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Digital twin of the road infrastructure with announced non-connectable
vehicles

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Abstract

The concept of a digital twin has become an important research direction in intelligent transportation systems, as it enables the creation of a virtual representation of road infrastructure that is continuously updated using real-time data. Such systems can improve traffic safety, situational awareness, and predictive capabilities of traffic management and autonomous driving applications. However, a significant limitation of current digital twin solutions is that many vehicles on the road are not equipped with communication technologies and therefore cannot directly participate in vehicle-to-everything (V2X) communication. As a result, these vehicles remain invisible to digital twin systems, which reduces the accuracy of traffic simulations and cooperative awareness.

This dissertation addresses the problem of integrating non-connectable vehicles into the digital twin of road infrastructure without requiring any modifications to their hardware. The proposed solution is based on the concept of announcement via proxy, where connected vehicles detect nearby traffic participants using onboard sensors and announce their presence to the digital twin. A data fusion method fusing LiDAR and camera data is proposed to estimate vehicle position and dynamic properties. In addition, a digital twin architecture based on a merged paradigm placed on the edge computing unit is designed to process and distribute this information while remaining compatible with existing ITS communication standards.

The proposed methods were evaluated using the KITTI Bird's Eye View benchmark dataset and verified through statistical analysis and formal modeling using colored Petri nets. The results demonstrate that the system can accurately detect and represent non-connectable vehicles within the digital twin using virtual Cooperative Awareness Messages. By extending the digital twin to include vehicles without communication capabilities, the proposed approach improves situational awareness and supports safer operation of intelligent transportation systems in mixed traffic environments.

Abstrakt

Koncept digitálneho dvojčata sa stal významným smerom výskumu v oblasti inteligentných dopravných systémov, keďže umožňuje vytvoriť virtuálnu reprezentáciu cestnej infraštruktúry, ktorá je priebežne aktualizovaná pomocou dát získaných v reálnom čase. Takéto systémy môžu prispieť k zvýšeniu bezpečnosti cestnej premávky a presnejšej predikcii dopravných situácií. Významným obmedzením súčasných riešení však je, že časť vozidiel na cestách nedisponuje komunikačnými technológiami a nemôže sa priamo zapojiť do medzivozidlovej komunikácie. Tieto vozidlá preto zostávajú pre digitálne dvojča neviditeľné, čo znižuje presnosť simulácií a mechanizmov kooperatívneho povedomia.

Táto dizertačná práca sa zaoberá problémom integrácie nepripojiteľných vozidiel do digitálneho dvojčata cestnej infraštruktúry bez potreby akýchkoľvek úprav ich hardvéru. Navrhované riešenie je založené na princípe oznamovania prostredníctvom sprostredkovateľa (announcement via proxy), pri ktorom pripojené vozidlá detegujú okolitých účastníkov cestnej premávky pomocou vlastných senzorov a následne oznamujú ich prítomnosť do prostredia digitálneho dvojčata. Navrhnutá je metóda fúzie dát kombinujúca údaje zo senzorov LiDAR a kamery na odhad polohy a dynamických vlastností vozidiel. Súčasťou riešenia je aj architektúra digitálneho dvojčata založená na kombinovanom prístupe využívajúcom Mobile Edge Computing, ktorá zabezpečuje spracovanie a distribúciu informácií pri zachovaní kompatibility s existujúcimi štandardmi ITS komunikácie.

Navrhnuté riešenie bolo porovnané pomocou benchmarku KITTI Bird's Eye View a overené prostredníctvom štatistickej analýzy a formálneho modelovania. Výsledky ukazujú, že systém dokáže presne detegovať a reprezentovať nepripojiteľné vozidlá v digitálnom dvojčati pomocou virtuálnych správ Cooperative Awareness Message. Rozšírením digitálneho dvojčata o vozidlá bez komunikačných schopností navrhovaný prístup zvyšuje situačné povedomie a prispieva k bezpečnejšej prevádzke inteligentných dopravných systémov v prostredí zmiešanej dopravy.

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Chapter 1

Introduction and motivation

The concept of a digital twin has gained significant attention in recent years across various engineering domains. A digital twin represents a virtual representation of a real-world system that is continuously updated using real-time data from the physical environment. In the domain of intelligent transport systems (ITS), digital twins are increasingly considered a key enabling technology for improving traffic safety, optimizing traffic flow, and supporting autonomous mobility [1, 2]. By creating a real-time digital representation of road infrastructure and traffic participants, it becomes possible to simulate traffic behavior, predict dangerous situations, and assist decision-making processes in connected vehicles.

The development of cooperative intelligent transport systems relies heavily on communication between traffic participants. Modern vehicles equipped with Vehicle-to-Everything (V2X) communication technologies can exchange information about their position, speed, direction, and other dynamic properties. This information is typically distributed using standardized messages such as Cooperative Awareness Messages (CAM) and Collective Perception Messages (CPM) defined within ETSI ITS standards [5, 6]. These messages allow connected vehicles and infrastructure to maintain situational awareness of surrounding traffic.

However, despite the ongoing deployment of connected vehicle technologies, a significant portion of vehicles currently operating on roads remains non-connectable. These vehicles lack the ability to communi-

cate using V2X technologies and therefore cannot directly participate in cooperative communication systems. As a result, they remain invisible to digital twin systems and connected traffic participants [3].

The inability to digitally represent non-connectable vehicles introduces several challenges. First, the absence of these vehicles from the digital twin leads to incomplete representations of traffic environments. This limitation reduces the accuracy of traffic simulations and predictive models. Secondly, connected vehicles relying on cooperative awareness may make incorrect assumptions about traffic conditions if non-connectable vehicles are not considered. Finally, safety-critical applications such as collision avoidance or trajectory prediction require comprehensive knowledge of all nearby traffic participants.

To address this problem, this dissertation proposes a method that enables the inclusion of non-connectable vehicles into the digital twin using indirect observation. Instead of requiring communication capabilities from every vehicle, the proposed approach uses fused sensory data from connected vehicles to detect and model nearby non-connectable vehicles. The detected vehicles are then represented within the digital twin through a process called Announcement via Proxy (AVP).

The proposed approach relies on data fusion from cameras and LiDAR sensors installed in intelligent vehicles. Using these sensors, connected vehicles can detect surrounding objects, estimate their positions and dynamics, and report them to the digital twin infrastructure. The infrastructure subsequently generates virtual messages representing these vehicles, enabling their participation in cooperative awareness mechanisms.

In addition to the detection and modeling of non-connectable vehicles, this dissertation also proposes a digital twin architecture designed specifically for road infrastructure. The architecture integrates vehicle-generated data with edge computing capabilities to provide data for real-time simulations and decisions.

The motivation behind this research lies in bridging the gap between the current mixed traffic environment and the future vision of fully

connected autonomous transportation systems. Until all vehicles become connected, solutions must exist that allow non-connectable vehicles to be incorporated into intelligent transportation systems without requiring modifications to their hardware.

By enabling the representation of non-connectable vehicles in the digital twin, the proposed approach increases situational awareness, enhances predictive capabilities, and improves the overall safety and efficiency of traffic systems.

Chapter 2

Objectives

The main objective of this dissertation is to develop a system that enables the integration of non-connectable vehicles into the digital twin of road infrastructure. This objective is achieved through three primary research goals.

The first objective is fusion method capable of detecting and estimating the position and dynamics of vehicles using sensor data from connected vehicles. Since non-connectable vehicles cannot directly communicate with infrastructure systems, their detection must rely on sensor-based perception. Therefore, the proposed method focuses on fusing LiDAR and camera data to detect surrounding vehicles and estimate their movement characteristics.

The second objective is the design of an architecture for the digital twin of road infrastructure that supports the integration of both connected and non-connectable traffic participants. The architecture must allow real-time processing of data collected from vehicles while maintaining compatibility with existing ITS communication standards such as CAM and CPM [5, 6].

The third objective is the development of a mechanism for announcing non-connectable vehicles into the digital twin using proxy participants. This mechanism ensures that information about detected vehicles is distributed across the network while minimizing redundant announcements and preventing duplicate representations.

To achieve these objectives, the following research theses were formulated:

- Propose and verify a method for fusing sensor data to estimate vehicle position and dynamics.
- Define and validate an architecture for a digital twin of road infrastructure based on a merged centralized–decentralized paradigm.
- Propose and verify a method for announcing non-connectable vehicles into the digital twin via proxy participants.

The fulfillment of these theses enables the digital twin system to incorporate vehicles that lack direct communication capabilities while maintaining accurate and reliable situational awareness.

Chapter 3

Methodology and Solution Design

The proposed solution consists of three major components: a sensor data fusion method, a digital twin architecture, and an announcement mechanism for non-connectable vehicles.

3.0.1 Data Fusion Method

The first part of the solution focuses on detecting vehicles and estimating their position and dynamics using sensor data collected by connected vehicles. The proposed pipeline processes LiDAR point clouds and camera images to detect objects and estimate their spatial properties.

The detection process begins by processing LiDAR data to identify clusters representing objects in the environment. Ground points are removed from the point cloud to simplify object segmentation. Detected clusters are then associated with image data obtained from the camera sensor.

To improve detection accuracy, the proposed approach performs fusion between LiDAR and camera data. LiDAR provides precise spatial measurements, while the camera provides semantic information about detected objects.

Vehicle positions are estimated using geometric modeling techniques. The visible sides of vehicles are approximated using linear interpolation based on detected points in the LiDAR point cloud.

In situations where parts of the vehicle are not directly visible from the sensor viewpoint, additional geometric approximations are applied. Once the vehicle position is determined, the system can estimate vehicle dynamics .

3.0.2 Digital Twin Architecture

The second part of the solution focuses on designing the architecture of the digital twin for road infrastructure.

The proposed architecture follows a merged paradigm, combining characteristics of centralized and decentralized systems. Computational tasks are distributed between vehicles and Mobile Edge Computing (MEC) infrastructure.

The architecture consists of the following key components:

- Ego vehicle subsystem
- Mobile Edge Computing (MEC) layer
- Information Distribution Service
- Cooperative awareness management module
- Message encoding and decoding modules

Connected vehicles act as data sources and perform preliminary data processing. These vehicles detect surrounding objects using onboard sensors and transmit perception information to the MEC infrastructure.

The MEC layer processes the received data and integrates it into the digital twin simulation. It also manages message distribution to other vehicles in the network.

The system uses standardized ITS communication protocols including CAM and CPM messages . However, since non-connectable vehicles

cannot generate these messages themselves, the system introduces a new message type called virtual Cooperative Awareness Message (vCAM).

3.0.3 Announcement via Proxy Mechanism

The third part of the solution addresses the problem of announcing detected vehicles into the digital twin.

The proposed Announcement via Proxy (AVP) mechanism allows connected vehicles to announce non-connectable vehicles on their behalf. When a connected vehicle detects a non-connectable vehicle using its sensors, the detection information is transmitted to the MEC infrastructure. The MEC system then creates a virtual representation of the vehicle and generates a vCAM message.

To prevent redundant announcements, the system implements a vehicle identification mechanism. The identification algorithm compares spatial proximity and motion characteristics to determine whether multiple detections correspond to the same physical vehicle.

Chapter 4

Evaluation and Verification

The proposed methods were evaluated using both experimental datasets and formal verification techniques. The evaluation focuses on the accuracy of the proposed data fusion method as well as the correctness of the overall system architecture.

4.0.1 Data Fusion Evaluation

The accuracy of the data fusion method was evaluated using the KITTI Bird’s Eye View (BEV) benchmark dataset, which is widely used for evaluating object detection algorithms in autonomous driving research [7]. The dataset contains camera images, LiDAR point clouds, and labeled objects, allowing evaluation of detection and localization performance in real-world scenarios.

The evaluation metrics include precision, recall, and average precision (AP). These metrics measure the ability of the algorithm to correctly detect vehicles and estimate their positions in the BEV representation. The results of the evaluation are summarized in Table 4.1. The proposed solution was compared with several state-of-the-art methods evaluated on the same benchmark dataset.

As shown in Table 4.1, the proposed method achieves results comparable to state-of-the-art solutions on the KITTI BEV benchmark. While several competing approaches achieve slightly higher accuracy, they

Table 4.1: Results from the KITTI Bird-Eye View benchmark.

Solution	Moderate	Easy	Hard	Inference Time (ms)	GPU
MMLAB-PV-RCNN	90.65%	94.98%	86.14%	80	Yes
DSA-PV-RCNN	90.13%	92.42%	85.93%	140	Yes
CIA-SSD	89.84%	93.74%	82.39%	30.8	Yes
Proposed Method	89.79%	93.33%	79.46%	137.2	No
3D-CVF at SPA	89.56%	93.52%	82.45%	75	Yes
SASA	89.51%	92.87%	86.35%	36	Yes

typically require powerful GPU hardware for inference. In contrast, the proposed method achieves competitive accuracy while operating on standard CPU hardware without GPU acceleration. This makes the method suitable for deployment in resource-constrained environments such as edge computing platforms or embedded systems.

4.0.2 Architecture Verification

The proposed architecture was verified using Colored Petri Nets, which allow formal modeling of distributed systems and message-based communication workflows. The Petri net model represents interactions between ego vehicles and the Mobile Edge Computing (MEC) infrastructure responsible for managing the digital twin environment.

The verification process confirmed that the system correctly processes message flows, generates virtual Cooperative Awareness Messages (vCAM), and prevents redundant announcements of the same detected vehicle. This validation ensures that the proposed Announcement via Proxy mechanism behaves deterministically and maintains consistent system state even when multiple vehicles detect the same traffic participant.

Chapter 5

Discussion

The proposed solution demonstrates that non-connectable vehicles can be successfully integrated into the digital twin of road infrastructure without requiring direct communication capabilities. One of the main advantages of the approach is its compatibility with existing ITS communication standards. By generating virtual CAM messages, the system enables non-connectable vehicles to participate in cooperative awareness mechanisms. Another advantage is the use of Mobile Edge Computing, which allows computationally intensive tasks to be performed close to the data source. This reduces communication latency and improves system scalability. However, several limitations remain. First, the accuracy of vehicle detection depends on the quality of sensor data. Environmental conditions such as poor lighting, weather effects, or sensor occlusion may affect detection performance. Second, the redundancy mitigation algorithm relies on spatial proximity thresholds that may require further tuning in dense traffic environments. Third, the deployment of such systems requires sufficient coverage of connected vehicles capable of sensing and announcing nearby traffic participants. Despite these limitations, the proposed solution represents an important step toward enabling digital twin systems in mixed traffic environments where both connected and non-connectable vehicles coexist.

Chapter 6

Conclusion

This dissertation addressed the problem of integrating non-connectable vehicles into the digital twin of road infrastructure.

The research presented three main contributions.

First, a data fusion method was proposed for detecting vehicles and estimating their position and dynamics using LiDAR and camera sensors. Secondly, a digital twin architecture for road infrastructure was designed using a merged centralized–decentralized paradigm based on Mobile Edge Computing. Moreover, a mechanism called Announcement via Proxy was proposed to enable connected vehicles to announce non-connectable vehicles into the digital twin using virtual Cooperative Awareness Messages.

The proposed solution was evaluated using the KITTI dataset and formally verified using Colored Petri Nets.

The results demonstrate that the approach can successfully incorporate non-connectable vehicles into the digital twin, improving situational awareness and enabling more accurate traffic simulations.

Future work may focus on improving detection accuracy using advanced machine learning methods, optimizing redundancy mitigation strategies, and evaluating the system in real-world deployments.

The presented research of integration of non-connectable vehicles into digital twin systems represents a crucial step toward achieving safer and more efficient intelligent transportation systems, therefore this work contributes to the knowledge in area of connected, cooperative and automated mobility.

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Chapter A

List of Publications

Following is a list of publications related to the studied issue. All items listed below are published, peer-reviewed scientific papers authored or co-authored by the dissertation author.

Conference papers

- JANEBA, Matej – LEHOCZKÝ, Peter – GALINSKI, Marek – MILESICH, Tomáš – DANKO, Ján – KOTULIAK, Ivan. *Evaluation of LTE and 5G qualitative parameters for V2X use cases*. In: *2022 IEEE Zooming Innovation in Consumer Technologies Conference (ZINC 2022)*. Danvers: IEEE, 2022, s. 165–169.

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