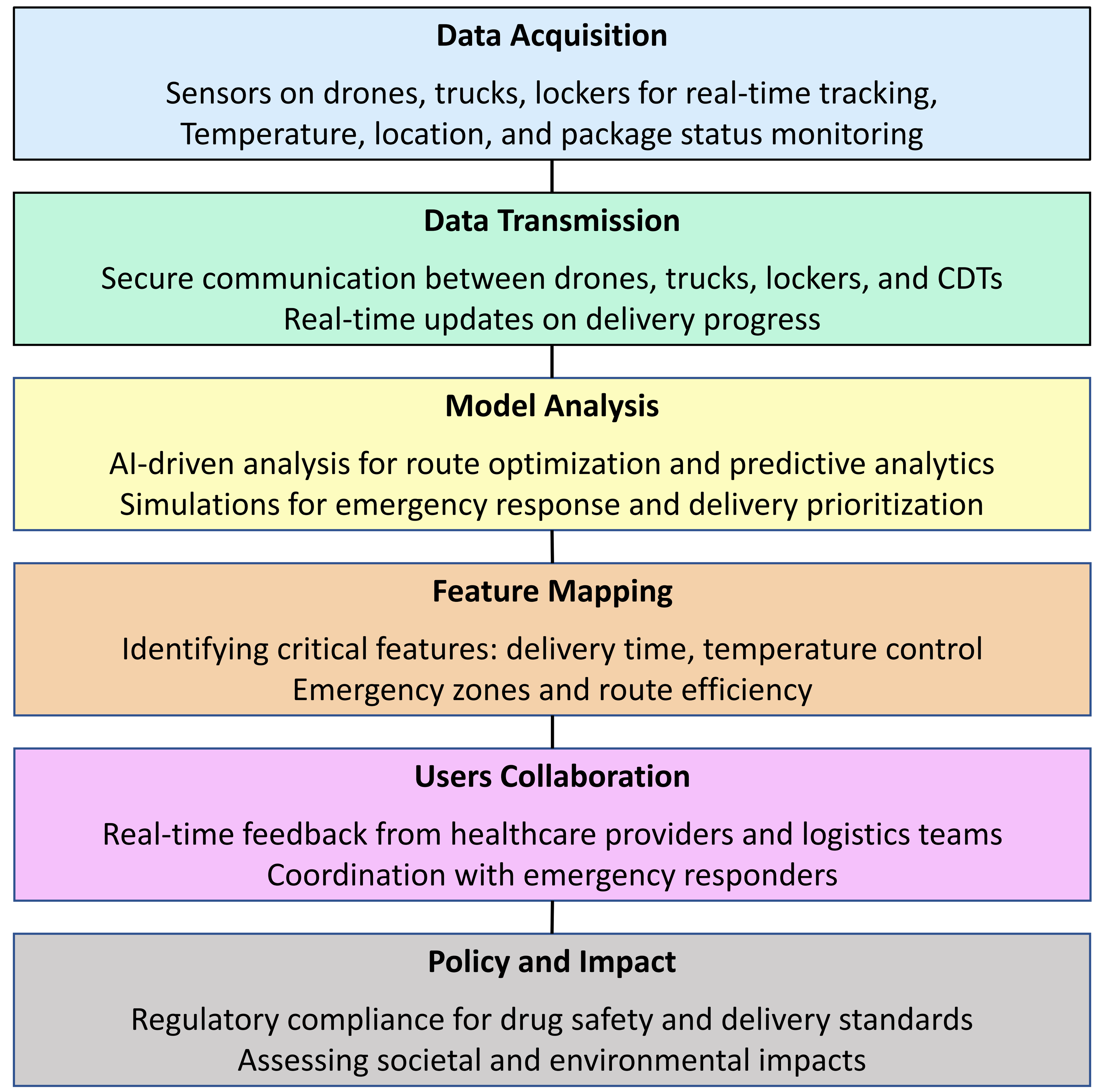

Figure 2: 6-Layer Architecture for Cognitive Digital Twins

We aim to answer the following questions:

- How can CDTs optimize the efficiency and security of supply delivery across multi-modal systems?
- What challenges exist in integrating real-time heterogeneous data?
- In what ways does the proposed architecture address the complexity of supply logistics?
- How can collaboration between stakeholders enhance CDT systems to improve response times and overall operational resilience?

We need to create a roadmap to specify the required algorithms that work best for both each layer and the entire system. These algorithms must be evaluated in the context of an integrated digital twin, considering their numerous interdependencies. Table 1 summarizes some proposed methods given the related literature and gives a holistic vision to the implementation of CDTs. In addition, we can effectively integrate Transformer-based models, Flow-based models, or Variational Autoencoders (VAEs) into the **Model Analysis Layer** and, to some extent, the **Data Acquisition Layer** and **Feature Mapping Layer**.

Table 1: A summary of different algorithms across layers

Layer	Objective	Algorithms
Data Acquisition	Collect real-time data	RESTful APIs, MQTT, Kalman Filters
Data Transmission	Secure and efficient data transfer	AES, gzip, LZ4
Model Analysis	Optimize routes and allocation of destination nodes to each transportation and predict disruptions (e.g., traffic, demand, …)	mathematical formulation and OR methods, ARIMA, LSTM, Genetic Algorithms, Ant Colony Optimization after the application of knowledge graphs and ontologies across layers
Feature Mapping	Identify key features	Random Forest, RFE, K-Means, DBSCAN
Users Collaboration	Facilitate real-time interaction	Collaborative Filtering, BERT
Policy and Impact	Ensure compliance and assess impacts	CART, Monte Carlo Simulation
Training & Improvement	Continuous model enhancement	GANs, Reinforcement Learning (DQN)

Conclusion and Future Research Trajectories

By leveraging real-time data, AI-driven analytics, and robust multi-layer architecture, CDTs promise to revolutionize supply logistics in both everyday operations and critical response situations. However, their core functionality must be considered holistically to ensure interoperability and extensibility. The following chart (Figure 3) provides a snapshot of needs for future CDT research based on an assessment of the relevant literature.

Figure 3: Future needs and directions for Cognitive Digital Twins

Acknowledgment

I extend my sincere gratitude to my advisor, Dr. Lattanzi, for providing me with this invaluable learning opportunity.

References

[1] Shahzad, N., et al. (2025). "Cognitive Digital Twins: A State-of-The-Art Review", SSRN

[2] Elayan, H., et al. (2021). "Digital Twin for Intelligent Context-Aware IoT Healthcare Systems“, IEEE Internet of Things Journal

[3] Kim, S. J., et al. (2017). " Drone-aided healthcare services for patients at home", Journal of Intelligent & Robotic Systems

[4] Deutsch, Y., & Golany, B. (2018). " A parcel locker network as a solution to the logistics last mile problem“, Transportation Research Part B: Methodological