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Digital Twin for Parking Management: A Comprehensive Perspective

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***Abstract*— Digital Twin (DT) technology has gradually emerged as a foundation in the evolution of urban mobility, particularly in the field of autonomous vehicle parking. The requirement of intelligent, responsive and scalable parking systems has grown significantly because of the increasing complexity and congestion of urban environments. This paper presents an analytical review on how 3D simulation techniques, incorporated with DT frameworks, are modelling vehicle parking processes. The core focus lies in influencing DTs for simulating real-time parking scenarios, enabling precise 3D object detection, adaptive path planning, and control strategies of self-driving vehicles. The research explores the integration of various technologies such as AI, IoT, 5G and simulation platforms like CARLA, SUMO, Unity3D and MATLAB/SIMULINK to imitate urban infrastructure in digital spaces. Advanced vision-based models such as YOLO, VGG16 and ResNet are implemented for their accuracy in object and slot detection under competitive conditions. The review also highlights hybrid ML systems that incorporate edge computing, cloud synchronization, and real-time feedback mechanisms, contributing to precise decision making and improved safety. Additionally, the paper highlights key obstacles such as dataset limitations, infrastructure rigidity, and sensor conformity, offering future directions that include mobile sensing, distributed processing, and the development of large-scale availability of 3D datasets. This comprehensive overview covers the revolutionary role of digital twins in enabling efficient parking environments, leading the way for more sustainable and technologically driven urban mobility.**

***Index Terms*— Digital Twin, 3D Simulation, Smart Parking, Autonomous Vehicles, Urban Mobility, Edge Computing and Real-Time Object Detection.**

I. INTRODUCTION

Urban mobility faces growing challenges due to rapid urbanization—traffic congestion, limited parking, safety issues, and environmental concerns. To overcome these, smart movement technologies have become essential. Among them, Digital Twin (DT) technology excels in replicating, simulating, and analysing physical systems in real time [1]. Originating in aerospace and manufacturing for lifecycle management, DTs now drive smart mobility by enhancing flexibility, visualization, and resource optimization [2]. Integrating multiple technologies, DTs use Artificial Intelligence for autonomous decision-making [3], IoT for real-time data from vehicles and infrastructure [4], and 5G/6G for low-latency, high bandwidth communication [5].

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Despite their promise, DTs face challenges including data privacy, interoperability, lack of standards, computational costs, and digital inequality [6]. Moreover, validation in complex real environments such as crossovers and unauthorized roads limits scalability and reliability [7]-[9]. This paper reviews four DT applications: autonomous vehicles, AI-driven parking, 3D perception, and adaptable mobility frameworks.

This paper summarizes the contemporary research across four focal areas that capture the breadth of DT applications in mobility. These include (1) DT-assisted autonomous vehicle creation, designing and testing, where virtual environments speeding up training and validation; (2) AI-assisted smart parking systems, which reduce search time and pollution; (3) real-time 3D perception systems for real-time object detection, crucial for AVs and smart intersections; and (4) adaptable frameworks and algorithmic models that enables the installation of smart transportation networks across urban scales.

II. Review of Previous Work on 3D Carparking Simulation

A. Review process

A systematic approach has been followed to examine advancements in the domain of 3D car parking simulation using Digital Twin (DT). The review process started with identifying key research questions, which was followed by a thorough search using terms such as ’digital twin,’ ’Smart parking’, ’autonomous vehicle testing’, ’3D car simulation’ and related terms.

TABLE I: Reviewed Articles

Year	Number of Journals	Number of Conferences
2020	1	22
2021	11	39
2022	21	96
2023	34	115
2024	54	141
2025	47	40

B. Key finding of the review

Key findings from the reviewed papers are listed below:

- Dataset considered
- Methodology
- Challenges and future directions

C. Retrieving information from literature

A literature review on the reviewed papers helps us to understand a variety of approaches for the simulation of car parking systems using the digital twin (DT) framework. A strong focus is placed on simulation platforms such as CARLA, SUMO, LGSVL, and Unity3D, which are used to replicate realistic urban parking environments and traffic. conditions to test autonomous vehicles and smart parking algorithms [1], [2], [4], [6].

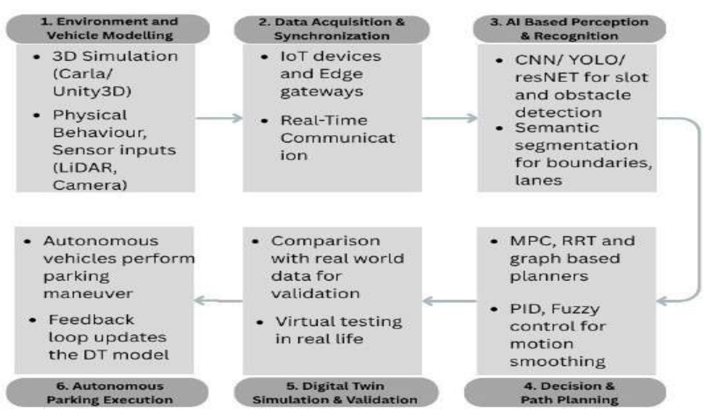
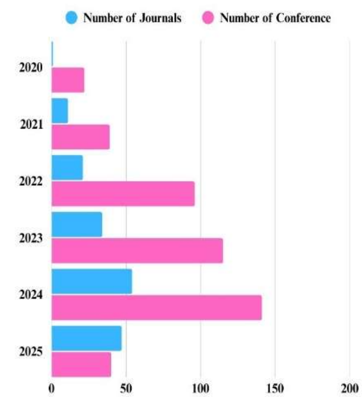


Figure 1. Basic Steps in The Digital Twin System for Autonomous Parking

Many studies employ object detection models like YOLOv5, ResNet18, VGG16, and mAlexNet to identify vacant spots that are being used correctly using thermal imaging from CCTV footage. These models are often enhanced with sensor fusion to improve accuracy in low visibility conditions [5], [13], [19], [23].
Other systems rely on sensor-based and IoT approaches, combining LiDAR, ultrasonic sensor input, and GPS with cloud services such as Blynk and Firebase to monitor parking availability in real time and provide live data [3], [10], [16], [25].
Various hybrid DT models have also been explored, which allow real-time interaction between virtual and physical vehicles, helping in scenarios such as navigation, car follow-up, and safety validation [9], [10], [12]. Recent work also highlights digital twin authoring tools (DTAT) that automate the creation of 3D environments from sensor inputs or CAD files, which makes large-scale mobility simulations more impactful.



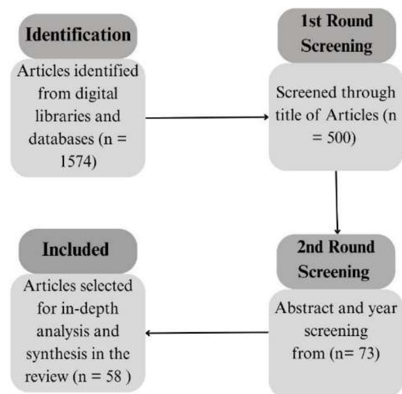


Figure 2. Trend of Number of Journals and Conferences from 2020 to 2025 Figure 3. Screening Process

III. Datasets Used

Across the reviewed studies, datasets form the backbone of modelling and validating 3D Car parking systems that use Digital Twin(DT) technology. One of the most frequently used dataset is the PKLot dataset, which offers over 12000 labelled images capturing parking spaces under various environmental conditions. It has been widely adopted in works such as [16], [30], for training Convolutional Neural Networks (CNNs), optimized for real-time models on edge devices. Similarly, the CNRParkEXP dataset, with its rich variability with factors such as weather and time, was used in [19], [30] to test the robustness of visual detection systems. For 3D object localization and perception, researchers often adopted the KITTI Dataset for DT simulations [1], [26], critically using CARLA to imitate LiDAR and multi-camera data. In addition to these datasets, researchers also use custom image and video data that were gathered from real-world scenarios using fisheye lens and dashcam footage for tasks like bounding box detection, road boundary detection, and curb detection [24], [27]. Datasets that are simulated through Unity3D, Sumo and FlexSim enables scalable testing of DT-based autonomous navigation in parking environments [2], [17], [49]. In addition, researchers have used GIS-derived urban layouts [16], [44] to capture largescale logistics in a typical city-like parking scenario. The various mentioned datasets—both real and synthetic—allowed researchers to calculate the safety and adaptability of DT enabled parking systems for a wide range of conditions
(occlusions, obstacles, adverse weather, etc.).

III. Methodology

A. Environment and Vehicle Modelling

The DT concept is based on realistic modelling. Several works have used Unity3D, CARLA and Gazebo to model car park environments in real-time [1], [2], [7], [17], [26], [34]. These platforms simulate physical behaviour, traffic interactions, and sensory inputs (LiDAR, radar, cameras) and thus enable accurate DT reconstructions. Vehicle dynamics were simulated by reduced kinematic models (e.g., bicycle model), or proprietary MATLAB/Simulink environments [17], [43]. These were used to simulate test vehicle motion planning and interaction with virtual infrastructure, usually combined with external navigation engines or satellite mapping [17], [44].

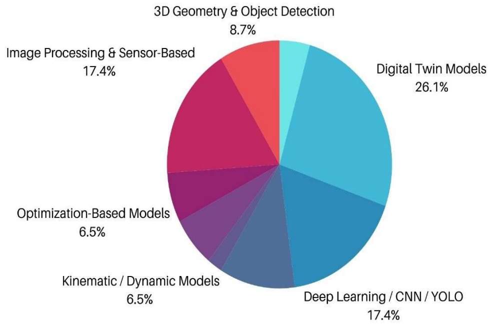


Figure 4. Distribution of Model Types

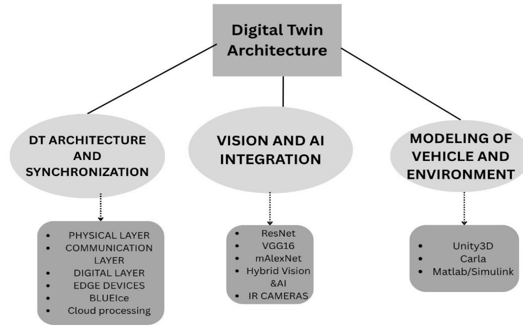


Figure 5. Environment And Vehicle Modelling In DT

B. Digital Twin Architecture And Synchronization

A few papers illustrate a layered DT architecture that includes physical (sensor-enabled vehicles), communication (V2G/5G), and digital layers (model servers) [2]–[4], [17], [38]. Papers like [43] have showcased synchronization of virtual and physical testbeds for enabling real-time validation through edge devices and smart gateways. Sustainable DT management has been ensured by container-based implementations, e.g., BlueICE [17], which combines vehicle control, environmental simulation, and cloud-based processing components. Real-time synchronization algorithms enabled seamless updating of simulation states according to real-world data streams.

C. Vision-Based Recognition And AI integration

A considerable amount of research employed CNN architectures for vehicle and parking lot detection [16], [19], [30]. Embedded systems had lightweight models (e.g., mAlexNet) [16], while VGG16, ResNet18/50, and Inception models were used to improve accuracy on datasets such as CNRPark-EXT and PKLot [30]. Hybrid solutions combined classical vision with machine learning—e.g., image processing and SVM for bi-class classification in conditions of constrained visibility [18], [33]. IR and thermal cameras were investigated in [24] for low-light detection, where precision exceeding 95 was obtained by ResNet-based models. Semantic segmentation by UNet and Mask R-CNN was applied in [27], [34] for curb detection, parking line detection, and boundary detection.

TABLE II: ANALYSIS OF MODELS USED IN VARIOUS WORKS

Model Type	Paper Citations	Total
Car-Following Models	[20], [40]	2
Digital Twin Models	[4], [6], [9], [14], [17], [22], [35], [42], [48], [49], [52], [58]	12
Deep Learning / CNN / YOLO	[13], [15], [18], [19], [23], [31], [38], [40]	8
Hybrid ML (SVM / KNN / etc.)	[18], [21], [24], [50], [53]	5
Agent-Based Models	[33]	1
Kinematic / Dynamic Models	[26], [40], [43]	3
Optimization-Based Models (AHP, PSO, MDP)	[33], [49], [53]	3
Image Processing & Sensor-Based	[3], [5], [10], [12], [16], [32], [38], [43]	8
3D Geometry & Object Detection	[11], [13], [29], [46]	4

TABLE III: ACCURACY COMPARISON OF MODELS USED IN 3D CAR PARKING SIMULATION

Model / Algorithm	Ref. No.	Accuracy	Comments
YOLOv5 + DehazeNet	[13]	95.71%	Excellent performance in foggy conditions.
YOLOv5 (CCTV feed)	[19]	94.01%	Real-time detection in CCTV-based parking areas.
YOLOv3 + mAlexNet	[31]	96.23%	Deep feature-enhanced slot detection combining CNN layers.
VGG16 + Faster R-CNN	[40]	97.45%	High slot classification performance with convolutional feature extraction.
CNN + Object Tracking	[38]	90.80%	Combines CNN with object tracking to maintain consistency over frames.
Thermal CNN	[23]	93.40%	Night-time and low-visibility detection using thermal imagery.
CNN + Sensor Fusion	[15]	94.30%	Fuses sensor and vision data for enhanced detection accuracy.
Neural Network (Basic)	[18]	91.50%	Simple neural net model for slot availability prediction.
AHP + IoT Decision Model	[53]	92.20%	Analytical Hierarchy Process (AHP) optimizes parking logic.
AI + Edge Computing DT	[35]	93.00%	Edge AI + digital twin integration enables low-latency predictions.

D. Path Planning and Control

Several approaches for autonomous parking and navigation were utilized. Vehicle motion planning employed model predictive control (MPC) or reactive control such as artificial potential fields [26], [43]. Simulated agents employed RRT (Rapidly-Exploring Random Trees) or graph-based planners to compute admissible parking trajectories in the presence of static and dynamic obstacles [17], [28]. PID and fuzzy logic controllers were widely used for local control operations such as angle correction and velocity smoothing in parking maneuvers [11], [22], [39].

E. Simulation Platforms And Urban Parking Models

Simulation tools like SUMO, FlexSim, and CARLA are widely used for testing Digital Twin Systems with proper detailing. SUMO was particularly used for agent-based traffic modeling in urban environments [49] and FlexSim supported 3D process flows for multi-agent routing [17]. GIS data and HD maps were integrated to develop real-time citywide parking environments [6], [44], enhancing macro-level parking policy evaluation. In [29], Unity3D and VR interfaces simulated human-parking interactions, which were highlighted by human-centric DT evaluations.

F. Optimization and Forecasting

Optimization techniques were applied to improve space management in public, reduce parking search time, and minimize energy consumption. [49] employed multi-objective optimization (e.g., Pareto Front, PSO) for slot assignment based on real-time environment in a DT framework. [18] used ARIMA models to anticipate parking availability based on historical trends. For real-time decision-making in multi-agent parking scenarios [28], [33] several studies suggested learningbased optimization which includes reinforcement learning and genetic algorithms.

G. Edge Computing and System Integration

To ensure low-latency response, many DT systems offloaded estimation to edge devices. CNN inference is processed by modules like Smart CCTV and on-board camera locally [19], [24], while more complex tasks (e.g., path optimization, prediction) are pushed further to cloud or fog layers [2], [3]. The MQTT / ROS-based communication layers controlled the synchronization of DT and the critical safety decision-making, which allowed real-time bidirectional flow between physical assets and virtual replicas [17], [43].

V. Challenges and Future Directions

A. Infrastructure Challenges

One of the main challenges in using Digital twin technology for simulations of 3D car parking comes due to the high reliance on fixed infrastructure. This happens due to the dependence on static sensor setups such as multi camera installations; this creates blind spots and hence it is difficult for these systems to adjust to changing environments. Due to this lack of flexibility in these type of systems. It also increases the maintainance cost specially when upgrades or changes are required [1], [4]. Another major obstacle is the complexity involved in integrating different types of hardware. Researchers have introduced many solutions that require bringing together various devices like ultrasonic sensors, CCTV cameras, thermal cameras and cloud platforms into a single cohesive system. This is not always straightforward and usually results in high maintenance challenges and setup costs particularly in areas with complicated infrastructure layouts [18], [21].
Network limitations are also a big hindrance. In various backward or least developed areas, this network infrastructure is not fast enough so that it can handle real-time parking updates which causes to reduce the accuracy of information of the parking process. [18], [25]. Low-cost setups specially those setups that use basic edge devices, suffer visually due to the slow speed of data processing and unstable connections [21]. Security risks are increased in these cases due to the poor communication channels, which are in constant danger of data leaks or hacking specially in open spaces.

B. Technical Challenges

From a technical perspective it is a constant challenge to handle different environmental conditions. Various detection systems specially the systems that use vision based AI models, struggle when they are faced wity=th adverse conditions like poor lighting, bad weather, or night time situations [1], [25], [29]. This becomes more noticeable in systems that only depends on regular cameras as problems like glare, shadows or occlusions causes the system to fail to classify objects properly [1], [29].

Another major challenge is the processing speed of advanced models. Techniques like YOLO, ResNet, or CNNLSTM often require significant computational power, which can slow down system performance. This becomes a real concern in real-time scenarios—such as helping drivers quickly locate available parking spots—where even slight delays in response time can reduce the effectiveness of the system [19], [23], [27].
A more fundamental limitation comes due to the lack of large, well-defined, and high quality datasets.There are just not enough comprehensive datasets that can represent real-life parking scenarios very well, specially with different adverse conditions like- poor lighting or sudden weather changes [1], [4]. Due to this many engineers are forced to rely on limited or artificial data, which affects the performance of the models in real-life situations [44].

C. Future Directions

In the coming years, there are numerous promising paths for the evolution of these systems. One highly promising path is the shift away from exclusive dependence on fixed infrastructure. By integrating mobile sensing technologies such as dashboard cameras or vehicle-mounted cameras with targeted fixed sensors, it is possible to decrease costs while simultaneously enhancing system flexibility [23]. Parking information collected from vehicles already in service can assist in minimizing blind spots and making parking systems more intelligent without the addition of large amounts of extra hardware. .
On the computation front, edge and cloud computing would be a suitable combination. Edge-local, fast processing is employed for time-critical computations, while more intensive computation is shifted to the cloud [32]. With 5G and V2X communication, such systems can be made much faster and more responsive.
There is a huge need for better datasets. Creating a large, open 3D parking dataset across various environments and conditions can potentially give researchers the resources they need to make a big leap forward in AI models. This would be a huge step-up for the field of autonomous parking as a whole.
Finally, as the use of these systems becomes more common, privacy and security needs to be taken most seriously. Future designs should include strong encryption (turning messages into secret code) and anonymization ways of doing things (promising that something will definitely happen or that something will definitely work as described) so that users' information is protected and kept private, especially in public or exposed surrounding conditions [39].

VI. CONCLUSIONS

This study explains the transformative potential of advanced simulation platforms and vision based models for smart parking systems. Compared to traditional Matlab or simple simulations ,platforms like CARLA ,Unity 3D etc offer far more realistic physics driven environments. For accurately replicating real world conditions and making them ideal for creating digital twins of transportation networks, these platforms integrates sensor data. Frameworks such as BlueICE ,which allows real time synchronization between virtual and physical systems supports the use of layered digital twin architectures while improving scalability and performance. On the AI side,models like YOLO v5,ResNet,VGG16 and vision transformers(ViT) deliver exceptional accuracy in detecting vehicles and parking slots. Thermal and infrared based CNNs further enhance system reliability , outperforming older hybrid machine learning models in challenging low visibility situations. Simulation tools such as SUMO,FlexSim and Unity3D acts as an symbiotic relationship in between each other by combining traffic modelling ,process optimization and immersive visualization to provide a brief view of system performance . Meanwhile, optimization and forecasting techniques like Particle Swarm Optimization(PSO), Analytic Hierarchy Process (AHP) and Reinforncement Learning enable smarter parking management and dynamic decision making than conventional ARIMA models . Finally, edge and fog computing ,combined with MQTT/ROS communication networks which ensure low latency data exchange between the digital and real layers . Altogether , for a scalable, intelligent and efficient smart mobility ecosystem ,the integration of Deep Learning , Digital Twins and Distributed Computing is done.

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