Technical University of Crete
School of Production Engineering and Management
Industrial and Digital Innovations Research Group

Development of an Application Framework for Digital Twin-Driven Intelligent Autonomous Vehicles

Ανάπτυξη ενός Πλαισίου Εφαρμογής Ψηφιακών Διδύμων σε Ευφυή Αυτόνομα Οχήματα

Doctoral Dissertation

Nikolaos M. Sarantinoudis

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against the doctoral committee consisting of

Associate Professor George Arampatzis [1]
School of Production Engineering and Management
Technical University of Crete

Associate Professor Eleftherios Doitsidis [1]
School of Production Engineering and Management
Technical University of Crete

Professor Michail G. Lagoudakis [1]
School of Electrical and Computer Engineering
Technical University of Crete

Professor Gregoris Mentzas
School of Electrical and Computer Engineering
National Technical University of Athens

Professor Nikolaos Tsourveloudis
School of Production Engineering and Management
Technical University of Crete

Professor Kimon Valavanis
Ritchie School of Engineering and Computer Science
University of Denver

Associate Professor Nikolaos Vitzilaios
Molinaroli College of Engineering and Computing
University of South Carolina

1 Advisory Committee Members

Ε Π Τ Α Μ Ε Λ Η Σ Ε Ξ Ε Τ Α Σ Τ Ι Κ Η Ε Π Ι Τ Ρ Ο Π Η

Τίτλος:

Ανάπτυξη ενός πλαισίου εφαρμογής Ψηφιακών Διδύμων σε Ευφυή Αυτόνομα Οχήματα

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ΔΙΔΑΚΤΟΡΙΚΗ ΔΙΑΤΡΙΒΗ

Νικολάου Μ. Σαραντινούδη

ΤΡΙΜΕΛΗΣ ΣΥΜΒΟΥΛΕΥΤΙΚΗ ΕΠΙΤΡΟΠΗ:

1. **Αναπλ. Καθηγητής Γεώργιος Αραμπατζής (Επιβλέπων)**
2. **Αναπλ. Καθηγητής Ελευθέριος Δοϊτσίδης**
3. **Καθηγητής Μιχαήλ Λαγουδάκης**

Εγκρίθηκε από την επταμελή εξεταστική επιτροπή την: 24 / 10 / 2025

(υπογραφή)

1. **Αναπλ. Καθηγητής Γεώργιος Αραμπατζής**
2. **Αναπλ. Καθηγητής Ελευθέριος Δοϊτσίδης**
3. **Καθηγητής Μιχαήλ Λαγουδάκης**
4. **Καθηγητής Γρηγόριος Μέντζας**
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7. **Αναπλ. Καθηγητής Νικόλαος Βιτζηλαίος**

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Abstract

The integration of digital twins with autonomous vehicles is a promising yet insufficiently explored research domain. Digital twins provide virtual representations of physical systems that enable real-time synchronisation, monitoring, simulation, and optimisation throughout the system lifecycle. Although extensively studied and applied in industrial and manufacturing contexts, the adoption of digital twins in autonomous vehicles remains fragmented, lacking a unified methodological framework. This doctoral dissertation addresses this gap by systematically investigating existing applications, proposing a structured conceptual framework for digital twin deployment in autonomous vehicle domain and validating the framework experimentally through representative case studies.

The research is structured in three main phases. The first phase comprises of a comprehensive literature review and bibliometric analysis, mapping the research and academic landscapes of digital twin applications in autonomous vehicles across land, aerial, surface, and underwater domains. Quantitative and qualitative analyses identify key trends, application areas, methodologies, and technological enablers. The study highlights an exponential growth of publications in the last five years, underlining both the increasing relevance of the field and the absence of standardised approaches that could support replication and scalability.

Building upon these insights, the second phase formulates a conceptual application framework. The framework is based on four main pillars: (i) system requirements and definition, (ii) communication middleware and data flow, (iii) digital modelling and (iv) physical-digital integration and validation. It provides a formalised methodology for embedding digital twins into autonomous vehicles, from design and development to testing, deployment, and operation. The framework emphasises interoperability, scalability, and replicability, positioning digital twins as a bridging mechanism between theoretical models and real-world implementations.

The third phase focuses on validation use cases. Three tests were conducted; two of them using scaled autonomous vehicle platforms and the third one using a high-fidelity simulator representing the physical system. The first validation employed a custom-made testing platform, while the second utilised a RoboRacer vehicle and extended this setup through hardware and sensor upgrades, enabling the evaluation of modularity and robustness. The third validation constitutes a scale-up by applying the framework to a full-scale simulated vehicle. Open-source ecosystems, such as ROS/ROS2, were used to establish bidirectional synchronisation between physical and digital environments, simulation and visualisation. The use cases demonstrated the framework's capacity

to support algorithm testing, perception and control integration, and performance evaluation under diverse operational conditions. Results confirmed the feasibility of reducing development costs, mitigating risks, and facilitating experimentation in scenarios that would otherwise be unsafe or impractical in real-world testing.

The contributions of this dissertation are threefold. First, it provides a systematic mapping of the research domain, offering a consolidated reference for scholars and practitioners. Second, it introduces a novel conceptual framework that formalises the application of digital twins in autonomous vehicles, addressing a critical gap in the literature and leveraging the paradigm of digital twins from Industry 4.0, a well-established domain for digital twins applications. Third, it presents experimental evidence of the framework's applicability and makes openly available resources to enable replication and extension by the research community.

In conclusion, this dissertation advances the state of the art by establishing a structured approach to digital twin integration in autonomous vehicles. By combining theoretical analysis, methodological innovation, and empirical validation, it contributes both to academic knowledge and to practical implementation pathways. The proposed framework lays the foundation for safer, more reliable, and cost-efficient development and operation of intelligent autonomous systems, while also creates opportunities for future extensions in cross-domain applications and real-world deployments.

Διδακτορική Διατριβή του

Νικόλαου Μ. Σαραντινούδη

με θέμα

Ανάπτυξη ενός Πλαισίου Εφαρμογής Ψηφιακών Διδύμων σε Ευφυή Αυτόνομα Οχήματα

Περίληψη

Η ενσωμάτωση των ψηφιακών διδύμων με τα αυτόνομα οχήματα αποτελεί έναν πολλά υποσχόμενο, αλλά ανεπαρκώς διερευνημένο, ερευνητικό τομέα. Τα ψηφιακά δίδυμα παρέχουν εικονικές αναπαραστάσεις φυσικών συστημάτων που επιτρέπουν τον συγχρονισμό, την παρακολούθηση, την προσομοίωση και τη βελτιστοποίηση σε πραγματικό χρόνο καθ' όλη τη διάρκεια της ζωής του συστήματος. Παρόλο που έχουν μελετηθεί και εφαρμοστεί εκτενώς στην βιομηχανία, η υιοθέτηση των ψηφιακών διδύμων στα αυτόνομα οχήματα παραμένει αποσπασματική, χωρίς ένα ενιαίο μεθοδολογικό πλαίσιο. Η παρούσα διδακτορική διατριβή προσπαθεί να αντιμετωπίσει αυτό το κενό, διερευνώντας συστηματικά τις υπάρχουσες εφαρμογές, προτείνοντας ένα δομημένο εννοιολογικό πλαίσιο για την εφαρμογή των ψηφιακών διδύμων στον τομέα των αυτόνομων οχημάτων και επικυρώνοντάς το πειραματικά μέσω αντιπροσωπευτικών μελετών περίπτωσης.

Η έρευνα δομείται σε τρεις κύριες φάσεις. Η πρώτη φάση περιλαμβάνει μια εκτενή ανασκόπηση της βιβλιογραφίας και βιβλιομετρική ανάλυση, χαρτογραφώντας το ερευνητικό και ακαδημαϊκό πεδίο των εφαρμογών ψηφιακών διδύμων σε αυτόνομα οχήματα ξηράς, αέρος, θαλάσσης και υποθαλάσσιου περιβάλλοντος. Ποσοτικές και ποιοτικές αναλύσεις αναδεικνύουν βασικές τάσεις, τομείς εφαρμογής, μεθοδολογίες και τεχνολογικούς παράγοντες. Η μελέτη υπογραμμίζει την εκθετική αύξηση των δημοσιεύσεων τα τελευταία πέντε χρόνια, αναδεικνύοντας τόσο το συνεχώς αυξανόμενο ενδιαφέρον για το πεδίο, όσο και την απουσία δομημένων προσεγγίσεων που θα μπορούσαν να υποστηρίξουν την ευκολότερη εφαρμογή των ψηφιακών διδύμων στα αυτόνομα οχήματα.

Βάσει αυτών των ευρημάτων, στην δεύτερη φάση της εργασίας αυτής διαμορφώνεται ένα πλαίσιο εφαρμογής. Το πλαίσιο αυτό βασίζεται σε τέσσερις κύριους πυλώνες: (i) απαιτήσεις και

ορισμό του συστήματος, (ii) ενδιάμεσο λογισμικό επικοινωνίας και ροή δεδομένων, (iii) ψηφιακή μοντελοποίηση και (iv) ενοποίηση και επαλήθευση φυσικού-ψηφιακού συστήματος. Παρέχει μια τυποποιημένη μεθοδολογία για την ενσωμάτωση των ψηφιακών διδύμων σε αυτόνομα οχήματα, από τον σχεδιασμό και την ανάπτυξη έως τη δοκιμή, την υλοποίηση και τη λειτουργία τους. Το πλαίσιο αυτό δίνει έμφαση στη διαλειτουργικότητα και την επεκτασιμότητα, καθιστώντας τα ψηφιακά δίδυμα έναν μηχανισμό γεφύρωσης μεταξύ θεωρητικών μοντέλων και πραγματικών εφαρμογών.

Η τρίτη φάση επικεντρώνεται στην πειραματική επαλήθευση του προτεινόμενου πλαισίου εφαρμογής. Πραγματοποιήθηκαν τρείς μελέτες περίπτωσης, δύο εξ αυτών χρησιμοποίησαν μικρής κλίμακας αυτόνομα οχήματα και το τρίτο έναν προσομοιωτή υψηλής πιστότητας που αναπαριστά το φυσικό σύστημα. Η πρώτη επαλήθευση βασίστηκε σε μια ειδικά κατασκευασμένη πλατφόρμα δοκιμών, ενώ η δεύτερη αξιοποίησε ένα όχημα τύπου RoboRacer, επεκτείνοντας το με αναβαθμίσεις υλικού και αισθητήρων, ώστε να αξιολογηθεί η ανθεκτικότητα και προσαρμοστικότητα του πλαισίου. Η τρίτη επαλήθευση αποτελούσε κλιμάκωση σε προσομοιωμένο όχημα πλήρους κλίμακας. Χρησιμοποιήθηκαν ανοικτά οικοσυστήματα, όπως τα ROS/ROS2, για τη δημιουργία αμφίδρομου συγχρονισμού μεταξύ φυσικού και ψηφιακού περιβάλλοντος. Τα πειράματα έδειξαν ότι το πλαίσιο μπορεί να υποστηρίξει την ενσωμάτωση αλγορίθμων αντίληψης και ελέγχου, καθώς και την αξιολόγηση επιδόσεων υπό ποικίλες συνθήκες λειτουργίας. Τα αποτελέσματα επιβεβαίωσαν τη δυνατότητα μείωσης του κόστους ανάπτυξης, περιορισμού των κινδύνων και διευκόλυνσης πειραματισμών σε σενάρια που διαφορετικά θα ήταν επικίνδυνα ή μη πρακτικά για δοκιμή στον πραγματικό κόσμο.

Οι κύριες συνεισφορές της παρούσας διατριβής είναι τρεις. Πρώτον, παρέχει μια συστηματική χαρτογράφηση του ερευνητικού πεδίου, προσφέροντας μια ενοποιημένη αναφορά για ερευνητές και επαγγελματίες. Δεύτερον, εισάγει ένα νέο εννοιολογικό πλαίσιο που τυποποιεί την εφαρμογή των ψηφιακών διδύμων στα αυτόνομα οχήματα, καλύπτοντας ένα κρίσιμο κενό στη βιβλιογραφία και αξιοποιώντας το παράδειγμα των ψηφιακών διδύμων της Βιομηχανίας 4.0, ενός καλά εδραιωμένου τομέα εφαρμογής τους. Τρίτον, παρουσιάζει πειραματικά δεδομένα που τεκμηριώνουν την πρακτική εφαρμοσιμότητα του πλαισίου και καθιστά όλους τους σχετικούς πόρους διαθέσιμους στο κοινό, όχι μόνο για αναπαραγωγή, αλλά και για επέκταση από την ερευνητική κοινότητα.

Συνοψίζοντας, η διατριβή αυτή προωθεί την τρέχουσα επιστημονική γνώση καθιερώνοντας μια δομημένη προσέγγιση για την ενσωμάτωση ψηφιακών διδύμων στα αυτόνομα οχήματα. Συνδυάζοντας θεωρητική ανάλυση, μεθοδολογική καινοτομία και εμπειρική επαλήθευση, συμβάλλει τόσο στη διεύρυνση της ακαδημαϊκής γνώσης, όσο και στη διαμόρφωση πρακτικών οδών υλοποίησης. Το προτεινόμενο πλαίσιο θέτει τα θεμέλια για ασφαλέστερη, πιο αξιόπιστη και οικονομική ανάπτυξη και λειτουργία ευφυών αυτόνομων συστημάτων, δημιουργώντας παράλληλα ευκαιρίες για μελλοντικές επεκτάσεις.

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Acronyms and Abbreviations

3D	Three-Dimensional
5G	Fifth-Generation Cellular Network
6G	Sixth-Generation Cellular Network
AEKF	Adaptive Extended Kalman Filter
AGV / AGVs	Automated Guided Vehicle(s)
AI	Artificial Intelligence
AMR / AMRs	Autonomous Mobile Robot(s)
API / APIs	Application Programming Interface(s)
AR	Augmented Reality
ARM	Advanced RISC Machines
ASV / ASVs	Autonomous Surface Vehicle(s)
AUV / AUVs	Autonomous Underwater Vehicle(s)
AV / AVs	Autonomous Vehicle(s)
AXKF	Adaptive Exogenous Kalman Filter
BAN	Burrows–Abadi–Needham
CARLA	Car Learning to Act
CAV / CAVs	Connected Autonomous Vehicle(s)
CC	Cloud Computing
CDVs	Cross-Domain Vehicles
CEP	Circular Error Probability
CFD	Computational Fluid Dynamics
CNN	Convolutional Neural Network
CPS	Cyber-Physical System
CPU	Central Processing Unit
CSV	Comma Separated Values
CUDA	Compute Unified Device Architecture
DBSCAN	Density-Based Spatial Clustering of Applications with Noise
DC	Direct Current
DCS	Decentralised Control System

DDPG	Deep Deterministic Policy Gradient
DL	Deep Learning
DNN	Deep Neural Network
DOI	Digital Object Identifier
DQN	Deep Q-Learning Network
DRL	Deep Reinforcement Learning
DT / DTs	Digital Twin(s)
ECU	Electronics Control Unit
EoL	End-of-Life
ESC	Electronic Speed Controller
EV / EVs	Electric Vehicle(s)
FBG	Fiber Bragg Grating
FEM	Finite Element Modelling
FL	Federated Learning
FMU	Functional Model Unit
FoV	Field-of-View
FPGA	Field Programming Gate Array
GB / GBs	Gigabyte(s)
GHz	Gigahertz
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPIO	General Purpose Input Output
GPRS	General Packet Radio Service
GPS	Global Positioning System
GPU	Graphics Processing Unit
GSM	Global System for Mobile Communications
GUI	Graphical User Interface
HAT	Hardware Attached on Top
HLA	High Level Architecture
HPC	High Performance Computing

I2C	Inter-Integrated Circuit
I2S	Inter-Integrated Circuit Sound
IEEE	Institute of Electrical and Electronics Engineers
IL	Imitation Learning
IMU	Inertial Measurement Unit
IoT	Internet of Things
IIoT	Industrial Internet of Things
IoV	Internet of Vehicles
ISO	International Organization for Standardization
IT	Information Technology
IVHM	Integrated Vehicle Health Management
LiDAR	Light Detection And Ranging
LPDDR4 / LPDDR5	Low-Power Double Data Rate 4/5
LPG	Liquefied Petroleum Gas
LQR	Linear-Quadratic Regulator
LSTM	Long Short Term Memory
LTE	Long Term Evolution Cellular Network
LTS	Long Term Support
MAS-DT	Marine Autonomous Systems Digital Twin
MBES	Multi Beam Echo Sounder
MBSE	Model-Based System Engineering
MDL	Model Description Language
MEC	Mobile Edge Computing
ML	Machine Learning
MPC	Model Predictive Control
MR	Mixed Reality
NASA	National Aeronautics and Space Administration
NMEA	National Marine Electronics Association
NSDLS	Numerical Stable Direct Least Squares
NSF	National Science Foundation

NVMe	Non-Volatile Memory express
OCT	Optimal Classification Tree
ODPD	Optimisation-driven Product Development
OMA-LwM2M	Open Mobile Alliance - Lightweight Machine to Machine
OpenAIRE	Open Access Infrastructure for Research in Europe
PID	Proportional Integral Derivative
PLM	Product Lifecycle Management
PN / PNs	Petri-Net(s)
PPO	Proximal Policy Optimisation
PWM	Pulse Width Modulation
QGC	QGround Control
RADAR	Radio Detection And Ranging
RAM	Random Access Memory
RC	Radio Control
RGB	Red Green Blue
RISC	Reduced Instruction Set Computer
RL	Reinforcement Learning
ROR	Real Oracle Random
ROS / ROS2	Robot Operating System / Robot Operating System 2
ROV / ROVs	Remotely Operated Vehicles
RQ	Research Question
RSU / RSUs	Road Side Unit(s)
RT	Ray Tracing
RViz	ROS Visualisation
SAE	Society of Automotive Engineers
SDF	Simulation Description Format
SemDT	Semantic Digital Twin
SL	Supervised Learning
SLAM	Simultaneous Localisation and Mapping
SMP-LSAP	Stable Marriage Problem - Linear Sum Assignment Problem

SPI	Serial Peripheral Interface
SSD	Solid State Disk
STGCN	Spatial-Temporal Graph Convolutional Network
ToF	Time of Flight
UART	Universal Asynchronous Receiver/Transmitter
UAV / UAVs	Unmanned Aerial Vehicle(s)
UE	Unreal Engine
UEFI	Unified Extensible Firmware Interface
UGV / UGVs	Unmanned Ground Vehicle(s)
ULTP	Urgency Level-based Trajectory Planning
USB	Universal Serial Bus
USC	University of South Carolina
USRL	Unmanned Systems and Robotics Laboratory of USC
USV / USVs	Unmanned Surface Vessel(s)
UUV / UUVs	Unmanned Underwater Vehicle(s)
V2V	Vehicle to Vehicle
V2X	Vehicle to Everything
VR	Virtual Reality
VTS	Vessel Traffic System

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Chapter 1

Introduction

1.1 Problem Definition

In recent years, intelligent autonomous vehicles have rose to prominence as a significant innovation across multiple fields. The technology has now reached a level of maturity, and commercialization is underway. These systems have profound impacts both internally and externally. Internally, they remove risks for human operators, facilitate access to otherwise unreachable or hazardous environments, and can be implemented globally. Externally, they offer enhanced safety, cost reductions, improved energy efficiency, and lower pollution levels. Despite recent technological advances, development of and experimentation with autonomous systems continues to be costly. Beyond the systems themselves, the need for high-quality sensors and robust processing units, integral to autonomous functionality, remain quite expensive. Moreover, trial and error — a key aspect of engineering — can increase testing costs due to the potential destruction of equipment. Therefore, establishing a framework to support the development of new autonomous systems or to test and optimize existing ones is becoming increasingly critical in order to overcome these challenges.

The advancement of real-time monitoring systems utilizing Big Data and Advanced Analytics, IoT as well as the IIoT, the new capabilities in connectivity and communication and the greater variety of available monitoring sensors, chipsets and storage media have laid the way for an unprecedented digital transformation [1, 2]. In order to harness such power and not waste the potential laying ahead, the concept of Digital Twins (DT) is taking a significant role in various domains. A DT is *"a virtual representation of an object or system that spans its life-cycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making"* according to IBM [3]. A conceptual overview of a Digital Twin is presented in Figure 1.1.

Although both fields of autonomous vehicles and digital twins are currently thriving, their integration may lead to unexpected advancements in the realm of autonomous driving. Digital twins can significantly influence every phase of an autonomous vehicle's life cycle. From the initial

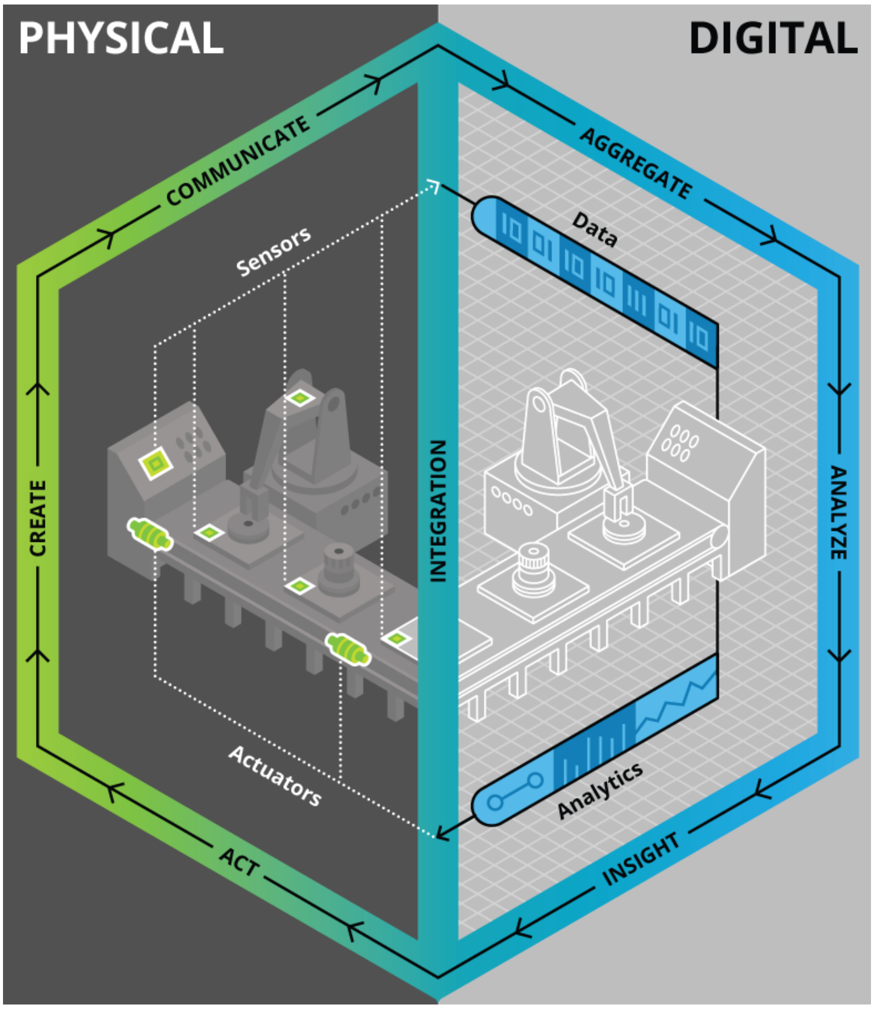

Figure 1.1: Conceptual overview of a manufacturing digital twin
Source: Delloite University Press

design stages and proof-of-concept to manufacturing, testing, refinement, optimization, system deployment, and maintenance, DTs can be pivotal. As regulations become stricter for autonomous vehicle testing and public scepticism around autonomous technologies grows, digital twins could be beneficial in addressing these limitations. They help alleviate concerns and reassure legislators and governments that autonomous vehicles are developed and tested under conditions they might never face in reality, while also ensuring continuous monitoring to reduce failures and accidents. Figure 1.2 presents an overview of a DT for an Intelligent Electric Vehicle according to [4].

Currently, efforts to integrate digital twins into autonomous vehicles are ongoing and these attempts have achieved relative success, albeit scattered across different applications. For example, digital twins have been utilised to create an autonomous system designed for high-temperature environments [5], for developing propulsion systems in autonomous electric vehicles [6], to enhance the dependability of autonomous driving [7], and to ensure safety and security in autonomous vehicles [8] among others, presented in detail in Chapter 2. Such diversity in the applications prove that DTs can be utilised to solve numerous problems in autonomous vehicles, however, the absence of a standardised framework for digital twin development complicates the application process. By analysing the field and current literature, the following observations can be made:

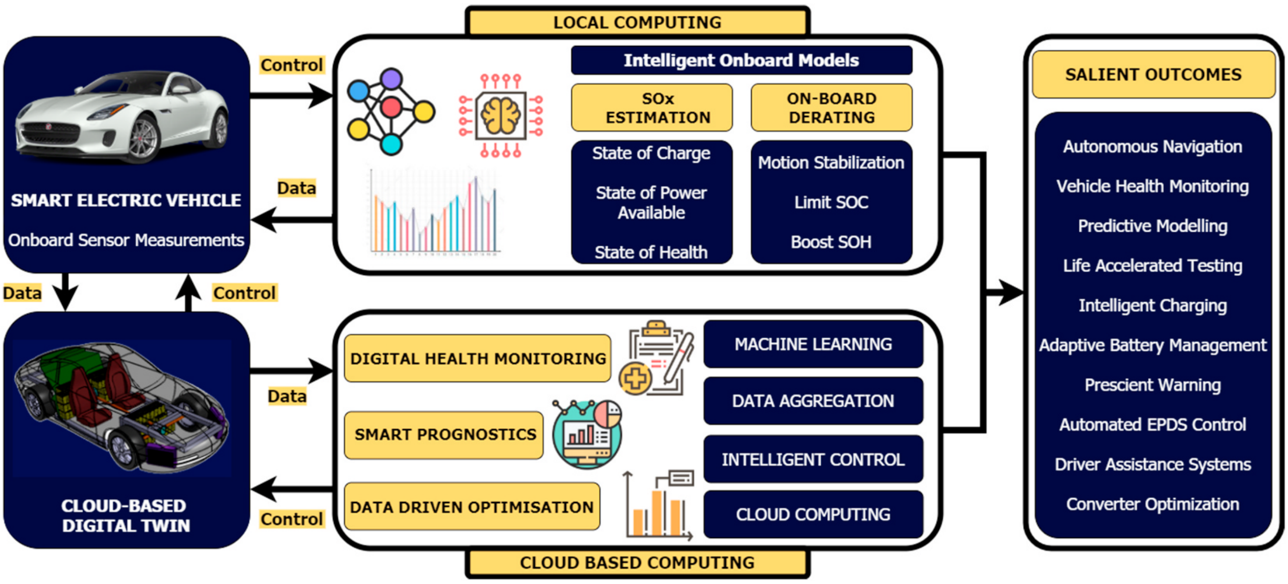

Figure 1.2: Overview of a Digital Twin for an Intelligent Electric Vehicle
Source: [4]

(a) Even though there are numerous applications of DTs in AVs met in literature, there is a lot of room for advancement, as most are still in their infancy.

(b) Despite the enablers, like real-time data, hardware, software, and connectivity, are fully developed, DTs are not widely applied in AVs.

(c) Theoretical and simulated research might be quite advanced, however bridging theory and practice still requires significant effort.

(d) There is a notable absence of an application framework for digital twins application within autonomous vehicles.

1.2 Research Questions and Methodology

The main goal of this doctoral research is to investigate the applicability of digital twins in the domain of autonomous vehicles and develop a conceptual application framework in order to ease the adoption in various stages of such systems' development and deployment. Based on the aforementioned realizations the author formulated the following research questions that will help navigate the doctoral studies. These questions have been organised hierarchically and correspond to the three main phases of the conducted work, as well as to the three main contributions of this dissertation; both discussed below. The naming convention of the research questions corresponds to these three phases/contributions with RQ1.x related to the first phase of the implementation, RQ2.x related to the second phase of the research and RQ3.x related to the third one.

RQ 1.1: Is there a significant research interest on the application of DTs in AVs ?

RQ 1.2: In what type of vehicles can DTs be applied to ?

RQ 1.3: Which are the most common applications of DTs in AVs ?

RQ 1.4: Which are the most common technologies and tools used in this domain ?

RQ 2.1: Is there an application framework for DTs application in AVs ?

RQ 2.2: How can then DTs be applied to AVs ?

RQ 2.3: Which are the basic principles required for a successful application of DTs in AVs ?

RQ 3.1: How the proposed framework can be validated through experimentation ?

RQ 3.2: Is it possible to replicate similar experiments and further advance the research domain ?

RQ 3.3: Can this framework be applied to diverse scale and vehicle types ?

The researcher's intention was not only to do theoretical work in the literature review and the conceptual framework, but also to test and validate the developed framework in autonomous vehicle platforms and provide insight and guidance to future researchers. According to [9], *"developing and testing safety-critical sense-plan-act functions will require a comprehensive digital twin"*, with the importance of "sense-plan-act" principle being explained further in Chapter 2.

In order to successfully complete the doctoral studies, a detailed methodology has been devised and followed. It consists of 3 distinct phases, with the completion of each one marking a milestone in the progression of the studies. A detailed description of each phase follows:

- **1st Phase: Theoretical Background and Literature Review of DT application in autonomous vehicles**

  In the first phase of the doctoral studies, an extensive literature review of relevant research was conducted. Similar applications and approaches were documented, evaluated and categorised in detail.

- **2nd Phase: Definition of the conceptual application framework**

  Definition of the conceptual application framework, background and requirements for the application of DTs in autonomous vehicles. Formalization of the framework and documentation of the guidelines for replication. Leveraging cross-domain knowledge from Industry 4.0 paradigm.

- **3rd Phase: Experimental Validation of the proposed framework**

  Testing and validation of the proposed framework in autonomous vehicles. Use of diverse vehicles in order to prove the applicability of the framework in numerous conditions. Documentation of the experiments and distribution to the community for further experimentation.

1.3 Contribution to the Research Community

This doctoral dissertation makes a threefold contribution to the research community by addressing the growing yet fragmented intersection of digital twins and autonomous vehicles domains. Firstly, it provides a comprehensive literature review that systematically maps the current landscape of DT applications in autonomous systems, identifying key trends, common applications, and the tools and technologies being utilised across land, air, and sea domains. Secondly, responding to the observed absence of a standardised approach, this work proposes a novel conceptual methodological framework designed to guide the deployment of DTs in AVs, aiming to bridge the significant gap between theoretical research and practical implementation adopting cross-domain knowledge, best practices and lessons learned from industry; a domain that digital twins have been successfully applied extensively. Finally, the dissertation offers a tangible validation of this framework through a series of representative use cases. The methodologies, software and tools implemented and the results of these validation use cases are made publicly available, providing a valuable resource for replication and fostering further research and development in this rapidly evolving field.

The aforementioned contributions at a glance are:

- ❐ **A comprehensive literature review of the applications of Digital Twins in Autonomous Vehicles.**
- ❐ **A conceptual methodological framework for Digital Twin deployment in Autonomous Vehicles leveraging the Industry 4.0 paradigm.**
- ❐ **Validation use cases of the proposed framework openly available to the community for replication and further experimentation.**

1.3.1 Publications

During this doctoral research the candidate authored or co-authored a number of publications; either directly related to the dissertation topic or indirectly, i.e. studying digital twins applications for a different domain that would however be mutually beneficial and where cross-domain knowledge could be leveraged from one domain to the other. Table 1.1 summarizes the number of publications according to the designated categories of the School of Production Engineering and Management.

At the time of compilation of this work, the total number of publications authored or co-authored by the doctoral candidate relevant to this work were seven. Two of them (28.6%) are publications

Table 1.1: Numbers of publication according to School of Production Engineering and Management designated categories.

Publication Type	No. of Publications
Peer-Reviewed Journals (Scopus)	2
Conference Proceedings (Scopus)	3
Conference Proceedings (Non-Scopus)	2
Under Review	2

in peer-reviewed journals indexed in Scopus, three (42.8 %) are publications in peer-reviewed conference proceedings with full text indexed in Scopus and two (28.6 %) are publications in conference proceedings not indexed in Scopus. There are also two publications currently under review in peer-reviewed journals, submitted on May 2025 and July 2025 respectively. The following list presents the aforementioned publications in further detail, with each listing accompanied by a short description summarizing the research and discussing the relevance to this doctoral dissertation.

A. Peer-Reviewed Journals (Scopus)

1. **N. Sarantinoudis**, G. Tsinarakis, P. Dedousis and G. Arampatzis, "Model-Based Simulation Framework for Digital Twins in the Process Industry", in IEEE Access, vol. 11, 2023 ➥ [10]

   This publication introduces a generic, model-based simulation framework specifically designed for digital twins in continuous process industries, using a methodology based on Material Flow Networks for flexible and scalable modelling. The framework includes a dedicated simulation tool that supports both offline and online applications for monitoring, analysis, optimization, and integration with physical systems through digital twinning. A case study demonstrates its application, and the authors discuss future challenges and extensions for enhanced data management and decision-making. Best-practices and knowledge from this work is being leveraged towards the creation of digital twins for the autonomous vehicles domain. Part of this work was a result of FACTLOG [11], an EU-funded Innovation Action.

2. G. Tsinarakis, **N. Sarantinoudis**, and G. Arampatzis, "A Discrete Process Modelling and Simulation Methodology for Industrial Systems within the Concept of Digital Twins", Applied Sciences, vol. 12, no. 2, 2022 ➥ [12]

   This publication introduces a modular methodology for discrete process modelling and simulation of industrial systems, using Petri-nets both offline and integrated online through digital twins for real-time monitoring and optimisation. It demonstrates the *approach with a steel reinforcement industry case study, highlighting bidirectional data exchange, scenario analysis, and the calculation of key performance indicators for enhanced system management. The methods enable dynamic adaptation and decision support by integrating real-time sensor data, analytics, and optimisation tools. Best-practices and knowledge from this work is being leveraged towards the creation of digital twins for the autonomous vehicles domain. Part of this work was a result of FACTLOG [11], an EU-funded Innovation Action.*

B. Conference Proceedings (Scopus)

1. **N. Sarantinoudis**, G. Tsinarakis, L. Doitsidis, N. Tsourveloudis and G. Arampatzis, "Bibliometric Analysis on Applications of Digital Twins in Autonomous Vehicles," 2023 31st Mediterranean Conference on Control and Automation (MED), Limassol, Cyprus, 2023 ➥ [13]

   This publication presents a bibliometric analysis of research on digital twins in autonomous vehicles, highlighting emerging trends, key technologies, and gaps in the literature. The study shows rapid recent growth in this interdisciplinary field, driven by advances in IoT and Industry 4.0, and proposes future research directions for stakeholders in autonomous systems. This work is part of Chapter 2.

2. **N. Sarantinoudis**, N. Vitzilaios and G. Arampatzis, "Applications of Digital Twins in UAVs," 2024 International Conference on Unmanned Aircraft Systems (ICUAS), Chania - Crete, Greece, 2024 ➥ [14]

   This publication presents an extensive survey on the applications of Digital Twins in Unmanned Aerial Vehicles. It categorizes over 70 relevant studies into key application areas including control/navigation, simulation/testing, and edge computing, highlighting how DTs enhance UAV performance, maintenance, and communication. The work also identifies the diversity of UAV types and technologies used, while addressing current challenges and future research directions in this emerging field. This work is presented in detail in Chapter 2. Part of this work was a result of the author's Fulbright visiting research scholarship.

3. **N. Sarantinoudis**, G. Tsinarakis, L. Doitsidis, S. Chatzichristofis and G. Arampatzis, "A ROS-Based Autonomous Vehicle Testbed for the Internet of Vehicles," 2023 19th International Conference on Distributed Computing in Smart Systems and the Internet of Things (DCOSS-IoT), Pafos, Cyprus, 2023 ➥ [15]

   This publication presents a ROS-based testbed for autonomous vehicles that integrates multiple sensors, communication devices, and microcontrollers to collect real-time data and enable the creation of Digital Twins. The platform provides an affordable, scalable, and practical solution for research and education, allowing users to experiment with autonomous vehicle control and navigation algorithms in a simulated yet physically scaled *environment. This framework facilitates hands-on learning and rapid prototyping without the need for full-scale vehicles, supporting further advancements in Internet of Vehicles applications. This work is presented in detail in Chapter 4.*

C. Conference Proceedings (Non-Scopus)

1. **N. Sarantinoudis**, G. Tsinarakis, K. Kalaboukas, P. Eirinakis and G. Arampatzis, "Cognitive Manufacturing: The role of process modelling and optimisation", 2021 31st European Conference on Operational Research (EURO-2021), Athens, Greece, 2021 ➥ [16]

   This paper introduces a framework for defining and standardising cognitive models to enable smart factories through Cyber-Physical Systems and Digital Twins. It proposes cognition as a vector of attributes supported by process-based models of production chains, supplemented with key extensions to enable digital cognition. The framework also outlines the practical and operational context in which these models would function.

2. P. Eirinakis, G. Arampatzis, A. Košmerlj, J. Rožanec, **N. Sarantinoudis**, "Utilizing an enhanced digital twin to optimize on-specs LPG recovery", 2021 31st European Conference on Operational Research (EURO), Athens, Greece, 2021 ➥ [17]

   Liquefied Petroleum Gas (LPG) purification requires meeting strict quality specifications, but anomalies in process units can lead to off-spec production. A Digital Twin enhanced with machine learning and Mixed Integer Programming is proposed to simulate and optimize refinery operations, guiding recovery actions to restore LPG quality while minimizing energy use.

D. Under Review

1. **N.Sarantinoudis**, N. Vitzilaios and G.Arampatzis, "A new open-source simulator using ROS2 and Gazebo", IEEE Robotics and Automation Practice ➥ [under review]

   This publication introduces a new open-source simulator for the RoboRacer platform, leveraging ROS2 and the latest Gazebo simulator (at the time) to create a highly accurate digital model of a 1:10 scale autonomous racing car. The vehicle, its sensors, and behaviour are replicated, and the simulator's accuracy is validated through a head-to-head comparison between real-world and simulated data. The work aims to support further research in digital twins for autonomous vehicles by providing the community with a robust and extensible simulation environment. This work supports the validation of the conceptual framework contributed by this dissertation. It was partially implemented during the author's Fulbright visiting research scholarship.

2. S. Plitsos, **N. Sarantinoudis**, G. Tsinarakis, J.M. Rozanec, P. Eirinakis and G. Arampatzis, "Efficient process operations via digital twins in the petrochemical industry: a case-study

on LPG purification", IEEE Access ➥ [under review]

This publication presents a digital twin framework for optimizing LPG purification processes in the petrochemical industry, integrating real-time sensor data, machine learning, simulation, and advanced optimization techniques to enhance monitoring and predictive analytics. The proposed solution achieved significant improvements at a refinery, including a 50% reduction in response time to product failures, a 30% decrease in off-spec production, and a 6% enhancement in product quality. The findings demonstrate that digital twins can substantially improve efficiency and sustainability in complex industrial environments. Part of this work was a result of FACTLOG [11], an EU-funded Innovation Action and PLOOTO [18], an EU-funded Research and Innovation Action.

In order to present visually the aforementioned manuscripts both published and under review, Figure 1.3 presents them in a chronological order. It allows for an easier understanding of the work conducted during the progression of this research over the years. In addition, Table 1.1 and Figure 1.3 offers the committee a visual summary of the publications in order for them to validate at a glance that the obligations for the completion of the doctoral studies at the School of Production Engineering and Management of the Technical University of Crete have indeed been met.

Figure 1.3: Publications timeline during the Doctoral Research

1.3.2 Experimental Datasets

In addition to the aforementioned publications that contribute the results of this work to the research community, another significant contribution is the datasets recorded during the validation use cases, explained in detail in Chapter 4. These datasets are compiled of data recordings, in ROS2 bag format, containing all sensor readings from cameras, both RGB and depth, LiDAR, as well as the odometry and the control inputs and outputs of the system. In order to be publicly available and easily accessible, all data have been uploaded to Zenodo; an open, multi-disciplinary digital repository that allows researchers and scholars to upload, preserve, and share all forms of research output, including datasets, software, presentations, and publications. Zenodo assigns a DOI to every upload, making it permanently citeable. Maintained by CERN and commissioned by the European Commission through OpenAIRE, Zenodo supports Open Access and Open Data principles by providing a trustworthy, non-profit platform for long-term archiving and discovery of research. Table 1.2 contains the DOIs to access the publicly available datasets.

Table 1.2: Publicly available datasets resulting from the validation use cases

Name	Description	Link
Simulated Test	A dataset containing simulated data that replicate the USRL test area and the experiments.	Simulated Test DOI Link
Physical Test (USRL Test Area)	A dataset containing physical data from the experiments conducted in USRL test area.	Physical Test (USRL Test Area) DOI Link
Physical Test (McNair Aerospace Centre)	A dataset containing extended data from the experiments conducted in McNair Aerospace Centre building.	Physical Test (McNair Aerospace Centre) DOI Link

1.4 Dissertation Outline

This doctoral dissertation is organised as follows. Chapter 1 is the introduction of the dissertation discussing the problem definition, the methodology of this work and the research questions attempted to be answered, the main contributions to the research community and the outline of the dissertation. Chapter 2 discusses the literature review of the domain under study, introducing basic concepts on the digital twins, autonomous vehicles, as well as the intersection of the two accompanied by a bibliometric analysis of the domain and detailed surveys on different types of vehicles; namely land, air and surface/underwater vehicles. Chapter 3 introduces the conceptual methodological applications framework, stating its cross-domain nature, its fundamental principles and explaining its phases in detail, as well as through figures, graphs and flowcharts. Chapter 4 discusses the validation efforts undertaken during this research through three use cases with different scale vehicles, as well as diverse software and hardware set-up. Finally Chapter 5 concludes this dissertation by summarizing the findings, elaborating on the impact, as well as the limitations and challenges identified and proposes potential future work.

Chapter 2

Literature Review

To establish a solid foundation in the field, an in-depth examination of the current literature has been conducted. This chapter delves into a detailed study of the two pivotal areas crucial to this dissertation: digital twins and intelligent autonomous vehicles. This review has two primary objectives: firstly, to provide the essential theoretical framework by analysing each technology in detail, and secondly, to critically assess their convergence and ascertain the current state-of-the-art, significant trends, and, most importantly, the research gaps that justify the focus of this doctoral research.

To gain a comprehensive understanding, the literature review adopts a top-down approach. It starts with a foundational exploration of digital twins, examining their development and identifying their essential components and supporting technologies. Furthermore, an overview of autonomous vehicles, highlighting the fundamental “sense-plan-act” paradigm and the standardised SAE levels of autonomy to shed some more light in the term autonomy is presented.

The chapter’s central focus converges on the synergies between these two domains. Initially, a quantitative bibliometric analysis is conducted to map out the academic field, uncovering increased research interest, key publications, and major keywords linking DTs and autonomous systems. Expanding upon this quantitative framework, the review engages in a thorough qualitative assessment of current applications, methodically classifying them by vehicle type; land, air, and surface/underwater vehicles. Through a critical evaluation of the findings from this comprehensive study, the chapter aims to clearly establish the existing capabilities and limitations in the area, ultimately highlighting the lack of a standardised framework that this dissertation proposes to address.

Throughout this chapter the first main contribution of this work, the comprehensive literature review of applications of Digital Twins in Autonomous Vehicles is presented in detail with research questions RQ 1.1, RQ 1.2, RQ 1.3 and RQ 1.4 being answered.

2.1 Digital Twins

Digital twins are digital counterparts of physical objects or systems, replicating their actions and performance in real-time. By integrating data from diverse sources, like sensors, machinery, and other devices, with modelling and simulation methodologies, a digital analogue of the physical system is created. This virtual counterpart serves the purpose of monitoring, analysing and enhancing the performance of the physical entity or system. Various fields, such as manufacturing, energy, healthcare, and transportation, can benefit from the applications of digital twins technology [19, 20].

Digital twins have seen a sharp rise in popularity, leading to numerous definitions in literature. A DT is typically viewed as a computer-generated model that mirrors and simulates a physical entity (such as a product or a system) along with its environment and interactions, offering the most accurate representation of the entity's real-time behaviour. DTs enhance transparency, optimize processes, and expedite operational decision-making, aims shared by traditional model-based decision support systems. However, the defining feature of a DT is its connectivity and real-time synchronisation with the physical object, facilitating data analysis to pre-emptively address issues, minimize downtime, open up new possibilities, and plan for the future through simulations. Critical to the DTs concept is the notion of Digital Shadow, which manages and analyses real-time (or near real-time) data from the physical counterpart and acts as a foundation for the creation of the digital twin; lacking although the bidirectional communication that is fundamental for a digital twin.

A more concise definition according to [21] is, *"A digital twin represents a digital counterpart of an active, unique product (which may include a real device, object, machine, service, or intangible asset) or a distinctive product-service system (encompassing a product alongside a related service) that embodies its selected attributes, characteristics, conditions, and behaviours through models, information, and data across a singular or multiple life cycle phases."* Specifically, by reflecting and simulating a physical entity (such as a product or system), along with its environment and interactions, a digital twin endeavours to provide an accurate depiction of how that object operates under various conditions. A significant innovation associated with DTs is that models transcend their traditional roles as mere design or predictive tools that replicate the state of physical systems; they are now regarded as dynamic components capable of engaging with the physical systems [12].

The concept of an operational digital twin can be identified in NASA's Apollo program, which employed mirrored systems to track and resolve the issues of inaccessible objects through simulation and analytical tools. Although the term "Digital Twin" was introduced in 1997, as referenced in [22], pertaining to the creation of 3D digital models in civil engineering in order to address limitations of traditional design processes, it wasn't until 2002 that the term gained significant attention. This occurred during an industrial presentation by Michael Grieves at the University of Michigan's Executive Course on Product Lifecycle Management [23]. Grieves' DT model, was composed by three main components 1) a real space containing a physical object; 2) a virtual space containing a virtual object; 3) the link for data flow from real space to virtual space and for information flow from virtual space to real space [19]. Digital twins are directly associated with Cyber-Physical Systems (CPS) across various dimensions, such as engineering methodologies, cyber-physical integration, and fundamental components. The concept of CPS was introduced in 2006 by the NSF to depict systems of growing complexity that could not be accurately captured using conventional IT terminology [24, 25].

The rise in the popularity of digital twins coincided with the introduction of Industry 4.0, an initiative launched by the German government that encompasses technological advancements in manufacturing. This initiative establishes a strategic policy framework aimed at preserving the global competitiveness of German industry [26]. Industry 4.0 is primarily concerned with the idea of factories, where machines are equipped with intelligent and autonomous systems enhanced by technologies, such as IoT, 3D printing, artificial intelligence, machine learning, big data, and augmented reality [27]. This concept signifies a revolutionary era marked by the interconnectivity and interaction of computers, machines, and humans, which leads to increased manufacturing efficiency, greater production volumes, more sustainable environmental solutions, and an improved quality of life [28]. A key aspect of this fourth industrial revolution is the automation of decision-making and problem-solving processes. Many authors support that the fifth industrial revolution is already underway, focusing on blending the adaptable capabilities of Cyber–Physical Production Systems with human intelligence to create synergetic factories that support personalised and autonomous manufacturing [29].

Digital twins have gained significant popularity, easily discernible by the substantial number of publications and practical use cases documented in the literature. The authors in [30] perform a bibliometric analysis on the one hundred most cited articles within the realm of digital twins for smart manufacturing, aiming to identify key research directions, limitations, and challenges in the examined field. Digital twins applications span across numerous fields, including manufacturing, aviation, energy, smart cities, industry, telecommunications, construction, healthcare, automotive, asset management, lifecycle management, traffic management, project management, education, and the study of human behaviour and environmental interaction; [31] provides a survey of digital twins applications across 13 distinct industrial sectors, while [32] explores relevant literature through a scientometric approach. The state-of-the-art of the field, which encompasses fundamental concepts and components, current advancements, significant industrial applications, and potential promising areas, are detailed in [33]. In [34] authors present a comprehensive review of the historical background, alternative definitions and models, along with six categories of critical enabling technologies. Additionally, [35] examines the role of digital twins in enhancing the design of smart manufacturing systems.

2.2 Autonomous Vehicles

Autonomous vehicles as a concept has always been fascinating for researchers, and has gained significant popularity over the past decade. Such vehicles are equipped with multiple sensors that allow them to perceive their environment, evaluate conditions, and autonomously navigate to specific destinations without human intervention, all while adjusting to the ever-changing and unpredictable aspects of their surroundings. Focusing further on autonomy, like any robotic system, autonomous vehicles rely on the "sense-plan-act" paradigm. Utilizing a suite of sensors, these vehicles gather real-time environmental data [36]. The data are analysed and integrated, enabling the vehicle to understand its environment. Decisions are then made for the vehicle's operation. A typical configuration of an autonomous vehicle is outlined in [37] while Figure 2.1, visualises the three-step autonomy workflow described earlier.

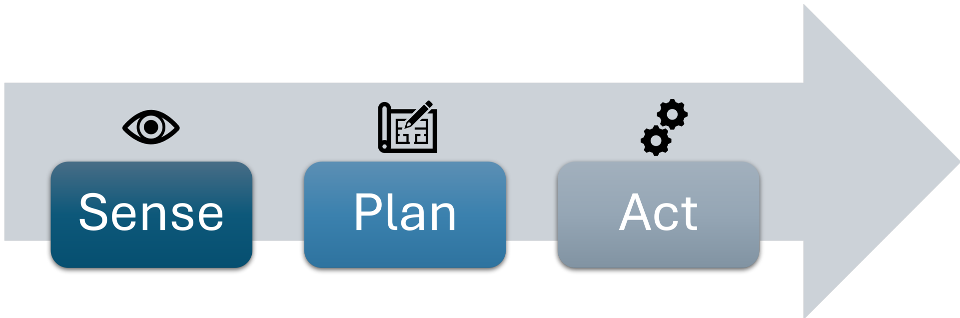

Figure 2.1: Simplified workflow of autonomy

The foundation of autonomous driving lies in sensing. Without knowledge of the vehicle's surroundings, reaching any destination becomes impossible. The precision and detail necessary for autonomous driving necessitates the deployment of various interdependent sensors. Sensors can be divided into two main categories: perception and localisation devices with both of them having a significant role in autonomous navigation. Perception sensors commonly used in autonomous vehicles include LiDARs, radars, ultrasonic sensors and cameras. A LiDAR sensor projects a laser beam at surfaces and calculates the reflection time to ascertain the distance between the vehicle and surrounding objects. Due to LiDAR's high precision, autonomous vehicles depend on it as a primary sensor for creating detailed maps, positioning themselves during movement (by referencing these maps), and identifying obstacles. Cameras are primarily employed for object recognition and tracking, such as identifying other vehicles, lanes, traffic signals, and pedestrians. To improve safety, current systems typically install multiple cameras around the vehicle to detect, identify, and track objects in every direction. Radars and ultrasonic sensors function mainly as a safety net in avoiding obstacles, providing information for objects in the vehicle's close vicinity. Localisation relies on GPS, IMU and odometers. The GPS/IMU combination provides global positioning estimates alongside high-frequency inertial updates, which are crucial for the vehicle's localisation. While GPS offers reasonably accurate positioning, its update rate is limited to 10 Hz, falling short of real-time needs. In contrast, IMU's accuracy declines over time, but can deliver updates at rates of 200 Hz or more, meeting real-time demands. Merging GPS and IMU offers both precise and timely localisation updates for the vehicle.

The planning stage involves interpreting data gathered from various sensors and then making decisions based on this information. Raw data streams do not inherently convey any meaning to a computer. To turn these outputs into meaningful information, algorithms, such as object recognition, object tracking, and path planning, are implemented. Object recognition and tracking enable the vehicle to identify its surroundings and track changes in position relative to those objects. The primary objective is to prevent collisions between the vehicle and any moving entity, whether it's another vehicle or a pedestrian. Path planning involves choosing a safe route to the destination, considering both expected events (like stop signs and traffic signals) and unexpected occurrences (such as pedestrians or road incidents). It is crucial that these processes operate continuously and in real time, which highlights the necessity for significant computational power in autonomous navigation systems [38].

Acting involves converting the previous stage into actual car movement. The central processing unit manages all key driving systems (steering wheel, throttle, brake). This is made feasible through drive-by-wire technology, where all vehicle operations are electronically controlled. The processing unit interacts with each system's local controller, delivering real-time instructions as a human driver would.

An explicit definition of what autonomy is would also be beneficial, since the term on its own can be quite vague, potentially causing confusion about the capabilities of vehicles that operate without human intervention. To address this issue, SAE International published the document *J3016: Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles* in 2014, with an update in 2021 [39]. SAE noted, *"This document provides a classification with comprehensive definitions for six levels of driving automation, ranging from no automation (Level 0) to full automation (Level 5).".* Although this categorisation primarily targets road vehicles, it also serves as a basic framework for various vehicle types, including aerial vehicles, as well as surface and underwater vessels. In essence, SAE's taxonomy delineates six specific levels of driving automation, beginning with Level 0, which involves no automation, up to Level 5, which is full automation. Each level illustrates a progression in the vehicle's automation capabilities. Presented below is a detailed explanation of SAE's taxonomy along with examples for easier comprehension, while Figure 2.2 presents the formal descriptions of SAE Autonomy Levels in a tabular format.

- Level 0: Constant human intervention is necessary. The automated system can issue alerts and make brief interventions, but it does not maintain continuous control of the vehicle.
- Level 1 ("hands on"): Vehicle control is shared between the driver and the automated system. For instance, Adaptive Cruise Control allows the driver to manage steering, while the system handles the speed; Parking Assistance automates steering, but leaves speed control to the driver. The driver must be ready to assume complete control at any moment.

- Level 2 ("hands off"): The automated system fully manages the vehicle's operations, including accelerating, braking, and steering. The driver must observe the driving and be able to take over immediately if the system fails. The term "hands off" should not be misinterpreted, as physical contact with the steering wheel is often required during SAE Level 2 automated driving to ensure the driver is prepared to take control.
- Level 3 ("eyes off"): The driver can safely divert attention from driving tasks. The vehicle can address scenarios needing immediate action, like emergency braking. The driver must still be ready to intervene within a manufacturer-specified time-frame, when the vehicle requests it.
- Level 4 ("mind off"): Similar to Level 3, but driver attention is never required, enabling the driver to sleep or vacate the driver's seat. Autonomous driving is supported only within designated areas (geo-fenced) or specific situations, like traffic congestion. If the vehicle exits these areas or conditions, it must be capable of aborting the trip safely, such as parking, without driver intervention.
- Level 5 ("steering wheel optional"): The system operates independently without the need for any human intervention at any point.

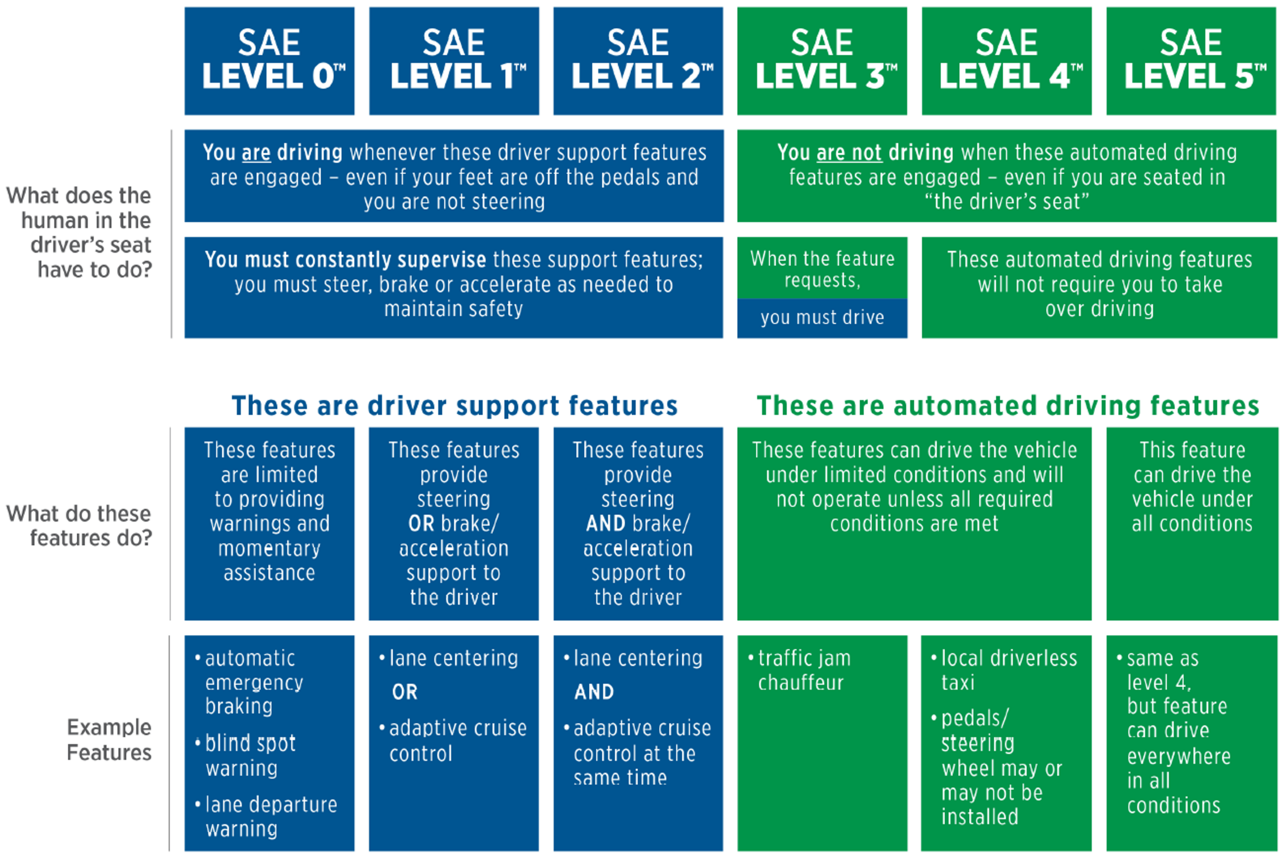

Figure 2.2: SAE Autonomy Level
Source: SAE International

Recent technological advancements have led to the application of autonomous vehicles across a wide area of sectors, as highlighted in [40]. Among the most prevalent applications are tasks, such as monitoring and surveillance, remote sensing, search and rescue missions, disaster response, agricultural work, and the examination of various unstructured environments. In addition, AVs have been employed as taxis and shuttles for human transportation and as delivery vehicles for tasks ranging from last-mile logistics to autonomous freight movement. Lately, there have been initiatives to equip heavy machinery with autonomous navigation capabilities for operation in hazardous settings. As outlined in [41], a comprehensive review covers the advancements, strategies, and challenges faced by autonomous vehicles, while [42] focuses on the evaluation criteria for the behavioural safety of vehicles in automated driving scenarios.

2.3 Digital Twins in Autonomous Vehicles

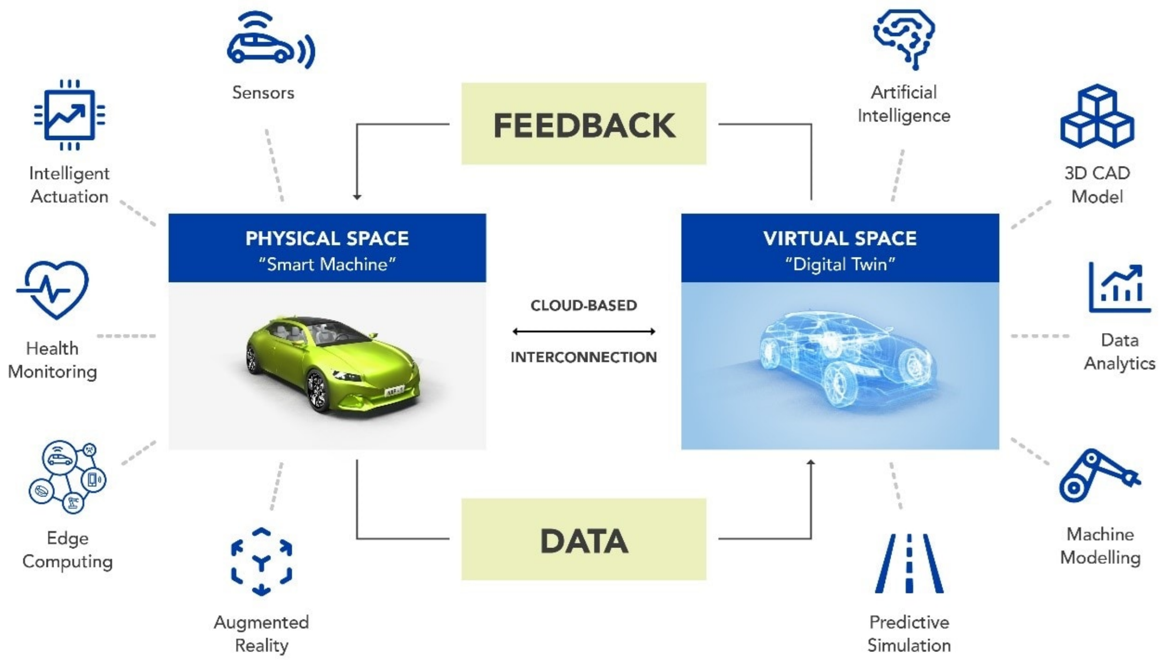

Figure 2.3: Ingredients and features of a vehicular digital twin
Source: NXP Semiconductors

Digital twin technology has emerged as a transformative force in autonomous vehicle development, creating virtual replicas that mirror real-world vehicle behaviour and environmental conditions. These sophisticated digital models enable unprecedented capabilities in testing, validation, and operational optimisation; revolutionizing how self-driving cars are developed, deployed, and maintained. Digital twins in autonomous vehicles create comprehensive virtual replicas of physical systems, encompassing the vehicle itself, its sensors, and the operational environment. Unlike traditional simulation tools, these dynamic models continuously receive real-time data from their physical counterparts through embedded sensors and IoT devices. The core components of autonomous vehicle digital twins include detailed vehicle models that replicate mechanical and electronic systems, simulations for perception sensors, and environment simulations that recreate real-world driving conditions including roads, traffic, weather, and pedestrians. This comprehensive approach creates a synchronised virtual environment, where every aspect of autonomous vehicle operation can be monitored and analysed.

By creating a virtual replica of an autonomous vehicle, developers can simulate and assess its behaviour across various scenarios and environments, aiding in the detection of potential issues and optimize its performance [43]. Specifically, for autonomous land vehicles, a digital twin can simulate the vehicle's operation under diverse traffic conditions, weather scenarios, and road configurations. This helps developers to fine-tune control algorithms, setup sensors and test decision-making processes [44]. Moreover, digital twins are capable of real-time performance monitoring of autonomous systems, enabling early problem identification, malfunction prediction, and performance improvements. Implementing digital twins in autonomous systems has the potential to enhance also their safety, reliability, and efficiency, promoting their widespread adoption in various fields [45]. In [46], the researchers conduct an extensive survey on the current state of development regarding ideas and concepts related to digital twins in the realm of the Internet of Vehicles. Various aspects of these applications (intra-vehicle and inter-vehicle) are explored, categorised per type and presented in the following chapters. Figure 2.3 visualises the ingredients and features of a vehicular digital twin, while most prevalent applications of digital twins in autonomous vehicles are visualised in Figure 2.4, before being explained in detail below.

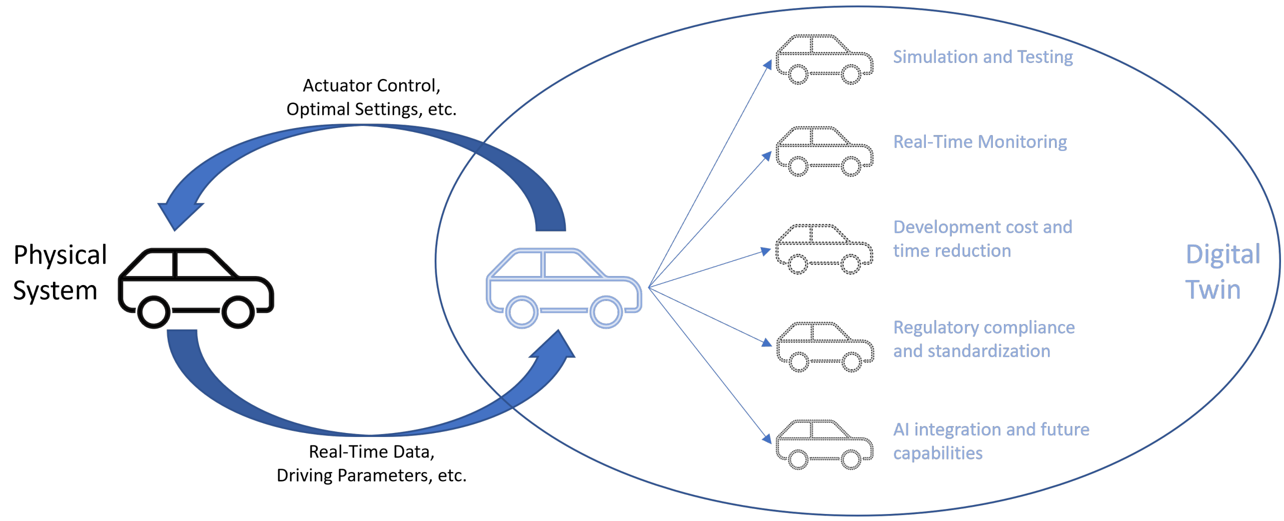

Figure 2.4: Digital Twin applications in Autonomous Vehicles

2.3.1 Simulation and Testing

Virtual Validation and Safety

Digital twins address one of the most significant challenges in autonomous vehicle development: comprehensive safety validation. Traditional testing methods face substantial limitations, requiring significant kilometres of test driving to validate autonomous systems. Digital twins provide a scalable alternative by enabling simulation of millions of driving scenarios, including rare edge cases that would be dangerous or impossible to recreate physically. These virtual environments allow developers to test autonomous systems across thousands of scenarios safely and efficiently, from extreme weather conditions to complex traffic situations. The ability to control every parameter — from road friction to lighting conditions — enables systematic evaluation of system behaviour under precisely defined conditions.

Sensor Simulation and Perception

Modern autonomous vehicles rely heavily on sensor fusion from multiple sources including cameras, LiDAR, radar, and ultrasonic sensors. Digital twins enable realistic simulation of these sensors with high fidelity, incorporating artifacts like false detections, clutter, and aliasing that occur in real-world conditions. This level of detail is crucial for trustworthy validation of perception systems. Advanced sensor simulation platforms now provide physically accurate sensor modelling that enables testing of multi-sensor configurations in Software-in-the-Loop (SiL) and Hardware-in-the-Loop (HiL) contexts. These capabilities ensure that ADAS and autonomous vehicle systems perform reliably under any operating condition.

2.3.2 Operational Improvements Through Real-Time Monitoring

Predictive Maintenance and Fleet Health

Digital twins excel in monitoring vehicle health and predicting maintenance needs before failures occur. By analysing real-time sensor data from engines, brakes, batteries, and other critical systems, these virtual models identify early signs of wear and potential failures. This predictive capability is particularly valuable for autonomous vehicle fleets, where unexpected breakdowns can be costly and disruptive. Fleet operators using digital twin technology report significant improvements in operational efficiency through reduced unplanned downtime, optimised maintenance scheduling, and extended vehicle lifecycles. The technology enables condition-based maintenance rather than relying on fixed schedules or reactive repairs.

Enhanced Fleet Management and Optimisation

Digital twins provide fleet managers with comprehensive, real-time visibility into vehicle operations. This includes monitoring fuel consumption, route optimisation, driver behaviour analysis, and vehicle utilisation patterns. The technology enables dynamic route adjustments based on traffic conditions, weather, and vehicle load, resulting in improved fuel efficiency and on-time performance.

2.3.3 Accelerating Development and Reducing Costs

Faster Development Cycles

Digital twins significantly reduce development time and costs by enabling virtual prototyping and testing. Engineers can iterate designs rapidly in the digital environment, identifying and resolving issues, before building physical prototypes. This approach is particularly valuable for autonomous vehicle development, where traditional testing is expensive and time-consuming. The technology enables continuous validation throughout the development lifecycle, with real-world data feeding back into digital models to improve accuracy and reliability. This creates a feedback loop that accelerates innovation, while maintaining safety standards.

Cost-Effective Safety Assurance

Virtual crash testing and safety validation through digital twins eliminate the need for numerous physical prototypes and destructive testing. Organisations can conduct comprehensive safety analysis, including System-Theoretic Process Analysis for systems, like Automatic Emergency Braking, within the digital environment.

2.3.4 Regulatory Compliance and Standardisation

Digital twins are becoming increasingly important for regulatory compliance, as global authorities recognize simulation-based testing for type approval. The technology provides the structured validation framework required by standards, such as the UN Economic Commission for Europe's New Assessment/Test Method framework. The ability to document and reproduce test conditions precisely makes digital twins valuable for demonstrating compliance with safety standards and regulations. This capability is essential, as autonomous vehicle regulations continue to evolve globally.

2.3.5 Advanced AI Integration and Future Capabilities

The integration of artificial intelligence and machine learning with digital twin technology opens new possibilities for autonomous vehicle development. Generative AI can create entirely new test scenarios beyond captured real-world data, preparing autonomous systems for unprecedented situations. AI-powered digital twins can perform metamorphic testing, systematically generating realistic driving scenes with variations in weather, road topology, and environmental features, while maintaining scenario semantics. This capability significantly enhances test coverage and effectiveness compared to traditional testing methods.

Leading automotive manufacturers are actively implementing digital twin technology across their operations. Digital twins are used to monitor vehicle performance and optimize features, like autopilot and full self-driving capabilities. A comprehensive digital twin platform has been created for accelerating autonomous vehicle development through integrated real-time data and high-fidelity simulations. The technology's impact extends beyond individual manufacturers to the broader mobility ecosystem. Digital twins support the development of connected and autonomous vehicle infrastructure, enabling simulation of vehicle-to-everything (V2X) communication and smart city integration. Digital twins represent a fundamental shift in autonomous vehicle development and operations, providing the comprehensive testing, validation, and monitoring capabilities necessary for safe deployment of self-driving technology. By creating accurate virtual replicas of vehicles and their operating environments, this technology addresses critical challenges including safety validation, cost-effective development, and regulatory compliance. As autonomous vehicle technology continues to advance, digital twins will become increasingly sophisticated, incorporating advanced AI capabilities and expanding integration with smart infrastructure systems. The technology's ability to bridge the gap between virtual simulation and real-world deployment makes it an indispensable tool for realizing the full potential of autonomous mobility, while maintaining the highest standards of safety and reliability.

2.4 Bibliometric Analysis

Section redrafted and updated from:

N. Sarantinoudis, G. Tsinarakis, L. Doitsidis, N. Tsourveloudis and G. Arampatzis, "Bibliometric Analysis on Applications of Digital Twins in Autonomous Vehicles," 2023 31st Mediterranean Conference on Control and Automation (MED), Limassol, Cyprus, 2023, pp. 95-100

While the fields of autonomous vehicles and digital twins are experiencing significant growth, integrating DT frameworks with autonomous vehicles can substantially enhance their operational effectiveness and efficiency. DTs are integral throughout the entire lifecycle of an autonomous vehicle, starting from the design and prototype stages to manufacturing [47], followed by testing, refinement, and performance optimisation, leading to system development [45], deployment, maintenance, and ultimately, end-of-life processes. In the automotive industry, DTs fulfil numerous diverse roles [48]. This bibliometric analysis seeks to explore these interconnected components.

Current research begins with a simple quantitative analysis of publications, sourced from Scopus database, containing either term "Autonomous Vehicles" or "Digital Twins", in order to understand the progression of the research in these two discrete domains, before looking into their correlations.

In Figure 2.5, the annual number of publications pertaining to the subject "Autonomous Vehicles" sourced from Scopus is illustrated. This bar chart highlights a remarkable surge, particularly from 2015 onwards, with publications increasing from 2,752 in 2015 to 15,504 in 2024. In 2025, for the first 5 months of the year, already 7,949 documents have been published, thus the trend clearly indicates that even more manuscripts relevant to autonomous driving will be published in 2025. It is important to clarify that the term Autonomous Vehicles in this analysis encompasses ground, aerial, maritime surface and underwater vehicles.

In Figure 2.6, the annual publication trend for articles categorised under the "Digital Twins"

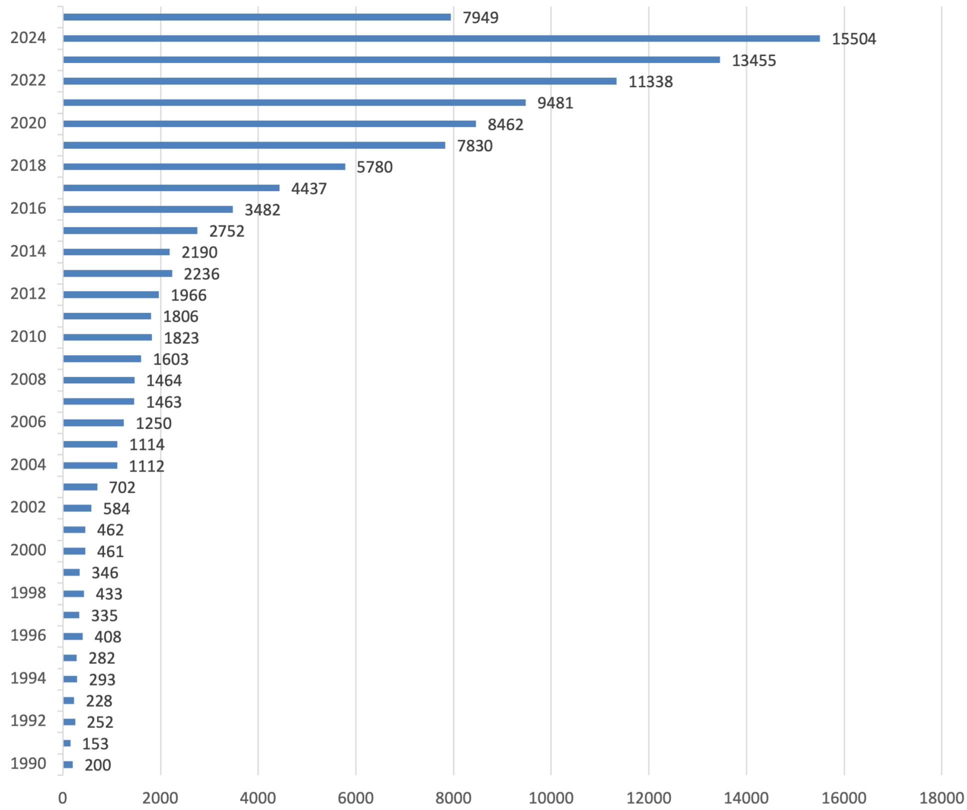

Figure 2.5: Trend analysis in number of publications per year on articles regarding autonomous vehicles (as of May 2025)

topic from Scopus is illustrated. This bar chart demonstrates a significant rise in the number of manuscripts related to Digital Twins, particularly post-2019 (1,161 publications) through to 2024 (10,301 publications). Recent advancements in the Internet of Things, Cyber-Physical Systems, Industry 4.0, Big Data analytics, and hardware have facilitated the implementation of the digital twin paradigm across numerous domains and for various applications; this trend elucidates the heightened interest exhibited by the research community towards digital twins; which is clearly continuing with 5,801 manuscripts published already in the first five months of 2025.

Despite the numerous bibliometric analyses conducted on digital twins, such as [49], and on autonomous vehicles, as noted in [50], a comprehensive study integrating these two domains has not been extensively explored. This can be attributed to the relatively constrained application of digital twins technology within autonomous vehicles, which has only recently become feasible due to significant advancements in their enablers.

A bibliometric analysis comprises both quantitative and qualitative assessments of research activities and scientific advancements. The increasing necessity for evaluation of research outcomes at personal, institutional, and regional scales has boosted the significance of bibliometrics recently [51]. This kind of analysis is essential for pinpointing emerging trends, collaboration networks, research voids, and significant research components, as well as for investigating the intellectual framework within a particular academic domain [52].

Figure 2.7 illustrates the core steps in the search strategy employed in this study to retrieve relevant

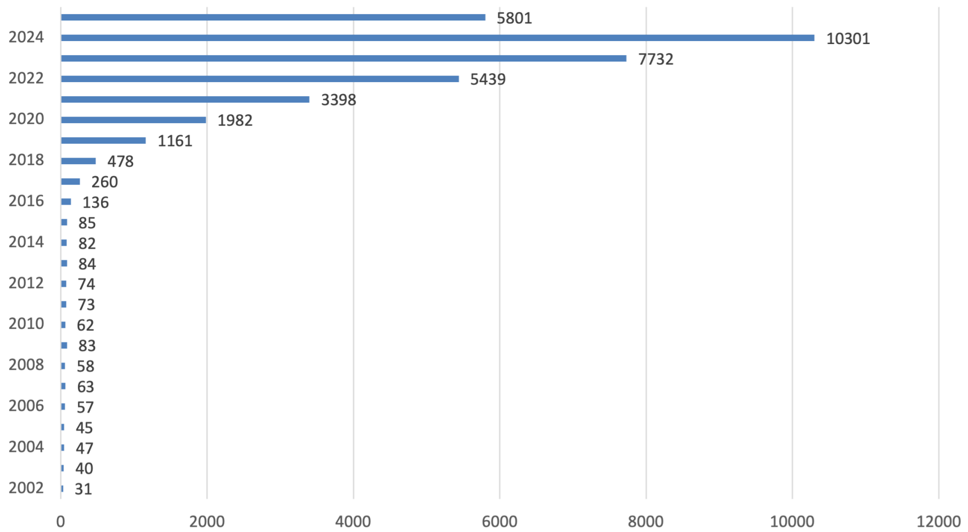

Figure 2.6: Trend analysis in number of publications per year on articles regarding digital twins (as of May 2025

articles from scholarly databases. Initially, the subject and scope of the investigation are defined, followed by establishing criteria such as the study's time-frame. Subsequently, both primary and alternative search queries are formulated, and articles undergo an evaluation process, where duplicates and irrelevant entries, i.e. conference and workshop proceedings or erroneous listed manuscripts are removed to improve precision. The resulting bibliographic data is downloaded in CSV format from Scopus to perform analyses on trends, citations, and co-occurrences. VOSviewer software [53] is then used to extract research terms, their co-occurrence patterns and create the bibliometric maps presented below.

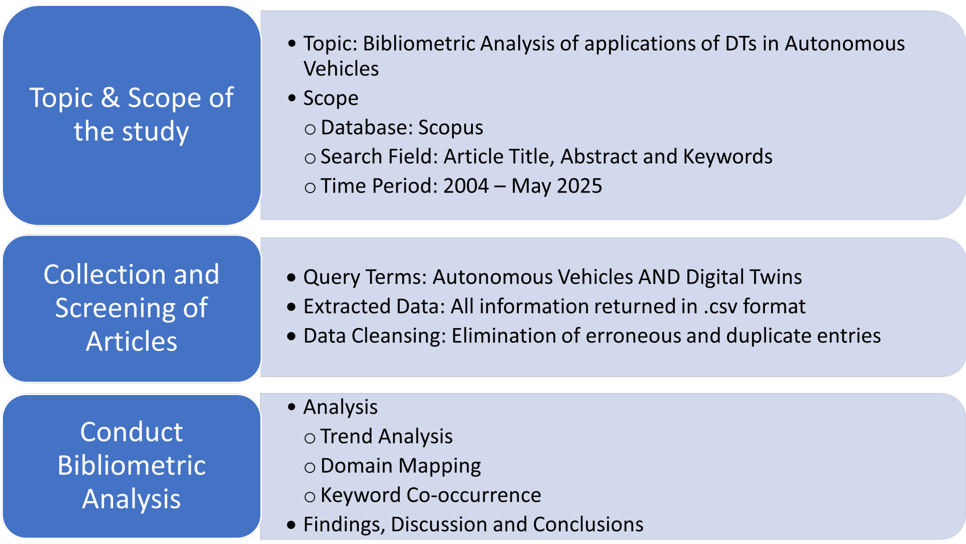

Figure 2.7: Structure of the followed bibliometric approach

This bibliometric analysis is driven by the need to reveal and describe the link between autonomous vehicles and digital twins, to emphasize the growing interest in applying the DT paradigm in the autonomous vehicle sector, and to uncover emerging trends alongside potential research paths and future advancements in this niche area. Simultaneously, it aims to provide a thorough overview

Table 2.1: Number of occurrences on various citation databases for selected search queries

Database	Search Query	Publications
Scopus	Autonomous Vehicles AND Digital Twins	710
Scopus	Autonomous OR Automated Vehicles AND Digital Twins	941
Scopus	Autonomous OR Intelligent Vehicles AND Digital Twins	1197
Web of Science	Autonomous Vehicles AND Digital Twins	332
Google Scholar	Autonomous Vehicles AND Digital Twins	42.300

and serve as an analytical tool for practitioners, researchers, and all stakeholders in the field. In particular, by conducting this bibliometric analysis, the aim was to explore and answer the following five research questions:

RQ1: Which are the emerging trends in the application of DTs in the domain of AVs?

RQ2: Which are the most popular research fields regarding DTs and AVs?

RQ3: How many times each manuscript is cited and which are the most cited ones?

RQ4: Which are the most popular terms regarding DTs and AVs?

RQ5: In which publication category do the results belong and how are they distributed?

In the current research, key scholarly databases for article collection have been tested such as Scopus [54], Web of Science [55], and Google Scholar [56]. Within Scopus, three variants of the main search query ("Autonomous Vehicles AND Digital Twins") to map the domain comprehensively have been investigated. As the results from these searches were similar, only the data from the primary search query were considered for analysis. For comparison's sake, the same primary search term was applied in the Web of Science, producing minimal results, and in Google Scholar, which resulted in a substantial number of publications. Due to the wide variance in these outcomes—either too few or too many—it was decided to use Scopus as the primary data source for this study. As noted in [57], Scopus contains over 90 million core records from renowned publishers (like Springer Nature, Wiley Blackwell, Taylor and Francis, IEEE, Elsevier, etc.) dating from 1970, with regular updates. Table 2.1 presents the results from searches conducted within Scopus and the other mentioned databases, providing a quantitative summary of earlier discussions and a visualisation of the fluctuation among the various database.

Based on outlined methodology for gathering data, the dataset eventually analysed comprises of 710 publications, as shown in Table 2.1. This number is relatively modest in comparison to that of digital twins and autonomous vehicles stand-alone domains, however integrating DT concepts into autonomous vehicles is a rather new idea, with significant complexity, and the essential software and hardware have become available only recently. Nonetheless, it is important to consider Rogers *et al.* [58], who in their study on institutional research assessment, state that *"A dataset of 50, or even 100 records, yields results with limited chances of accurately discerning and distinguishing true values, and only when the dataset attains 200 entries does a noticeable differentiation begin to manifest"*. Thus, even though small in comparison to the individual domain of autonomous vehicle and digital twins, is more than adequate to extract pivotal information.

According to that, an attempt to answer the first research question is presented in Figure 2.8, by visualising the number of articles per year dealing with both digital twins and autonomous vehicles. The period under study has been defined with respect to the presented trend analysis of DTs term (as autonomous vehicles have become popular much earlier than DTs) and ranges from 2004 until May 2025; with the start date being defined from the formal introduction of digital twins from Grieves. According to Figure 2.8, the number of papers began to gradually increase lately. As expected, after 2019, the annual number of DT and autonomous vehicles related papers increased rapidly (more than 50% per year), reaching a peak of 236 articles published in 2024 and with an increasing trend for 2025; since already in 5 months there have been 103 published manuscripts.

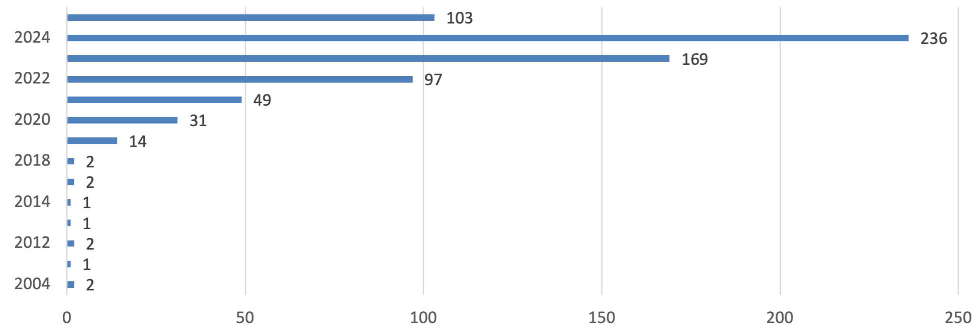

Figure 2.8: Trend analysis in no. of publications per year on articles regarding combination of autonomous vehicles and digital twins (as of May 2025)

The analysis of manuscript categories exported from Scopus database is presented in the pie chart visualised in Figure 2.9 and is addressing the second research question. All manuscript categories with less than 30 occurrences have been accumulated into *Other* subject area. In the pie chart, three dominant subject areas with shares over 10% and in particular *Engineering* with 31%, *Computer Science* with 30 % and *Mathematics* with 11% are identified. The emerging results are in line with what was expected, as computer science, engineering and mathematics constitute primary scientific fields of the application of DTs in autonomous vehicles. Also it's worth mentioning the appearance of decision sciences, materials, energy and environmental science related terms in the results of documents' category analysis.

Citation analysis serves as a tool to evaluate the impact and quality of a manuscript by counting its citations from other works. This process employs mathematical, statistical, comparative, inductive, abstract, general, and logical methods to examine a wide range of scientific journals, papers, citation subjects, and cited phenomena, aiming to unveil the attributes of quantitative methods and the

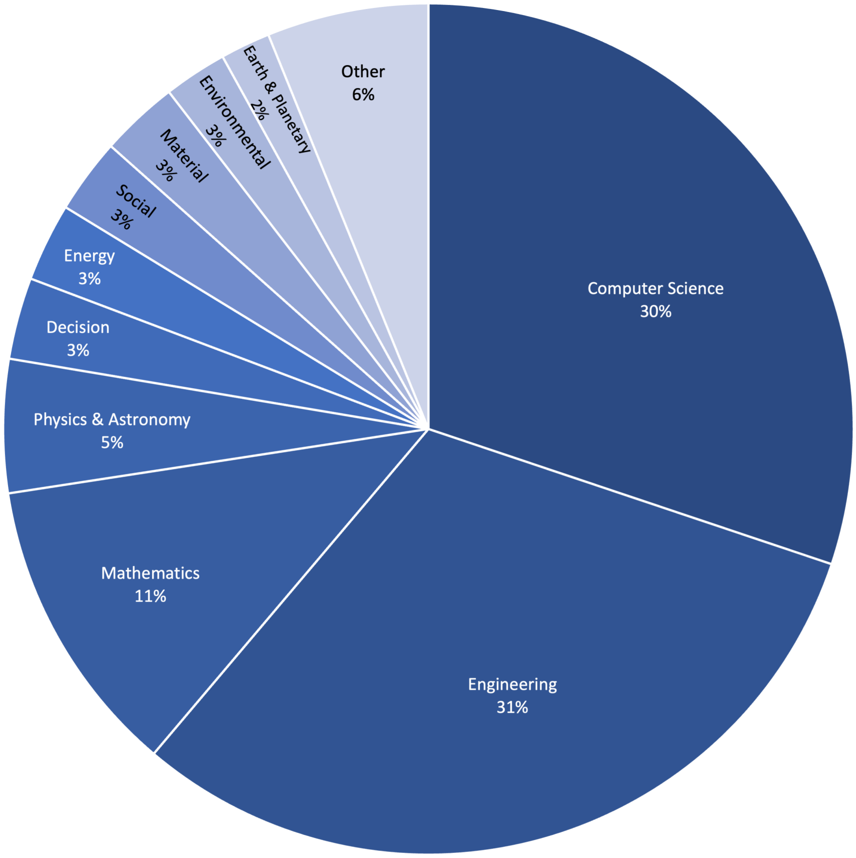

Figure 2.9: Documents distribution according to subject area

intrinsic principles of bibliometric analysis methods [59]. Key citation analysis types include examining citation counts, exploring citation relationships, and developing bibliometric maps for organizing knowledge. While further analysis could delve into publication citation patterns, this involves a complex procedure due to substantial variability across different paper types and research fields. The approach focuses on categorizing publications based on the citation counts they have amassed and on constructing a bibliometric map.

Despite the fact that most manuscripts included in this bibliometric review have been published within the last 5 years, a number of them have already received a significant amount of citations, indicating their substantial impact on the respective field. Table 2.2, which addresses the third research question, categorises these documents based on their citation counts. Three documents have been referenced 201 times or more, six have garnered up to 200 citations, while 17 have been cited as many as 100 times, and 41 up to 50 times. A significant amount of the entries (163) have citation counts ranging from 6 to 25, whereas the majority of the publications (471) have been cited 5 times or less.

The 5 most influential documents are [4], a journal article published on May 2021 cited 392 times, [60], an IEEE conference paper presented on September 2020 cited 305 times, [61] a journal paper published in February 2023 cited 295 times, [62], a journal publication from January 2020 cited 139 times and [63] a journal publication from September 2020 cited 131 times. Even though these publications are relatively new, they have been already cited a considerable amount of times,

Table 2.2: Number of citations per document

Citations per document	No. of Documents
201 and more	3
101 - 200	6
51 - 100	17
26 - 50	41
6 - 25	163
0 - 5	471

ascertaining the research interest on the domain.

Co-occurrence analysis is a method used to identify and examine how often two or more items — such as words, events, or features — appear together within a specific context. It helps reveal patterns, relationships, or associations between elements and is employed in this work in order to analyse keywords relevance and to visualize the results in a comprehensive manner. In order to perform the co-occurrence analysis, VosViewer, a tool for constructing and visualizing bibliometric networks [53] allowing three types of visualisation (network visualisation, overlay, and density visualisation) has been used.

The manuscript-related data were clustered using network visualisation, employing keyword co-occurrence. Each keyword is depicted as a point on a bibliometric graph in two dimensions. Colour-coding highlights the similarity among studies, while node size reflects occurrence frequency. Co-occurring keywords are connected by arcs, where arc width corresponds to co-occurrence strength, and the space between nodes indicates term dissimilarity.

A minimum number of 20 occurrences of a keyword was set as threshold in order to reduce map's complexity and extract meaningful results. This resulted in 41 terms remaining from the 5341 initially identified. In addition, through carefully studying these terms, the ones are both present in singular and plural form have been merged. Thus, the final list consisted of 37 terms. The map, depicted in Figure 2.10, is composed of 641 links with 3138 total link strength organised in four colour coded clusters. Cluster 1, which is the most populated, is represented with red and consists of 13 terms, Cluster 2 is green and is made up of 10 terms, Cluster 3 is blue and contains 8 terms and Cluster 4, shown in yellow, consists of 6 terms and it is the least populated.

Table 2.3 summarises the distribution of the 37 terms in the 4 clusters described above and answers the fourth research question. In addition, it presents the ten most common keywords in bold text with the number of occurrences following in the parenthesis. From this table, it can be deducted that Cluster 1 mainly consists of articles related to DTs application domains, Cluster 2 exhibits methodologies used for communication, Cluster 3 has terms focusing on machine learning and artificial intelligence techniques and finally Cluster 4 points out vehicle types.

To address the fifth research question, Table 2.4 provides an analysis of the frequency of occurrences by publication type. Conference papers lead in popularity, accounting for 384 out of the 710 total

Table 2.3: Clustering of the co-occurring keywords

Cluster 1 (Red)	**Cluster 2 (Green)**	**Cluster 3 (Blue)**	**Cluster 4 (Yellow)**
Autonomous Driving (118)	5G Mobile Communication Systems	**Deep Learning (46)**	Aerial Vehicle
Autonomous Vehicle(s) (307)	Artificial Intelligence	Deep Reinforcement Learning	**Antennas (43)**
Digital Twin(s) (332)	Decision Making	**E-Learning (46)**	Drones
Intelligent Systems	Digital Storage	Learning Systems	Motion Planning
Intelligent Transportation Systems	Edge Computing	Performance	Real-Time
Intelligent Vehicle Highway Systems	Embedded Systems	Real-World	**Unmanned Aerial Vehicle(s) (82)**
Magnetic Levitation Vehicles	**Internet of Things (40)**	**Reinforcement Learning (49)**	-
Metaverse	Network Security	Unmanned Surface Vehicles	-
Motor Transportation	Real Time Systems	-	-
Roads and Streets	V2V Communications	-	-
Simulation	-	-	-
Vehicles	-	-	-
Virtual Reality (59)	-	-	-

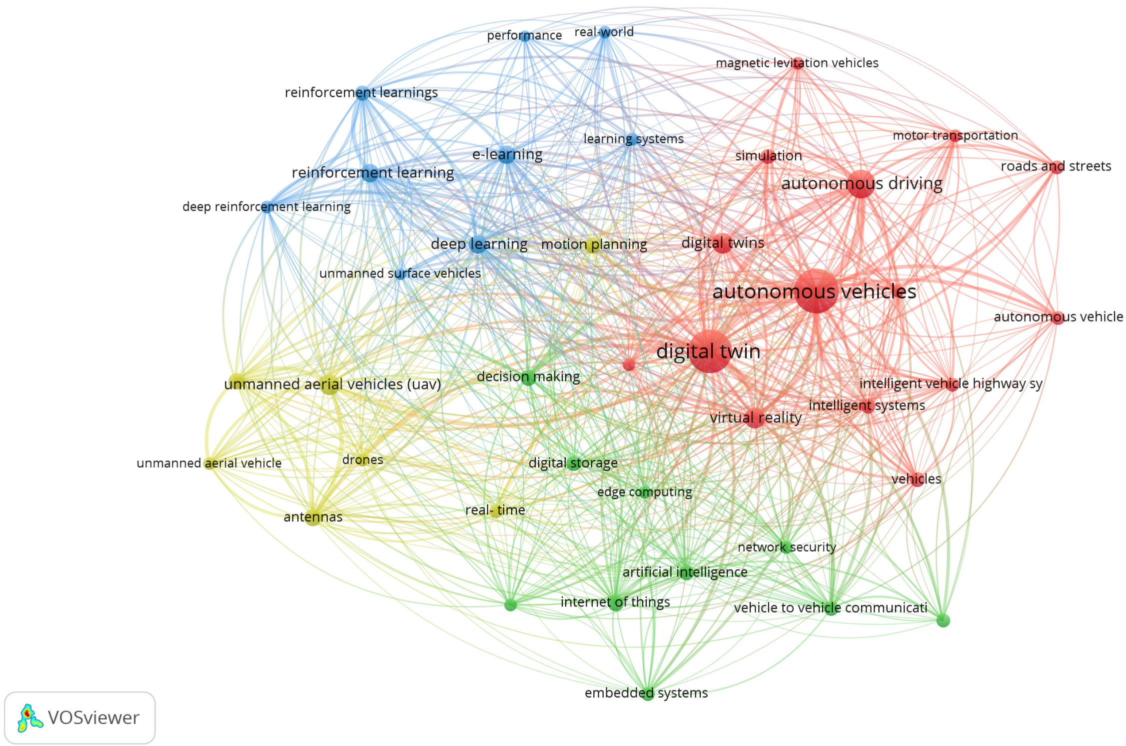

Figure 2.10: Keyword co-occurrence map in autonomous vehicles and DTs

Table 2.4: Numbers of manuscripts per publication category

Publication Type	No. of Publications
Conference Papers	315
Conference Reviews	69
Journal Articles	274
Journal Reviews	25
Book Chapters	23
Books	4

publications, with 69 being conference reviews and 315 being conference contributions. Moreover, journal publications add up to 299, consisting of 25 review/survey papers and 274 standard journal articles. Lastly, up until May 2025, 23 book chapters and 4 full books have been published on this subject.

With legislation getting stricter in autonomous vehicle, testing and scepticism around autonomous machines rising rapidly, DTs might come in fashion as a development, test, monitoring, performance and behaviour optimisation platform of general use under different conditions.

Bibliometric analysis insights from this publication can help stakeholders identify gaps, limitations, technologies, trends, and opportunities, paving the way for the integration of new methods, techniques, and tools that advance the field. Future extensions should explore various geographic, institutional, chronological, technological, and efficiency factors (using alternative metrics like the h-index), as well as domain-specific aspects of the publications. Additionally, co-citation analysis of the manuscript dataset and examination of potential citation patterns could yield valuable insights, conclusions, and recommendations for experts. Given that the field is relatively new, with most publications dating from 2020 onward and an annual publication growth rate of 50%, regular updates of the analysis are crucial.

The bibliometric analysis performed provides insights into the current state of research, trends and impact in the applications of DTs in autonomous vehicles. Motivation for the accomplishment of the current study has been the increased interest on the specific research domain that has grown rapidly in recent years mainly due to the latest advances regarding IoT and Industry 4.0.

2.5 DTs in Land Vehicles

Autonomous land vehicles can be of numerous types such as cars, trucks, buses, automated guided vehicles or autonomous mobile robots and can serve diverse roles such as personal transportation, ride-hailing (robotaxis), freight, logistics and last-mile delivery, industrial and mining vehicles and agriculture [64, 65]. Regardless of the type though, they all share the same basic operating principles and they all can equally benefit from the application of digital twins to enable real-time monitoring and diagnostics, enhanced safety and reliability, accelerated testing and validation, predictive maintenance, simulation and optimisation and cybersecurity [66, 67].

Thus, an analytical survey was performed to identify the aforementioned and shed some light in the domain. In order to carry out this review, a well-defined methodology consisting of four steps has been followed. Initially, the definition of the research scope and the research questions to be answered took place. The second step is to identify and obtain the required literature to perform this review. The main idea is to start broad enough in order not to exclude any potentially useful articles and narrow the dataset of publications to keep only the ones related to the topic under study. The most important step for a successful review, is the third step, which contains the critical analysis of the final dataset through a meticulous study of the publications and the creation of a summary of key points and results of each publication. Work performed in this step will allow for the discovery of relationships and interconnections among the work of various researchers and would be the foundation that helps answering the research questions formulated in the first step. Finally, the last step is to organize and categorize all these interconnections identified into meaningful results in order to be used not only under this research but also from other researchers.

As stated, the definition of the research questions is of imperative importance in order to pinpoint and guide the survey. Thus, through this literature review, an attempt to answer the following research question would take place:

RQ1: Do Digital Twins technology applied in autonomous land vehicles ?

RQ2: Which are the main applications of DTs in land vehicles ?

RQ3: Are there certain types of vehicles DTs being applied to ?

RQ4: Are there specific tools and technologies being used ?

Following the research questions, the required literature needs to be gathered and critically evaluated in order to have as accurate results as possible. The dataset was obtained on the 28th of May 2025 from Scopus citation and abstract database by querying the terms "Autonomous Vehicles" and "Digital Twins". These terms have been broad in purpose to contain as much relevant manuscripts as possible. The initial results consisted of 710 files which contained conference and journal publications, book chapters, conference proceedings and any document on the database that met the broad search criteria. Since DTs have gained popularity in the last five years, initially the record set was limited to manuscripts published from 2020 onwards, reducing their number to 663. Afterwards, the conference proceedings, erratum and workshop proceedings included in the query results were removed, eliminating 66 documents and reducing the total to 597. The most important part of the dataset analysis is the study of titles and abstracts. Through careful study of the abstracts, manuscripts not referring to applications of digital twins in autonomous vehicles have been identified and removed; they mighty simply refer to the terms in the introduction/future work/conclusion or they might create a DT of a city or building in order to test autonomous navigation algorithms. In this step 321 manuscripts have been removed. The remaining 276 documents are also screened for availability and language since lately publications written in other languages but having the title and abstract in English are met more and more often in the literature. Thus the final set consists of 249 publications. From those, 144 or 58% are referring to land vehicles, so these consist the final dataset to be used for the literature analysis related to DTs applications in land vehicles. These results allow to positively answer the first research question; querying if digital twins technology can indeed be used in land vehicles applications.

Through the aforementioned study of all manuscripts, important information for the literature review have risen, presented in Appendix A. This table consists of four columns; the first indicates the reference number of the work under study, the second briefly describes the work undertaken in each referenced manuscript, the third discusses identified tools or technologies used and the fourth the type of vehicle each solutions is focusing/tested upon. It must be noted here that in cases where a Tool/Technology was not clearly identified the notation N/A has been used while for the vehicle type the term "Vehicle Agnostic" is used; in this case either it was mentioned that it can be applied to various types of vehicles or it could be derived that this can occur. Many of the solutions discussed are referring in general to autonomous land vehicles and are dependent to sensors and data sources used and not vehicles themselves, thus the term agnostic was selected.

In order to understand the domain, better summarize it and retrieve useful outcomes and not only a seven-page long table representation, the key advances that the concept of DTs can offer to land vehicles were identified. The main applications of digital twins in autonomous land vehicles are summarised below. The preceding comprehensive analysis of the relevant literature resulted in the following identified categories which are in purpose generic since they would be used (with appropriate adjustments) also for the air and surface/underwater vehicles analysis in order to be easier to compare the results across the different types of autonomous vehicles that will be studied under this chapter.

- **Components / Maintenance**

  Digital Twins play a crucial role in the effective management and upkeep of autonomous vehicle components by acting as virtual counterparts that replicate the actual state and functioning of the vehicle throughout its lifecycle. These digital models offer detailed simulations of essential vehicle components like the powertrain, propulsion system, batteries, suspension, and braking systems, enhanced by real-time data from various onboard sensors such as LiDAR, radar, cameras, GPS, and IMU. This constant, two-way data flow enables DTs to transform maintenance practices by facilitating predictive maintenance and proactive health monitoring. Through the application of AI and Machine Learning on the gathered data, DTs can forecast potential breakdowns, identify issues, and determine the remaining service life of components, which results in reduced downtime, cost savings, and prolonged operational lifespan of AVs. This method ensures improved safety, reliability, and efficiency of autonomous driving systems through condition-based maintenance and remote inspections.

- **Solutions / Frameworks**

  Digital twins offer sophisticated solutions and frameworks for autonomous vehicles by merging real-time data, simulation models, and AI algorithms into an integrated virtual space. They allow for new smart sharing models, software defined vehicles, establishment of the Internet of Vehicles even new ways of delivering driving lessons. These frameworks allow for continuous learning by putting real-world data back into the digital counterpart, thereby enhancing algorithmic efficiency over time. Additionally, they enable over-the-air updates, cybersecurity assessments, and compliance verification, creating a scalable, comprehensive platform for the development and deployment of autonomous vehicles. These solutions are mostly new and emerging applications of Digital Twins in land vehicles, thus this category has a significant importance for the research community.

- **Simulator / Testing**

  Digital twins improve the simulation and testing processes for autonomous vehicles by generating detailed virtual models that accurately mimic the vehicle and its surroundings. These virtual representations enable developers to run simulations of numerous driving scenarios, including uncommon or hazardous situations, for diverse applications such as farming or for larger infrastructure such as cities, utilizing real-life miniatures. Addressing simulation and testing through digital twins can expedite validation, lower development expenses and enhance safety and reliability of autonomous driving systems prior to their deployment in the real world. Integration of new technologies such as Hardware/Software in the Loop testing and generative-AI are gaining momentum too. An integral benefit of DTs lies in their capacity to close the gap between simulation and reality, known as the "sim2real" gap. This is accomplished by developing high-fidelity simulations that closely replicate real-world conditions and by enabling continuous updates and enhancements of algorithms through real-time data feedback from the physical system to its virtual model. This process guarantees that control algorithms and decision-making frameworks undergo comprehensive validation prior to actual deployment, thus speeding up development and reinforcing confidence in autonomous technologies.

- **Control / Navigation**

  Digital Twins are essential in order to advance autonomous vehicle control and navigation, as they create high-precision virtual models that interact dynamically with their real-world counterparts. In terms of navigation, DTs play a critical role by ensuring accurate localisation and mapping, allowing AVs to comprehend their location and environment by merging data from sensors like LiDAR, radar, cameras, and GNSS/IMU into a global coordinate framework. They facilitate dynamic path planning and trajectory tracking through the simulation of complex scenarios, route optimisation, and offering real-time feedback for accurate steering and speed control. Regarding control, DTs empower autonomous decision-making by processing extensive sensor data and transferring complex computations to cloud or MEC servers, thus relieving the vehicle's constrained onboard processing. They enhance cooperative driving and platooning by enabling AVs to share real-time data and information with other vehicles and infrastructure, broadening perception capabilities and delivering insights about global traffic conditions. DTs are vital for testing control algorithms in a virtual setting before their physical implementation, which reduces the costs and risks associated with real-world experiments. This holistic approach significantly improves safety and efficiency in autonomous driving.

- **Safety and Security**

  Digital Twins play a crucial role in improving the safety and security of autonomous vehicles by acting as digital counterparts for thorough testing, predictive analysis, and ongoing monitoring. These virtual replicas mimic the physical vehicle and its environment, allowing for detailed, repeatable, and secure simulations of driving scenarios, particularly those that are extreme, dangerous, or expensive to reproduce in reality. This functionality assists in foreseeing potential accidents and other hazardous situations, enabling preventive measures that enhance road safety overall. The continuous, real-time synchronisation of data collected from various sensors (such as LiDAR, radar, cameras, and GPS) and external sources like RSUs is essential for ensuring that the digital twin accurately reflects the current state of the vehicle and its surroundings. Additionally, DTs are vital for cybersecurity and

Table 2.5: Categorisation of publications under study

#	Category Name	Ref	Count
1	Reviews	[4, 13, 44, 46, 68–87]	24
2	Components / Maintenance	[6, 88–97]	11
3	Solutions / Frameworks	[98–110]	13
4	Simulation / Testing	[15, 43, 111–140]	32
5	Control / Navigation	[67, 141–162]	23
6	Safety and Security	[7, 8, 137, 163–184]	25
7	Communication / Edge Computing	[185–197]	16

privacy by implementing features like data encryption and strong authentication protocols to safeguard sensitive data transmitted over open networks, thereby reducing the risk of malicious activities such as data manipulation or theft. This comprehensive strategy for safety and security aims to speed up development timelines, cut costs, and build confidence in autonomous technologies before they are widely adopted.

- **Communication and Edge Computing**

  Digital Twins are critical in advancing communication and edge computing for autonomous vehicles by creating digital counterparts of the vehicles and their surroundings. This system depends on a strong communication network for real-time, two-way data transfer between the physical and digital realms. Intra-twin communication allows for a continuous flow of data from the vehicle to its digital twin, typically hosted on cloud or MEC platforms, thus reducing the vehicle's computational burden by offloading intensive tasks. Moreover, inter-twin communication promotes data exchange and AI learning among cloud-based digital twins, thus enhancing the perception capabilities of autonomous vehicles and delivering detailed traffic insights. Cutting-edge communication technologies like 5G, and soon 6G, are essential for meeting the demands of low latency and high data throughput, while RSUs serve as key points for data gathering and preliminary edge processing.

Apart from the aforementioned categories, an equally important category which is crucial for the literature review is the reviews/surveys. They might not present a specific key advantage or application of digital twins in land vehicles, but they are very informative and summarize work that lays the foundations of the domain. A significant part, i.e. 24 manuscripts (roughly 16.5%) of the dataset consists of review and survey publications, showcasing the importance of the literature analysis which is also performed as part of the author's doctoral studies.

Overall, seven categories of main applications and key advances of digital twins in autonomous land vehicles were pinpointed. One can clearly identify the diversity of applications by studying the Table 2.5 where the publications per category and their count is reflected.

The number of publications is distributed among all categories with Components and Maintenance containing 11 manuscripts (~7.5%), Solutions and Frameworks having 13 documents (~9%), Simulation and Testing with 32 documents (~22%), Control and Navigation with 23 manuscripts (~16%), Safety and Security containing 25 entries (~17%) and Communication / Edge Computing having 16 documents (~11%). In order to easier visualize this spread of the relevant work among the key applications identified, the author visualised them in a pie chart, which can be seen in Figure 2.11. The aforementioned analysis makes it easier to answer the second research question.

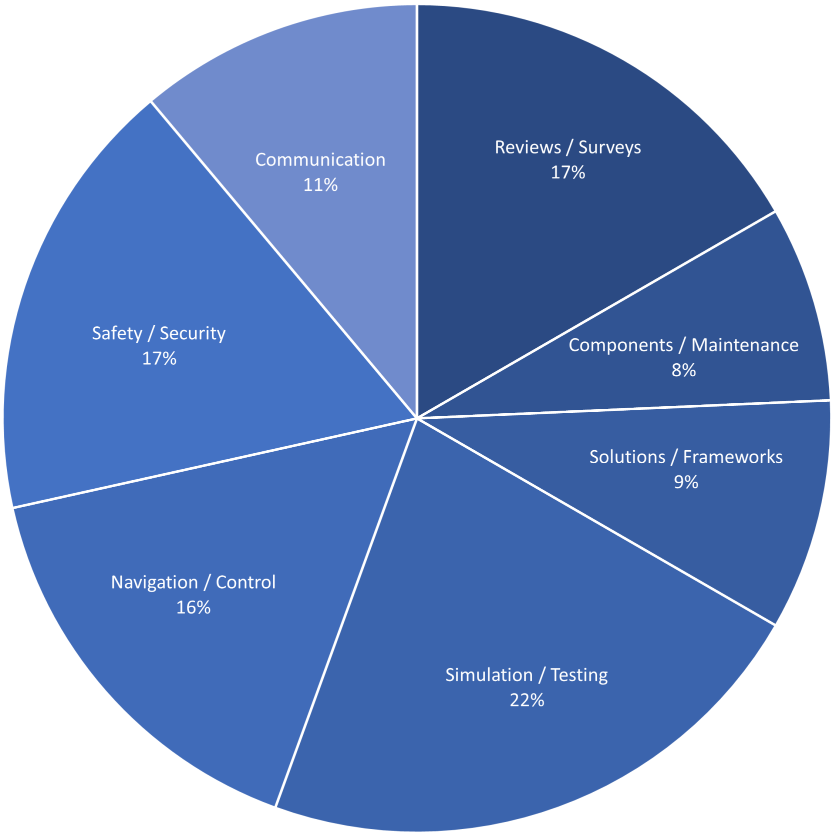

Figure 2.11: Number (#) and percentage of publications per category.

Through this literature review what could be also easily identified is that in most cases the application is vehicle agnostic, i.e. the type of land vehicle does not specifically affect the way the proposed research is going to be applied. This acts as an enabler for the research community which can easily integrate the different proposed novel technologies to diverse types of land vehicles and advance the domain even further. However, it acts as a limitation also and creates a gap between theory and practice because technologies that are vehicle agnostic are difficult to be tested in any type of physical systems without a lot of tweaking and integration procedures. This conclusion, not only answers the third research question, but also raises another more significant one that will be answered by this research; how can digital twins be actually applied in autonomous vehicles bridging theory and practice.

Last but not least, it is apparent also that different and diverse tools and technologies are being used in the domain and one cannot say that a certain simulator or Machine Learning technique is ideal for the application of digital twins technologies in autonomous vehicles. Each application employs the most relevant tool/technology for the intended result. This can also be affected by the expertise of the researcher, the trends at the time of the research, previous work of other researchers and numerous other factors. As a domain currently under development, this result is not unexpected; this diversity will help identify the best and eliminate the worst tools and techniques in order to ease and further advance the domain. Consequently, the fourth research question is also answered.

In conclusion, this brief literature review sheds some light on the domain and the applications of digital twins in land vehicles, answering some critical research questions and summarizing the manuscripts identified in a comprehensive format. This research not only acts as a stepping stone for this doctoral research but also helps identify a domain gap that this work tries to address; how the theoretical knowledge and the simulated tests will be applied in real life and on physical vehicles.

2.6 DTs in Air Vehicles

Section redrafted from:
N. Sarantinoudis, N. Vitzilaios and G. Arampatzis, "Applications of Digital Twins in UAVs," 2024 International Conference on Unmanned Aircraft Systems (ICUAS), Chania - Crete, Greece, 2024, pp. 450-457

Unmanned Aerial Vehicles (also known as drones) have been extensively used in the last decade on an abundance of applications, like aerial photography, disaster management, wildlife monitoring, military applications, deliveries and many more [198]. The combination of UAVs with cutting edge technologies such as cloud computing, Internet of Things, artificial intelligence and blockchain, has fast-forwarded the development in the domain. An amalgamation of the well-established UAV domain with the concept of digital twins, utilizing the aforementioned technologies as enablers [1], [199], has provided a new perspective for researchers and guided the author's work into investigating the potential applications of this technology on drones too. In this section, the synergies between DTs and UAVs will be identified through a comprehensive analysis of the existing literature in order to understand how DTs can be utilised in UAV domain and what they can offer.

A four-step methodology has been followed to conduct this work. At a glance, the steps are a) definition of the research scope and research questions, b) identification and gathering of the required literature, c) critical analysis of the literature in question and d) organising and categorising outcomes into meaningful results for presentation. The research questions that have been identified in order to formulate the expected outcomes of this study are:

RQ1: Are Digital Twins being used in UAVs?

RQ2: Which are the applications of DTs in UAVs?

RQ3: Can DTs be applied in all types of UAVs?

RQ4: Are there any specific tools or technologies used?

As the main source of publications, Scopus abstract and citation database, maintained from Elsevier, containing more than 45 thousand academic sources has been used. The search on the database was performed by using two key terms; "Digital Twins" and "UAVs". This broad search query returned 254 documents, on a search performed on January 8^{th}, 2024. An integral part of a literature review is the pre-processing of the dataset; books of proceedings referring to a conference but not to a specific publication, duplicates, and publications not available in English, have been removed. Through screening of the abstracts of each publication, the documents that where not applying DTs in UAVs (but just mentioning both terms or using UAVs as a mean to create a DT) have also been removed leading to a final set of 73 manuscripts consisting of conference publications, journal publications and book chapters. The existence of 73 publications discussing the applications of Digital Twins in Unmanned Aerial Vehicles allows to positively answer **RQ1**. A full list of these publications is provided in Appendix B.

Studying the aforementioned final set, all these publications have been organised into categories based on the work described. This was an iterative process, that required meticulous study and understanding of the publications in order to categorize them appropriately. Eventually, eight categories have been created and enumerated from 1 to 8. The corresponding name is descriptive of the work included on each category. For example in Category #1 all the publications dealing with aspects such as predictive maintenance and monitoring of the structural integrity of UAVs have been included. In Table 2.6 all eight categories with their corresponding name and the publications belonging to each are presented. The work to categorize these results allows to identify the different applications of UAVs in DTs and answer **RQ2**.

Table 2.6: Categorisation of publications under study

#	**Category Name**	**Ref**	**Count**
1	Reviews	[200–202]	3
2	Maintenance / Structural Integrity	[203–210]	8
3	Component / Product Development	[211–218]	8
4	Simulation / Testing	[219–231]	13
5	Control / Navigation	[232–247]	16
6	Safety and Security	[248–251]	4
7	Communication	[252–258]	7
8	Edge Computing	[259–272]	14

In addition to the information provided in Table 2.6, a quantitative analysis of the number of publications per category has been performed. It can be easily deduced from the pie chart in Figure 2.12 that there are three main categories where DTs are applied in UAVs; 22% of the publications (16 out of 73) are dealing with UAV control and navigation while 18% (13 out of 73) are tackling simulation and testing; and that was expected since DTs have proven their functionality both in control/navigation through their application in other types of vehicles as well as in simulation/testing which they are extensively being used not only in other types of vehicles but in industrial applications too. However, the third main category which covers 19% of the overall dataset (14 out of 73) comes as a surprise since DTs are being used in conjunction with Mobile

Edge Computing applications. These three categories are covering 59% (43 out of 73) of the whole dataset, with the remaining 5 categories having each 11% or less. The least populated category, which reinforces the need for this extensive review, is the *Reviews* category covering only 4% with just 3 publications.

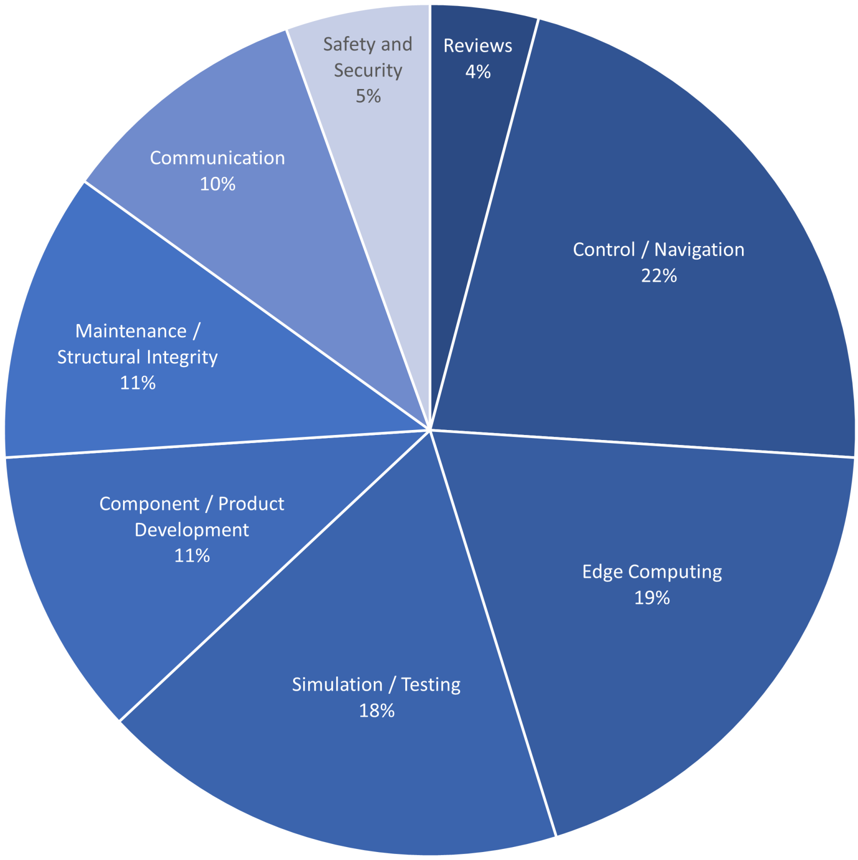

Figure 2.12: Number (#) and percentage of publications per category.

Appendix B summarises the results of this literature review (excluding only the three review papers). The table consists of five columns; the first is the corresponding reference number, the second briefly summarises the work presented, the third mentions the tools and platforms used, the fourth discusses the utilised technology to achieve the intended outcome, and the fifth column presents the type of UAV used in each work. The notation N/S is used in cases where the relevant information was not specified in the publication. A discussion per category follows to help gain some insight on the material under study.

The reviews category is the least populated with only 3 publications (4%) being identified. The first is an overall review on the applications of Digital Twins in the aviation industry [200] which tackles also the topic of applications in UAVs while the others are very pinpointed at a specific topic; i.e. [201] at the use of DTs of UAV in order to assess and aid the Regulatory Compliance in European Union while [202] at the use of DTs for ML enabled wireless networks for UAVs. As it is easily derived, those are either too generic including the whole aviation industry or very specific focusing only on a single domain; thus contributing a more generic view on the overall applications of DTs in a specific type of aircraft such as the unmanned aerial vehicles has indeed scientific merit.

The second category consists of publications that tackle the topic of maintenance and structural integrity in UAVs. Eight publications have been identified in this topic, with [203], [204], [206] exploiting the digital twins for optimal placement of sensors in order to monitor their structural integrity, [205], [207], [209], [210] creating digital twins for fault diagnosis and predictive maintenance and [208] designing and building a hardware testbed for a digital twin enabled UAV. An interesting result from studying Category #1 is that with one exception all applications have been designed for fixed wing UAVs. This does not come to a surprise as fixed wing UAVs experience heavy aerodynamic strains in their wings and fuselage and monitoring the conditions or even predicting such failures will allow for timely maintenance without sacrificing service time or even avoid a catastrophic failure during operation.

The publications belonging to the third category are either discussing the creation of a digital twin for a single component, e.g a propulsion system similar to [213], [216], [214] or a landing system as in [215] while others deal with the whole product development phase of a UAV such as [211], [212], [217], [218]. Similarly to the previous category, most of the publications are dealing with fixed wing aircraft, while two are discussing applications on single rotors, a not very common type of UAV due to its higher cost, difficulty to fly and application specific abilities (e.g. high payloads) in comparison with multi-rotors.

One of the most common usage of digital twins is to help the simulation and testing of new vehicles or components without the need of physical testing. Multiple publications have been identified in category four ([219–231]) all utilizing quad-rotor UAVs. Since the creation of a DT for simulation and testing requires data from a physical systems and cross-validation of the results, it makes absolute sense to use quad-rotors, the most easy-to-use, low-cost and easy-to-find drones on the market. Even though getting a vehicle is not difficult, the mechanism to create accurate simulation platforms is not an easy task. It requires the coordination of multiple tools and platforms to achieve the intended result. The most common tools used in the publications present in the dataset are Matlab/Simulink, ROS/Gazebo, AirSim, Unreal Engine and Unity. Each of these tools are used for a specific part of the DT creation but have to work together in order to create a meaningful simulation and testing platform.

The most significant application of DTs in UAVs identified is control and navigation either of a single UAV ([235]- [238], [240]- [242], [244], [246], [247]) or of a UAV swarm ([232]- [234], [239], [243], [245]). The majority of the work in fifth category utilises DRL and develops DTs that train / re-train offline the control and navigation algorithms without having to continuously utilize the relatively low-powered on-board computers, reducing energy consumption and thus extending flight time and/or payload capabilities. The main tools used are Python programming language and PyTorch or TensorFlow ML frameworks with some applications adding also ROS/Gazebo in the mix. The fact that most of the control and navigation applications have been studied or tested on quad-rotors and a handful only on fixed wing or VTOL fixed wing it is also very interesting.

DTs are also utilised, but not extensively, to detect intrusions and anomalies in UAV networks as demonstrated by [249, 251] or to suppress interference as shown by [248]. All wireless networks are prone to interference from the multitude of adjacent networks and mobile communications used nowadays or from malicious attacks. A DT could help identify such issues and make it easier to deal with them in an early stage. As explained by [250], DTs can also be used to explore the structure and safety performance of the airspace they are operating. Learning algorithms are used to solve such problems which are independent of UAV type and are mostly exploiting Python programming language and/or Matlab to be implemented.

Another area of applications is related to the communication mechanisms and data transmission methods. DTs are allowing for latency minimisation [253, 254] of end-to-end communication or for flow routing adjustment in UAV networks [257]. Optimal data transmission is another application area; efforts to accommodate time-variant channel parameters for dynamic systems [252], offer rapid medical resource delivery in epidemics through appropriate data transmission [258] or utilize a communication framework in the realm of green IoT [256] have been encountered in literature. These applications are also UAV agnostic and are utilizing different technologies to get the intended results; from Ray Tracing to DRL.

The second most popular application that harnesses the power of digital twins for UAV applications is Edge Computing, i.e. a distributed computing paradigm that brings computation and data storage closer to the sources of data. In most cases, the DT is used for resource scheduling and allocation ([259], [261], [262], [264], [265], [271], [272]) in UAV-assisted MEC networks. Task offloading with the help of DTs, as presented in [260], [263], [266], [267], is of imperative importance as the transfer of computations, data, and other dependent libraries to a remote server and obtaining the results from the server needs to be implemented flawlessly for an effective MEC network. DTs are also supporting dynamic and efficient task assignment as described in [262] and [268]. The use of DTs in MEC, will have a profound effect on the performance and energy efficiency of UAVs. Paired with cutting-edge ML techniques such as DRL, FL, DQN and Genetic Algorithms it seems that this domain definitely has a lot of potential in the years to come.

Through this detailed analysis per category a better insight on the applications of digital twins in the unmanned aerial vehicles domain is obtained and documented. It can be easily identified now, that digital twins can be applied to various types of UAVs, having listed applications in fixed wing, VTOL fixed wing, single rotor and quad-rotor aircraft. In Figure 2.13, a pie chart representing the number of applications per UAV type is presented. It should be noted here that in some applications the UAV type was either not mentioned or are UAV type agnostic. This answers **RQ3**, however it must be pointed out here that some applications are more useful in a specific type of UAV than another; e.g. strain detection on fixed wing.

As far as tools used, there is an abundance of them depending on the application. Matlab and Simulink as well as ROS/ROS2, Gazebo and RViz are extensively utilised. Equally popular is the use of Python programming language and ML frameworks such as PyTorch and TensorFlow. Game engines such as Unity and Unreal Engine are also used predominantly for three dimensional

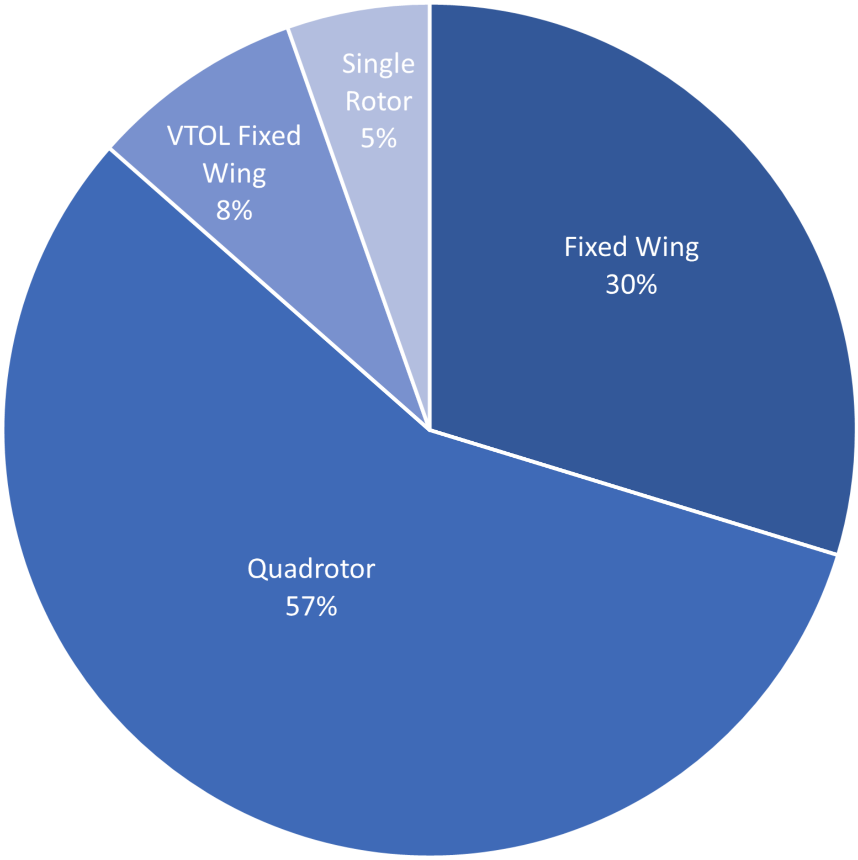

Figure 2.13: DT Applications per UAV type.

visualisation. In Figure 2.14 the tools being used most frequently are visualised.

ML techniques such as DRL, FL and DQN have been identified in numerous solutions used in combination with the aforementioned tools. Thus, the answer on **RQ4** is not that obvious. These tools and technologies are the ones met in the publications under study, however none can be used standalone and there is a need to combine those depending on the application to achieve the required results. Consequently, the answer to **RQ4** is that no specific tool or technology is used to apply digital twins to UAVs, rather a combination of the most appropriate ones depending on the application.

It must be noted here that in Figure 2.13, the percentages have been calculated on the basis of the publications that specified the UAV type (38 out of 70), while in Figure 2.14 on the basis of the publications that are specifying the utilised tools in question (42 out of 70). In this chart tools that are only listed in one or two papers across the literature under review have been excluded.

This section presents an extensive literature review on the applications of digital twins in the UAV domain. This survey has been accomplished through a well-defined methodology where the publications (queried from Scopus) have been meticulously pre-processed and screened to comprise a useful dataset that provides insights on how DTs are applied in the UAV domain. The publications have been sorted in categories based on the type of work and a quantitative analysis per category is also presented. The results of this review are discussed throughout this manuscript and summarised

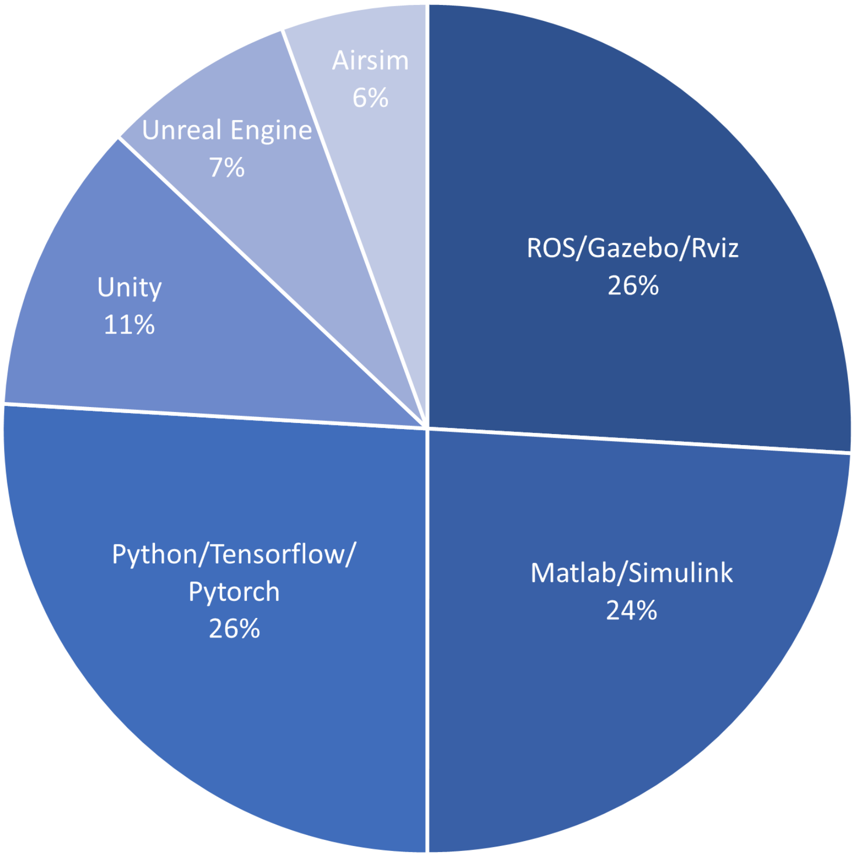

Figure 2.14: Most frequently used tools and platforms.

in Appendix B, where the work performed on each paper, the tools or platforms used, the utilised technology and the type of UAV discussed, are presented. It becomes apparent that digital twin applications in UAVs are not only a trend but provide significant aid to otherwise difficult to resolve tasks. Through the advancement of enabling technologies, such as machine learning, robotics simulators and 3D engines, an easier path is paved for the application of digital twins in UAVs in the near future.

However, as an emerging technology, DTs are weighted with various limitations that need to be addressed in order to fully exploit their potential such as cost, information complexity, lack of standards and regulations as well as communication and cybersecurity risks [273]. In order to tackle these, as mentioned in [274], it would be interesting if future research on the domain focuses on a) the utilisation of 5G networks for faster and safer communications, b) the reduction of computational complexity in simulation and modelling techniques, c) the use of ML and AI for big data analysis, d) the exploitation of the capabilities of edge and cloud computing and e) the interoperability and integration of simulation, modelling, analysis and visualisation software.

2.7 DTs in Surface and Underwater Vehicles

Digital Twins have the potential to profoundly impact the maritime industry by being effectively applied to both surface and underwater vessels. They are reshaping activities from the design and building phases to operations and maintenance. This comprehensive virtual modelling enhances efficiency, improves safety, and extends the lifespan of these advanced assets. Regarding surface and underwater ships, digital twins have become integral to the industry's digital evolution. Shipbuilders and operators create detailed and dynamic virtual replicas of their real-world vessels. These twins go beyond mere static 3D models; they are continuously updated with real-time data obtained from onboard sensors and also include operational and environmental information.

The same four step methodology as previously has been followed to organize the relevant survey for the surface/underwater vehicles and similar research questions have been formulated:

RQ1: Can Digital Twins be used in surface/underwater vehicles ?

RQ2: How DTs help surface/underwater vehicles?

RQ3: In what types of surface/underwater vehicles are DTs applied?

RQ4: Most common tools/technologies used for surface/underwater vehicles?

A concise exploration of the evolution and use of digital twins technology within the realm of autonomous maritime vessels, including both surface and underwater vehicles, has been conducted. This comprehensive literature review uncovered a total of 32 manuscripts addressing the potential applications of digital twins in maritime vehicles. While not as detailed as the similar studies for land and air vehicles, a discussion, classification, presentation of the findings in tabular format and answering of the posed research questions will take place. Already, the first research question can be positively answered since 32 publications have indeed been identified.

Having meticulously studied the aforementioned manuscripts, a presentation similar to the other vehicle categories in a tabular format is provided in Appendix C. The table in question consists of four columns; the first column is the reference number of the publication, the second column is a short description of the discussed contribution, the third column lists identified tools/technologies mentioned (if any) and the fourth column states the vehicle type that the study focuses (if defined).

The survey revealed research focused on the role of digital twins in boosting operational efficiency, particularly in tasks such as navigation and control of surface and underwater ships, simulation and optimisation and predictive maintenance, by merging real-time sensor data with advanced simulation models. Many studies emphasize the crucial role of communication infrastructure and artificial intelligence, including machine learning and reinforcement learning algorithms, to ensure reliable data exchange, accurate control, and improved decision-making for autonomous operations. Some researchers also discuss real-world implementation challenges, like data latency, model uncertainty, and the necessity for standardised architectures, while noting the potential for increased safety and efficiency.

Diving deeper, the main Digital Twin applications identified for surface and underwater ships are the following:

- Control / Navigation: For both surface and underwater vehicles, a digital twin can offer multiple benefits to operators. It allows for easier development of relevant algorithms such as path planning and path following or collision avoidance. It allows for facilitating precision in navigation and successful completion of intricate tasks in demanding scenarios.
- Simulation and Optimisation: Digital twins enable the simulation of voyages to determine the most fuel-efficient routes and speeds based on weather forecasts, ocean currents, and vessel loading conditions. This can lead to significant fuel savings and a reduction in greenhouse gas emissions for example.
- Product Development: Naval architects have the capability to create an entire virtual model of a vessel or a specific part. This enables thorough simulations and analyses to assess performance, hydrodynamics, structural soundness, and energy efficiency across diverse sea conditions, resulting in designs that are more optimised and durable.
- Maintenance: Regularly observing the condition of essential components such as engines, propulsion systems, and hull integrity using their digital twins enable operators to transition from traditional reactive or scheduled maintenance to a predictive approach.
- Safety and Security: Complex operational and emergency scenarios can be simulated in a safe virtual environment, allowing crews to train for various situations, from equipment malfunctions to abandon-ship drills, thereby enhancing their preparedness and decision-making skills.
- Communication: Marine autonomous systems utilize a broad range of communication technologies and applications, facilitating improved situational awareness, management, and data sharing in diverse operational contexts.

As intended, the identified categories related to surface and underwater vessels are similar to those identified in both land and air vehicles in order to be easier to compare the types of applications per vehicle type. Table 2.7 sorts all publication in their corresponding category.

Performing a quantitative analysis on the results, the most popular application of DTs in surface and underwater vehicles, containing 14 out of 32 publications (44%) is the Control/Navigation, with second being the Simulation/Optimisation with 5 publications (16%). In the third place the Product Development applications containing 4 publications (13%) can be found while Maintenance category contains three relevant applications (9%). All Safety and Security, Communication as well

Table 2.7: Categorisation of publications under study

#	Category Name	Ref	Count
1	Reviews / Surveys	[275, 276]	2
2	Control / Navigation	[277–290]	14
3	Simulation / Optimisation	[291–295]	5
4	Product Development	[296–299]	4
5	Maintenance	[300–302]	3
6	Safety and Security	[303, 304]	2
7	Communication	[305, 306]	2

as Review/Survey categories contain only two publications (6%). This qualitative and quantitative analysis allows the author to answer the second research question.

Studying the last column of Appendix C in order to answer the third research question, not a specific type of vehicle that DTs for surface and underwater vehicles being applied was identified. Indeed, some specific vehicles are mentioned in certain research endeavours, such as the SPARUS II UUV, the BlueROV2, the Otter and the Petrel Glider. Most of the publications either mention a generic vehicle type, i.e. sailboats or gliders or not mention the type of vessel at all. However, this analysis allows for the realisation that 19 of the 32 publications (60%) are tackling with surface vessels while the remaining 13 (40%) refer to underwater vessels.

In a similar fashion, in order to answer the fourth research question the third column of Appendix C allow the author to easily understand that there is not a specific tool or technology to easily apply DTs to surface and underwater vehicles. Depending on the application, the most relevant technology to achieve the best result is employed; i.e. some researchers apply machine learning (RL, IL, SL, Meta-L), others apply filters such as Kalman and its variants and others apply control techniques such as LSTM and MPC.

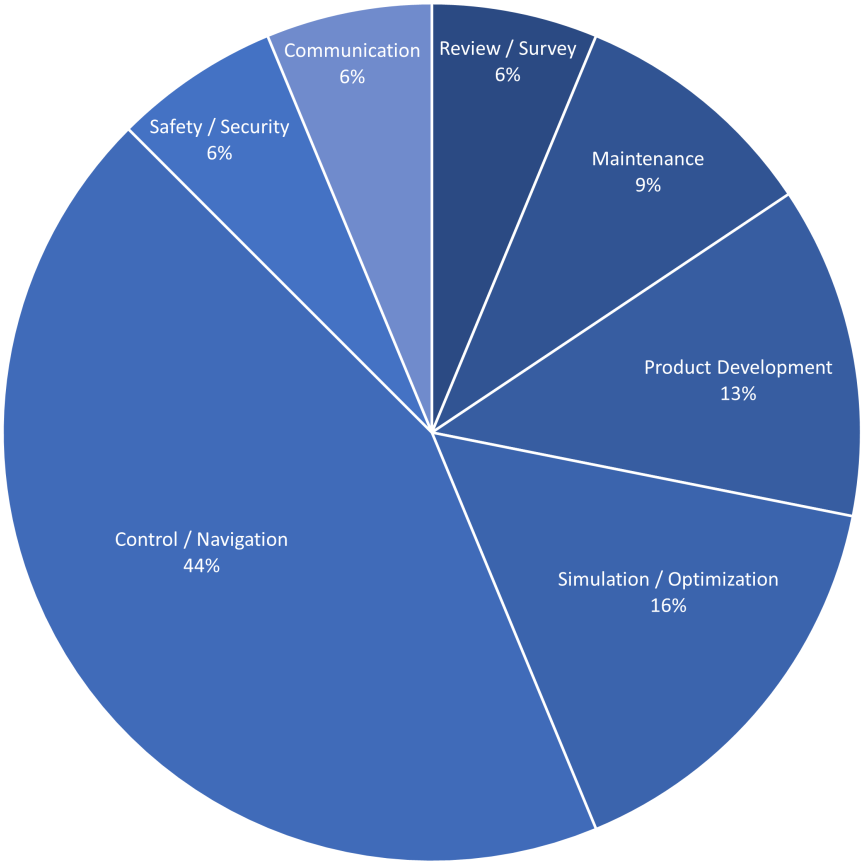

Figure 2.15: Number (#) and percentage of publications per category.

2.8 Conclusion, Opportunities and Challenges

This chapter offers an in-depth examination of the growing convergence between digital twins and autonomous vehicles. After presenting a basic overview of DTs, exploring their historical backdrop, and emphasizing their key role in the Industry 4.0 framework, the focus then shifted to the primary aspects of autonomous systems, specifically the "sense-plan-act" cycle. A bibliometric analysis followed, highlighting the rapid increase in research interest both in each field independently and in their joint applications, uncovering significant trends, leading research disciplines such as engineering and computer science as well as the most influential publications to date. Comprehensive literature reviews, sorted by vehicle category — land, air, and surface/underwater — methodically outlined the major uses of DTs. Common themes across these domains included simulation and testing, control and navigation, and predictive maintenance, demonstrating the broad advantages that digital twins technology can offer in autonomous vehicles.

The work on this chapter supports answering research questions RQ 1.1 to RQ 1.4. The first question (RQ 1.1) can be answered positively due to the large numbers of publications identified; a testimonial for the interest on the cross-section of the DT and AV domains. As far as the second research question (RQ 1.2) is concerned, three main types of autonomous vehicle that DTs can be applied have been identified; land vehicles, air vehicles and surface/ underwater vehicles. Details for the vehicles on each category can be found on the preceding analysis and Appendices A, B, C. The most common applications identified (RQ 1.3), are either related to control and navigation of autonomous vehicles or simulation and testing of systems and vehicles in a digital environment while the most common technologies used (RQ 1.4) are AI/ML (and their different types such RL, SL, etc.) and the most common tools identified (RQ 1.4) in the applications are Python, ROS/Gazebo, Matlab/Simulink and diverse robotics simulators such as CARLA / IPG Carmaker (on land vehicles), AirSim (on air vehicles) and MarineSIM (on surface/underwater vehicles) as well as game engines such as Unity and Unreal Engine.

The study further demonstrates that although the use of Digital Twins is rapidly progressing, there is often a considerable discrepancy between theoretical models and actual real-world deployment. A consistent finding across land, air, and sea vehicles is the "vehicle agnostic" attribute of numerous proposed solutions. This characteristic, while fostering wide applicability, frequently neglects the specific integration issues necessary for practical application. The research also highlighted a varied yet fragmented array of enabling tools and technologies, where different simulation platforms, AI, and machine learning systems, as well as IoT technologies, are utilised based on the particular application. The chapter ultimately determines that digital twins are a transformative technology set to expedite development, improve safety, and optimize the functionality of autonomous systems. Future advancements will hinge on closing the "sim2real" gap, standardizing development frameworks, and refining the integration of physical and digital systems.

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Chapter 3

Conceptual Framework

For a conceptual application framework for digital twins in autonomous systems to be realised, one has to identify existing solutions and applications in order to obtain the required background knowledge to understand the domain in depth and establish the foundations the rest of this work will be based on. The comprehensive literature review in Chapter 2 uncovered an active and swiftly growing field of study, where digital twins meet autonomous vehicles. A major obstacle identified was the lack of a standardised application framework for DTs in this context, despite the presence of numerous tailor-made solutions. This fragmentation complicates development, impedes the replication of findings, and delays the implementation of promising theoretical ideas in practice — a well-known issue in robotics termed as "sim2real" gap. The current landscape often resembles an attempt of trying to construct a complex structure without a clear blueprint; while each part might be well-designed, their assembly might lack cohesion.

Initially, the researcher identifies the cross-domain knowledge obtained from the application of digital twins in industry; a domain that the application of this technology has been more advanced. By leveraging knowledge from the author's work on that domain, the application framework in question would be established easier. Best practices and most relevant technologies have been identified, while limitations and hurdles already faced can be easily avoided.

Following, this chapter tackles the significant gap by suggesting a structured conceptual methodological framework for creating and applying digital twins in autonomous vehicles. The primary objective of this framework is to offer transparent, replicable and flexible guidelines for both researchers and practitioners by standardizing the creation process of a high-fidelity, synchronised digital model of an autonomous vehicle. As a result, the framework is intended to significantly reduce the "sim2real" gap, allowing algorithms and systems validated in virtual settings to be deployed on physical hardware with increased assurance and minimal re-engineering.

Moreover, this framework has been created with a significant focus on addressing the requirements of the academic and research sectors. A fundamental principle is the emphasis on open-source and/or widely available tools, such as ROS/ROS2, Gazebo/CARLA simulators and Matlab/Simulink, which are frequently cited in the existing literature. By utilizing open-source/widely available platforms, this framework aims to boost a collaborative research environment, where experiments can be easily replicated, and the community can work together on a common foundation. The subsequent sections will elaborate the main principles, supporting this conceptual framework and provide an in-depth presentation.

Throughout this chapter, the second main contribution of this work, the conceptual methodological framework for digital twin deployment in autonomous vehicles, leveraging the Industry 4.0 paradigm, is presented in detail, while research questions RQ 2.1, RQ 2.2 and RQ 2.3 are answered clearly.

3.1 Leveraging Cross-Domain Knowledge

Digital twin technologies have matured significantly in industrial domains, such as manufacturing, process industries, energy, and asset management, driven by requirements for predictive maintenance, process optimisation, and real-time system monitoring. In these sectors, best practices have emerged around modular system architectures, standardised interfaces, and scalable deployment processes, which enable flexible simulation, data-driven analysis, and integration of heterogeneous systems.

The author's significant cross domain work in [10], [12], [17] and [16] document the aforementioned realisations and establish the interconnection among the industrial applications of digital twins and the knowledge that can be transferred from one domain to the other. In order to visualize the relevance among these two diverse domains, Figure 3.1 compares the proposed applications of digital twins in industry published in [10] with potential applications within the autonomous vehicles domain.

The maturity of the applications of digital twins in industry have been well documented by numerous authors not only within the concept of Industry 4.0 [307–309] but lately also within Industry 5.0 [310]. The relevant enablers such as machine learning/artificial intelligence, internet of things, simulation, modelling, optimisation, virtual and augmented reality have all grown rapidly lately and are being significantly utilised in an abundance of applications such as predictive maintenance, energy and process optimisation, order (re)scheduling, failure recovery and so much more. This extensive application of digital twins in industry has indeed formulated the relevant knowledge and the optimal way DTs can be applied to the domain. Numerous occurrences of this hypothesis validation can be met in relevant literature fostering the idea of applying a technology that is proven in industry into a diverse domain such as autonomous vehicles. Such an effort is met in [10] with the build process industry digital twin being not only described methodically but also validated. In summary, the methodology in question contains the following steps:

I. System Definition

II. Factors and Mechanisms Identification

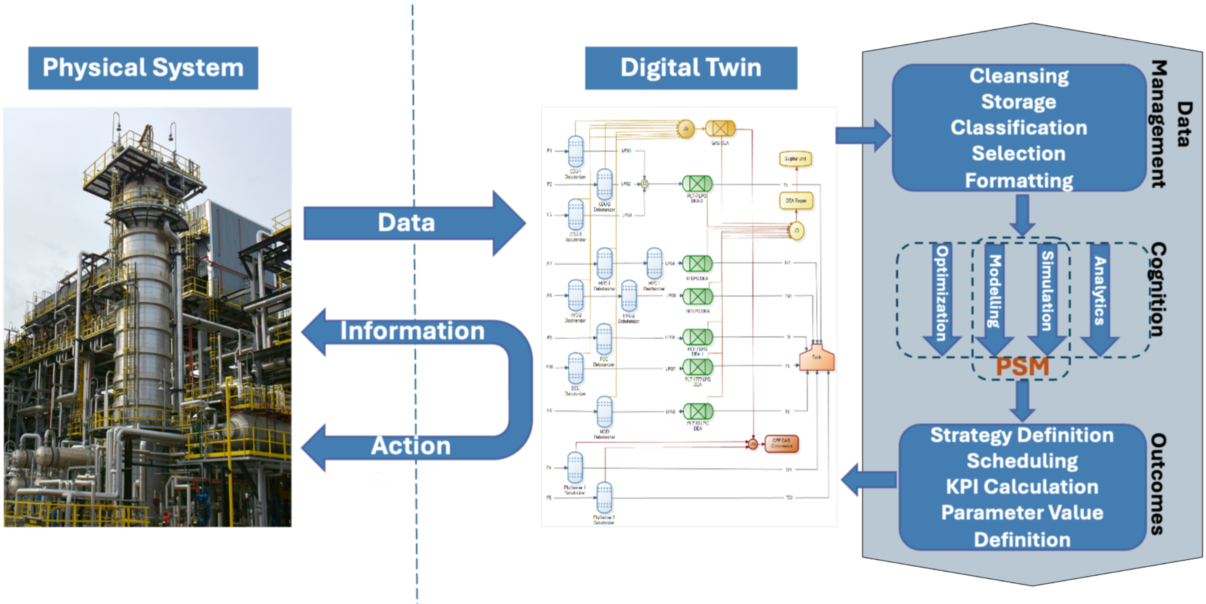
III. Data Evaluation

IV. Model Development

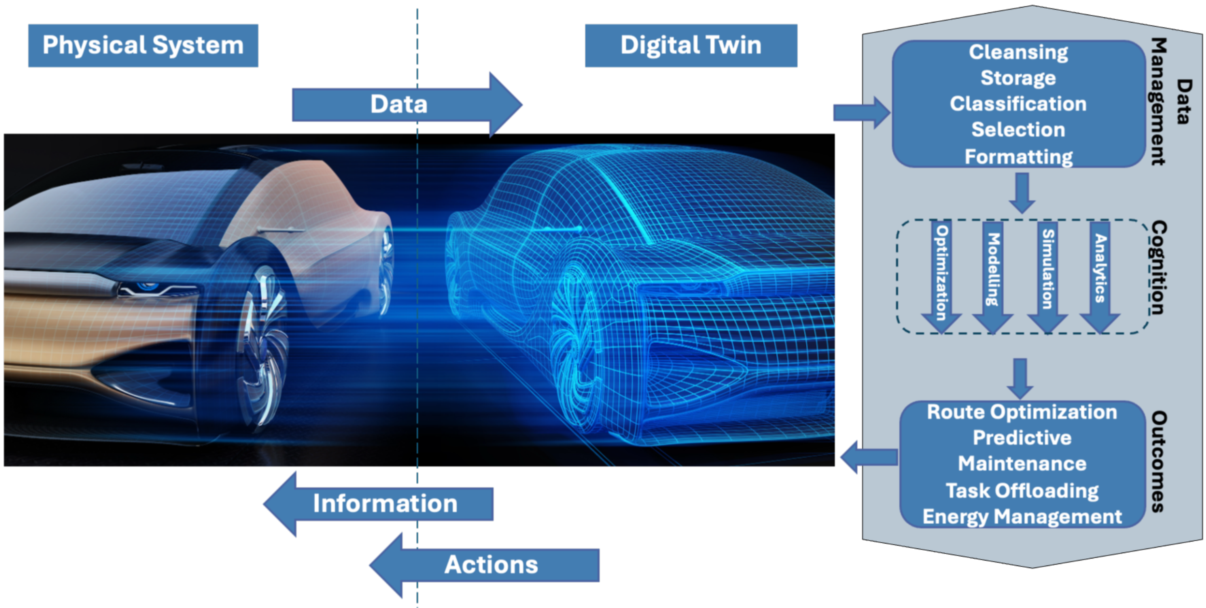
V. Solution Methodology Selection

VI. Model Verification

VII. Model Validation



(a) Digital Twins in industrial application
Source: [10]



(b) Digital Twins in autonomous vehicles

Figure 3.1: Comparison of industrial and autonomous vehicles digital twins

These well-established and tested methodological guidelines have heavily influenced the conceptual framework for the application of digital twins technologies in autonomous vehicles. This influence is visualised in Figure 3.2, where part of the model building and operation procedure of the industrial application is directly comparable to the four phases of the application framework defined below.

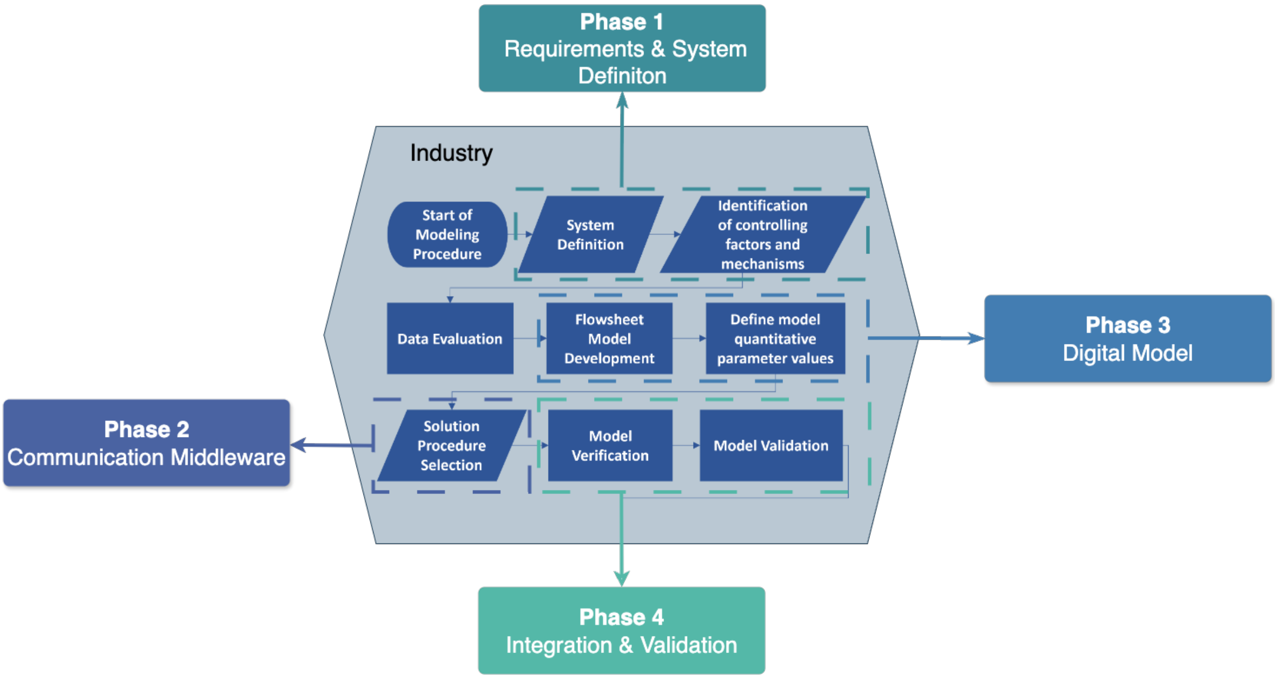


Figure 3.2: Direct comparison of industrial and autonomous vehicle application frameworks

The structured methodologies from industrial digital twins — such as model-driven engineering, service-oriented integration, and the use of open communication protocols — offer a blueprint for overcoming equivalent challenges in autonomous vehicles. These include the need to model complex, interconnected subsystems; to synchronize physical and virtual states in real time; and to support iterative testing, validation, and refinement as systems evolve or face unpredictable environments. Notably, recent advancements in manufacturing and process industries have demonstrated the benefits of composability, plug-and-play component replacement, and the maintenance of digital threads across product and system life cycles. Translating these principles into the realm of autonomous vehicles entails adapting modular modelling, real-time data streaming architectures, and simulation-integrated feedback mechanisms to domains characterised by physical mobility, dynamic operation, and evolving sensor/actuator suites. Additionally, lessons drawn from challenges and solutions in industrial data governance, cyber-physical security, and standards adoption can directly inform the construction of resilient, interoperable, and flexible digital twin architectures in autonomous vehicle development and deployment.

This cross-domain approach not only accelerates the transfer of validated techniques to autonomous vehicles digital twin development, but also provides a concrete foundation for addressing the "sim2real" gap, a core impediment in robotics and autonomous vehicle research. By building upon methods already proven in large-scale industrial applications, the proposed framework ensures that solutions are robust, scalable, and readily adoptable by the wider research and practitioner community. As such, the conceptual framework outlined in this chapter is consciously designed to exploit these transferable strategies, ensuring high relevance and immediate impact for both academic researchers and industry developers.

3.2 Fundamental Principles

Before detailing and visualizing the conceptual framework, it is essential to lay down the fundamental principles that form its foundation. This framework is not simply a series of sequential steps but it is firmly based upon those principles which act as the theoretical foundation that guides the development, ensuring that the resulting digital twins are not only resilient and scientifically sound but also beneficial for advancing autonomous vehicle research. Derived from the primary challenges and opportunities highlighted in Chapter 2, these principles, visualised in Figure 3.3, are established in order to ensure that the framework creates digital models that are:

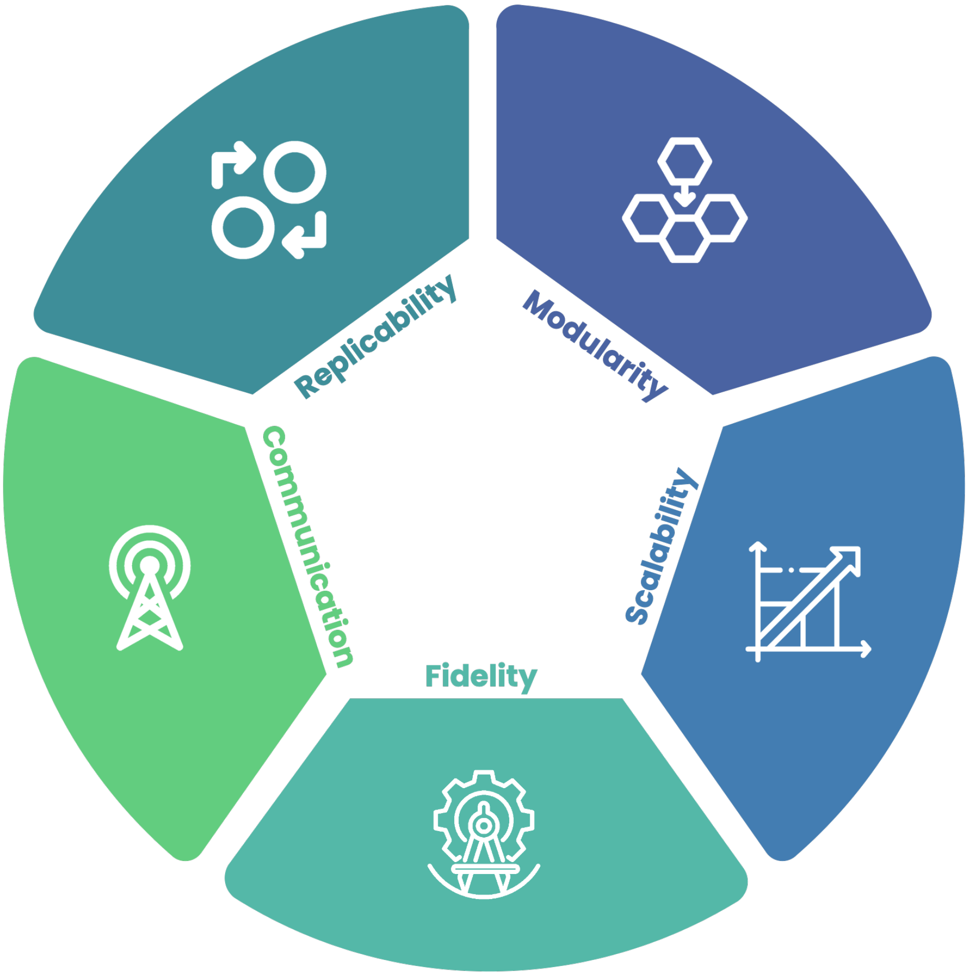


Figure 3.3: Fundamental Principles of the conceptual framework

1. **Modular**

   The concept of modularity involves structuring the digital twin as an assembly of distinct, interchangeable, and precisely defined components. Instead of relying on a single, unified simulation, a modular digital twin reflects the structure of the actual vehicle, enabling discrete modelling and validation of subsystems like perception, actuation, and communication. This method supports researchers in creating and experimenting with a detailed model of a new component — such as an innovative LiDAR sensor or a predictive battery management algorithm — by integrating it into pre-existing, validated models of other vehicle components. This capability is essential for concentrated and productive research, as it reduces the overwhelming complexity of an entire autonomous vehicle, supports simultaneous development efforts, and establishes a clear route for updating or substituting specific parts of the digital twin as research evolves. This approach directly addresses the wide range of applications documented in the literature, where DTs are employed for purposes ranging from comprehensive vehicle testing to the development of specialised propulsion systems.

2. **Scalable**

   Scalability refers to the framework's applicability to autonomous vehicles of varying sizes and complexities being used across different application domains. The essential approach to develop a DT must remain uniform, irrespective of whether the physical asset is a low-cost, 1:10 scale educational platform like the ones used in two of the subsequent experimental validation or a full-sized autonomous vehicle. Although implementation specifics such as the physics engine, sensor model complexity or computational resource demands will scale in tandem with the relevant system, the core process outlined in the conceptual framework remains consistent. This maintains the framework's durability and widespread applicability, making it more than just a tailored solution for a single platform. A scalable framework provides a universal set of guidelines adaptable to land, air, and marine vehicles, thereby promoting cohesion in an industry currently marked by diverse solutions.

3. **Highly Accurate**

   Central to the "sim2real" challenge is the concept of fidelity, which refers to how accurately a digital model reflects the properties and actions of its physical equivalent. To serve as a reliable proxy for testing and validation, a Digital Twin must exhibit a high degree of fidelity in the aspects pertinent to its function. This does not imply that every component needs to be simulated, but the important features must be accurately represented. For instance, a Digital Twin created to test perception algorithms requires highly precise models of its camera and LiDAR sensors, faithfully reproducing their viewing scopes, resolutions, and noise features under different conditions. On the other hand, a Digital Twin meant for validating the logic of vehicle platooning would focus on achieving fidelity in vehicle dynamics and communication models.

4. **Synchronised in Real-Time**

   Real-time Communication is a crucial element that transforms an digital shadow into a digital twin. It requires a continuous, bi-directional, and low-latency data connection between the physical asset and its digital counterpart, enabling the virtual model to be constantly updated with live data from the sensors of its physical counterpart. This results in a dynamic and accurate virtual representation of the asset in its real-world setting. The connectivity must also permit bidirectional communication, so that instructions or updated settings from the virtual space can be transmitted back to the physical system. Real-time communication is essential for enabling sophisticated functionalities like remote system monitoring, predictive maintenance using live operating data, and dynamically testing algorithms in a virtually controlled environment that reflects real-world scenarios. Achieving robust real-time communication involves careful middleware selection tailored to system requirements and constraints. Metrics such as message latency, jitter, and data throughput must be rigorously evaluated to maintain synchronisation accuracy within milliseconds, essential for safety-critical autonomous functions. Integration with emerging 5G/6G network capabilities and edge computing infrastructures empowers this principle, enabling distributed processing and lowered communication delays that conventional cloud-centric approaches cannot match. The framework needs to accommodate these advances, anticipating future-proof deployment scenarios.

5. **Designed for Replication**

   The principle of replicability emphasises that, especially in an academic setting, it is crucial for methods and tools to be transparent, accessible, and straightforward to replicate. Advancement in science relies on researchers' abilities to validate, scrutinize, and extend previous work. Utilizing closed, proprietary software and hardware can significantly hinder this collaborative effort. Consequently, this framework promotes employing open-source standards, along with software and hardware made from widely accessible components. Upholding this principle not only ensures the credibility of research findings but also provides a valuable asset to the community. It allows others to reproduce experiments, modify the framework for their own systems, and collectively speed up innovation in the field, which is a central contribution of this dissertation.

The conceptualisation of these fundamental principles arises directly from the systemic challenges identified in autonomous vehicle digital twin research. For instance, 'sim2real' gap underscores the necessity for high fidelity and real-time synchronisation to ensure meaningful model transfer to physical deployment. Modularity is critical because it allows incremental development and testing of discrete vehicle subsystems, reducing complexity while fostering collaboration across specialised research teams. Scalability ensures the framework's applicability to a broad spectrum of autonomous platforms, from low-cost research vehicles to full-scale commercial systems, aligning with the diverse applications documented across land, air, and maritime environments. Replicability supports the academic principle of open science, promoting reuse and extension by the broader research community and accelerating collective efforts. Last but not least, real-time communication is critical to be established as it constitutes the core of a digital twin and differentiates it from plain digital shadows that lack connectivity and interoperability.

3.3 Conceptual Framework

One of the main contributions of this research is the following four-fold framework targeting to facilitate the systematic creation of a digital twin for an autonomous vehicle. Figure 3.4 presents a simplified visualisation of the framework phases, showcasing their logical flow.

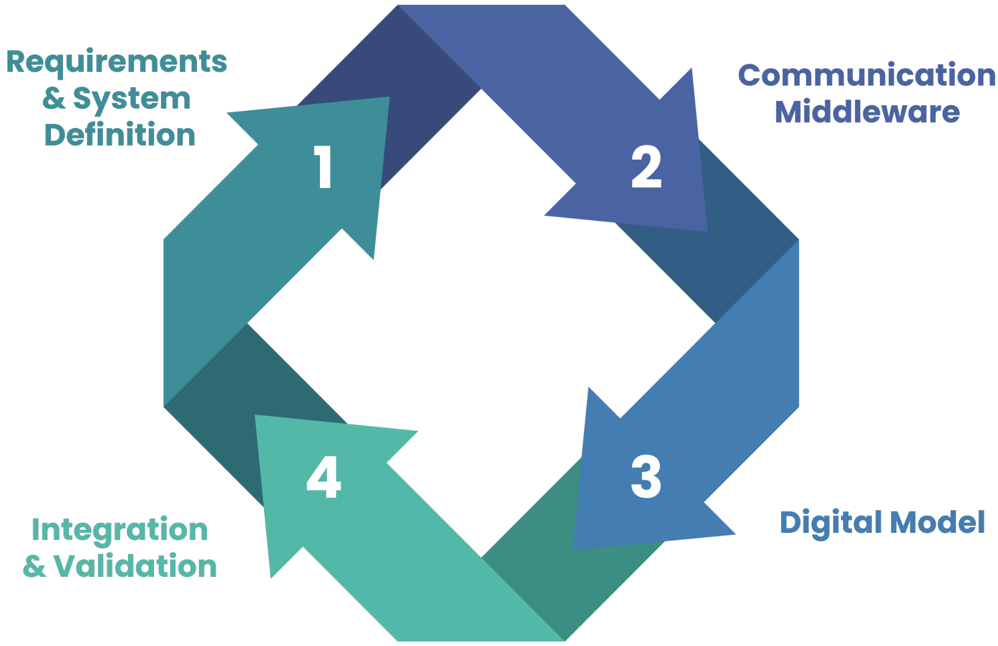


Figure 3.4: Conceptual framework main phases

This framework offers a well-established and validated (as described in Chapter 4) methodological approach, guiding researchers from initial high-level concepts to practical application and validation. Although the four phases are presented in sequence, the framework is inherently iterative, placing significant emphasis on feedback loops that utilize insights from each process to enhance and refine each and every step recognizing that achieving ideal practical deployment demands continues refinements. Real-world testing frequently uncovers discrepancies leading to model adjustments and communication protocol tuning. Reinforcement learning and AI-driven fidelity optimisation are promising methodologies for automating these iterative improvements at a later stage, dynamically adapting digital twin parameters to reflect evolving physical system behaviours and environmental conditions.

Combining the fundamental principles that define the framework and the four aforementioned phases, a high-level representation of the developed framework can be seen in Figure 3.5. The need to adapt during framework utilisation is facilitated by explicit feedback loops, promoting continuous convergence towards a high-fidelity operational digital twin. More details on these feedback loops can be seen not only on the overall flowchart of the framework at Figure 2.7, but also on the visualisation of each and every phase in Figures 3.6, 3.7, 3.8, 3.9. The detailed description of the objectives, rationale, and primary activities in each phase are outlined in the following subsections, while the whole process is visualised in a comprehensive flowchart.

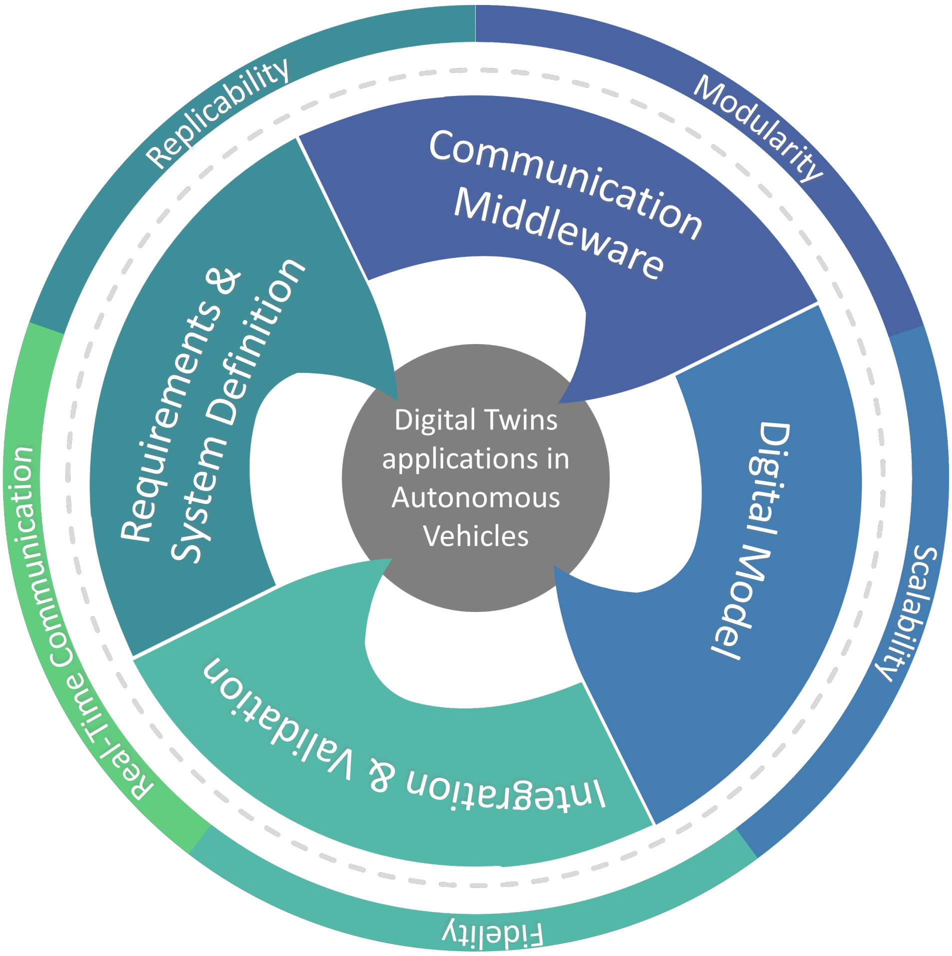


Figure 3.5: Conceptual framework visualisation

3.3.1 Requirements and System Definition

A critical phase in developing an effective digital twin is clearly the definition of the system to be replicated, along with setting the objectives and aims of the digital twin, while mapping all essential components and interfaces. If these are not accurately specified, the digital twin might fail to fulfil its intended purpose, thereby spending time and resources that could have been better utilised. A visualisation of this phase can be seen in Figure 3.6.

This phase can be split in three steps; the first step involves studying and thoroughly characterizing the physical system. This includes documenting its mechanical specifications, dimensions, and baseline performance characteristics. The subsequent step involves specifying the necessary model fidelity, which in turn influences the complexity of the model. For example, a DT used to validate a perception algorithm necessitates sensor models with high fidelity, but can accept less detailed vehicle dynamics. On the other hand, a DT utilised for assessing a high-speed trajectory controller requires a model with high precision vehicle dynamics. Finally, a complete inventory of all relevant hardware and software components needs to be compiled. This includes all sensors and actuators, i.e. all the systems that can supply information or be controlled by the digital twin. The outcome should be a detailed description of the system under study; for example, a system architecture diagram or any other format. This would act as a blueprint for the subsequent phases of the framework.

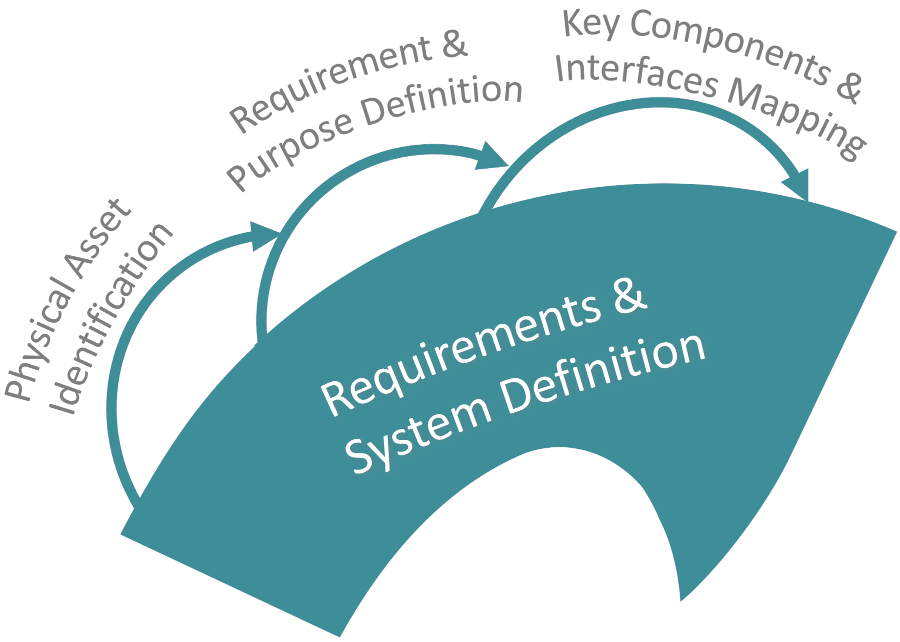


Figure 3.6: Visualisation of Phase 1 of the framework

3.3.2 Communication Middleware

This phase builds the essential communication bridges that enables real-time synchronisation and is considered critical, since without robust, reliable and low-latency communication the physical system will not be able to communicate with its digital counterpart in order to establish the core principle of digital twins; the bi-directional communication between the two systems. The sensor drivers are deployed to establish the availability of data from the physical to the digital system, as well as the corresponding control in order to allow actions triggered from the digital twin to be implemented later on. Finally, the proper communication middleware is selected depending on the requirements set under Phase 1. Figure 3.8 visualises the second phase of the application framework. It should be mentioned here that even though the communication middleware is selected, the physical and the digital system have not yet been connected in order to create the digital twin; rather until know the physical side of the system has been established.

In this phase, attention to detail is crucial in order to properly convey the messages without loss of data, delays and conflicts. It should be mentioned that the required drivers might potential be readily available for the sensors vendors, however integration into the overall system and proper scheduling for message exchange needs to be carefully studied.

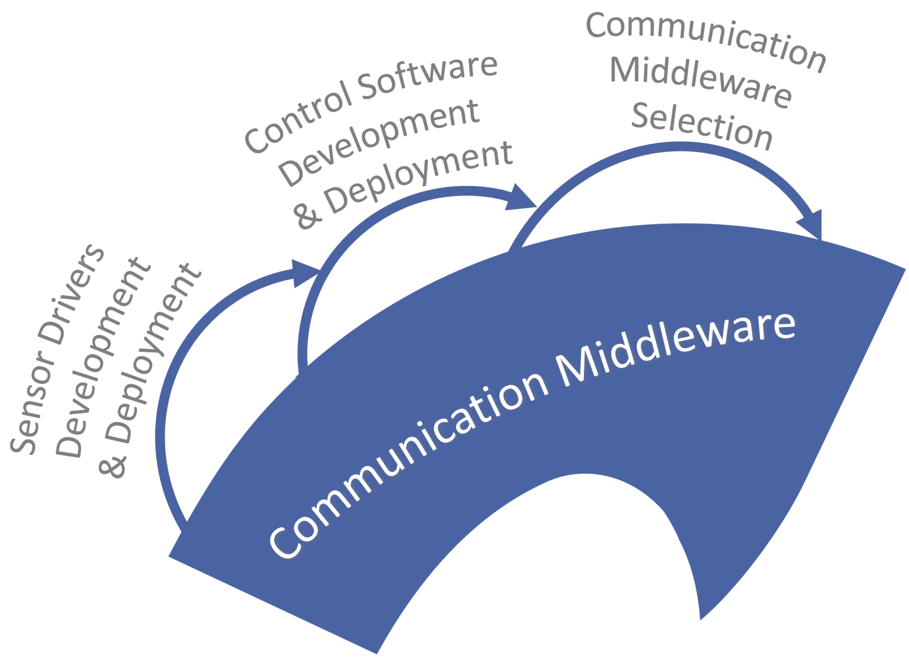


Figure 3.7: Visualisation of Phase 2 of the framework

3.3.3 Digital Model

In the third phase the creation of a high-fidelity representation of the asset as well as its operational environment is required. The system and the sensors are created with as much detail as required according to Phase 1 definitions. It needs to be pointed out that the accuracy of the virtual model will affect the overall fidelity of the digital twin and that it is of imperative importance to build a model that can minimize the "sim2real" gap. Phase 3 is represented graphically in Figure 3.7.

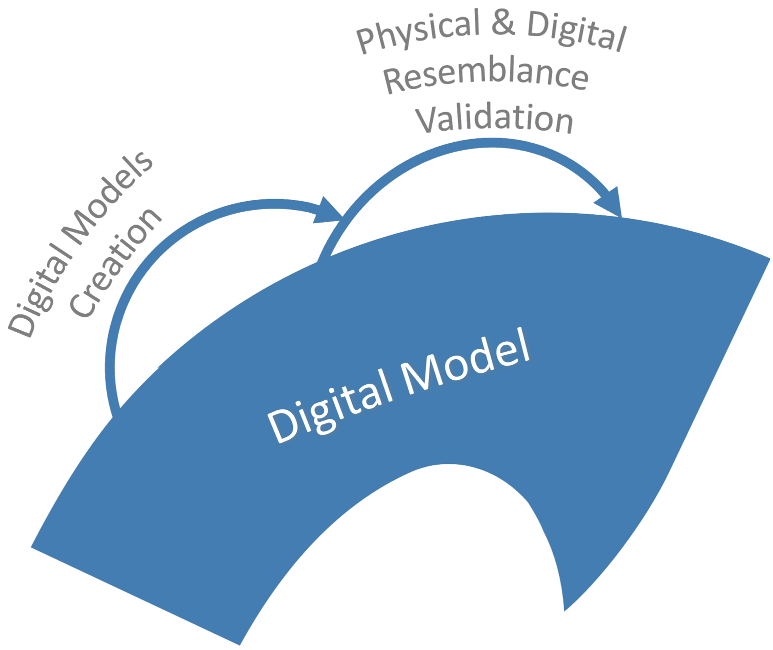


Figure 3.8: Visualisation of Phase 3 of the framework

This phase can be split in two distinct steps. Initially, the model that replicates the physical characteristics and features of the asset are created taking into account the mass, inertia and geometries. In addition, the digital counterparts of the physical sensors needs to be implemented taking into account the hardware specifications such as field of view, update rates, range and resolution. Last but not least, the environment that the digital model resides should also created. The second step on this phase is the comparison of the physical and the digital system and the validation of physical and digital resemblance. This resemblance can assure that the digital model could be successfully used to create a digital twin after being connected to one another. It should be mentioned here that the digital model, depending also on the Phase 1 requirements, might not always resemble the whole vehicle but rather a system that we need to test or control.

3.3.4 Integration and Validation

Having completed the aforementioned phases, now the physical and the digital counterparts with the established communication system have to be brought together. The bi-directional communication mentioned earlier needs to be put to the test and ensure that the state of the virtual model is a precise representation of the physical model's state. The system onboard the vehicle and the digital environment are linked and create the required data exchange in order to establish the digital twin. In Figure 3.9 the fourth phase of the framework is represented.

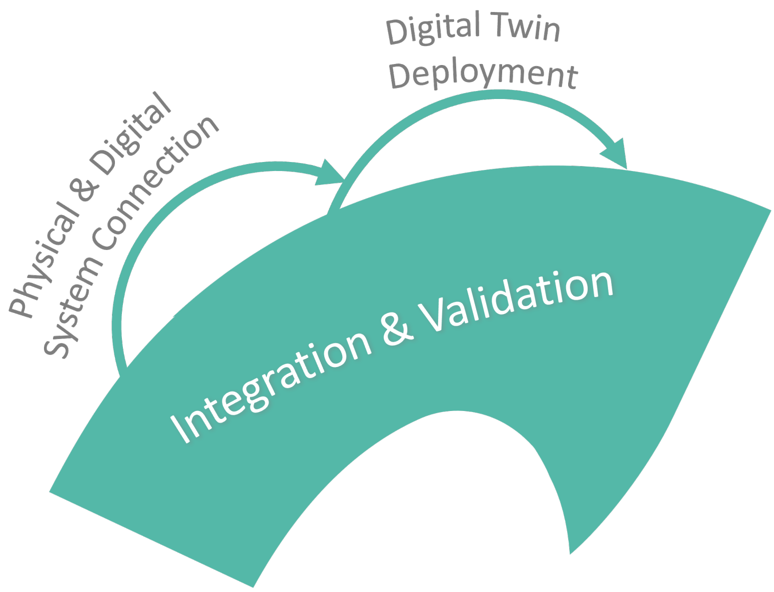


Figure 3.9: Visualisation of Phase 4 of the framework

In order to understand the actual value of a DT, it needs to be tested for its intended purpose. This is the only way to validate it and build trust in the digital model in order to use it as a replacement for certain applications and testing. Performing identical tests on both the physical and the digital assets and comparing the results will allow to identify the accuracy and potential refinements required that will trigger the feedback loops of the proposed framework.

Depending on the reality gap identified, a feedback loop might require to re-evaluate any of the aforementioned Phases in order to enhance the expected outcome. It should be mentioned here that these feedback loops are not triggered only at the end of the final phase but the framework's performance is also validated along its use and a return to any of the previous phases can be triggered at any point.

3.4 Conceptual Framework Flowchart

Figure 3.10 visualises the four aforementioned phases of the conceptual framework described above accompanied by the feedback loops that have to be taken into consideration. The visualisation follows a typical flowchart format using the well-established conventions; using ellipsis for start/end, rectangular for processes and diamond shape for decisions. In addition, each of the four phases described earlier has not only been colour coded, following the colouring pattern of Figure 3.4 but also enclosed in a dashed line. It becomes apparent by studying the flowchart that decisions are taking in between phases mainly. That does not forbid however to get back and forth on a process during the execution of a specific phase if required, even though only minor aspects could be addressed without reapplying every process of a phase. For the sake of clarity of the flowchart the decisions among every step of the process were not visualised in the overall flowchart, however in the partial high-level graphs presented in Figures 3.6, 3.7, 3.8, 3.9 they can be seen.

Explaining further the flowchart, the process of creating a digital twin for an autonomous vehicle starts from identifying the physical asset and its mechanical characteristics such as dimension, weight, power and any other aspect that define it. These characteristics should be documented in detail as they will be the basis for the creation of the digital twin later on. Following, the intended purpose of the digital twin needs to be defined as well as its functional requirements. The purpose that will be served will affect the required level of accuracy a DT will require; as mentioned before if a perception algorithm has to be validated the vehicle dynamics could be less detailed while if a high speed-trajectory controller needs to be defined vehicle dynamics should be as accurate as possible. Last but not least, all the key components and interfaces present in the physical system have to be identified; ideally a system architecture diagram should be created that will act as a guideline for the DT creation. These steps conclude the first phase of the application framework. At the end of the first phase, all system requirements must have been adequately defined. If that's not the case, then a return to any of the aforementioned steps depending on what was not properly defined is required; e.g. if the requirements are not fully transparent the second step should be revisited or if a component was not mapped the third step should be executed again.

The second phase relates to the communication among the physical and the digital asset. Up to this point the physical asset was studied and documented in Phase 1 so all system requirements would be properly defined. The second phase contains the steps to develop and deploy the sensors and actuator drivers in order to receive all information and be able to control the system. Such drivers are commonly provided with the sensors/actuators and either need to be adapted or tweaked for the specific architecture of the physical system or the specific requirements in each case or they might have to be custom-made to serve the process in a specific manner. In this phase the selection of the communication middleware also needs to take place, probably one of the most important steps of the process. This selection can be dictated either from internal factors such as requirements for communication speed, processing, intended use of the digital twin, system of final integration or from external factors such as hardware compatibility, existence of drivers that ease the overall integration or limitations on hardware. In any case, there are numerous ways how one can establish communication between the physical and the digital system and needs to be decided taking into account all the relevant requirements. If the communication then is properly established the next step can be invoked, otherwise a revisit of any of the previous steps might be required.

Proceeding through the flowchart, Phase 3 contain the creation of the digital models, not only for the vehicle itself following the physical properties (mass, inertia, geometries) identified earlier but also for all sensors and actuators according to the technical specifications retrieved from their data-sheets as well as for the digital environment (or environments) that the digital twin will exists. In this phase also a validation between the physical and the digital resemblance should take place, depending on the defined requirements. At the end of this phase it should be verified that the models have been properly defined and serve their purpose. If not, the process returns to the appropriate step depending on what was not adequate. If the digital model is complete and satisfactory, the next step of the process can be then applied.

The final phase of the implementation contains the connection of the physical and the digital system in order to establish communication and eventually create the digital twin. This communication among the two systems is what eventually makes a digital twin; the bi-directional flow of sensor data and control commands between the physical system and its digital counterpart. Following this aforementioned steps, a functional digital twin of an autonomous vehicle could be created. Last step would be to deploy the digital twin and utilize it for its intended purpose. If it can serve this purpose well enough and with the required level of detail then the process is completed and the process presented in this flowchart reaches its end. However, if the digital twin is not adequate then the whole process can starts from scratch and a new digital twin with different characteristics can be created. It should be mentioned here that the loop returns back to the second step of Phase 1; that is the case because the physical asset for which the digital twin is being build for has not changed but the DT itself was not adequate enough and has to be recreated. If the physical asset changes, then the whole process needs to start from scratch.

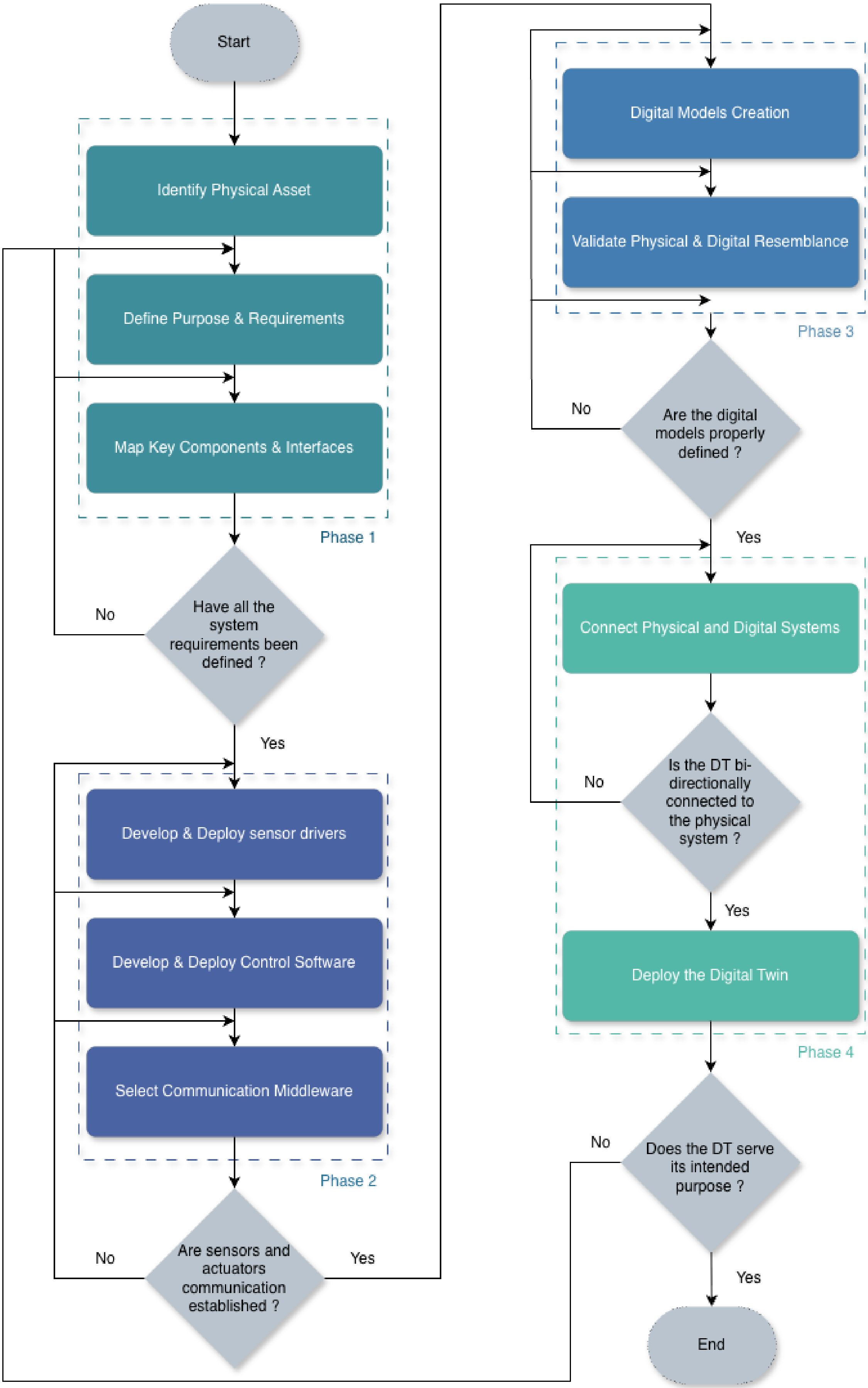


Figure 3.10: Flowchart of the conceptual framework

3.5 Conclusion, Opportunities and Challenges

Summarizing, this chapter introduces a novel, four-step conceptual methodological framework to establish digital twins for autonomous vehicles driven by the absence in literature, to the author's best knowledge, of a standardised approach to address this matter. Build upon five fundamental principles that act as stepping stones in order to create a successful DT, this framework provides guidelines for researchers and innovators in order to bridge the physical and the digital worlds, contributing to the "sim2real" convergence. It must be mentioned here that this conceptual framework presented above has been developed by exploiting prior knowledge and expertise gained from the industry domain, leveraging published work such as [311] and [12] where similar application frameworks have been developed for industrial applications. In addition, this work provides the realisation that a conceptual application framework has limited value if not validated in real conditions. Therefore, in Chapter 4 theory will be put into practice by presenting relevant experiments verifying the applicability and effectiveness of this framework.

The work presented on this chapter provides the answer to research questions RQ 2.1, RQ 2.2 and RQ 2.3. As already discussed, there is not a specific and well-defined framework or standard on how digital twins can be applied on the domain of autonomous vehicles. This realisation not only answers the first research question (RQ 2.1) but drives also the creation of the conceptual framework in discussion. The framework presented here provides a structured way of applying the DT technology into AVs and provides the answer of how can this been done, as posed in the second research question (RQ 2.2). In order for the framework to be successfully applied and serve its intended purpose not only it needs to be clear and concise but also it needs to adhere to the following basic principles of modularity, scalability, fidelity, replicability and real-time communication. This realisation, which has been discussed in detailed previously, provides the answer to the third research question (RQ 2.3).

Future potential enhancements of the framework could incorporate advanced AI integration, enabling predictive adaptation and autonomous parameter tuning within digital twins. Integration with federated learning systems and blockchain-enabled security mechanisms will further augment trustworthiness and scalability across distributed autonomous vehicle ecosystems. These directions align with the identified challenges of sensor fidelity, real-time data reliability, and cybersecurity identified in the literature review. While the framework establishes a rigorous methodological foundation, its value hinges on practical validation. The following chapter demonstrates this through experimental applications of the framework to distinct autonomous research platforms, verifying key principles including modularity, real-time communication, and fidelity. The following case studies illustrate the framework's versatility and provide a reference blueprint for future implementations within the autonomous vehicle research community.

Chapter 4

Validation Use Cases

The previous chapters have established the importance of digital twins applications in autonomous vehicles and identified the need for a standardised application framework to fully exploit the capabilities of DTs. The literature review in Chapter 2 identified a gap between the abundance of applications and the methodologies used, often resulting in a "sim2real" gap between the physical and the digital system. Chapter 3 introduced a novel conceptual methodological framework in order to allow for a structured, replicable and scalable pathway to build digital twins for autonomous vehicles.

A framework however without experimental validation to prove its usefulness and functionality holds limited value. Chapter 4 describes the validation efforts through use cases structured to document the design, construction and deployment of a digital twin for an autonomous vehicle utilizing scale cars or full-size digital vehicles. Two of the testbeds are based on a 1:10 scale vehicle equipped with a comprehensive sensor suite per intended application while in a third validation use case, due to lack of a physical full-scale vehicle a simulated system has been used. Aligning with the framework's fundamental principle of replicability, the use cases are built utilizing off-the-shelf components and open-source or widely available in the academic community software, ensuring that anyone can replicate the experiments. Each of the following three use cases focuses on different aspects of the process, progressively validating the framework's applicability and proving its usefulness. The flow of the validation use cases is visualised in Figure 4.1.

Each use case progressively validates a different phase of the aforementioned framework. The first use case validates Phases 1 and 2 of the framework with the help of a scale vehicle. The second use case validates Phases 1, 2 and 3 and uses a more advanced scale vehicle while the third use case intends to prove the overall framework applicability as well as provide a scale-up, thus uses a full-size vehicle although in a digital format.

In addition to this document and the published work, software and detailed description of the use cases are publicly available through GitHub repositories while dataset as well as videos from the validation are available through Zenodo platform. In order to properly demonstrate the use of the

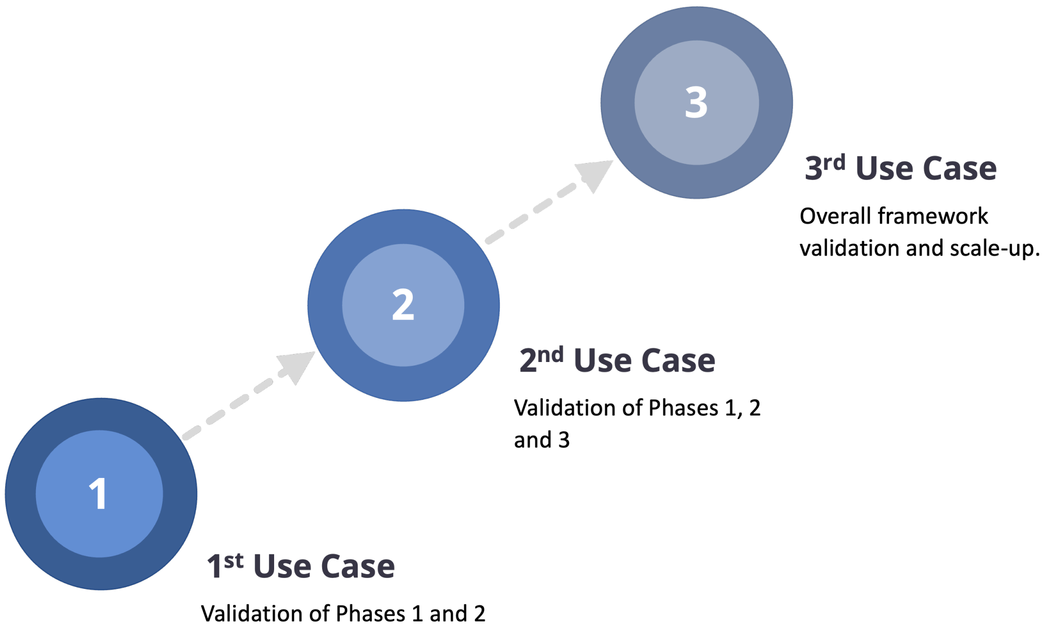


Figure 4.1: Validation Use Cases flow

framework, this chapter follows the four phases outlined previously and applies the corresponding phases during the validation use cases. Ultimately, this chapter aims to present the third main contribution of this work; the validation of the proposed framework in representative cases that would be openly available to the community for replication and further experimentation. In addition, research questions RQ 3.1, RQ 3.2 and RQ 3.3 are going to be answered.

4.1 Use Cases Key Components

In order to experimentally validate the framework in question, there are three main components that have to be defined beforehand:

1. Physical System
2. Communication Middleware
3. Digital System

In the following use cases the physical and digital systems are not the same in every one of them; that proves that the framework can be applied to different types or scales of land vehicles. The first and second use case utilize a 1:10 scale car while the third use case uses CARLA, a realistic high-fidelity vehicle simulator that represents the physical systems, due to unavailability of a full-scale physical system. Similarly, the digital counterpart is on one hand Gazebo simulator and on the other hand Matlab/Simulink. These prove not only the flexibility but also the applicability of the framework in diverse digital environments, which can be selected depending on the requirements of the digital twin that needs to be created.

Even though both physical and digital systems are diverse, one constant in our experimental validation, and a critical components for the digital twins concept, is the communication middleware being used. On every experiment, ROS/ROS2 has been used in order to facilitate both sensor and systems control as well as communication between the physical and the digital system. That turns ROS/ROS2 into an active component of the digital twin playing a crucial role in the overall architecture implementation, making ROS/ROS2 not only a great set of software libraries and tools for building robot applications but an integral component of a digital twin; one that can efficiently handle communication between the physical system and its digital counterpart.

4.2 Validation Use Case of Phases 1 and 2

Section redrafted from:

N. Sarantinoudis, G. Tsinarakis, L. Doitsidis, S. Chatzichristofis and G. Arampatzis, "A ROS-Based Autonomous Vehicle Testbed for the Internet of Vehicles," 2023 19th International Conference on Distributed Computing in Smart Systems and the Internet of Things (DCOSS-IoT), Pafos, Cyprus, 2023, pp. 726-733

The first validation use case mainly focuses on the first and second phases of the framework and describes in detail the physical asset and its characteristics, the sensor specifications and the key components and interfaces mapping as well as the communication middleware. This platform was fully developed from scratch with funding received from the Region of Crete for the development of a digital-twin driven autonomous scale testing platform for research and education purposes.

The goal of this experiment was to create a platform capable of realistically simulating a full-scale vehicle. To this end, a $1 : 10$ scale battery-powered RC car was chosen as the base platform. The vehicle underwent several modifications, and various sensors and microcontrollers were installed, as will be detailed in the following sections. The typical architecture of an autonomous vehicle [312] was implemented and modified to suit the specificities of a scale model. A Decentralised Control System [313] was employed, with dedicated microcontrollers for each system. Although this may add complexity, it provides a more accurate simulation of a full-sized vehicle and ensures a fundamental level of hardware redundancy, which is essential in autonomous vehicles.

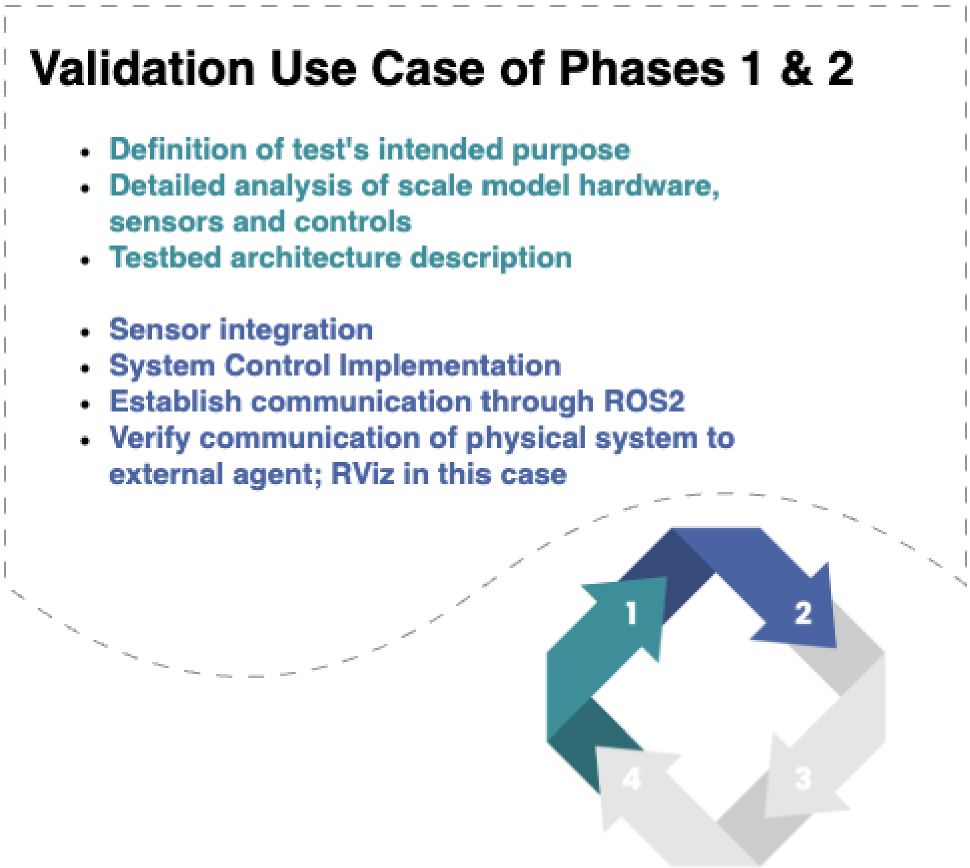


Figure 4.2: First use case relevance to framework phases

4.2.1 Experimental Platform

The platform's side profile, depicted in Figure 4.3, reveals all installed and connected sensors and systems, with the exception of the propulsion batteries. The platform is organised into a discernible four-layer structure, illustrated in Figure 4.4 and Figure 4.5. Describing the layers bottom-up, the first layer (Figure 4.4.(a)) hosts the motor (1), motor controller (2), and propulsion battery (3), which is not present on the dismantled test-bed. The second layer (Figure 4.4.(b)) includes the electronics battery (4), which is a separate power circuit from the propulsion system (also not attached on the dismantled testbed) along with the combined GSM-GPRS/GNSS/Bluetooth module (5), CPU (6), and a powered USB hub (7) for connecting all sensors to the CPU. The third layer (Figure 4.5.(a)) is equipped with the ToF sensors (8), IMU (9), and servo driver (10) for controlling throttle, brake, and steering. Finally, the fourth layer (Figure 4.5.(b)) holds the camera (11) and LiDAR sensors (12).

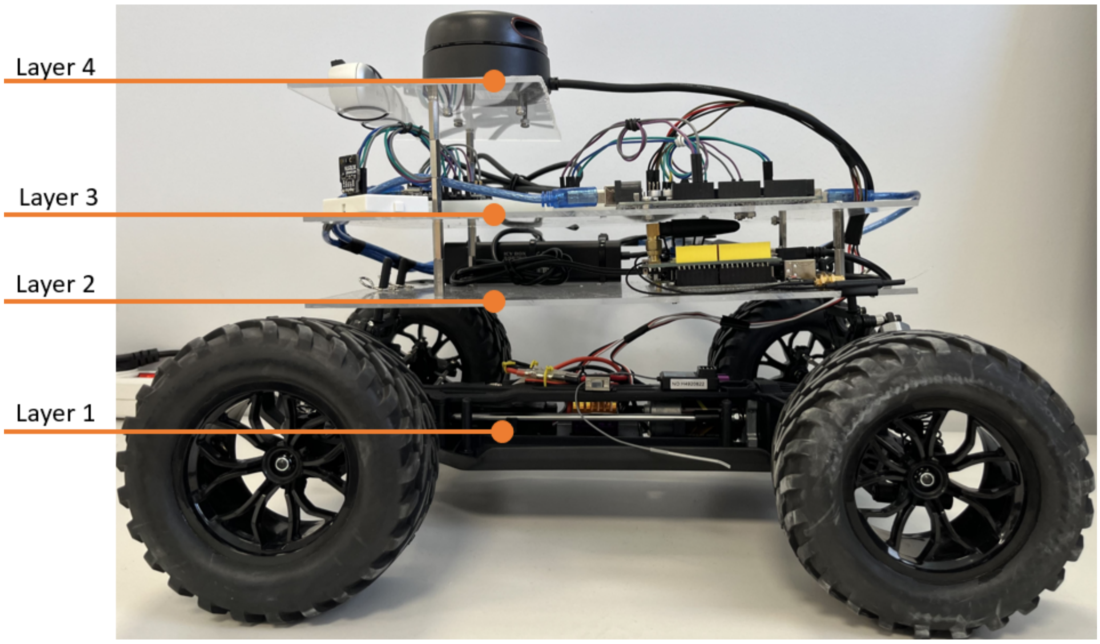


Figure 4.3: Side view of the testbed

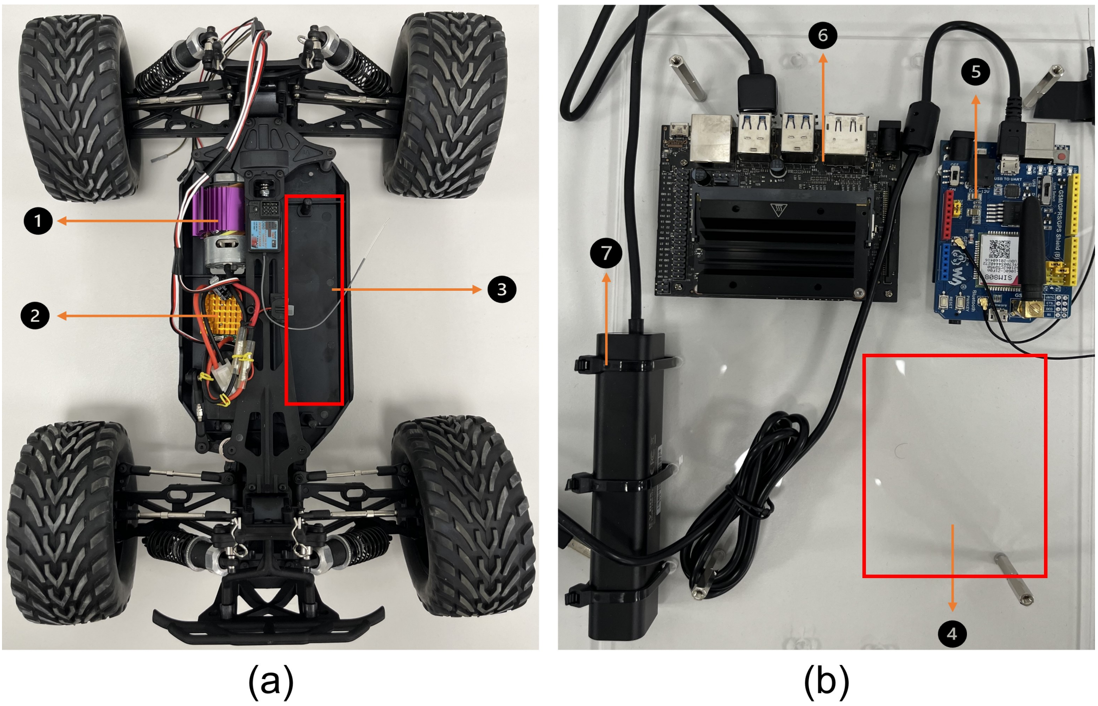


Figure 4.4: First and second layer top view

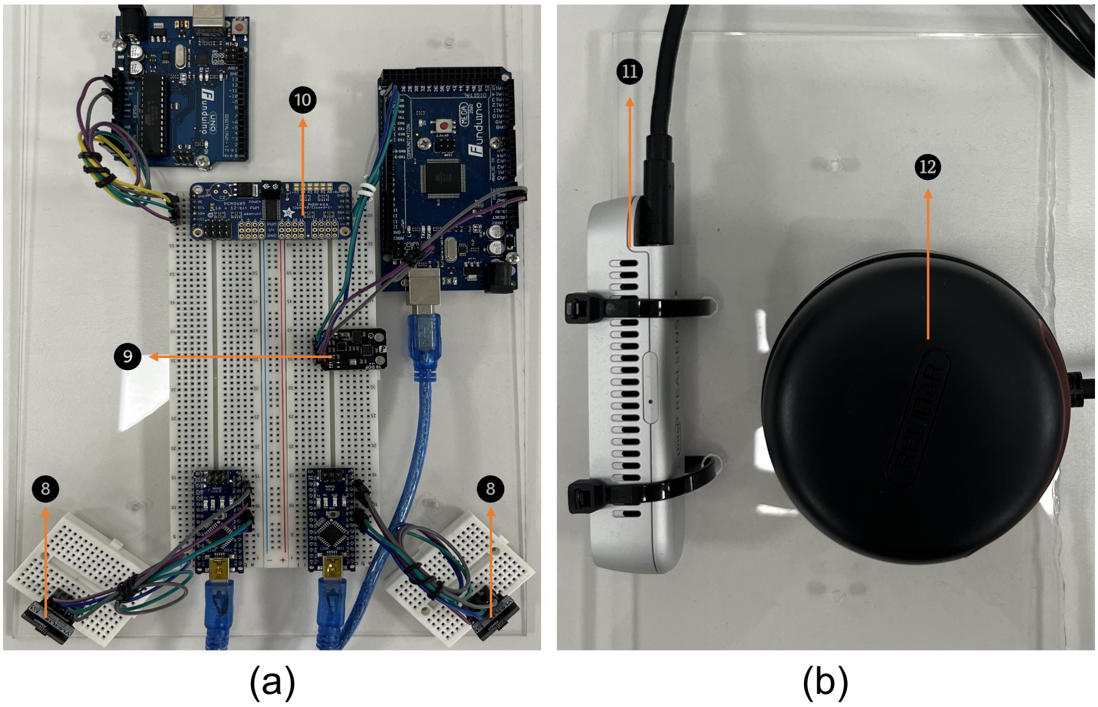


Figure 4.5: Third and Fourth layer top view

4.2.1.1 Scale Car

The vehicle selected to become the donor for this experimental platform is a typical $1:10$ scale electric radio-controlled vehicle. Specifically, VRX Racing RH1011 model [314] was used, measuring $415 \times 328 \times 156mm$, with a wheelbase of $290mm$ at the front and $295mm$ at the back, a gear ratio of $11.2:1$, tires measuring $120mm$ of diameter and $60mm$ of width, ground clearance of $35mm$ and a total weight of $2800g$. The vehicle type is usually called a "*truggy*", i.e. a combination of a truck and a buggy, equipped with four-wheel drive and long suspension travel. This type of vehicle was deliberately selected since the required equipment and sensor suite installed in the vehicle is adding a considerable amount of weight to the car. It comes with pre-installed servos for steering and throttle/brake, motor controller, propulsion battery, and radio control receiver; which eventually is removed since it is not required in an autonomous vehicle after all. The vehicle is shipped as a ready to run kit, saving also a lot of time from the required initial set up.

4.2.1.2 Onboard Sensors

Sensors play an essential role in autonomous vehicles, allowing them to detect their environment and move accurately and securely. Frequently used sensors in autonomous vehicles include Cameras, Time of Flight, Radio Detection and Ranging, Light Detection and Ranging, Inertia Measurement Units, and Global Navigation Satellite Systems. As classified in [315], these sensors are divided into two main categories: Perception Sensors and Position Estimation Sensors. A thorough description of the sensors present in the developed testbed is provided below.

4.2.1.2.1 Perception Sensors

i. Camera
Cameras are one of the most widely-used perception sensors in autonomous vehicles since they can provide high-resolution images, allowing vehicles to recognize objects and navigate in complex environments. There are a lot of different types of vision sensors; in this case a depth camera has been used, specifically Intel RealSense D415 depth camera [316]. It utilises stereoscopic depth technology with a field of view of 65 deg $\times 40$ deg, a minimum depth detection distance at $\sim 45cm$, and a depth accuracy of $< 2\%$ at $2m$ distance. The RGB sensor has a FoV of 69 deg $\times 42$ deg with a 1920×1080 pixels resolution and 30 frames-per-second frame rate. It measures $99mm \times 20mm \times 23mm$ and utilises USB 3.0 connectivity. As seen in Figure 4.3, the camera is located at the front part of Layer 4 to have an unobstructed view.

ii. Light Detection and Ranging
LiDAR sensors, which use laser beams to detect objects and calculate the distance from their centre, are also commonly used in autonomous vehicles, since they can provide accurate 3D information about the surrounding environment. However, three-dimensional LiDARs are

considerably expensive and bulky for a small-scale platform. A two-dimensional LiDAR has been used, the Slamtec RPLIDAR A2 [317], which has measuring capabilities ranging from $0.2m$ up to $16m$ and an angular resolution of 0.9 deg. The accuracy error is 1% for $<= 3m$ range, 2% between $3m$ and $5m$ and 2.5% for range greater than $5m$. Physically, it measures $76mm \times 41mm$ and weighs only $190g$, making it a very compact and efficient sensor. In order to have an unobstructed 360 deg view, it is placed in the topmost layer of the platform together with the camera.

iii. Time of Flight
Time of flight sensors are a type of 3D imaging sensor that measures the time it takes for light to travel from the sensor to an object and back. ToF sensors emit a short pulse of light, such as an infrared laser, and measure the time it takes for the light to reflect back from the object it bounces to the sensor. By measuring the time of flight of the light pulse, ToF sensors can calculate the distance to an object. Pimoroni's VL53L1X [318] sensors have been used, having measuring capabilities from $4cm$ to $400cm$ with a 27 deg FoV and a $\pm 25mm$ accuracy. There are two sensors installed in the platform on the front left and right corners of the third layer (see Figure 4.3) in order to detect lower and close vicinity objects, that the depth camera or the LiDAR might not be able to perceive.

4.2.1.2.2 Position Estimation Sensors

i. Global Navigation Satellite System
GNSS plays an essential role in autonomous vehicles, providing them with accurate position, navigation, and timing information in order to localize themselves and plan their route. A GNSS-compatible system can use satellites not only from the well-known Global Positioning System but also from other networks increasing its accuracy and reliability. The GNSS receiver installed on the experimental platform has 33 tracking and 99 acquisition channels and is of L1 GPS C/A type. It has a sensitivity of $-165dBm$ and an accuracy of $< 2.5m$ CEP. The GNSS system is part of an integrated Waveshare GNSS/GPRS/Bluetooth HAT module [319] installed in the second layer of the architecture, paired with an Arduino Uno required for its operation, since this is a Hardware Attached on Top unit (i.e. a unit that needs to be placed on top of a microcontroller to become operational) and not a standalone module.

ii. Inertia Measurement Unit
An IMU is a sensor that measures and reports a vehicle's specific force, angular rate, and surrounding magnetic field, using a combination of accelerometers, gyroscopes and magnetometers. IMUs are commonly used in autonomous vehicles to provide accurate and reliable measurements of the vehicle's orientation and motion while the magnetometer measurements are used to define (after appropriate calculations) the orientation, similar to a magnetic compass. The testbed is equipped with DFRobot 10 DoF IMU Sensor [320] utilizing ADXL345 accelerometer, ITG3200 gyroscope, HMC5883L magnetometer and

BMP280 temperature and barometric pressure sensor. It is quite a small sensors measuring only $26mm \times 18mm$. It can be found in the third layer of the architecture, as isolated as possible, to have the least amount of interference from the electronics and motors (servos, propulsion system) of the testbed, since IMUs are very susceptible to electromagnetic interference.

4.2.1.3 Central Processing Unit

An autonomous system's CPU must be robust enough to handle inputs from various sensors while ensuring energy efficiency for prolonged autonomous operation. NVIDIA specialises in developing embedded systems tailored to robotics and autonomous machines. In this instance, an NVIDIA Jetson Nano 4GB [321] Developer Kit has been used. This developer kit is a compact, energy-efficient computing device intended for embedded use, including applications like autonomous navigation. It features a quad-core ARM Cortex-A57 CPU, a 128-core NVIDIA Maxwell GPU, and 4GB of LPDDR4 RAM. It combines small size and substantial computing power making it an excellent choice for autonomous navigation systems. The GPU is specifically optimised for Machine Learning tasks, facilitating the development of sophisticated neural networks for perception and decision-making. Moreover, the NVIDIA Jetson Nano 4GB is engineered for low power usage, making it suitable for embedded applications where battery life extension or operation in power-constrained environments is crucial. Additionally, it offers a plethora of input/output options, including 4 USB 3.0 and USB 2.0 micro ports, Gigabit Ethernet, and GPIO headers supporting I2C, I2S, SPI, and UART protocols. Storage options include a microSD card or an external M.2 SSD/NVMe disk. These powerful features and connectivity options are packed into a compact design, measuring just $100mm \times 79mm \times 30mm$, making it perfect for a 1:10 scale platform..

4.2.1.4 Communication Hardware

Such testbeds are utilised to kickstart the experimental development of sophisticated autonomous systems that can interact with their environment, collect and share data, and make informed decisions in real time. This can enhance safety, improve efficiency, and enable the development of new autonomous applications. Thus, a critical component is the ability to communicate and interact with other devices and systems. In order to facilitate this need, the platform is equipped with multiple wireless data transfer technologies. The aforementioned Waveshare HAT [319], except GNSS, it also supports GSM/GPRS connectivity with the use of a SIM card, compatible with four bands (GSM 850/EGSM 900/DCS 1800/PCS 1900 MHz) as well voice and SMS text messaging. In addition, Bluetooth 3.0 connectivity is offered from the same board. Last but not least, a TP-Link Archer T2U AC600 Wi-Fi dongle has been directly connected to one of the NVIDIA Nano USB ports, providing connectivity to both $2.4GHz$ and $5GHz$ bands.

4.2.1.5 Additional Hardware

The testbed setup includes several microcontrollers from the Arduino family, specifically the Arduino Nano, Arduino Uno, and Arduino Mega, which are used in designing the DCS system. Each sensor or subsystem is interfaced with a microcontroller using the Inter-Integrated Circuit (I^2C) protocol, while each Arduino communicates with the CPU via USB using serial communication. This setup facilitates easier management of individual sensors, provides redundancy in hardware failure situations, and models a full-sized vehicle more accurately, which typically features dedicated controllers for each system, all connected eventually to the ECU. Additionally, the platform is equipped with a PWM/Servo Driver to manage steering and throttle/brake servos, controlled similarly through an Arduino, as well as a USB hub with an external power source to connect all devices to the CPU and supply the necessary power for all sensors and microcontrollers. Furthermore, the vehicle includes a DC/DC converter to maintain a stable $5V$ voltage for the electronics, regardless of fluctuations in the battery's output voltage caused by its State of Charge (SoC).

A comprehensive design methodology has been employed prior to building this test platform. Each component has undergone individual testing, and the compatibility across systems was verified and validated before the platform's final assembly. The equipment utilised consists from off the shelf components, accompanied by extensive documentation and software to facilitate connectivity and operation. To assist the reader in comprehending the platform's architecture, which has been described incrementally, a detailed schematic is presented in Figure 4.6.

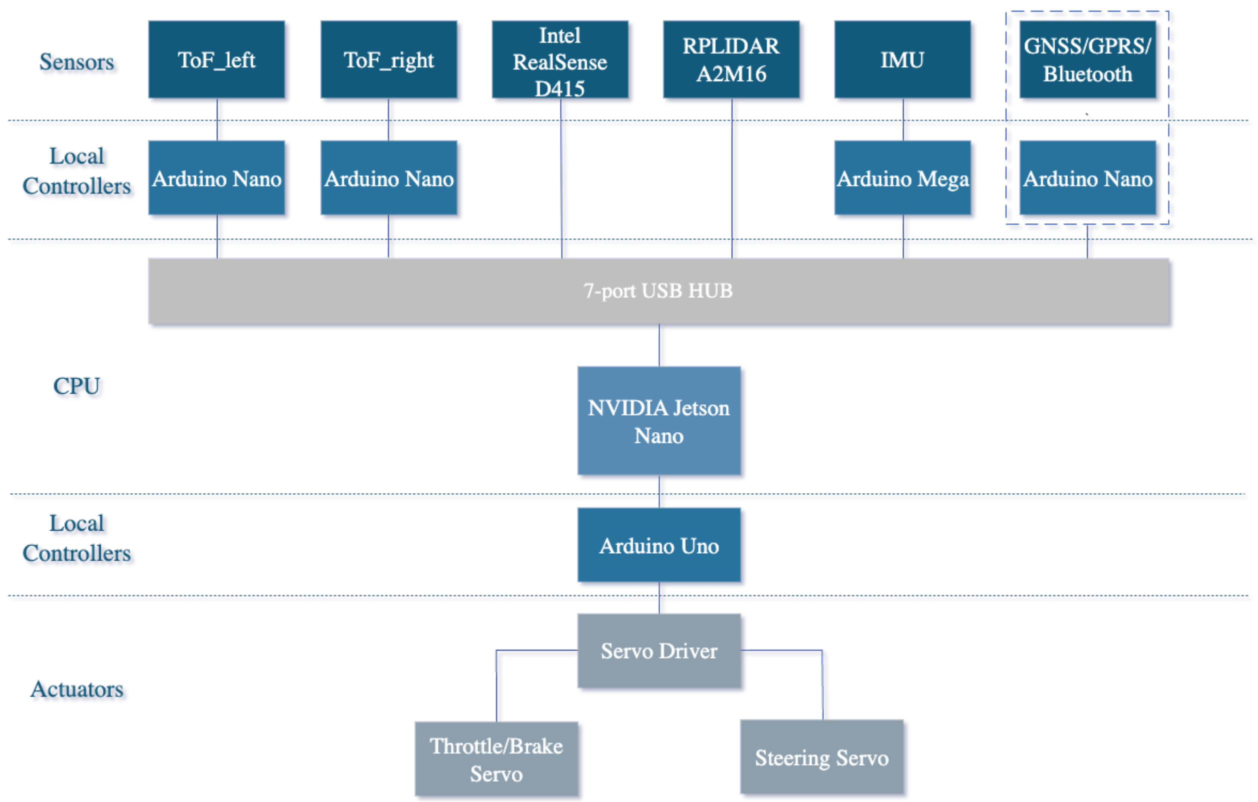


Figure 4.6: Block Diagram of the testbed

4.2.2 Software

In addition to the hardware development of the testbed, custom software packages to achieve the intended functionality and communication across the CPU and the supporting microcontrollers have to be developed. Since the platform is intended for research purposes, ROS [322] has been selected to speed up the development and integration of sensors and control systems. ROS is an open-source software framework designed for robotics applications. It offers a collection of libraries, tools, and drivers that facilitate the creation of complex robotics systems, such as autonomous vehicles. It can also be used to develop autonomous vehicle perception, decision-making, and control systems offering a modular and scalable architecture that permits the integration of various sensors and control components into a single system. This allows developers to create autonomous systems that are adaptable to a variety of environments. ROS is also largely supported by the community [323], offering a vast selection of libraries and tools for computer vision, machine learning, and motion planning as well as libraries for the integration of almost any sensor. Also, ROS has already been proven throughout the years and will help to have a shorter development cycle for the intended solutions. It is truly multi-platform and even though it is 100% open-source it is commercially friendly and has the support of the industry, making it an ideal software stack for the current application.

ROS framework includes also a 3D visualisation utility, called RViz. It provides a real-time representation of data generated by ROS-based applications and enables developers to visualize the data generated in a 3D environment, which facilitates application debugging, testing and optimisation. It offers a variety of display formats, such as point clouds, images, and meshes, along with interactive controls for modifying sensor settings and other parameters.

ROS uses a publish/subscribe architecture model. This publish-subscribe model is a communication paradigm to exchange messages between distinct nodes. Nodes in ROS are autonomous processes that execute specific duties, such as processing sensor data or executing control commands. These nodes communicate by publishing and subscribing to specific ROS topics. A ROS topic is a named channel that facilitates message exchange between nodes. A node can publish a message to a topic, and other nodes that are interested in receiving the message can subscribe to the topic. Multiple nodes can publish and subscribe to the same topic. Also, multiple nodes can publish and subscribe to multiple topics. When a node publishes a message to a topic, all nodes presently subscribed to that topic receive the message. Each node receives the message and performs the required processing based on the message's content.

This standard architecture was utilised in the creation of this testbed. The essential node, known as the ROS core, subscribes to the publisher nodes of each sensor. Sensors including cameras and LiDAR had specialised ROS packages developed by their manufacturer which have been integrated into this framework. A ROS community package was employed to read and decode GNSS messages, while custom packages for the IMU, ToF, and Servo Driver were created to enable communication with the CPU. This accounts for another reason the local controllers depicted in Figure 4.6 were implemented. These controllers function as middleware, collecting sensor readings via low-level protocols, compiling ROS messages, and directing them to the ROS core. Table 4.1 provides a detailed description of all the topics published by each node.

4.2.3 Validation

To assess the operational capabilities of the proposed testbed, it is essential to examine the sensor data and servo operations. A straightforward method for achieving this is leveraging the RViz tool included in the ROS framework to both visualize and validate the data. As previously mentioned, each component functions as a node that broadcasts a specific topic. These topics can either be accessed via RViz or directly through a terminal, each conforming to a predetermined format known as message, which depends on the nature of the data being communicated. Messages in ROS are represented using a straightforward, text-based protocol called the Message Definition Language, which details the structure and contents of the message. Each message comprises of one or more fields, featuring distinct names and data types. The spectrum of supported data types ranges from basic types like integers, floating-point value and strings, to more intricate types such as arrays, nested messages, and timestamps. Once a message is defined, nodes can utilize it to transfer data over ROS topics using a publish-subscribe model. Table 4.1 encapsulates all relevant published topics, sorted by sensor, with the message types clearly specified.

Table 4.1: Published ROS Topics

Sensor	Topic Published	Message Type
Camera	/camera/color/camera_info /camera/color/image_raw_info	sensor_msgs/CameraInfo sensor_msgs/Image
	/camera/color/metadata_info	realsense2_camera/Metadata
	/camera/depth/camera_info	sensor_msgs/CameraInfo
	/camera/depth/image_rect_raw	sensor_msgs/Image
	/camera/depth/metadata_info	realsense2_camera/Metadata
	/camera/extrinsics/depth_to _color	realsense2_camera/Extrinsics
	/camera/realsense2_camera _manager/bond	bond/Status
	/camera/rgb_camera/auto_exposure _roi/parameter_descriptions	dynamic_reconfigure /ConfigDescription
	/camera/rgb_camera/auto_exposure _roi/parameter_updates	dynamic_reconfigure/Config
	/camera/rgb_camera/parameter_descriptions	dynamic_reconfigure /ConfigDescription
	/camera/rgb_camera/parameter_updates	dynamic_reconfigure/Config
	/camera/stereo_module/auto_exposure_roi /parameter_descriptions	dynamic_reconfigure /ConfigDescription

	/camera/stereo_module/auto_exposure_roi /parameter_updates	dynamic_reconfigure/Config
	/camera/stereo_module parameter_descriptions	dynamic_reconfigure /ConfigDescription
	/camera/stereo_module/parameter_updates	dynamic_reconfigure/Config
GPS	/gps/fix	sensor_msgs/NavSatFix
	/gps/heading	geometry_msgs /QuaternionStamped
	/gps/time_reference	sensor_msgs/TimeReference
	/gps/vel	geometry_msgs/TwistStamped
ToF	/left_tof/left_tof	std_msgs/String
	/right_tof/right_tof	sensor_std/String
LiDAR	/scan	sensor_msgs/LaserScan
IMU	/imu/imu	std_msgs/String
Servo Driver	/servo_control/servo	std_msgs/UInt16

Subscribing to the aforementioned messages allows for collecting and displaying all sensor data. For instance, if a setting needs adjustment or an actuator requires control, you can do so by publishing to the correct topic. To manage the platform's throttle, braking, and steering, you need to post to the *servo_control* topic. The visualisation of topics from the Camera and LiDAR is facilitated by RViz, as illustrated in Figure 4.7. In a top-down view, LiDAR data is shown in the central gridded window, while at the bottom part, the stereo camera feed is displayed; the left side shows the depth, and the right side displays the RGB image.

The remaining sensors, such as the GPS, ToF, and IMU, are not depicted in RViz because their outputs are primarily text-based. Instead, the results are shown by presenting the message output via the terminal. This is illustrated in Figure 4.8, where (a) and (b) display the ToF sensors' readings at a specific timestamp, (c) shows the parsed NMEA message, and (d) the IMU readings. It's important to note that in (b), due to the sensors' range limits, a reading of -1 occurs, indicating that no obstacle is detected within the sensor's maximum distance of $400cm$. Additionally, in (c), as the screenshots were taken in a lab setting, no satellite fix was available; however, the GPS functionality was confirmed in an open environment where a reliable satellite fix could be obtained.

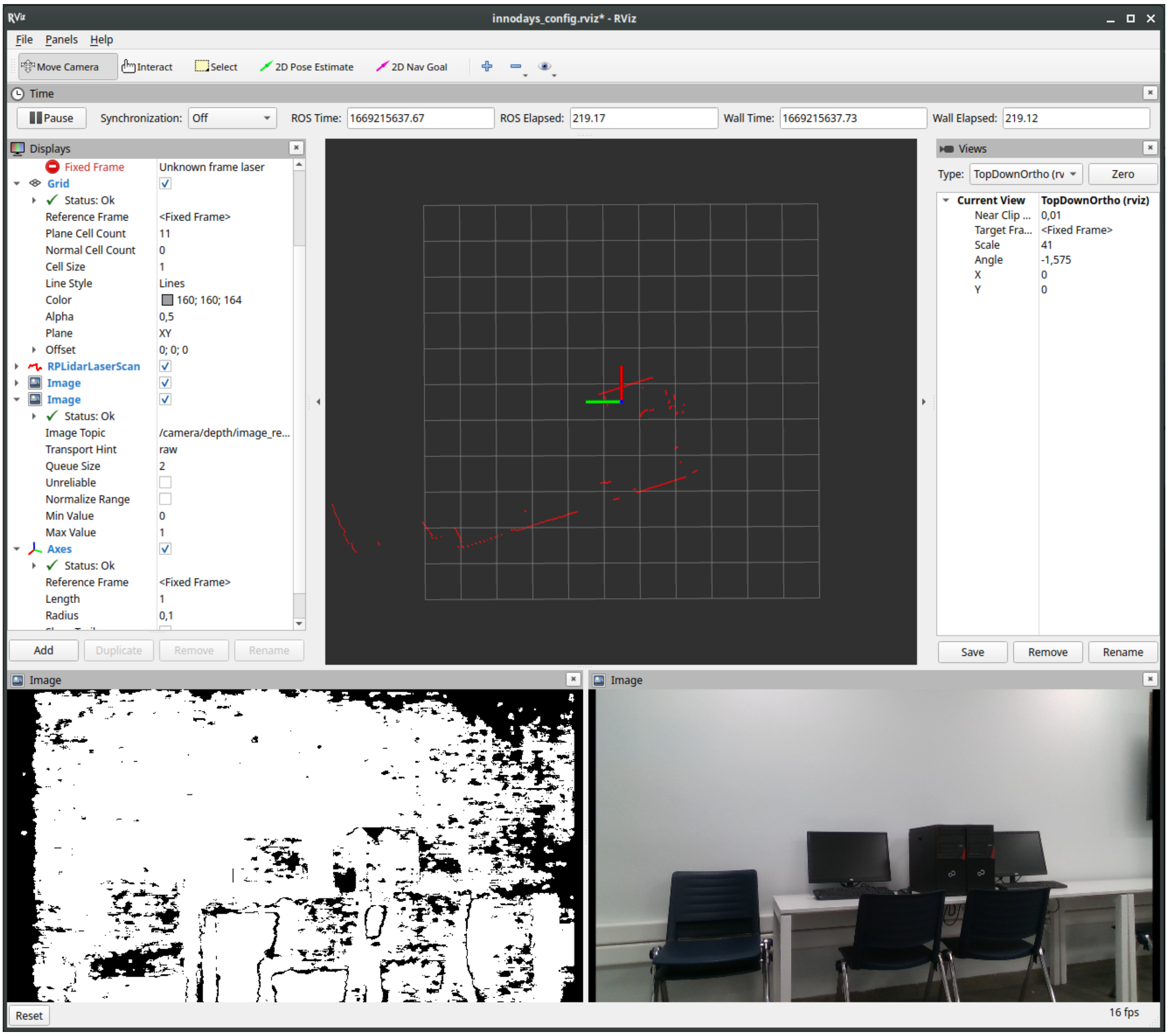


Figure 4.7: Visualisation of LiDAR and Stereo Camera in RViz

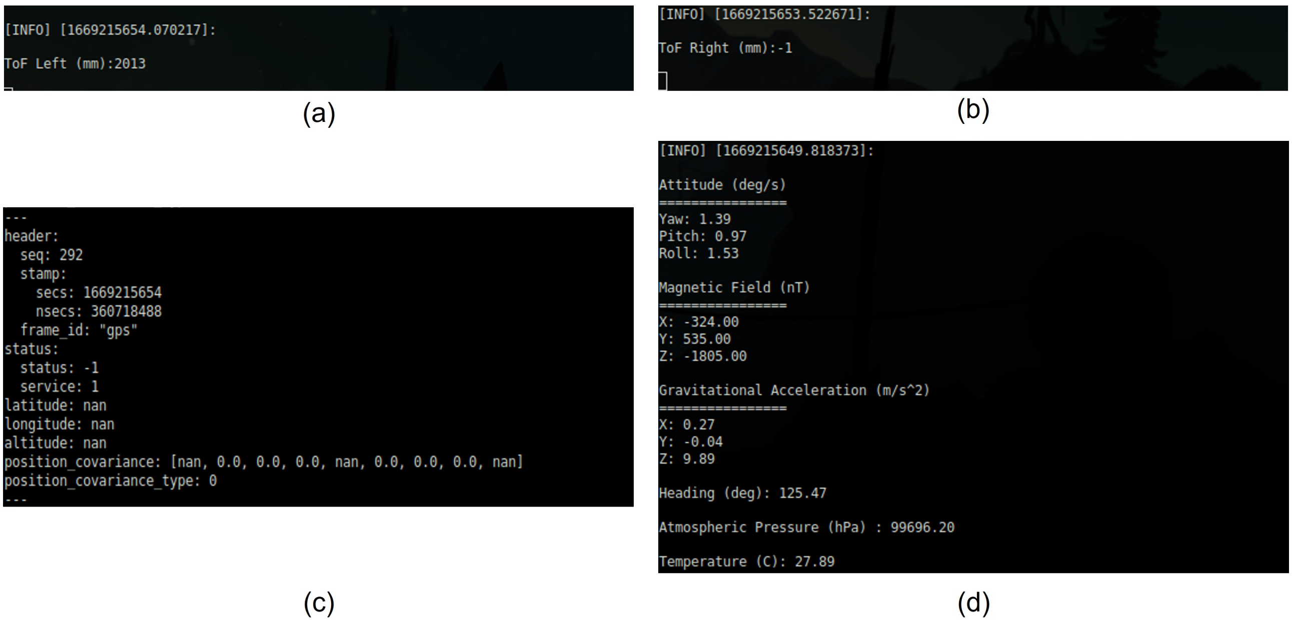


Figure 4.8: Visualisation of ToF (a,b), GPS (c), and IMU (d) messages

4.2.4 Conclusion and Next Steps

This experiment presents a ROS-based testbed for autonomous vehicles, which integrates multiple perception sensors, such as Stereo Cameras, LiDARs, and Time-of-Flight sensors, along with localisation sensors such as GPS and IMU, to enable autonomous navigation. Wi-Fi, Bluetooth, and GPRS communication infrastructure has also been integrated into the testbed. ROS framework allows for easy integration and visualisation of sensors and systems and offers simulation capabilities through the integrated Gazebo simulator. This platform provides a flexible and scalable framework for researchers to rapidly prototype and test their navigation and control algorithms.

In addition, the proposed platform through its design meets all the requirements to be used as a basis for a digital twin of the system. According to the flowchart presented in Figure 2.7 at the beginning a detailed identification of the physical asset is performed along with the definition of its purpose and requirements. Then a detailed mapping of the key components is documented and the overall architecture is visualised. Confirming that all these have been properly completed, both the sensor drivers and the control software have been deployed and the communication middleware has been established. Thus, both Phase 1 and Phase 2 on the aforementioned framework have been successfully applied, proving its applicability in real life experimentation.

Future extensions of this platform may include redesigning electrical wiring for easier sensor connection and replacement, using 3D-printed components to minimize construction time, and adopting the newest ROS versions, such as ROS2 or newer higher accuracy sensors. Many of these suggestions have been implemented in the second use case. Overall, the platform design and development procedure and the presented sensors and connectivity mechanisms provide a flexible and scalable low-cost testbed for efficient research and development as well as operation and deployment of autonomous vehicles experiments. Also, as discussed it lays the foundation for the creation of a digital twin by putting to the test the two first phases of the conceptual framework.

4.3 Validation Use Case of Phases 1, 2 and 3

Section redrafted from:
N. Sarantinoudis, N. Vitzilaios and G. Arampatzis, “A new open-source RoboRacer simulator using ROS2 and Gazebo” - **Submitted on IEEE Robotics and Automation Practice (RA-P) - Currently under review**

The second use case validates the first, second and third phases of the conceptual framework. This use case, in addition to the first one, focuses also on the implementation of the digital model of the vehicle, the sensors as well as the digital environment and compares the physical and the digital system to ascertain similarity. This validation use case has been conducted at the Unmanned Systems and Robotics Lab of the Department of Mechanical Engineering at the College of Engineering and Computing at the University of South Carolina during the author’s Fulbright visiting research scholarship.

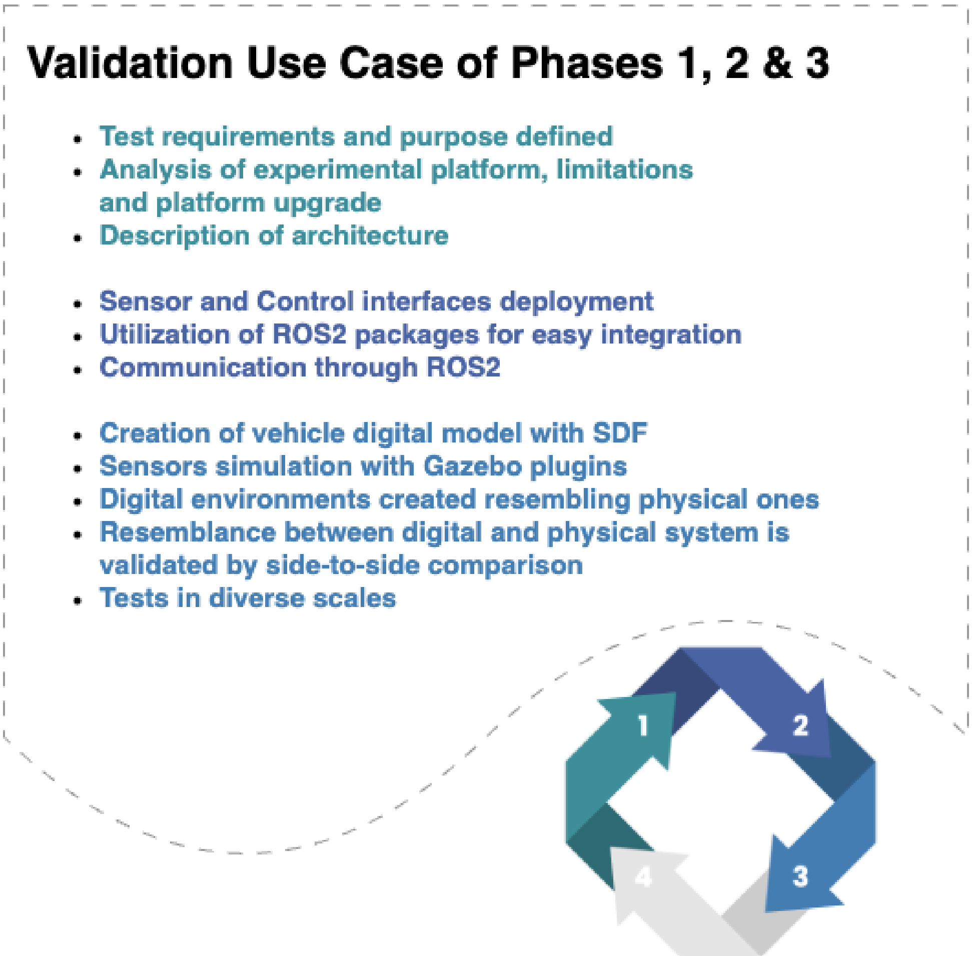


Figure 4.9: Second use case relevance to framework phases

4.3.1 Experimental Platform

Across literature there is an abundance of scale cars used in academic set-up for easy and cost effective autonomous navigation research and experimenting. Such examples are the MIT Racecar [324], the Berkeley Autonomous Racing Car (BARC) [325], the ASIMcar [326], the JetRacer [327] and most notably the F1Tenth [328] recently renamed as RoboRacer [329]. RoboRacer not only is an open-source autonomous racing platform which everyone can build following the publicly available detailed information and guidelines, but also hosts autonomous racing competitions in tandem with robotics conferences, has a dedicated community and supports the education of the new generation of engineers. Such a platform has a profound significance for the community and served a crucial role over the past years, however potential shortcomings and required updates that would greatly benefit not only RoboRacer as a platform but also the community overall have been identified.

Thus, instead of building a new platform like the previous use case, in this the target is to use an existing RoboRacer platform and bring it up-to-date with the newest hardware and software in order to future proof it. This work is publicly available through the repositories listed below to the community.

4.3.1.1 Existing Platform

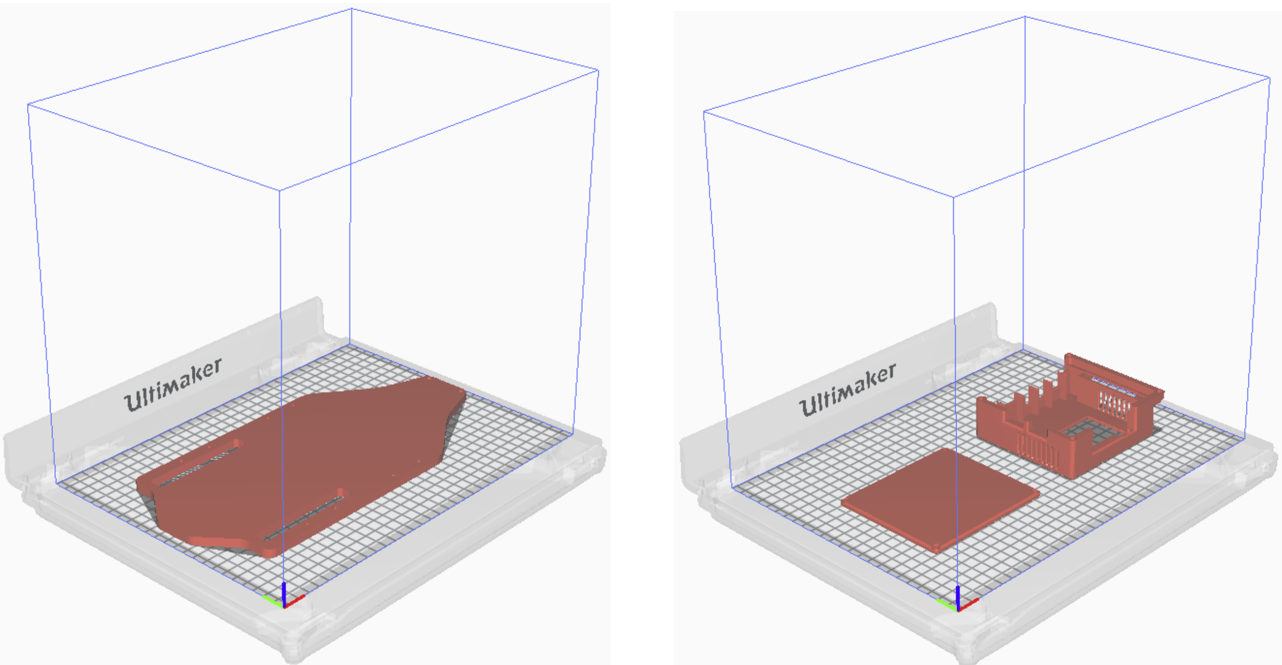
The first version of RoboRacer has been originally designed in 2016 and is presented in Figure 4.10. Since then there have been various alterations and hardware changes. The most important are the compute module changes; initially starting from the Jetson TX2 Developer Kit, then replaced by the Jetson Xavier NX Developer Kit, both by NVIDIA. These boards are not produced any more and have not only reached their EoL but also are not capable to support the latest versions of NVIDIA JetPack software, the latest Linux headers and consequently the newest version of ROS2. A recent Bill of Materials update (June 10, 2024) suggests the use of Jetson Orin Nano, however no more guidelines have been updated yet and still all refer to the previous hardware . At the same time, the use of ROS2 Foxy Fitzroy is suggested, but similarly this ROS2 distribution has reached its EoL too. In addition, the suggested simulator utilises RViz for basic simulation tasks while some more advanced efforts [330,331] support either older ROS2 versions only or use Gazebo Classic simulator, which reached its EoL in January 2025.

Figure 4.10: RoboRacer (formerly F1-Tenth) Original Platform

Based on these, considerable effort has been concentrated to upgrade an existing RoboRacer platform. Following, not only the physical installation of the Jetson Orin Nano board onto the vehicle and the use of new 3D-printed base plate and case but also the installation of the F1 Tenth software stack (with the appropriate modifications) in order to work with ROS2 Humble Hawksbill (ROS2 LTS version at the time of experimentation) as well as the creation of a new detailed 3D model of the RoboRacer in order to be used with Gazebo Simulator. In order to keep the cost of the upgrade low and since both the camera (ZED stereo camera) and the LiDAR (Hokuyo UST-10LX) have drivers still supported by the newest ROS2 version the author opted to reuse them in the upgraded platform. The same goes for the electronic speed controller and the main power board of the system.

4.3.1.2 Hardware Upgrades

An overall upgrade of the existing RoboRacer system starts from the physical installation of the new Jetson Orin Nano on the vehicle itself. The existing system was completely dismantled and in order to seamlessly integrate the new board with the existing sensors, power board and electronic speed controller, a new base plate had to be 3D printed. An existing design, which provided the overall shape and mounting points onto the vehicle frame has been adapted for this purpose. In addition, a case for the main board has been also 3D printed to provide not only the required mounting points but also protect the Jetson Orin Nano Developer Kit. In Figure 4.11 the 3D models for the aforementioned parts can be seen. Both the base plate and the case, which consists of two parts, require roughly 5 hours of printing time in an Ultimaker S5 3D printer.



(a) Base Plate (b) Board Case

Figure 4.11: (a), (b) The 3D printed parts required for the platform upgrade

As a consequence of the new base plate and case, an overall restructure of the components placement and re-wiring has taken place. The sensors reside in the front of the car, with the LiDAR positioned on top of the camera, in a bracket created for the specific scale car model, a Traxxas Ford Fiesta ST 1/10 4WD Rally Car. The NVIDIA developer board is at the centre of the vehicle to maintain a central weight balance and the electronic speed controller (VESC 6 MkVI) stands below the power supply module on the back end of the car. The hardware in question installed onto the 3D-printed base plate can be seen in Figure 4.12.

As mentioned earlier, the most important upgrade of the existing platform is the replacement of

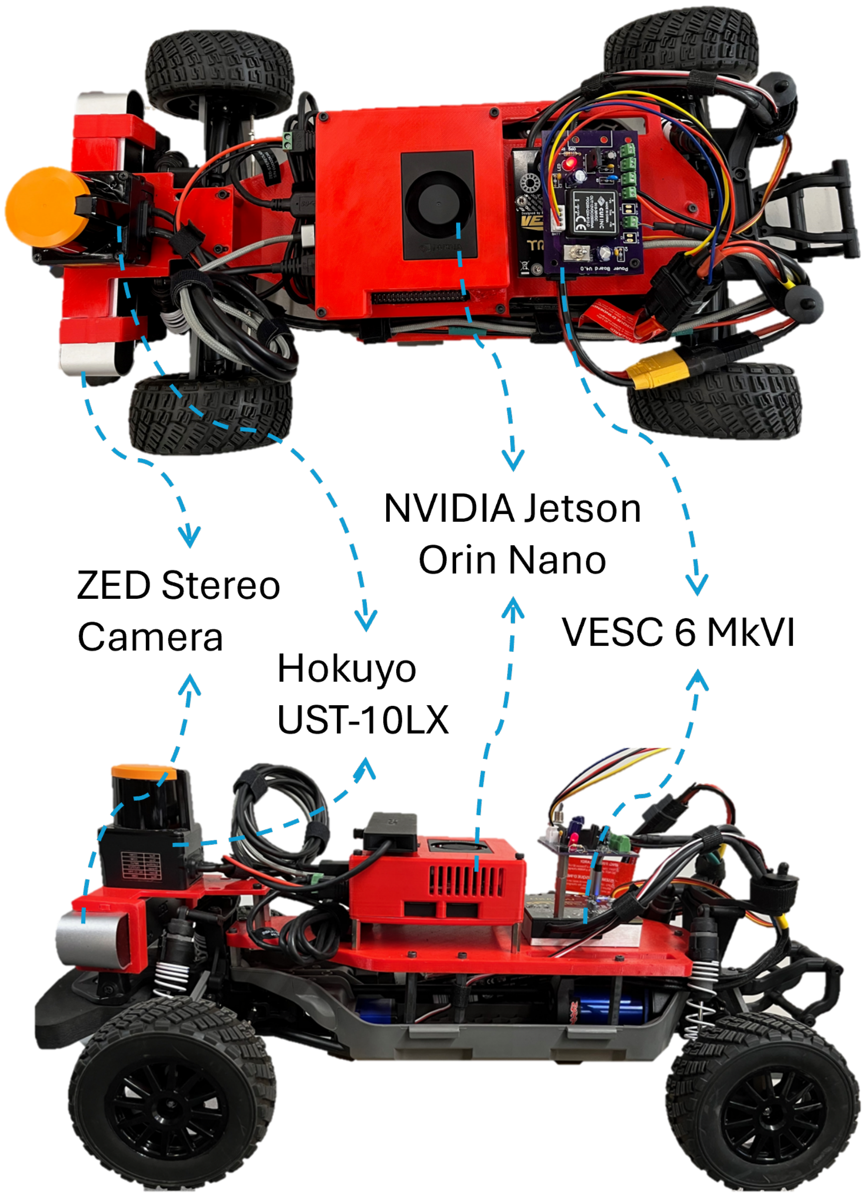


Figure 4.12: Overview of the updated vehicle

the previous generation board with the newest Jetson Orin Nano Developer Kit. The previously suggested board, was not only less powerful but has also reached its EoL and consequently does not support Jetpack 6.0, NVIDIA's software stack for Jetson Developer Kits, which is based on Ubuntu 22.04 required for ROS2 latest versions. A comparison between the two boards can be seen in Table 4.2. It should be mentioned here that even though the Orin Nano supports microSD storage and is the proposed way of setting up the board, a well-documented [332] error causes sometimes the loss of data from the microSD card. Thus, a 500GB Samsung 980 SSD NVMe has been used as boot and storage device on this set-up, not only providing stability and read/write speeds much higher than a microSD card but also additional storage required for recording experimental data since couple of minutes of an experimental run produce several GBs of data, especially from the stereo camera.

It should be mentioned here that the both the camera and the ESC have to be connected to the board through USB while the LiDAR has to be connected over Ethernet. The overall system utilises the

Table 4.2: Main On-Board Computer Comparison

	Jetson Orin Nano	**Jetson Xavier NX**
CPU	**6-core ARM Cortex-A78AE 64-bit 1.5MB L2 + 4MB L3**	6-core ARM NVIDIA Carmel 64-bit CPU 6MB L2 + 4MB L3
GPU	**1024 CUDA cores and 32 Tensor cores**	384 CUDA cores and 48 Tensor cores
Memory	**8GB 128-bit LPDDR5 @ 68GB/s**	8GB 128-bit LPDDR4x @ 51.2GB/s
Software	**Ubuntu 22.04 base**	Ubuntu 20.04 base
Storage	**microSD & NVMe**	microSD & NVMe & 16GB eMMC

integrated Wi-Fi for external connectivity.

4.3.1.3 Software Upgrades

The hardware upgrade of the platform, as described above, would not be useful however if not accompanied by the corresponding software. Following, the required upgrades that would render the platform fully functional and ready to run are described. At first, the newest version of NVIDIA Jetpack has to be installed on the board itself. At the moment this work was being compiled the newest available stable version was JetPack 6.0 with Linux 36.3, using Linux kernel 5.15, UEFI based bootloader and Ubuntu 22.04 root file system. The later has a great significance since ROS2 Humble Hawksbill, the LTS version of ROS2 used in this use case, is supported in Ubuntu 22.04 and newer, allowing for an easier and well-documented installation. JetPack 6.0, allows to fully exploit the boards capabilities, however, some more tweaking is required before proceeding to the installation of ROS2 on the board. It has been identified that JetPack 6.0 does not come with full joystick integration, required for remote control of the RoboRacer vehicle during testing due to the customised Linux kernel that NVIDIA uses. Thus, kernel customisation in order to connect the controller had to take place. In order to perform the required kernel rebuild, first of all one must consult NVIDIA's Developer Guide for the corresponding Linux version (Linux 36.3) and use a host computer with Ubuntu 22.04. Before the rebuild process takes place, some configurations have to be enabled on the defconfig file (can be found under *.../kernel/kernel-jammy-src/arch/arm64/configs/defconfig*) by simply adding the following entries at the end of the file:

- CONFIG_LOGITECH_FF = y
- CONFIG_INPUT_JOYDEV = y
- CONFIG_INPUT_JOYSTICK = y

After the rebuild process has been completed, the *Image.iso* file created under *.../source/kernel/kernel-jammy-src/arch/arm64/boot/Image* has to be copied to the board and placed on */boot* replacing the existing one and allowing for the detection of the controller.

Table 4.3: Software Stack Dependencies

ROS2 Package	Info
ackermann_msgs	ROS messages to handle ackermann steering commands
urg_node	Hokuyo LiDAR drivers
joy	Joystick drivers
teleop_tools	Teleoperation tools
vesc	ESC drivers
ackermann_mux	Multiplexing ackermann messages
zed-ros2-wrapper	ZED camera drivers

Having validated that the controller can now be detected as an input device, the next step is to proceed with the installation of ROS2. Humble Hawksbill ROS2 version has been selected instead of the Iron Irwin version, which was the latest version at the time of conducting this work, because the support for Humble will continue until May 2027 since its an LTS version while Iron support will cease in November 2024, which has already past at the time of compilation of this dissertation. After verifying the proper installation of ROS2 through the demos, the installation of the software stack that controls the vehicle can now take place. The starting point was the existing software on roboracer.ai and the corresponding repo. This software has been created for the previous version of ROS2 (Foxy Fitzroy) and is no longer compatible with Humble, thus multiple errors are met upon trying to build it on the updated system, which have been tackled and corrected. There are multiple external dependencies, listed in Table 4.3 that have to be met in order to properly control the whole system and minor or major adjustments had to be made, however a fully working and tested software stack for ROS2 Humble is now available to the community through the public repositories listed in Table 4.5.

4.3.2 Digital Model

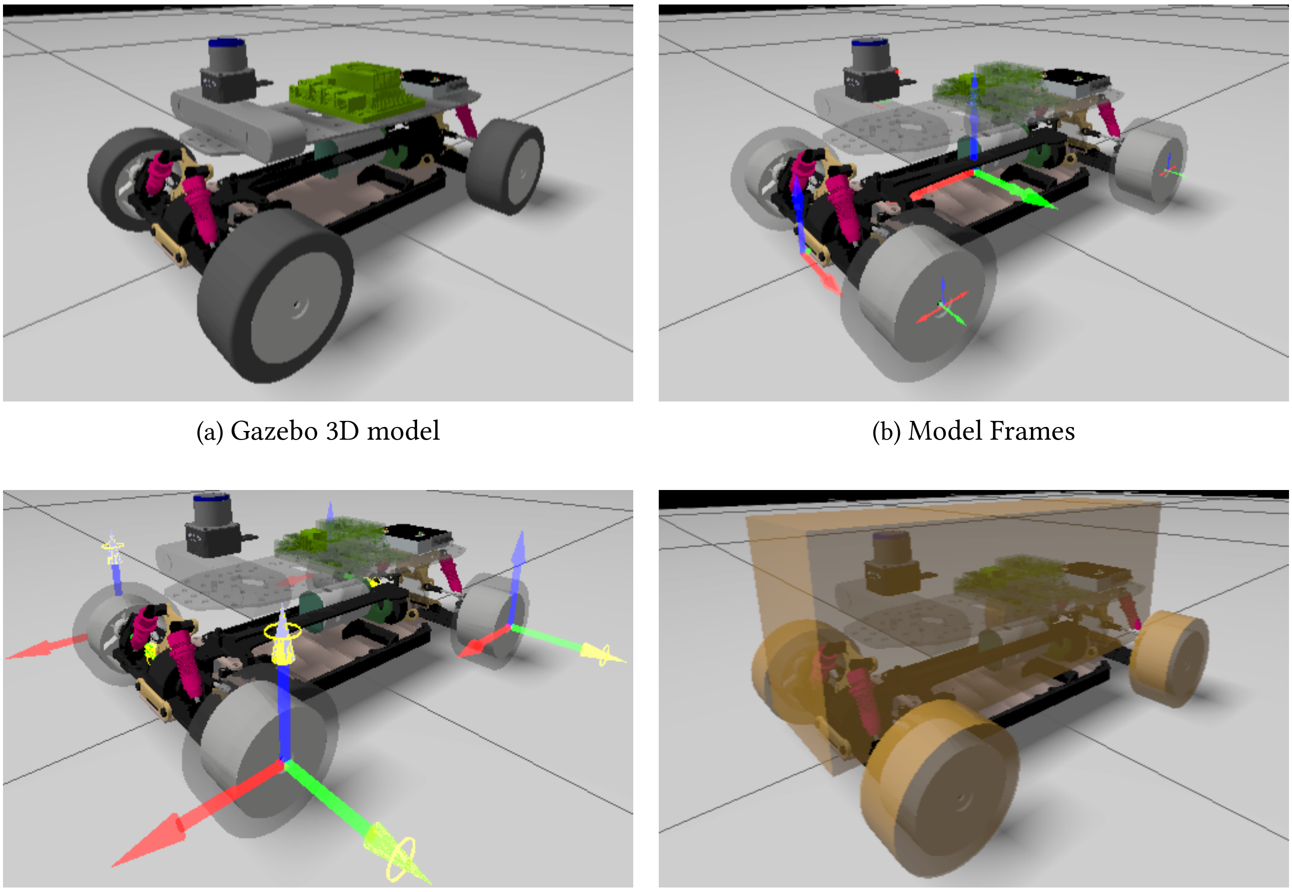
In order to build a realistic digital model for the RoboRacer scale car, it should be as true to reality as possible. The researcher's intention was not only to describe the vehicle through its links, joints and collisions on the Gazebo environment but to create a realistic model both in functionality and appearance. Thus, the first step is the study of the physical model and identify the main equipment that should be represented. In this case, as already mentioned, the physical system is a 1:10 scale car, equipped with an NVIDIA Jetson Orin Nano main processing unit, the VESC 6 MkIV electronic speed controller, a ZED stereo camera and a Hokuyo UST10-LX LiDAR. In order to realistically visualize the vehicle, a thorough research for the relevant 3D models of each components has been conducted. This resulted in the creation of a relevant library (provided under additional material) that includes models of all components as well as the car itself, preprocessed by removing unnecessary details such as cables and converted to Collada files (.dae) in order to be easily integrated in the final model.

In order to utilize the model, a relevant description using the Simulation Description Format, and specifically SDF version 1.8, the most recent at the time of development had to be created. Through SDF, the relevant frames, joints and links that describe the robot had to be defined and the appropriate mass, inertia and collisions according to the physical vehicle dimensions had to be assigned. The detailed description of the model can be found in under Appendix E. The model consists of seven frames; the main body (including all sensors into a single frame for simplification), the four frames representing the wheels of the vehicle and two additional frames to handle steering. In accordance, since there are 6 moving objects on the model under development, the four rotating wheels plus the two front wheels that also turn, six revolute joints have been defined in order to address the parts that have to move. As far as the sensor's 3D models are concerned, they have been defined under the main body as visual elements since there is no movement in order to require a separate link/joint. It should be mentioned here that visual representations are added also to the main body of the vehicle and the wheels in order to create a realistic model.

Last but not least, as it is of great importance for accurate simulation results, the plugins attached to the model have to be defined in order to facilitate control and sensors simulation. The newly introduced Ackermann Steering plug-in has been utilised, in order to define that this model is a vehicle that follows the Ackermann steering principles, while from the sensors suit, the gpu_lidar type sensor to simulate the Hokuyo UST-10LX, the camera type sensor to simulate the RGB part of the ZED camera and the depth_camera type sensor to facilitate the depth functionality of the ZED have been used. These plug-ins required explicit definition of parameters in order to accurately simulate the physical systems obtained through measurements (dimensions, weight, wheel radius, wheel-base, etc.) or through the specification data-sheets of the sensors (camera field of view, resolution, range of lidar, number of samples, etc.). The aforementioned plug-ins used in the experimental platform are summarised below:

- ackermann_steering_system - Plug-in that simulates the Ackermann steering principles; it requires detailed information such as wheel base, wheel separation, wheel radius, etc.
- gpu_lidar - Plugin simulating the Hokuyo LiDAR. Similarly the number of samples, the minimum and maximum angle, the range and the resolution have to be defined.
- camera - Simulating the ZED camera by defining image width and height, frame rate, format and field of view.
- depth_camera - For the simulation of the depth component of ZED camera, a different plug-in is used. Information for image width and height, frame rate, format and field of view are required too.

The resulting model, integrating both visual and functional characteristics, can be seen in Figure 4.13. Subfigure 4.13a shows the model in full visualisation with all the 3D files attached to represent the physical model as accurate as possible while in Subfigure 4.13b the aforementioned frames that are required in order to assemble the model are presented. In Subfigure 4.13c the revolute joints defined can be clearly seen; all the wheel joints can rotate along the Y-axis while the two front can also rotate around the Z-axis, and in Subfigure 4.13d the simplified collisions of the model are shown; each wheel represents a separate collision while the main body and sensors are considered as a single entity for easier handling and reduced processing requirements.



(a) Gazebo 3D model (b) Model Frames

(c) Model Joints (d) Model Collisions

Figure 4.13: The model on Gazebo simulator

While in order to achieve a highly accurate model, proper functionality and realistic simulation the description is of imperative importance, equally important is to properly simulate the sensors, to allow them to produce virtual output. For that the three sensor plug-ins discussed earlier have been utilised to realistically simulate the LiDAR and the camera; both RGB and stereo view. The plug-in parameters are carefully set according to the physical parameters drawn from the sensors manuals and data-sheets in order to produce the required results. Figure 4.14 presents the sensors output on Gazebo interface. The LiDAR is visualised with the blue rays while both RGB view (top window) and stereo view (bottom window) of the camera can be seen on the right. Two objects; a cube and a sphere have been added in the environment in order to act as reference points for the viewer.

At the same time, RViz in order to visualize the sensors as well as the odometry of the vehicle has been also used. One has to remember that Gazebo simulates the physical system, both the vehicle and the sensors, so RViz is issued for visualisation purposes only. In Figure 4.15 you can see a side by side view of Gazebo environment and RViz where a simple test has been performed. By using

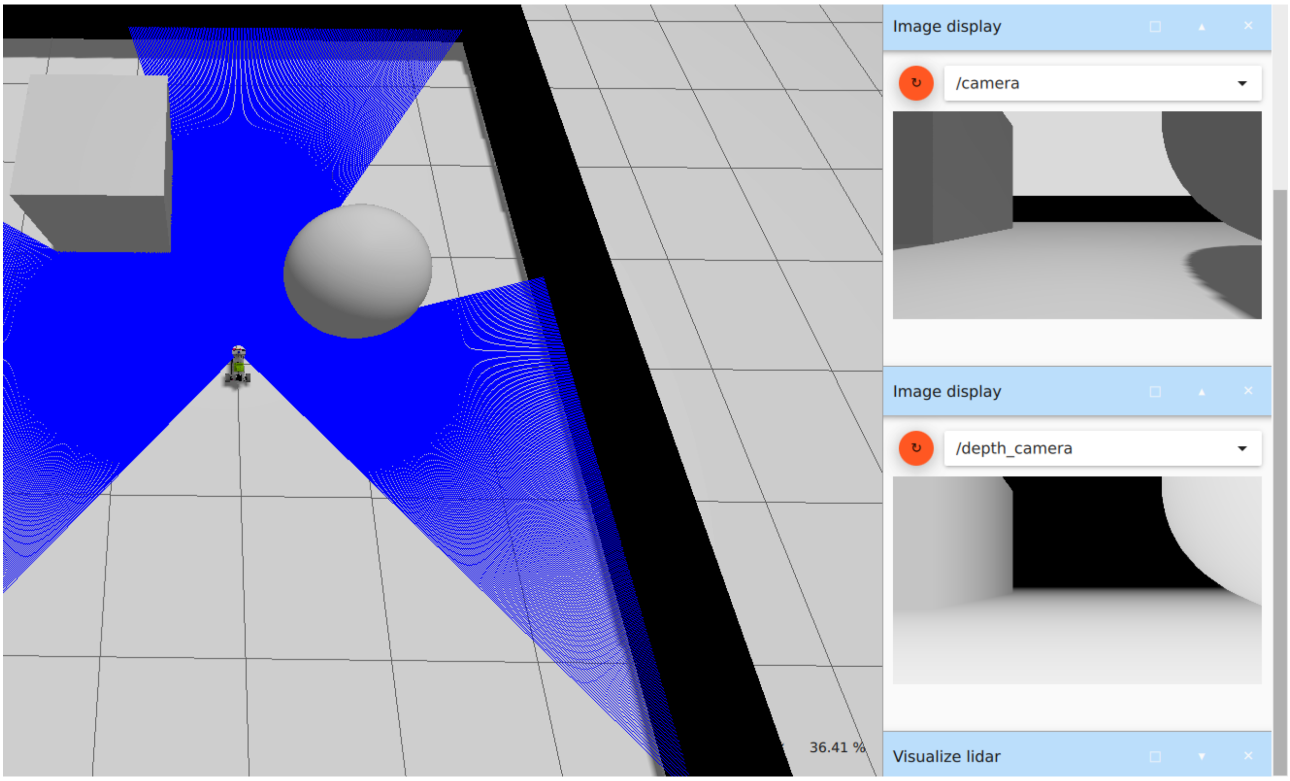


Figure 4.14: Sensors on Gazebo interface

the teleoperation add-on on Gazebo simulator the car was driven on a figure eight path around the obstacles. On the left part of the image Gazebo with the control add-on can be seen while on the right side RViz is depicted. Looking in further detail, the path that the car has followed in the simulator (odometry), the visualisation of both RGB and depth views of the camera and the laser scan produced by the simulated LiDAR as white points can be identified. Using the obstacles as reference points, an initial verification that the simulated system is properly visualised in RViz can take place. A video of this test can be found under supplementary material table in Appendix E.

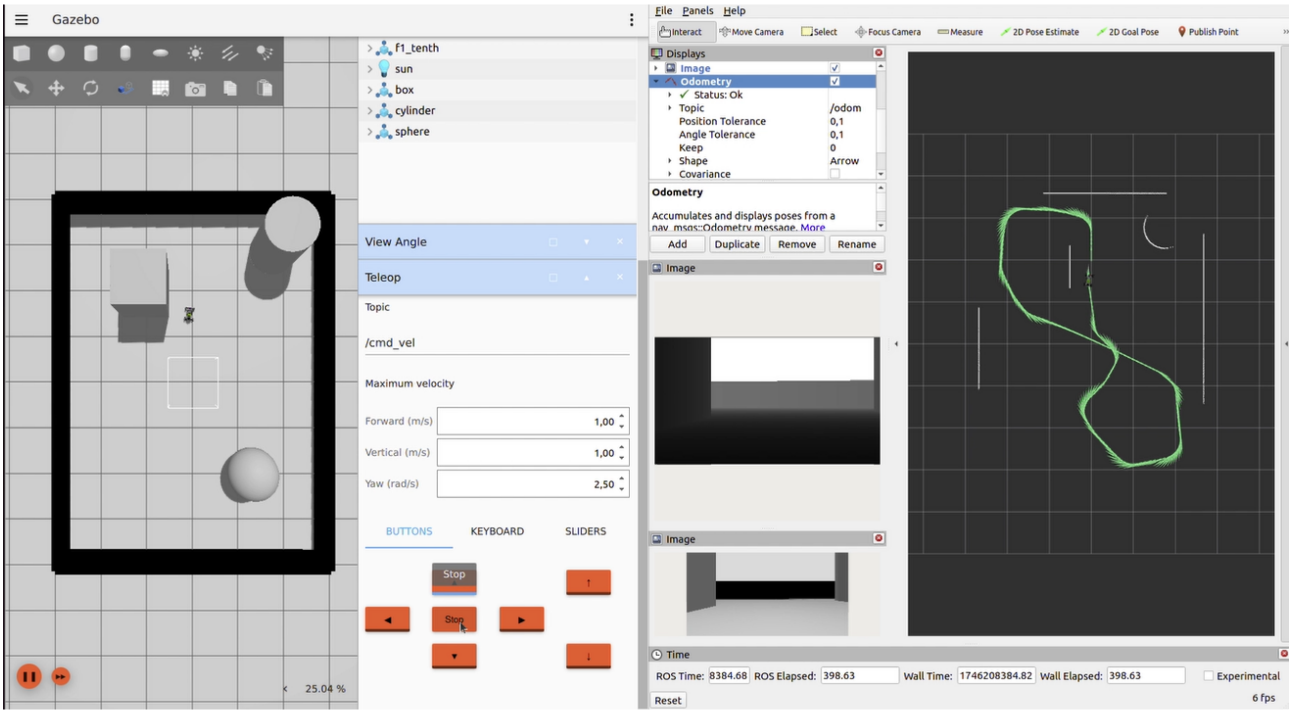
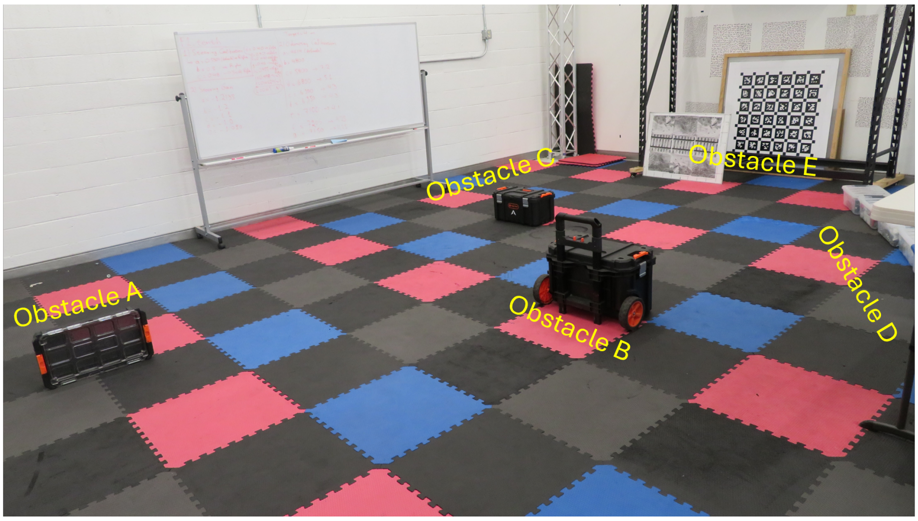


Figure 4.15: Gazebo and RViz visualisation

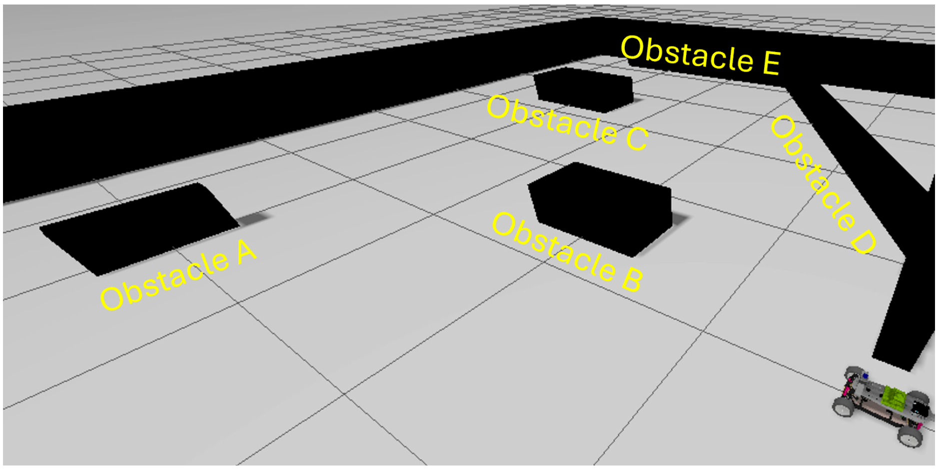
4.3.3 Physical and Digital Comparison

In the above section, a description of the digital model creation and the addition of mesh visualisations, sensors and controls as well as the presentation in Gazebo, verification of sensor functionality as well as visualisation and validation through RViz have been discussed. However, in order to prove the real value of the simulator it must be compared with the physical system in order to understand how close to one another are and prove that this digital model can be used for initial testing and validation of concepts before physically testing on the actual vehicle. For that reason, the testing area of the Unmanned Systems and Robotics Lab has been employed; an obstacle course for the vehicle has been set-up, the system was manually driven around the course and all data were recorded through ROS in *ros_bag* format. Then the same obstacle testing area was replicated virtually in Gazebo and the digital experiment in order to record and compare the results with the physical system has been run. That allows to prove the simulated models accuracy, directly compare the physical and the simulated system and understand not only similarities but also discrepancies. It should be mentioned here, even though is well-documented and heavily debated among practitioners [333–338], that even the most realistic model and simulator can never fully replace the physical system testing and the numerous unknown environment variables that can be met during field experiments. By comparing the physical and the simulated results it will be easy to determine the aforementioned unknowns and understand better the need for both simulation and physical testing. In Subfigures 4.16a and 4.16b the physical and the simulated obstacle course used in the use case are presented respectively.

A predetermined path that has been followed physically has been duplicated on the digital counterpart and all sensors, i.e. LiDAR, RGB and depth camera as well as odometry have been



(a) Physical Course



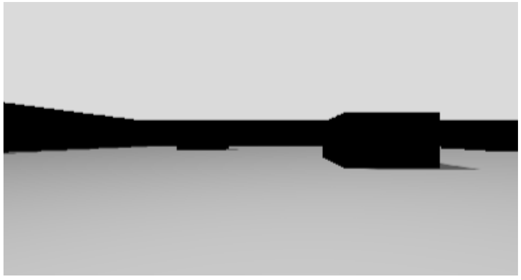
(b) Digital Course

Figure 4.16: Physical and Digital Obstacle Course

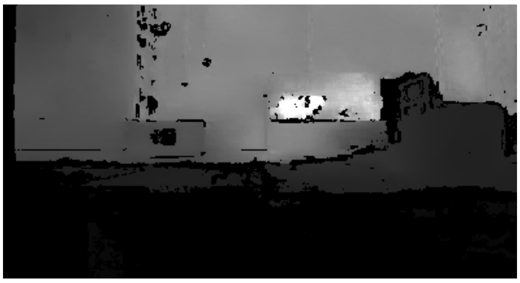
recorded in *ros_bags* which are publicly available. Following, the presentation and analysis of the aforementioned tests takes place in order to validate the current work. However, since it would be considerably beneficial, potential drawbacks and needs for improvement are also going to be discussed. The side-by-side comparison presented in Figure 4.17 makes it easier to study the overall result of this work. In the left column the physical system sensors are visualised while in the right column the simulated system. It can be easily identified that there are significant similarities in all sensors; in the RGB images it is easy to pinpoint the obstacles in view in both cases, i.e. Obstacle A and Obstacle B as referenced previously in Figure 4.16, in the depth images the depth element in both cases can be perceived while the LiDAR readings are discernible and outline the environment adequately.

There is however much more uncertainty in the physical sensor reading in comparison with the digital and that is due to the complexity of the surrounding environment. The number of objects not directly related to the validation use case, the shadows these cast, their reflective abilities, the shocks from the moving car and numerous other parameters that can not be controlled and are not directly linked to the use case can affect the sensor readings but not up to the point that it is not possible to simulate them on the near perfect environment created on Gazebo.

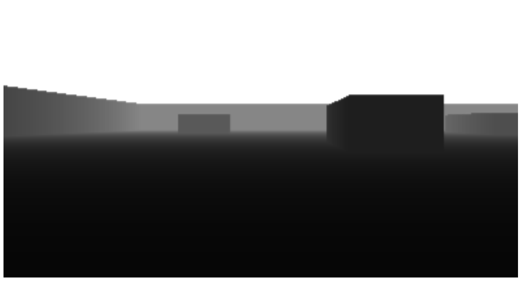
(a) Physical RGB sensor



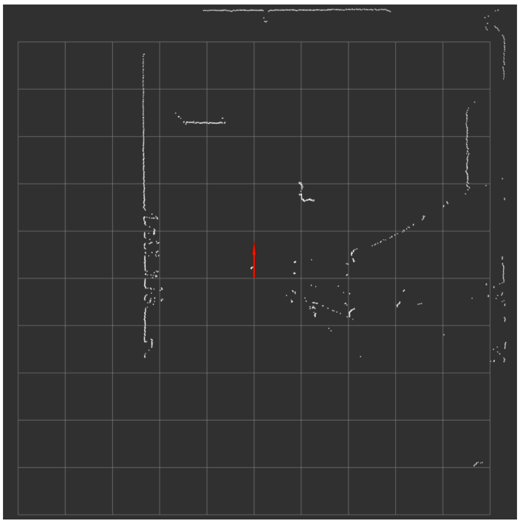
(b) Simulated RGB sensor



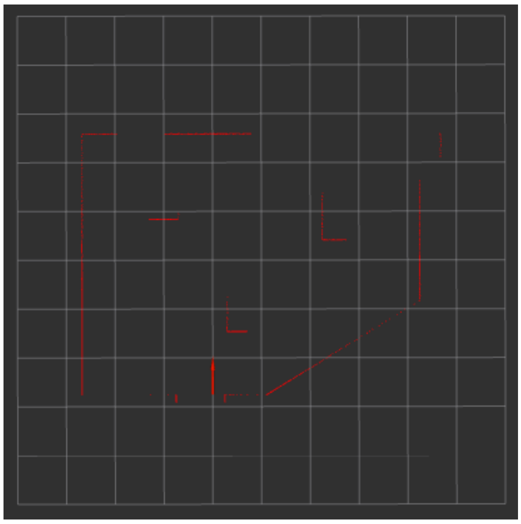
(c) Physical Depth sensor



(d) Simulated Depth sensor



(e) Physical LiDAR sensor



(f) Simulated LiDAR sensor

Figure 4.17: Comparison of physical and simulated data

In addition to the sensor visualisation and comparison, by applying SLAM, a map of the test environment, both physical and digital has been created. Similarly with the sensors visualisation, there are plenty of similarities and the usefulness of the simulator is proven once again, but the environmental parameters are causing interferences that make the mapping process more difficult. The two maps, resulting from physical and digital sensor data respectively, can be seen in Figure 4.18.

The aforementioned validation use case was performed in the test area of the Unmanned Systems and Robotics Lab, and even though it is ideal for initial testing and validation, it is somewhat limited in space. Thus, to test and validate the platform and the resulting digital model another test in

(a) Physical Data Map (b) Simulated Data Map

Figure 4.18: Maps from Physical and Simulated Data

a non-confined area took place in order to prove that the platform can perform in diverse and more complex environments and support longer experimentation efforts. The test in question was performed in the premises of the McNair Aerospace Centre of the University of South Carolina, where the Unmanned Systems and Robotics Lab is located. The corridors of the building acted as a testing course allowing for physical obstacles and diverse lighting conditions to be applied. However, the large size of the test area posed a significant limitation on how to replicate it in the digital environment. In order to ease the experimental burden, the established mapping capabilities have been utilised to create a 3D map of the test area; initially a test run across the building with the physical car driven by an operator was conducted and the logged data were converted to a map and consequently to the required 3D model for the simulator. The resulting map and the 3D model that will act as the digital test environment later on can be seen in Figures 4.19 and 4.20.

Utilizing the 3D map created, the digital test by using the previously created digital vehicle model has been established. Figure 4.21 presents two screenshots from the simulated environment in Gazebo, where the simulated LiDAR sensor (the blue rays) and the RGB camera (window on the side bar) can be seen. The first recorded instance is from the starting point of the test outside of the lab's entrance while the second is at an intersection of three corridors of the building.

In Figures 4.22 and 4.23 the same exact instances are presented; first through the physical system and the actual sensors and then through the digital model. The visualisation of the RGB and depth sensor on the left side bar can be seen while the LiDAR is visualised on the main window. In addition, the odometry is also visualised by the arrows on the main window. It can be easily inferred by studying the visualised results that the larger space and the higher complexity and unpredictability of the environment causes more difficulties in the replication of the sensors with more uncertainty being introduced in both LiDAR and camera. This does not render the digital model unable to perform its role, however more details and fine-tuning of the sensors parameters might be required if testing in larger environments is commonly intended.

In addition to the figures listed above and the details provided, all tests have been documented in videos and shared with any interested reader of this dissertation. Also, supplementary material such as the ros_bags recorded during the test and the 3D Mesh files used for the digital representation of the platform are shared too. All these can be found in Appendix E.

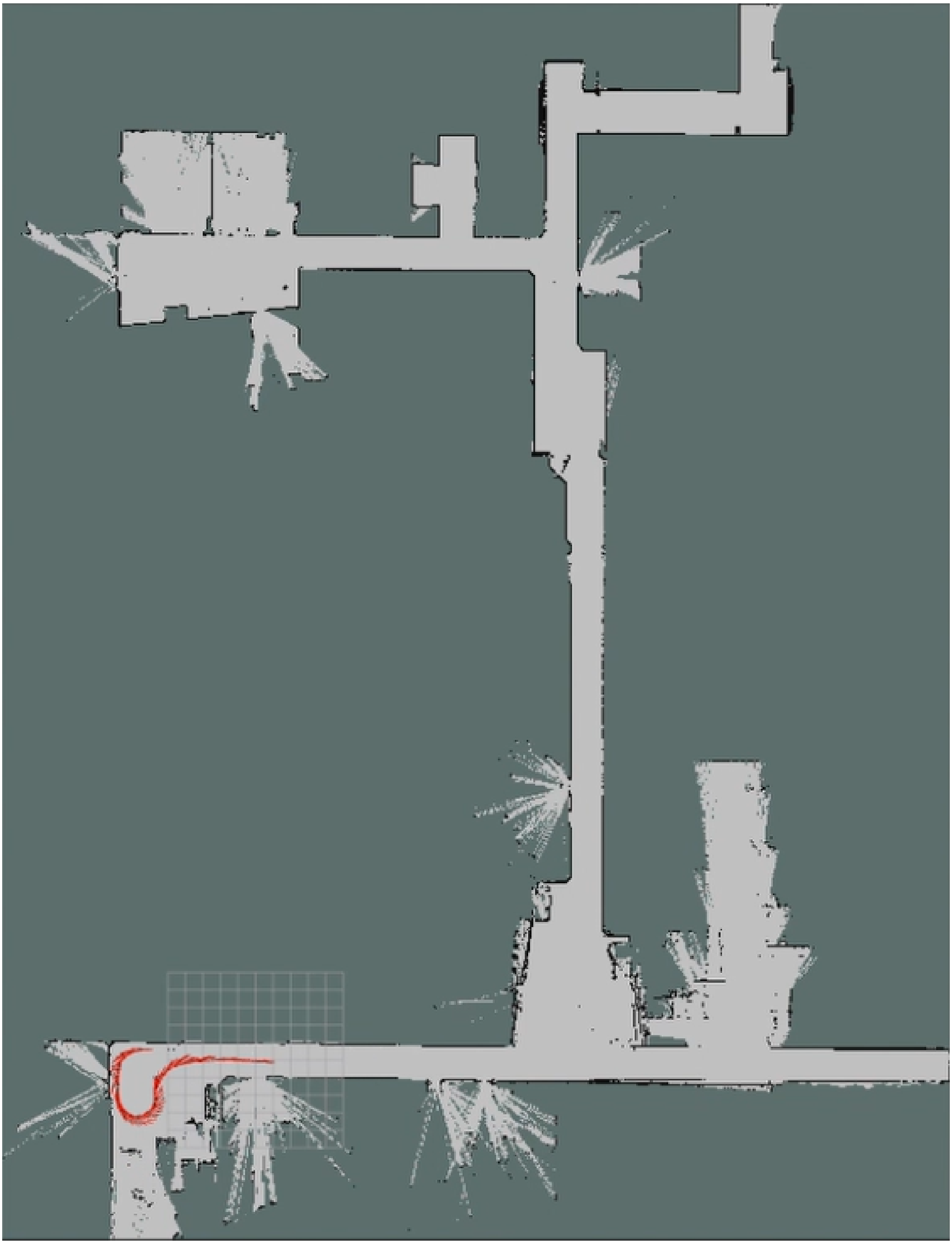


Figure 4.19: Map of McNair Aerospace Centre represented in RViz

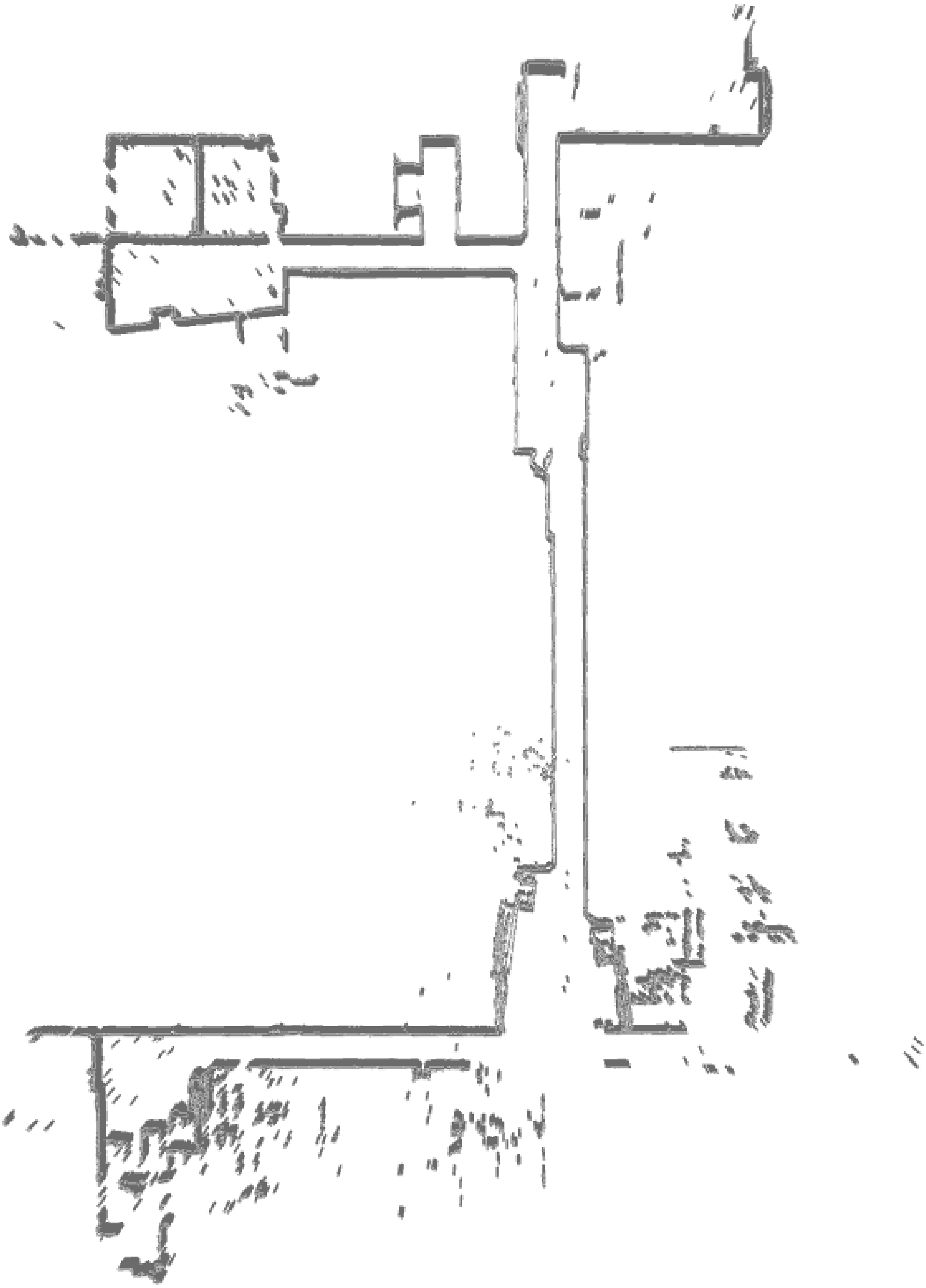
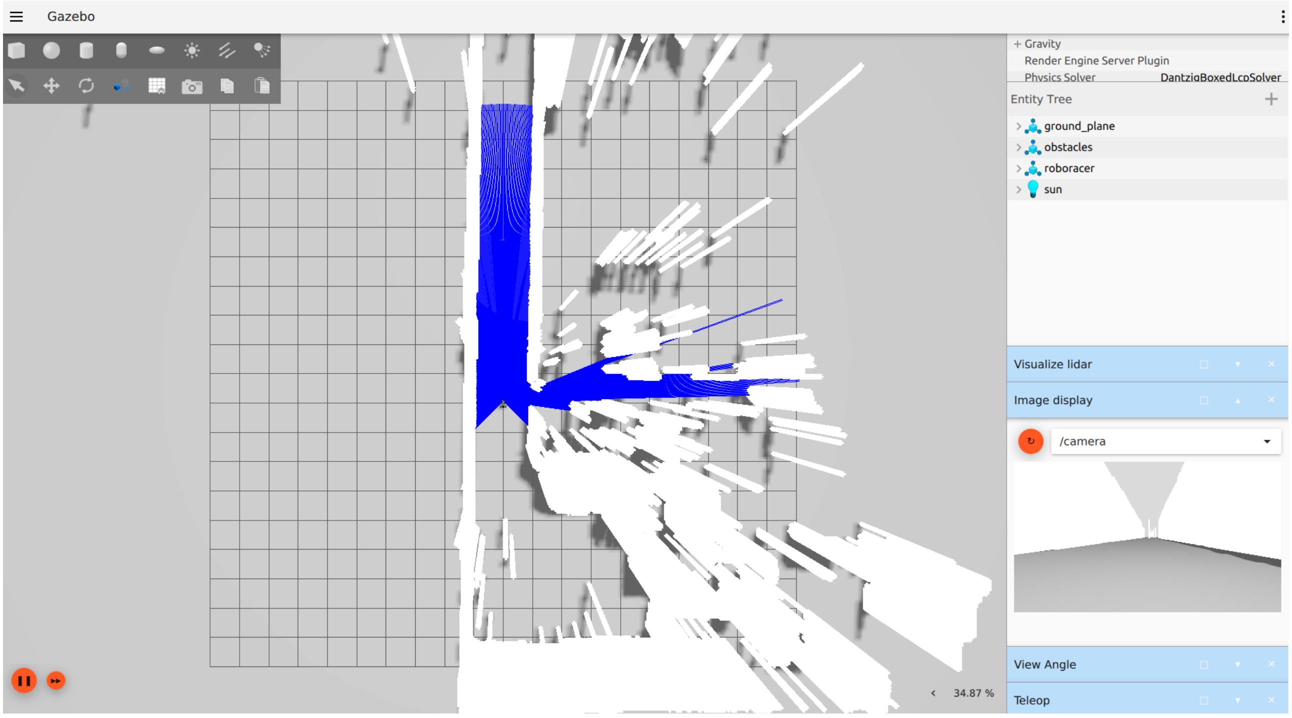
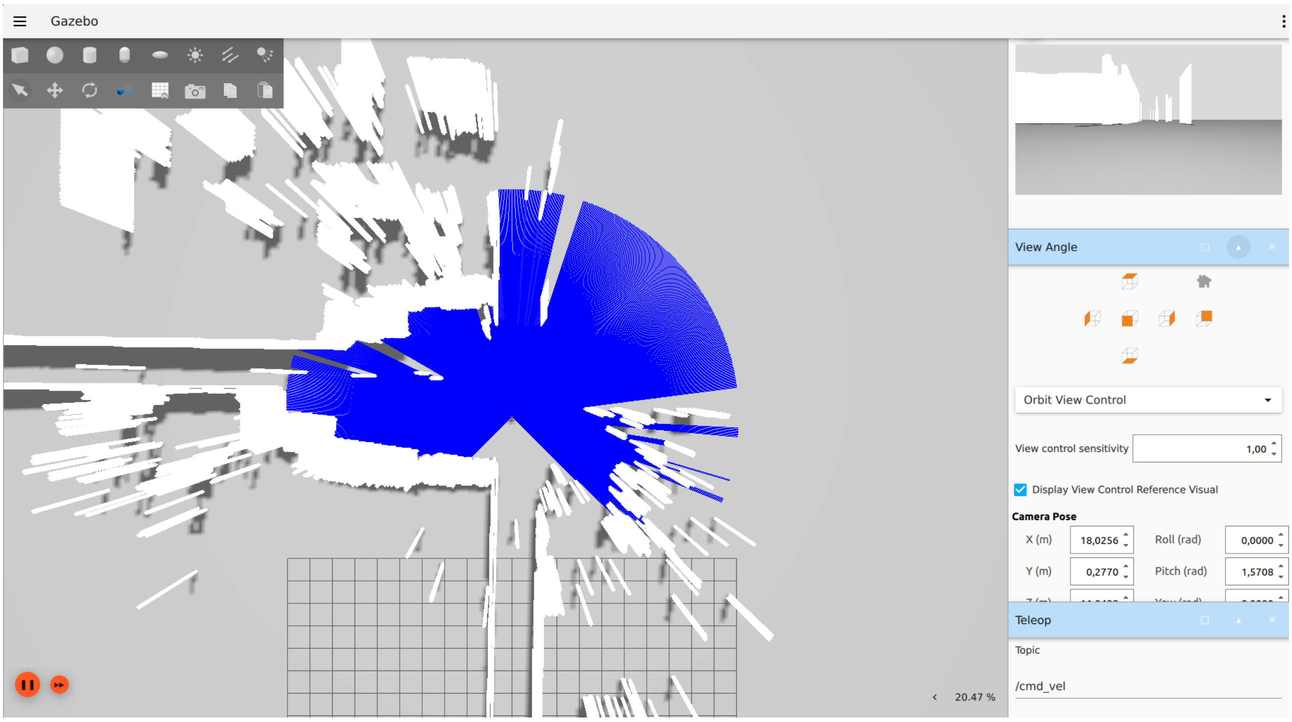


Figure 4.20: 3D reconstruction of the McNair Aerospace Centre map

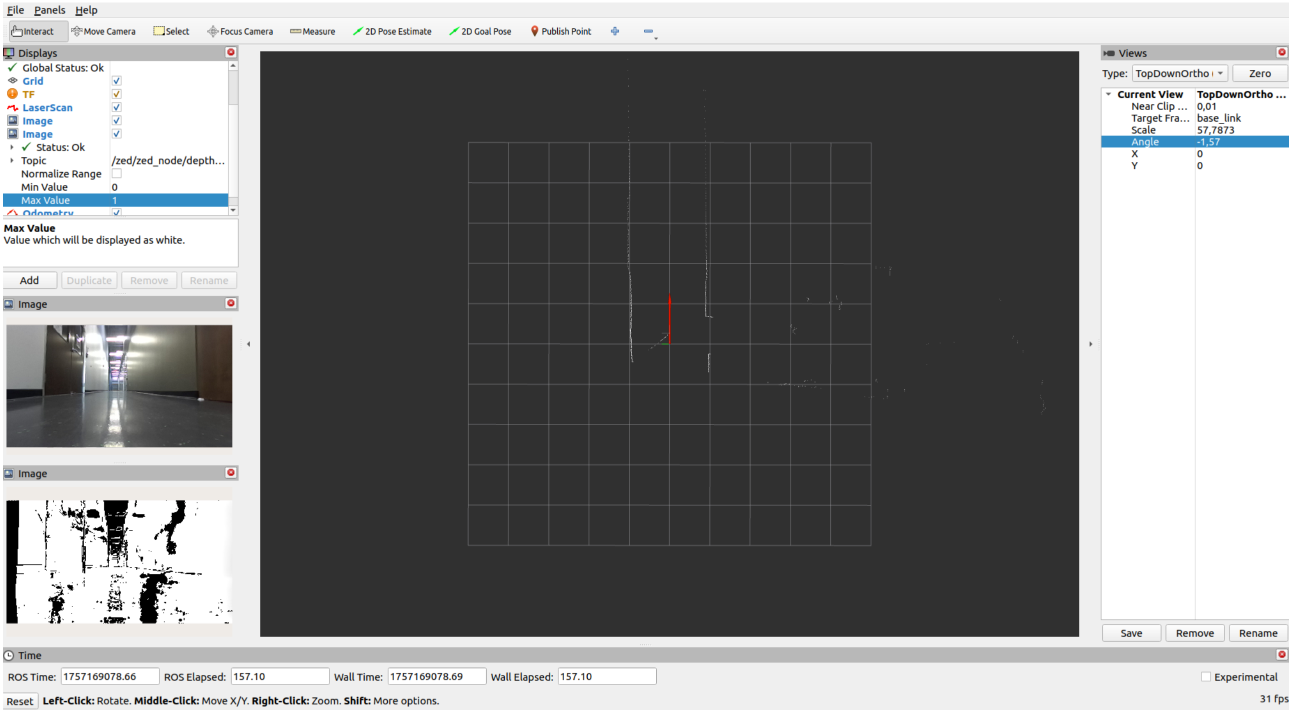


(a) Starting point of the test

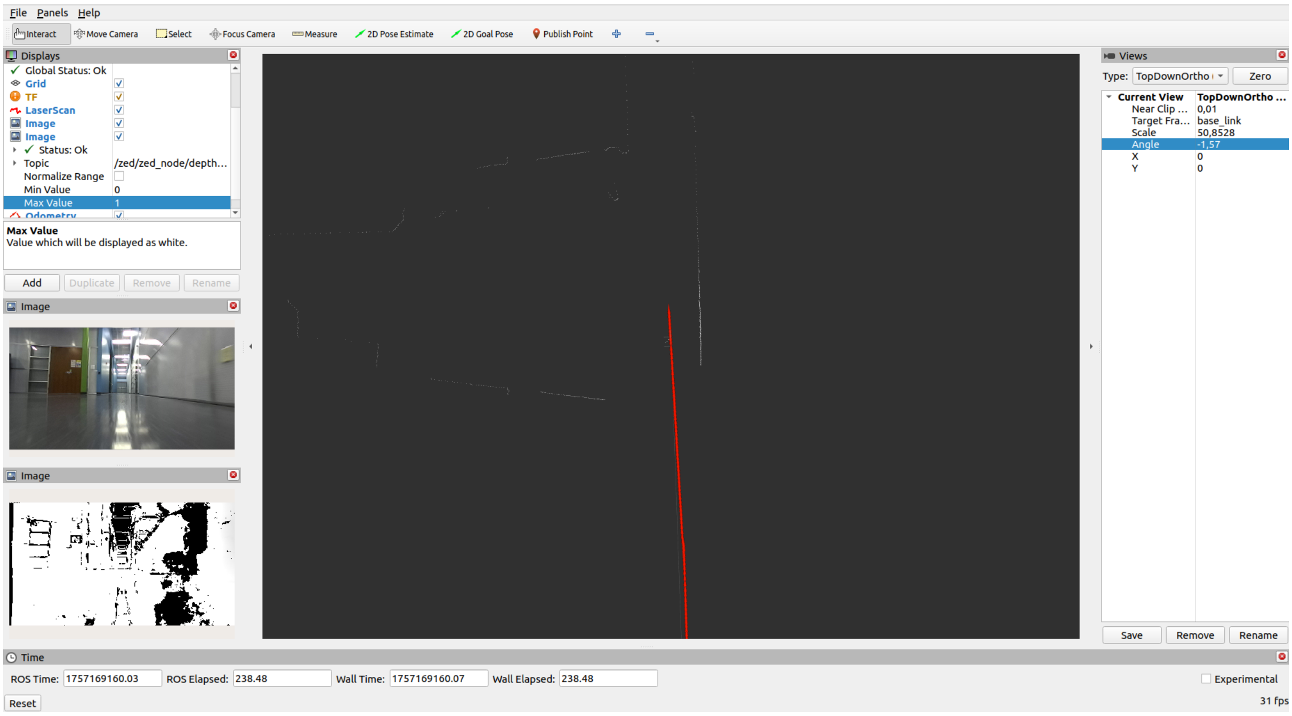


(b) Three-way junction on the test environment

Figure 4.21: Simulated testing on McNair Aerospace Centre environment

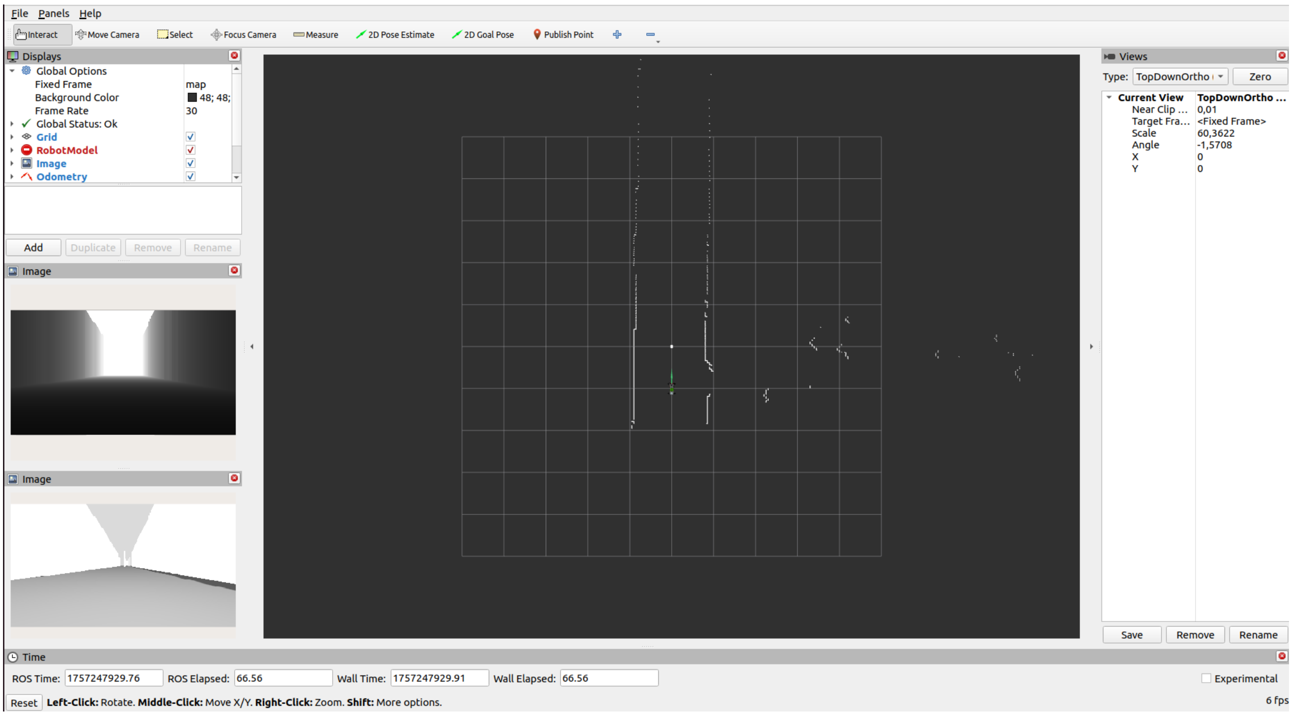


(a) Starting point of the physical test

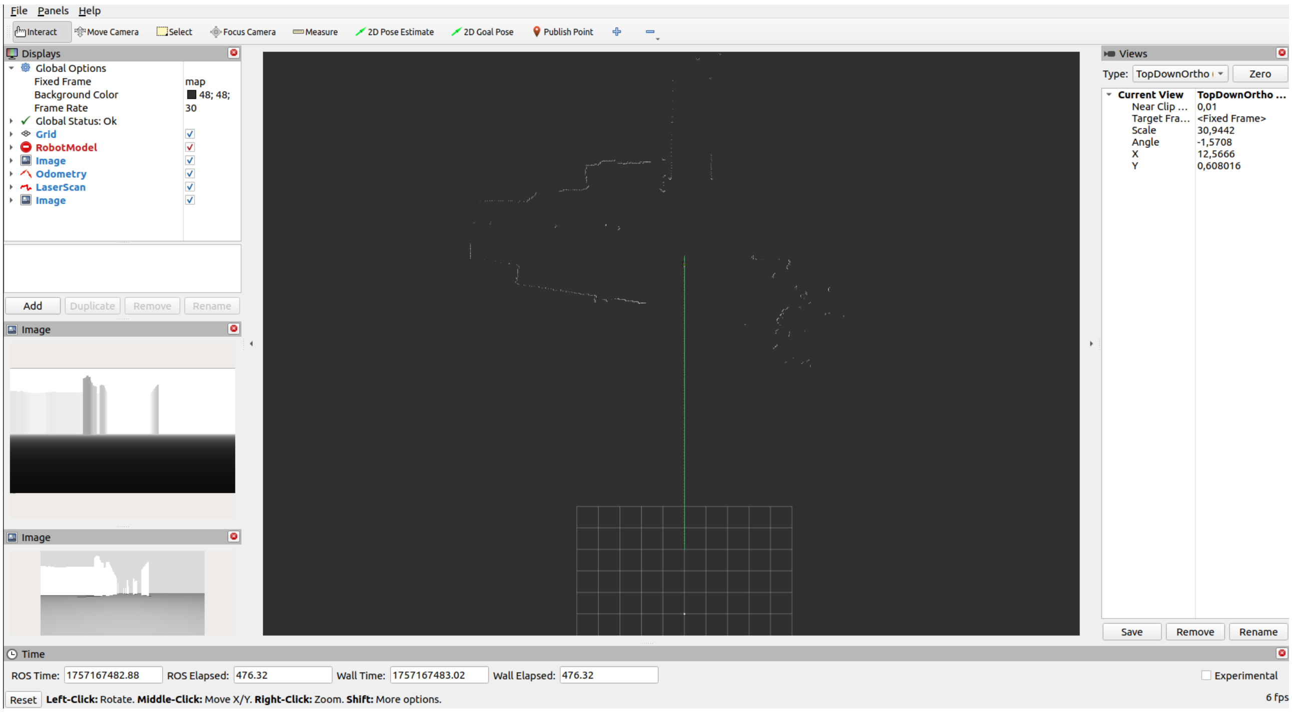


(b) Three-way junction on the physical test area

Figure 4.22: RViz representation of the physical test



(a) Starting point of the simulated test



(b) Three-way junction represented on the simulated environment

Figure 4.23: RViz representation of the simulated testing

4.3.4 Conclusion and Future Research

The second use case's target was to prove the applicability of the three phases of the conceptual framework in a diverse vehicle and ascertain that it is properly defined and well-documented to allow replicability from other robotics community members.

A well-documented upgrade process of both the hardware and the software of an existing RoboRacer platform has been initially described. As far as the hardware is concerned, not only the guidelines but also the material in order to 3D print the required parts and install them into the vehicle have been provided. On the software front, the new board allows ROS2 integration, specifically ROS2 Humble Hawksbill. Adaptation of existing software to make it compatible with ROS2 was required. One of the intended targets was to provide various launch files to the end user that help him start experimenting and testing various algorithms faster and easier. That's why all the aforementioned software solutions have been publicly available to the community through the GitHub repositories listed in Table 4.5. The main driving force for the software update was the notion that a new software stack would provide better support and compatibility to state-of-the-art algorithms and newly developed ROS2 packages and also exploit the higher computing power available to produce more accurate results in a shorter time, extending also the lifetime of the platform until the end-of-life of its components.

The proposed digital model potentially has the greatest impact however, due to the fact that no similar solution has been identified, to the best of the author's knowledge, built on the new Gazebo simulator yet. Using the new simulator would become inevitable after the EoL of Gazebo classic and the community would greatly benefit from such a solution. At first, a detailed description of the physical system and the digital model it is presented. All physical parameters have been taken into consideration in order to create a model as close as possible to the physical one. All links, joints and collisions have been meticulously described to replicate the physical system's functionality and detail 3D models have been acquired and utilised for visualisation purposes. At the same time, to simulate sensors and controls, Gazebo plug-ins have been put into use; by providing mechanical and technical characteristics of the sensors drawn from manuals and technical data-sheets a proper replication can be assured.

Finally, a head-to-head comparison between the physical system and its digital counterpart is performed to evaluate and validate the proposed system. The comparison has been performed through RViz and allows to directly compare the odometry of the system, the LiDAR sensor as well as both RGB and depth views of the camera. SLAM was also used to provide another means of validation by creating a map of both physical and digital environment. All these prove that the digital counterpart is accurate enough for initial testing and validation but as always is the case in robotics, it cannot fully replace real-life testing as unknown environment variables are interfering with the physical systems that can not be projected on simulators.

Since a physical system has been described in detailed and the requirements established (Phase 1), all sensors and controls have been set-up and ROS2 acts as a communication middleware (Phase 2) and digital models of the vehicles, sensors and systems have been established and compared with the physical ones (Phase 3) the three framework phases have been indeed validated. However, the most important step, the bi-directional communication among the physical and the digital systems have not yet been established in order to create the digital twin and prove that the framework is capable of supporting the creation of DTs for autonomous vehicles. The last phase is validated on the third and final use case which also consists a scale-up to full-scale.

4.4 Overall Validation Use Case and Scale-Up

The two aforementioned use cases have validated the first three phases of the proposed framework in a scaled environment. However, a significant aspect of the digital twin concept; the bidirectional communication and the control a digital twin can exert to the physical system have not yet been validated. In addition, one can argue that the validation have all been performed only under scale vehicles, thus this use case is also going to provide a scale-up and test the application of the digital twin framework in physical scale. Lacking a full-size testbed, the physical counterpart will also be simulated with the help of CARLA [339].

Through this use case, the applicability of the framework in diverse types and scales of vehicles would be strengthened while the real value of a digital twin would be validated by proving not only upstream (data streaming towards the digital counterpart) but also downstream communication (control through the digital twin). In addition, off-the-vehicle data processing, crucial for offloading critical hardware and reducing energy requirements would be validated, proving another advantage of the digital twins for autonomous vehicles.

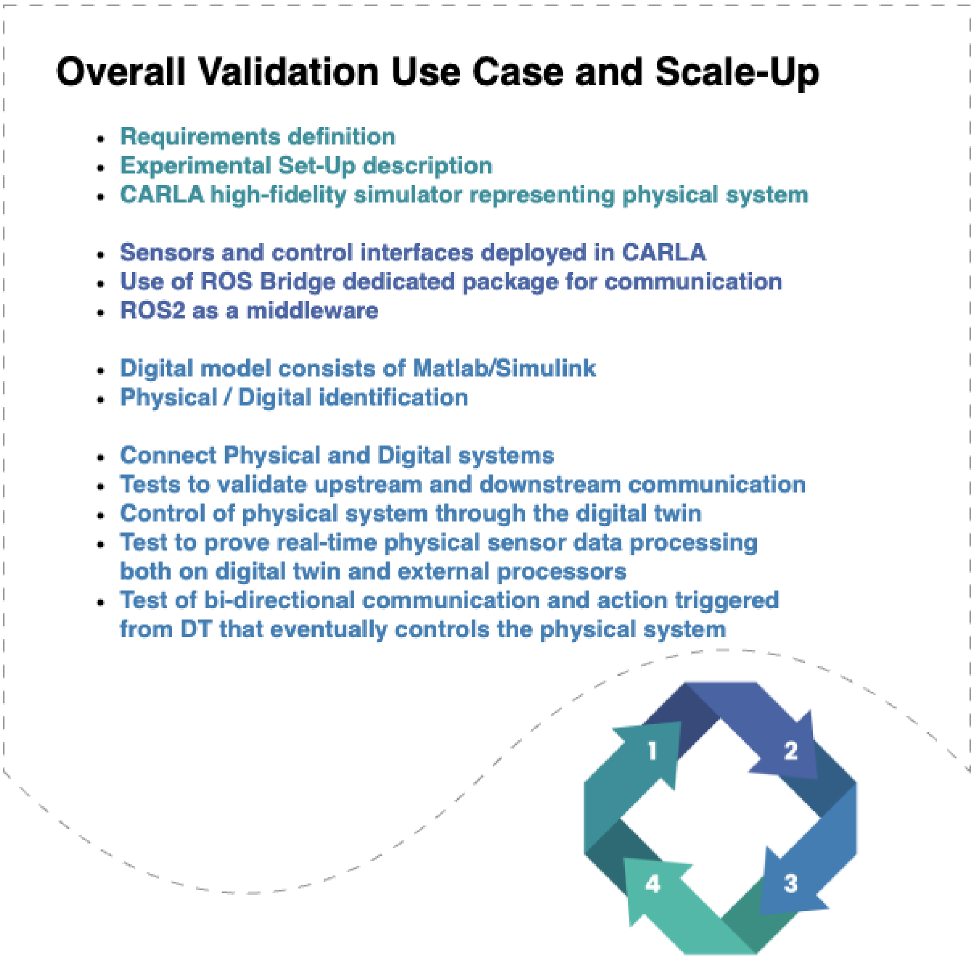


Figure 4.24: Third use case relevance to framework phases

4.4.1 Experimental Set-Up

The experimental setup consists of three main parts; CARLA simulator, ROS2 and Matlab/Simulink. CARLA, is an open-source autonomous driving simulator, created to provide a safe and flexible virtual environment for developing, training, and testing self-driving systems. The simulator provides highly realistic 3D urban and suburban environments that include roads, buildings, traffic signs, vehicles, and pedestrians. Users can customize conditions such as weather, time of day, and traffic scenarios, which makes it possible to test autonomous driving systems under diverse and challenging circumstances. Another important feature of CARLA is its ability to simulate the sensors that real autonomous vehicles use, such as cameras, LiDAR, radar, GPS, and inertial measurement units. CARLA can be controlled programmatically through APIs in languages like Python and C++, which allows researchers and developers to integrate it with machine learning frameworks and use it for reinforcement learning, computer vision research, and robotics applications. In this use case, CARLA acts as the physical system, due to the lack of a full-scale vehicle for validation.

ROS2, similar to the previous use cases, serves as the communication middleware that allows for the required real-time bidirectional communication between the physical and the digital system to be established while Matlab and Simulink are employed to act as the digital counterparts of the system. MATLAB is a high-level programming language and environment designed for numerical computing, data analysis, and visualisation. It is widely used in engineering, science, and applied mathematics because it provides powerful tools for working with matrices, solving mathematical problems, and creating algorithms. Simulink, on the other hand, is an add-on product to MATLAB that provides a graphical environment for modelling, simulating, and analysing dynamic systems. Simulink is often used to simulate real-world systems like cars, robots, or communication networks before building them physically. In practice, MATLAB and Simulink complement each other.

Last but not least, in order to establish the communication between CARLA and ROS2, ROS Bridge module has been utilised, allowing for the two way communication between ROS2; the middleware in our experimental setup, and CARLA; the physical counterpart. Equally important is to define the experimental setup used in order for anyone in the community to be able to replicate the experiment since numerous hurdles occur if versions of the relevant tools that are not compatible to one another are being used. Table 4.4 summarises the aforementioned tools and the corresponding version required.

Table 4.4: Compatible Software Versions

Tool	**Required Version**
Host System	Ubuntu 20.04
CARLA	0.9.13
ROS2	Foxy Fitzroy
Matlab	R2023b

It should be pointed out here that these use cases required significant computational power to be performed and lack of such infrastructure might cause them to be very slow or even not be plausible to run. The hardware specifications for the tests presented below utilised a virtual machine from a shared infrastructure with 4 cores of Intel i9 10920X CPU, 30 GBs of RAM and dedicated use of an RTX 3080 GPU with 12GB of memory. These specifications were barely enough to perform the tests with a decent frame-rate, with RAM memory being the most stressed resource.

4.4.2 Validation Tests

A series of test in order to validate the usability and applicability of the developed framework in a scale-up environment has been carefully devised and executed. The five tests are the following:

- Upstream Validation
- Downstream Validation
- Object Detection
- Lane Detection

- Emergency Braking

Each test combines features and realisations from the previous one and gradually reaches the point to prove the bidirectional communication and the capability of a digital twin to control a physical system based on decisions taking on the digital counterpart. For each of the tests that are listed below relevant videos are provided publicly through Zenodo platform with their URLs listed in Appendix E.

In order to execute the tests described below, the experimental process requires at least the following processes to be running:

1. CARLA
   Carla simulator has to be launched at first. In these tests Carla 0.9.13 has been used which still utilises Unreal Engine 4. Thus, in order to start the CARLA core one just has to execute *./CarlaUE4.sh*. This will start CARLA core on a predefined map.

2. ROS Bridge
   ROS Bridge is a very important part of this experimental set-up. In order to run it, after navigating to the corresponding folder one has to execute *ros2 launch carla_ros_bridge carla_ros_bridge_with_example_ego_vehicle.launch.py*. A vehicle that can be either autonomously or manually controlled is spawned in a random position on the map. ROS bridge is also started and topics leveraging CARLA information can now be seen in ROS.

3. Matlab-Simulink
   Matlab and Simulink need to be running in order to receive the corresponding information and act as the digital twin of the ego vehicle.

For the two first tests the above are adequate. For the third and the fourth test, a different environment has been used. Thus, the town parameter on the corresponding *.launch* file had to be changed and the ROS package needs to be rebuild by invoking *colcon build*. After a successful build, the same launch command will spawn the ego vehicle on a different map.

In addition, depending on the test, additional processes might have to be invoked. For example, the object detection test requires some traffic on the environment in order to test the detector. This can be triggered through CARLA's PythonAPI and specifically with the help of *generate_traffic.py* example. As far as the emergency braking test is concerned, it requires not only spawning the vehicle in a specific position, thus adding *spawn_point_ego_vehicle* parameter on the launch command but also invoking *stationery_vehicle.py* to spawn the obstacle that will trigger the braking incident. For the first braking test the spawn position should be *300.0,-2.0,0.6,0,0,0* and for the second test the position should be *250.0,59.5,0,6,0,0,0*. While launch files and the traffic generator are part of ROS Bridge and CARLA respectively, so there is no need for them to be provided to the user as they are widely available, the stationery vehicle spawn software is included in the simulink_dt GitHub repository listed in Table 4.5.

4.4.2.1 Upstream Validation

The first test targets to prove that data from the physical system can be streamed to the digital twin; thus named upstream validation. This test is quite straightforward and utilises Simulink to subscribe to the ROS2 topics published from the middleware after being properly converted with the help of the ROS Bridge from CARLA to ROS format. The Simulink blocks utilised can be seen in Figure 4.25; for each sensor that needs to be visualised a ROS2 Subscriber block needs to be used. Depending on the sensor, either camera or LiDAR, a relevant block reading the corresponding format is applied to convert the ROS2 topic into a Simulink perceptible format. To further explain Figure 4.25 studying it from top to bottom and left to right we identify the following; RGB camera visualisation, event camera visualisation, segmentation camera visualisation and LiDAR visualisation. Following, the process of retrieving the data from each sensor is described in detail:

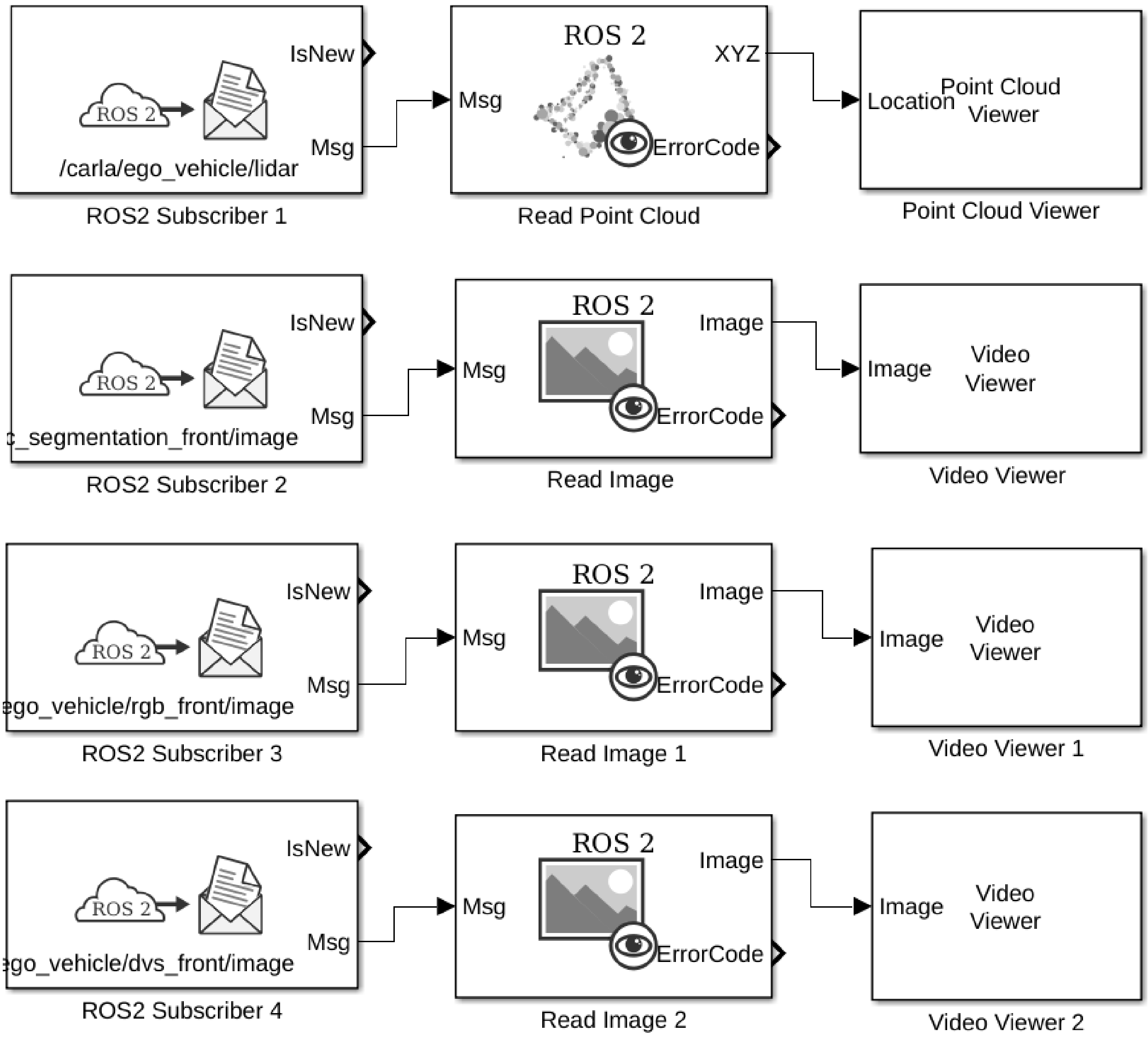


Figure 4.25: Simulink blocks of Upstream test

1. RGB camera

   The first set of Simulink blocks in Figure 4.25 is used in order to visualize the front

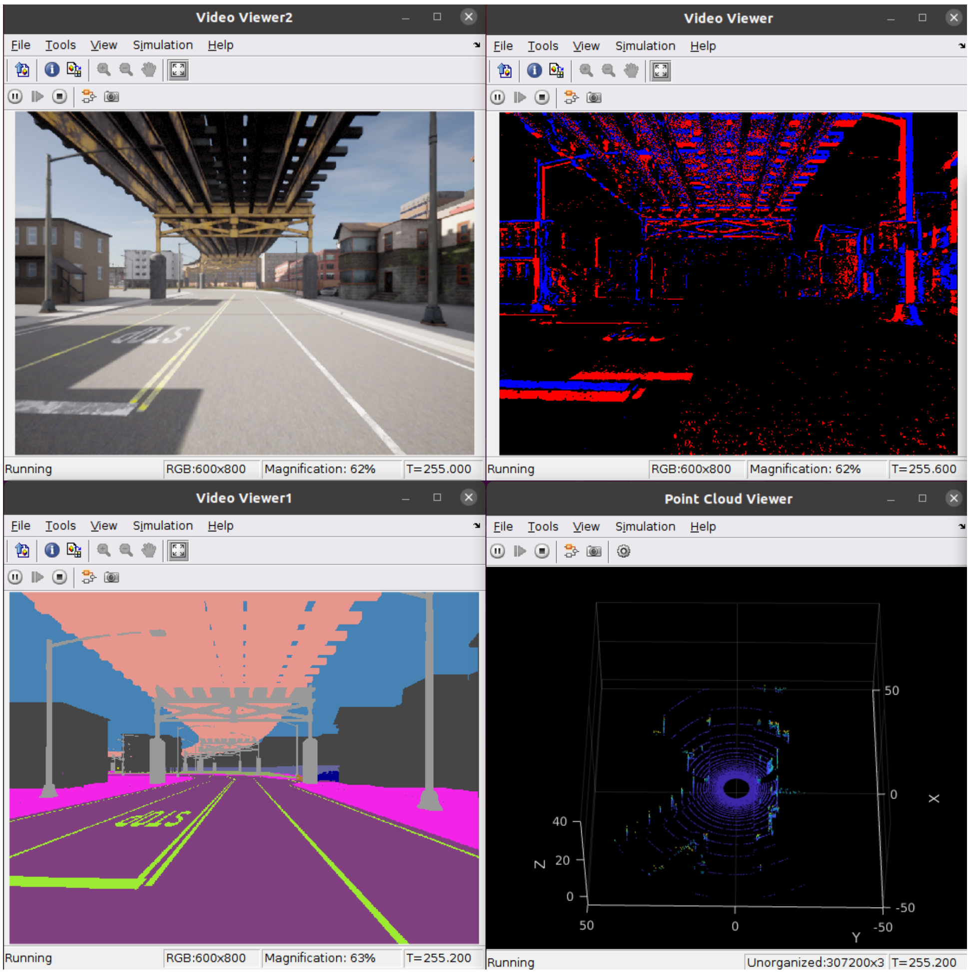
RGB camera. Initially, a ROS2 Subscriber block is used in order to subscribe to the */carla/ego_vehicle/rgb_image* topic that publishes the camera messages converted with the help of ROS bridge from CARLA to ROS *sensor_msgs/Image* message format. The output of the first block is then fed into a ROS2 Read Image block that converts the message into an image format perceptible by Simulink. Finally, the last block spawns a video viewer to graphically visualize the image to the user interface.

2. Event camera
   The visualisation of the event camera, is following the exact same flow as the RGB camera. The only exception is that the topic that the ROS Subscriber block has to subscribe is the */carla/ego_vehicle/dvs_front/image*.

3. Segmentation camera
   The visualisation of the segmentation camera is exactly the same as the aforementioned types of camera. The only exception is that the topic that the ROS Subscriber block has to subscribe is the */carla/ego_vehicle/semantic_segmentation_front/image*.

4. LiDAR
   The visualisation of the LiDAR sensor however does not follow the exact same procedure as the above, even though the basic principles remain the same. The ROS2 subscriber block subscribes to */carla/ego_vehicle/lidar* topic. However, LiDAR data do not come in image format, thus the ROS2 Read PointCloud blocks needs to be used. This block converts the ROS2 message received into a PointCloud format which is then visualised by utilizing the Point Cloud Viewer block.

The visualisation of the sensors in question can be seen in Subfigure 4.26a while Subfigure 4.26b presents a snapshot of the CARLA environment.



(a) Sensor visualisation of Upstream test

(b) CARLA visualisation of Upstream test

Figure 4.26: Visualisation of Upstream test

4.4.2.2 Downstream Validation

Likewise, this test targets to validate the ability to control the physical system through the digital twin; thus named downstream validation. In contrast to the first test, in this case a publisher Simulink block is utilised to publish the relevant ROS2 messages to the middleware and consequently to the physical system. The publisher block receives the inputs to control the vehicle and is formatted as the appropriate message by a Bus Assignment block using the relevant message structure, as seen in Figure 4.27. Deep diving into this figure, two main parts can be identified; the top part which is build to retrieve the speed of the vehicle and the bottom part which is the actual controller. The bottom part contains a Simulink group, which is further visualised in Subfigure 4.27b. Studying the Simulink blocks top to bottom, the following can be derived:

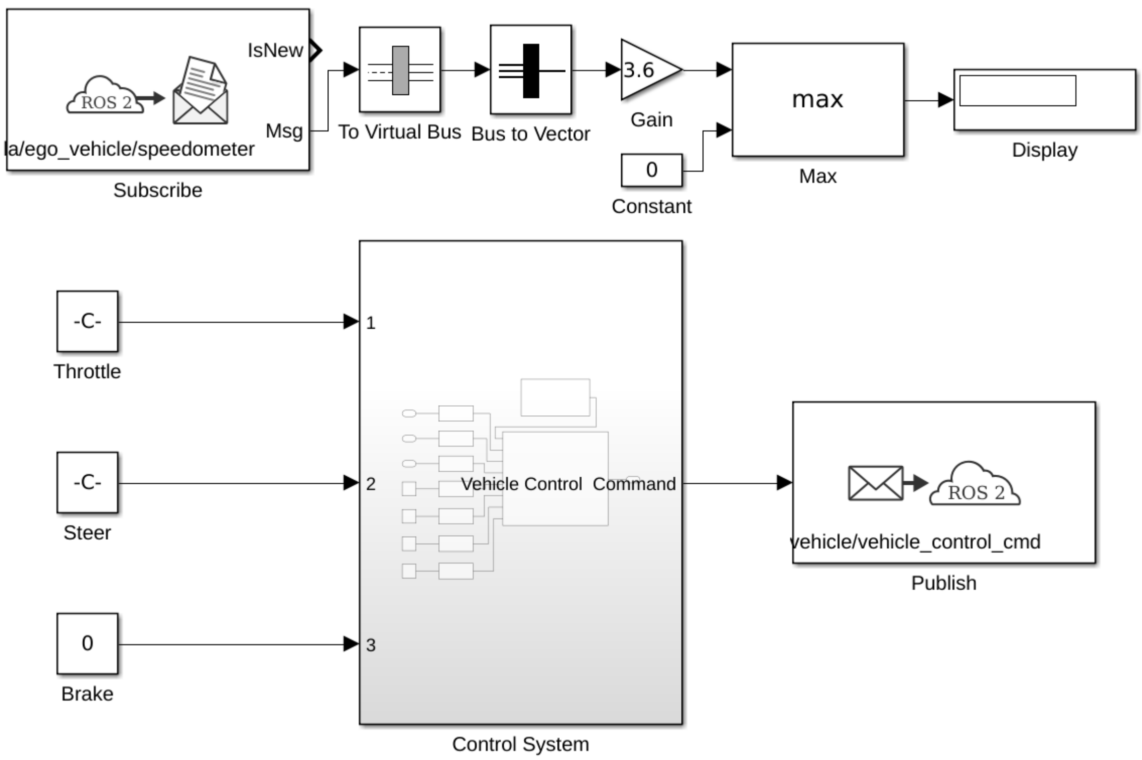
1. Speedometer
   The top set of blocks consists the process to read the speedometer of the vehicle. A ROS2 subscriber block is utilised in order to subscribe to */carla/ego_vehicle/speedometer* topic and read the relevant message. This message is not a plain number, but a bus, thus a Virtual Bus block is used to properly used it in Simulink. This bus has to be converted into a vector in order to be processed further, thus a Bus to Vector block receives the output of the Virtual Bus block as an input. The speedometer topic provides the distance in m/s thus a multiplication by 3.6 in order to convert it to km/h is required. The gain provided however was not precisely set at 3.6; a warning that the gain was 3.599999 was issued by Simulink do to its internal processing and calculations performed. This minor difference caused the speedometer value to fluctuate between zero and minor but negative values. In order to alleviate this shortcoming a Simulink block selecting the maximum number between speed value and zero has been used. In this case the value would always be zero or higher. To display the speedometer value a Simulink display block was used.

2. Vehicle Control
   The bottom set of blocks are the ones that control the vehicle and publish the commands issued from Simulink towards CARLA i.e. the downstream communication described previously. Three Constant blocks are used to define the throttle, brake and steering values that will end up controlling the vehicle. The main control system has been grouped into a subsystem, which can be seen expanded in Subfigure 4.27b. The three aforementioned constants are inputs to this block, namely 1,2, and 3. At the same time some additional constants controlling the handbrake, the driving direction (forward or reverse), the current gear and manual or automatic gear shift are used. To avoid conflicts, all control signals are formatted accordingly to ROS2 messages through type conversions (casting). Throttle, brake and steer signals are singles, handbrake, reverse and manual gears are booleans and gear is an int32. All signals have been pre-processed, however they should be concatenated into a Virtual Bus that can be fed to ROS and consequently the physical system. Thus a Bus Assignment block is used to map all control signals into the fields of the corresponding message, retrieved with the

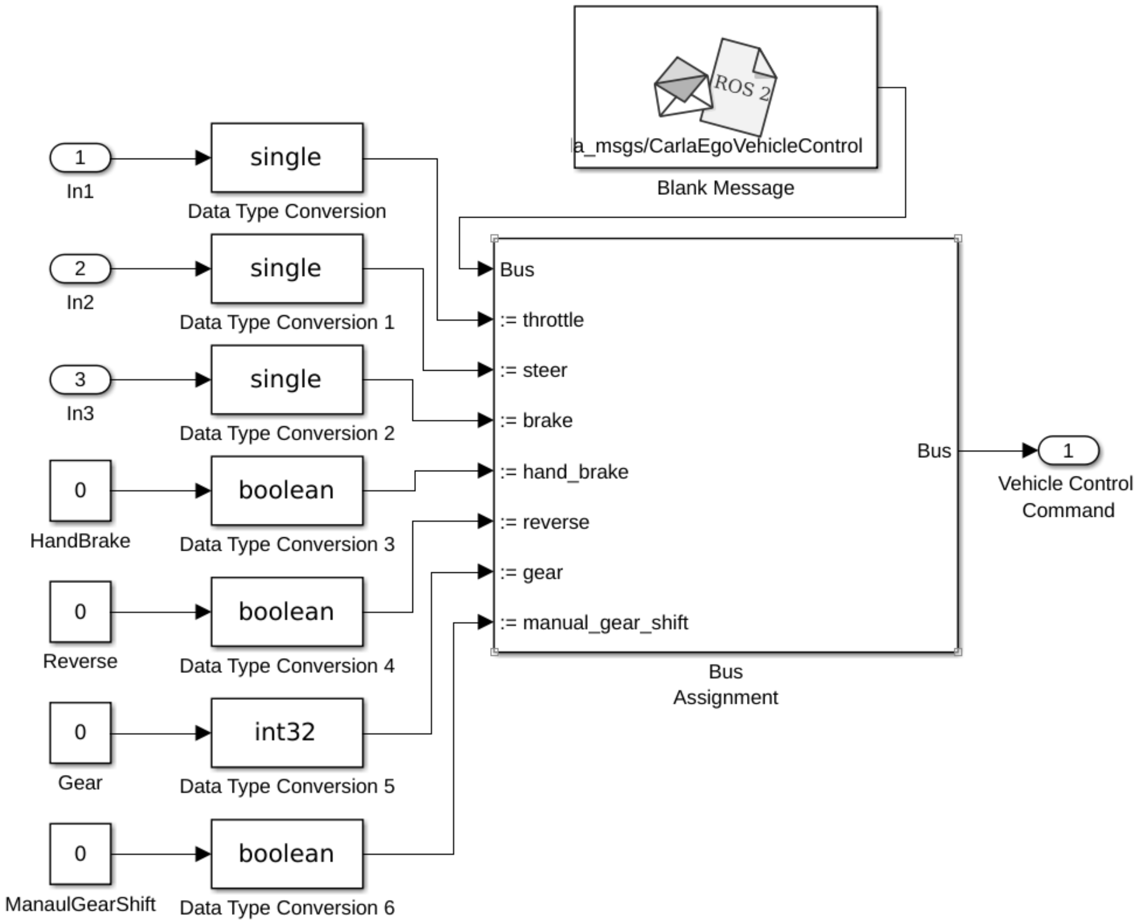
help of a Blank Message block that provides the message structure as input to the Bus Assignment block. The subsystem output, since it is a formatted ROS2 message with the relevant control values, is directly fed into a ROS2 Publisher block which publishes it to */carla/ego_vehicle/vehicle_control_cmd* topic.

3. GUI
   In addition to the previously described Simulink blocks, a graphical user interface to control the vehicle has been created as seen in Subfigure 4.28a. Three sliders have been used to control the value of throttle, brake and steering respectively, while a selector button controls the travel direction and a push button engages or disengages the handbrake. All these features are connected to the aforementioned constant blocks, thus a change in one of the sliders affects the value of the block and consequently the vehicle control. In addition to the control interfaces, a speedometer visualizing current vehicle speed, an indicator displaying forward (green) or reverse (red) direction and a steering angle gauge have been added to this control interface.

In Subfigure 4.28b a snapshot of vehicle being controlled is presented. Even though it is not easy to derive the control from a single image, a detailed study can show that the control values set through Simulink can be seen in the left part of CARLA interface. A concrete example of the downstream functionality is visualised through the relevant video.

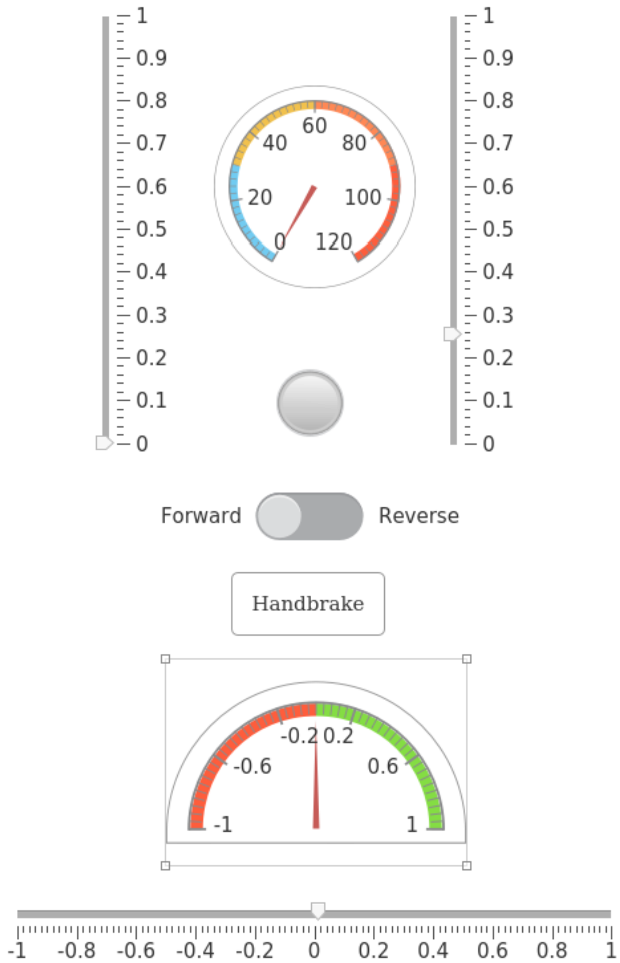


(a) Simulink Blocks of Downstream test



(b) Simulink Blocks of Control System

Figure 4.27: Simulink Blocks of Downstream test



(a) Graphical control interface of Downstream test

(b) CARLA visualisation of Downstream test

Figure 4.28: Visualisation of Downstream test

4.4.2.3 Object Detection

The following test proves the ability of a digital twin to process data deriving from the physical system in real time in order to facilitate decision making. In this basic test, the camera data streaming from the physical system into the digital twin are run through a pre-trained YOLO detection network in order to perform detection and categorisation. Simulink blocks subscribe to the camera topic, convert the ROS message to an image, run it through the detector and overlay the bounding boxes in the output image. Studying the Simulink blocks presented in Figure 4.29 the following are identified. As described earlier in the upstream test, a ROS2 Subscriber block is used in order to subscribe to */carla/ego_vehicle/rgb_front/image* topic and a ROS2 Image Read block to convert the relevant message into an image format that Simulink understands. A Deep Learning Object Detector block is then utilised. This block receives the image that will be processed as an input and a pre-trained detector saved in a $.mat$ format. This test utilises the tiny-yolov4-coco object detector, a one-stage object detector that can be easily obtained through Matlab and converted to the corresponding $.mat$ format. The detector block provides the bounding boxes (bboxes) and the labels for each detection. A Matlab function block, containing the corresponding function reads the image from the camera, overlays the bounding boxes and the labels and compiles the output image which is then visualised through a Video Display block.

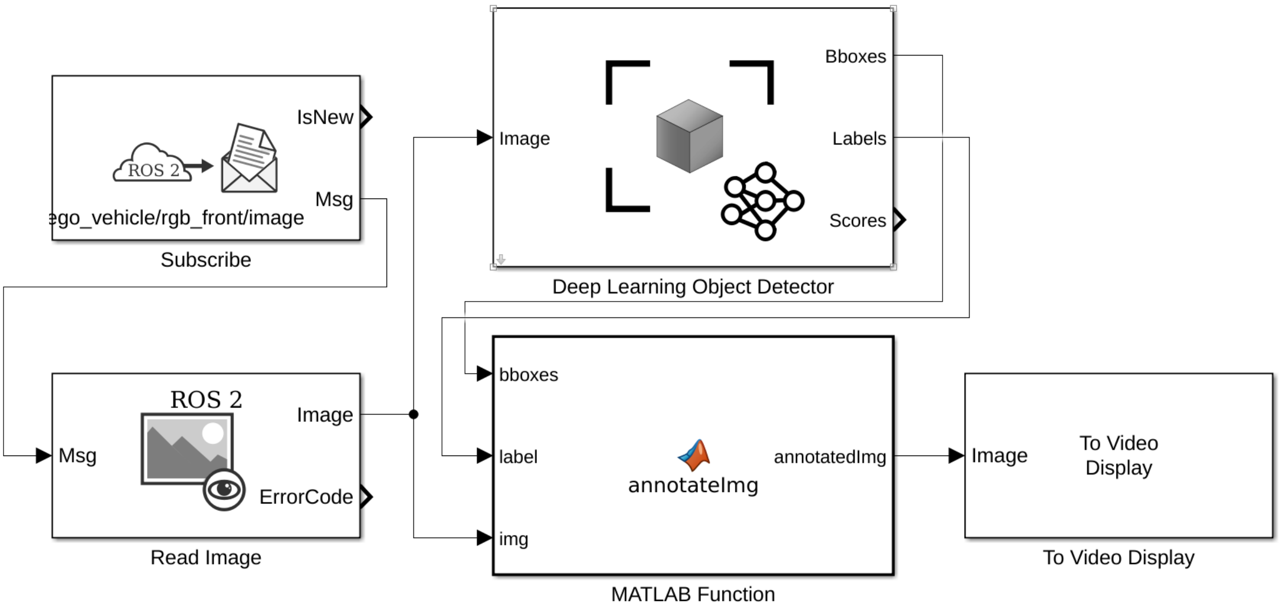


Figure 4.29: Simulink blocks of Upstream test

A snapshot of the detection results can be seen in Subfigure 4.30a while the CARLA interface can be seen in Subfigure 4.30b. This test, even though basic, it holds great importance for the digital twins concept since it proves that data streaming from the physical to the digital system can be processed in the digital counterpart in real time and be utilised for decision making or any other purpose proving one of the significant advantages of DTs; the processing of data in the digital environment saving up on computational resources and power requirements on the physical vehicle.

(a) CARLA visualisation (b) Detected objects in bounding boxes

Figure 4.30: Object Detection test visualisation

4.4.2.4 Lane Detection

This test, similar to the previous one, proves that the processing of real time physical data can not only occur from the digital twin itself, i.e. Simulink in our case, but also from external connected sources, in this example Matlab environment. In this case, the camera input is being utilised to detect road lanes. Even though the core experimental setup is similar to the object detection test, a detailed look in Figure 4.29 identifies the following. A ROS2 Subscriber block subscribes to */carla/ego_vehicle/rgb_front/image* topic and a ROS2 Image Read block converts the message into an image format similar to the previous test. However in this case the processing occurs not within Simulink but through a Matlab function. A Matlab Function block simply calls the relevant function and defines it as external by using the *coder.extrinsic()* command, provides the image as an input and returns the resulting image to be displayed with the lane detection overlays. This functionality allows to overcome limitation of Simulink and utilize the full potential of Matlab tool which has unparalleled image and signal processing capabilities as well as verifies that data can be processed outside of the digital twin in additional services.

Snapshots of the resulting test are presented in Figure 4.32. On the left side CARLA interface can be seen while on the right the lane detection overlay is visualised.

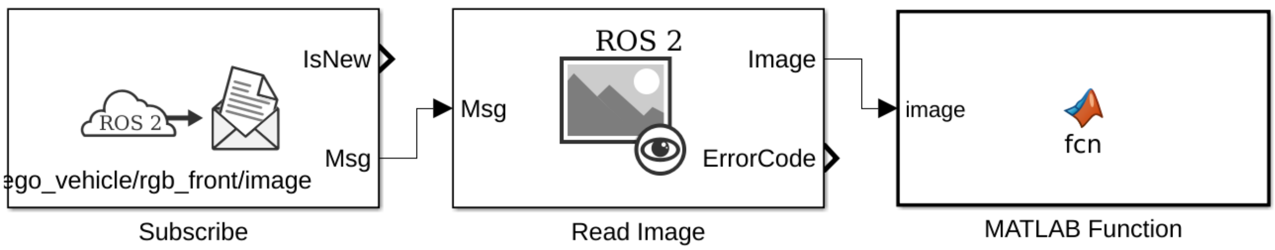
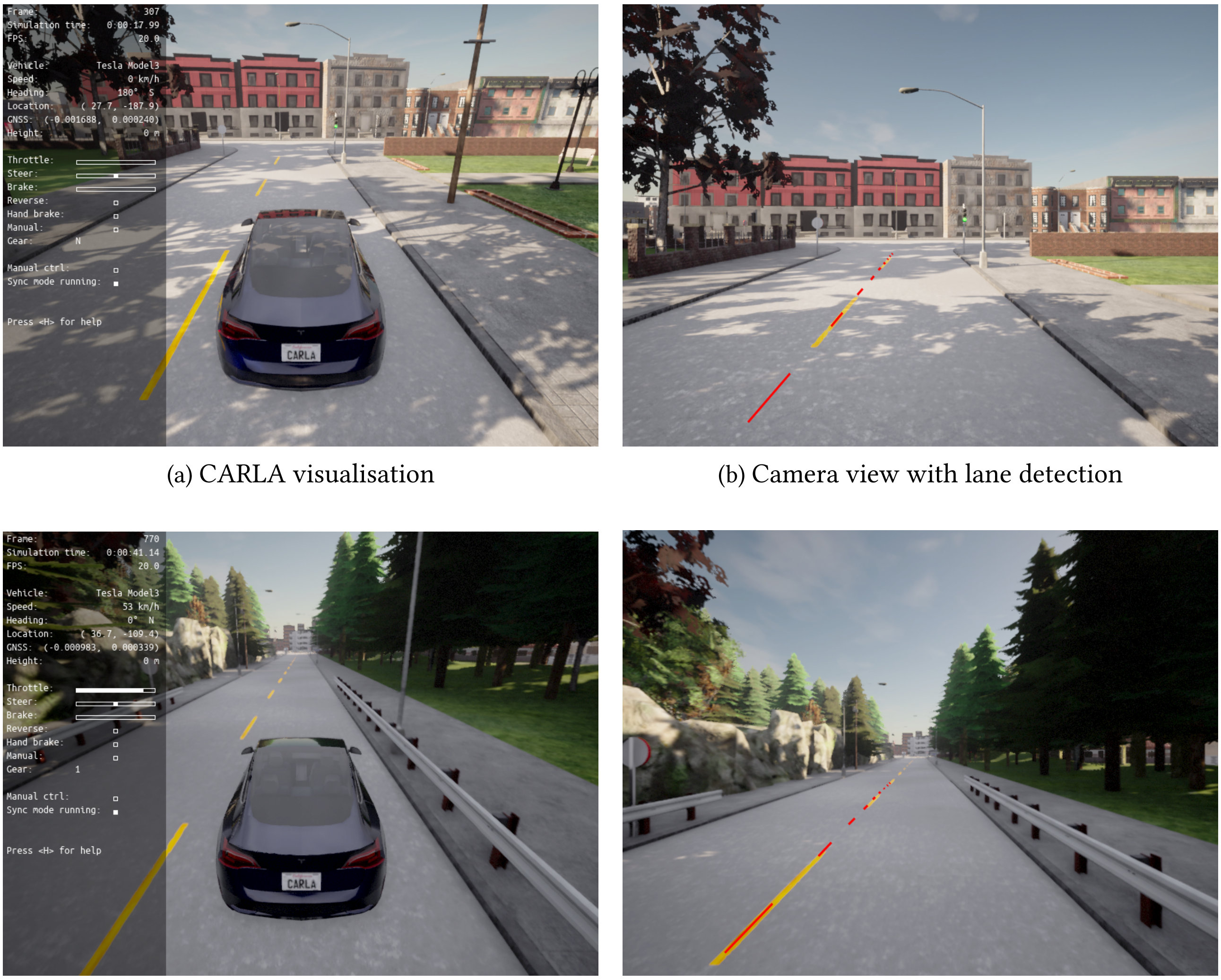


Figure 4.31: Simulink blocks of Lane Detection test



(a) CARLA visualisation

(b) Camera view with lane detection

(c) CARLA visualisation

(d) Camera view with lane detection

Figure 4.32: Lane Detection Test visualisation

4.4.2.5 Forward Emergency Braking

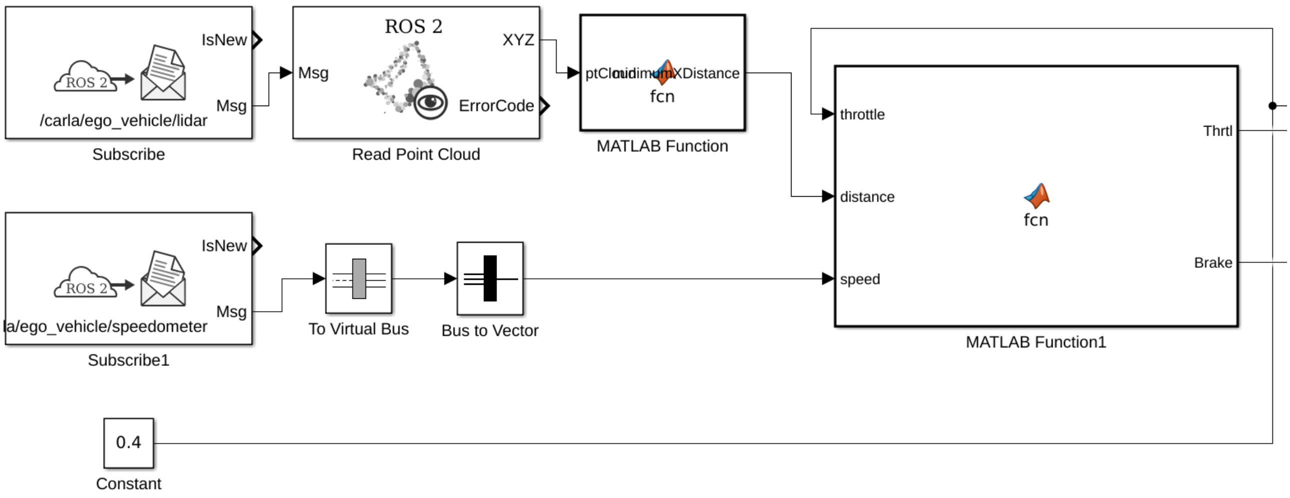
The last test performed under this validation use case process combines the knowledge obtained from the previous tests and intends to display the essence of the digital twins technology; the ability of the digital system to control the physical by processing the real-time data streaming from the physical one. In this test the researcher had the ability to control the vehicle through the Simulink blocks described earlier while relevant blocks subscribe to the LiDAR sensor and convert the message into a point cloud. The point cloud data are then processed in order to obtain only the information relevant to a forward emergency braking system, i.e. information in X coordinate that are only in front of the vehicle, in Y that are within 2 meters on each side of the vehicle and in Z that are not more than 2 meters below the sensor. An emergency braking system should take into account the speed of the vehicle since the braking distance in analogous to the travelling speed which can be calculate according to the Equation 4.1 where l_b is the braking distance in meters, V is the speed in kilometres per hour, g is the acceleration of gravity at 9.81 meters per second squared, $_b$ is the mean coefficient of friction, considered constant in CARLA with a value of 0.7 and s is the road grade, considered zero in our case as there is no slope in the test environment.

$$l_b = \frac{V^2}{2 \cdot g \cdot ({}_b + s) \cdot 3.6^2} \tag{4.1}$$

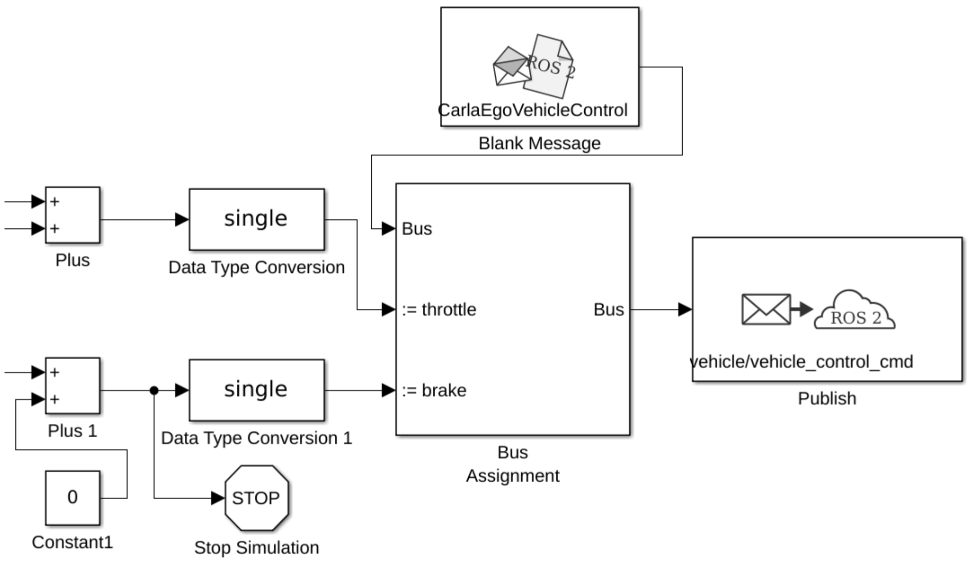
Taking into account Equation 4.1 the relevant Simulink blocks engages the brakes of the vehicle when an obstacle is identified bringing it safely to a stop. In Figure 4.33 the Simulink blocks used in this test are presented. For better visualisation the Simulink interface is split in two parts. Focusing on Subfigure 4.33a is is easily identified that the upper part of the system leverages the LiDAR upstream process by subscribing to */carla/ego_vehicle/lidar* topic and converting the message into the relevant point cloud. Then the point cloud is run through a Matlab Function block that applies the aforementioned transformation in order to limit the point cloud data only to the ones relevant to the forward collision system and calculates the point closest to the vehicle. The middle part of the system leverages the speedometer retrieve process by subscribing to the */carla/ego_vehicle/speedometer* running it through the Virtual Bus and the Bus to Vector blocks. One difference that is easily detected is the fact that the conversion from m/s to km/h is missing (through the Gain block). This conversion is integrated into the Matlab Function that will be discussed following. The bottom part of the blocks is a constant that sets the throttle value in order to drive the car at a constant speed towards the obstacle that would trigger the emergency braking. A Matlab Function block receives as input the throttle value, the distance to forward obstacles and the speed of the vehicle to calculate whether or not a crash is eminent and when the brakes need to be engaged depending on the speed of travel. This function has two outputs, the amount that throttle and brake should be adjusted. The rest of the functional blocks, which are visualised in Subfigure 4.33b, display that the throttle and brake output of the function are added with the current values of throttle (0.4) and brake (0). These values, as described in the Downstream test need to be formatted into a bus through the Bus Assignment block following the format of the relevant ROS2 message, specifically EgoVehicleControl message, which is provided as input to the block in question. By setting the bus values to throttle and brake numerical values, after casting them to singles in order to avoid formatting discrepancies, the relevant message is created and then conveyed to the vehicle through a ROS2 Publish block that publishes to the */carla/ego_vehicle/vehicle_control_cmd* topic.

In Figures 4.34 two different instances of the test are represented. In the first instance the obstacle that triggers the emergency braking is the road coming to a sharp turn though the driver not turning the wheel and thus triggering the system while in the second instance the obstacle is a stationery vehicle that triggers the system since the driver did not engage the brakes in order to avoid crashing into it

The emergency braking test concludes the experimental validation undertaken through the CARLA - ROS - Matlab/Simulink environment. These tests have gradually presented additionally functionality towards the creation of a digital twin that can eventually receive real time data, process those data accordingly without using any hardware resources of the physical system, decide on an action and eventually trigger the physical system to act accordingly.

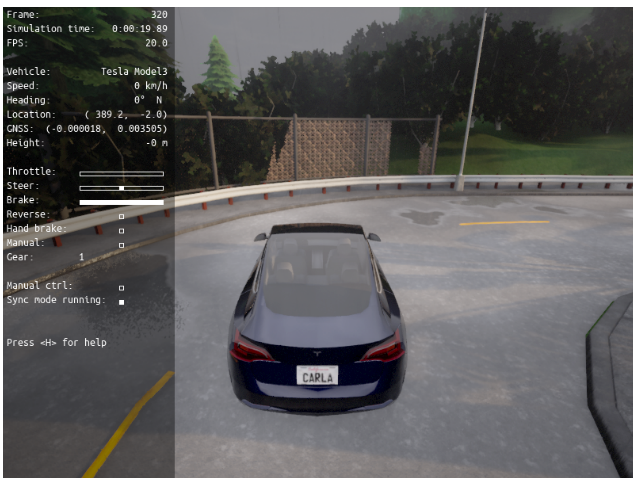


(a)



(b)

Figure 4.33: Emergency Braking test Simulink blocks



(a) Road curve emergency braking

(b) Stationery Vehicle emergency braking

Figure 4.34: Carla Visualisation of the emergency braking tests

4.4.3 Conclusion

The experimental validation tests presented in this section have successfully demonstrated the essential capability of a digital twin to exert control over its physical counterpart through bi-directional communication. The tests confirmed that the physical system's sensor data can be reliably streamed "upwards" to the digital twin for real-time processing, while control commands issued by the digital twin can effectively influence the physical vehicle ("downstream"). This bi-directional data flow validates the fundamental axiom of the digital twins and in addition proves their the ability to offload complex processing to the digital environment, thus reducing computational load and energy consumption on the physical system.

Furthermore, testing with diverse vehicles and simulation environments has shown the framework's scalability and adaptability across different platforms and hardware configurations. These results underline the practical utility of the proposed conceptual framework in bridging the gap between theoretical development and real-world deployment of digital twins in autonomous vehicles.

Looking forward, while these findings bolster confidence in digital twin technology, challenges such as achieving perfect physical-digital synchronisation in complex, uncontrolled environments remain. Future work should focus on expanding validations to physical full-scale vehicles, exploring more diverse and dynamic operational conditions, and enhancing the framework through advanced AI integration for adaptive and autonomous parameter tuning. Overall, the experimental outcomes affirm that the established framework enables the creation of functional, scalable digital twins, laying a strong foundation for their broader adoption and further advancement in intelligent autonomous vehicle research.

4.5 Public Repositories

As explicitly mentioned earlier, the software used for the second and third validation use cases is publicly available through GitHub repositories. This intention of sharing the software was to allow other researchers and engineers to be able to replicate the use cases, validate the framework on their own and use both it as a basis for further enhancement.

Three repositories have been established, the first contains the software required to control the updated RoboRacer vehicle, modified to run under ROS2 and specifically Humble Hawksbill version. The second repository contains the digital model created, the simulator the mapping application and the 3D map builder described earlier. The third repository contains all the Simulink models used in the third expeirmental validation. Table 4.5 lists the repository name, provides a short description and documents the link to access them through GitHub.

In order to ease the use of the software created, numerous launch files have been compiled and are included in the aforementioned repositories. A short description is presented here, however detailed

Table 4.5: Public Repositories Table

Repository Name	Description	Link
roboracer_sw_stack	A repository containing all the aforementioned packages and the software to control the upgraded RoboRacer vehicle	Software Stack Repository Link
roboracer_sim	A repository containing the simulated model and environments as well as visualisation, mapping and 3D map builder tools.	RoboRacer Simulator Repository Link
simulink_models	A repository containing the Simulink models described previously. CARLA, ROS Bridge, ROS2 and MATLAB/Simulink are required to re-create these tests.	RoboRacer Simulator Repository Link

readme files are posted in each repository too.

As far as the software stack is concerned, the following launch files can be utilised to not only to control the vehicle and perform tests but also to log ROS topics in ros_bag format.

I. *ros2 launch f1tenth_stack f1_tenth_gui.launch.py*
Launches the control and sensors stack together with RViz in order to visualize the sensor reading too. The car can be controlled through the Logitech F710 controller.

II. *ros2 launch f1tenth_stack f1_tenth_remote.launch.py*
Launches the control and sensors stack only. Helpful for running experiments. The car can be controlled through the Logitech F710 controller.

III. *ros2 launch f1tenth_stack rosbag_record.launch.py*
Records all topics published in ROS bag format. Requires the software stack to be running (one of the two previous launch files).

IV. *ros2 launch f1tenth_stack rosbag_record_no_camera.launch.py*
Records all other published topics except the camera to save storage space. Requires the software stack to be running (one of the two previous launch files).

It should be mentioned here that the aforementioned software stack even though it can be build successfully and without errors on any Ubuntu 22.04 with ROS2 and all the prerequisites installed, it is not possible to run without a fully functional scale vehicle with the aforementioned hardware setup. However, RoboRacer has been extensively used over the past years and it is not difficult for a researcher to obtain and upgrade one or build a custom vehicle with the same hardware set-up to replicate these experiments and use it as a foundation for future research efforts.

As far as the simulator is concerned, the launch files created are destined to run the simulator within the predefined environment, visualize the sensor data recorded in *ros_bags*, run a SLAM algorithm to create a map of the environment and turn the said map into a 3D model. It needs to be mentioned here that by creating new environment models and world files, Gazebo can load alternative environments; that's how the environment from the Unmanned Systems and Robotics Lab test facility to the McNair Aerospace centre in the previous tests has been altered.

I. *ros2 launch roboracer_bringup roboracer.launch.py*
   Launches the simulator and the RViz environment of the RoboRacer in the USRL test area.

II. *ros2 launch roboracer_visualization roboracer_visualization.launch.py*
   Launches RViz in order to visualize either real or simulated sensor data from the RoboRacer platform.

III. *ros2 launch slam_toolbox roboracer_offline_mapping.launch.py*
   Launches the mapping tool to create a map utilizing the slam_toolbox when data come from physical sensors.
   ros2 launch slam_toolbox roboracer_offline_mapping_sim_data.launch.py
   Launches the mapping tool to create a map utilizing the slam_toolbox when data come from simulated sensors.

IV. *python3 src/roboracer_sim/map2gazebo/map2gazebo/map2gazebo_offline.py –map_dir "filename.pgm"*
   Runs a converter that transforms the 2D image map into a 3D model.

Regarding the use of the Simulink models, they can simply be inserted into Matlab R2023b. This limitation comes from the fact that Simulink models are compatible to the version they have been build with.

4.6 Conclusion, Opportunities and Challenges

This chapter has presented comprehensive validation use cases of the proposed conceptual framework through three distinct yet complementary use cases, successfully demonstrating its practical applicability and effectiveness in creating digital twins for autonomous vehicles. The first use cases focused primarily on validating the initial two phases of the framework, presenting a detailed methodology for characterizing physical systems and establishing real-time communication channels. Through the development of a custom-built research platform equipped with multiple sensors (LiDAR, stereo cameras, IMU, GPS, and ToF sensors), this use case successfully demonstrated the framework's capability to document system requirements, map key components, and establish robust communication infrastructure using ROS. The use case validated the framework's emphasis on modularity and scalability by successfully integrating diverse sensor systems through a decentralised control architecture. The second use case provided a validation of the first, second and mainly third framework phase, utilizing an upgraded RoboRacer platform to demonstrate the digital model creation process. The comparative analysis between physical and digital systems revealed strong correlations in sensor data, odometry, and mapping results, effectively demonstrating the framework's ability to minimize the "sim2real" gap. The successful creation of accurate digital representations of both simple and complex environments further validated the framework's scalability principle. The third validation use case provided an overall framework validation and a scale-up to full-scale vehicles with a focus to prove the fundamental principle of the digital twins technology, the bidirectional communication between the physical and the digital system and the ability of the digital system to control the physical one. All three use cases adhered to the framework's fundamental principle of replicability by utilizing open-source (ROS/ROS2, Gazebo, CARLA), readily available hardware components or solutions well-established into the research community (Matalb/Simulink). The public availability of all software implementations, datasets, and experimental procedures through GitHub repositories and Zenodo platform ensure that the research community can replicate, validate, and extend these results. This commitment to open science directly addresses one of the key gaps identified in the literature review; the fragmentation of approaches and lack of reproducible methodologies publicly available to researchers.

The use cases results provide compelling evidence for the framework's effectiveness in addressing the relevant research questions. RQ 3.1 is answered positively through the successful validation across three different vehicle platforms and complexity levels, demonstrating the framework's robustness and adaptability. RQ 3.2 is addressed through the comprehensive documentation and public availability of all experimental materials, enabling replication and further research by the community. RQ 3.3 is validated through the successful application to different vehicle configuration and scale and the framework's inherent vehicle-agnostic design principles.

These use cases revealed not only the strengths but also limitations of the current approach. While the framework successfully created functional digital twins with demonstrable fidelity, perfect correspondence between physical and digital systems remains an ongoing challenge, particularly in complex environments with numerous unpredictable variables. These findings align with the broader "sim2real" challenge acknowledged throughout the robotics community and highlight areas for future improvement. The iterative nature of the framework was also validated through the validation process, with feedback loops being naturally triggered during the tests as system performance was evaluated and refined. This demonstrates the framework's practical utility in guiding real-world digital twins development rather than serving merely as a theoretical construct. Also, a challenge that needs to be addressed is the stability of the communication and the exchange of large volumes of data in high rates, something that was not taken into account in the validation use cases. Overall, the experimental validation presented in this chapter provides strong evidence for the effectiveness of the proposed conceptual framework in creating digital twins for autonomous vehicles. The successful implementation across diverse platforms, combined with the comprehensive documentation and open-source availability of results, establishes a solid foundation for the framework's adoption by the broader research community and its potential evolution into a standardised methodology for digital twin development in autonomous systems.

Chapter 5

Summary, Impact and Future Research

This doctoral dissertation is set out to address a critical gap in the intersection of digital twins and autonomous vehicles by developing and validating a standardised conceptual methodological framework. Through comprehensive literature analysis, framework development, and validation use cases, this research has contributed significant insights to both academic and practical domains. This chapter discusses the key findings, implications, limitations, and future research directions.

5.1 Summary of Contributions

In order to kick-start the discussion, initially a summary of the main contributions of this work follows. As defined in Chapter 1, the three contributions are the literature review of the domain, the development of a conceptual framework and the validation of said framework.

5.1.1 Literature Review

The comprehensive bibliometric analysis and literature review, presented in Chapter 2, revealed several interesting findings for the cross-section of autonomous vehicles and digital twins that shaped this doctoral dissertation. These findings are summarised below:

- **Growing Research Interest:** The analysis of 710 publications from Scopus demonstrated exponential growth in research combining digital twins and autonomous vehicles, with publications increasing from minimal numbers pre-2019 to 236 articles in 2024 alone. This trend validates not only the relevance, but also the importance of this research.
- **Fragmented Application Landscape:** Despite the growing interest, the literature revealed a highly fragmented landscape with diverse applications spanning land, air, and surface/underwater vehicles. While this diversity demonstrates the broad applicability of DT concepts, it also highlighted the absence of unified methodological approaches.

- **Theory-Practice Gap:** A consistent finding across all vehicle categories was the prevalence of "vehicle agnostic" solutions that, while theoretically sound, often lack practical implementation guidance. This observation was the driving force for the establishment of a conceptual application framework developed in this research.
- **Tool Diversity:** The analysis identified numerous tools and technologies (ROS, Gazebo, MATLAB/Simulink, Unity, etc.) being used across different applications, but without clear guidelines for selection or integration. This finding emphasised the need for framework-based tool selection criteria.

5.1.2 Conceptual Framework

The proposed four-phase conceptual framework addresses the identified gaps through the following key contributions:

- **Knowledge Leverage:** Cross-domain knowledge from industry has been adapted and applied in order to develop this conceptual framework. The Industry 4.0 paradigm and its success in utilizing DTs is used as a beacon for the application of the technology into a diverse domain.
- **Systematic Approach:** The framework provides a systematic, step-by-step methodology that transforms digital twin development from an ad-hoc process to a structured engineering discipline. The four phases form a process that can be followed regardless of vehicle type or application domain.
- **Fundamental Principles:** The framework is based in five fundamental principles (Modularity, Scalability, Fidelity, Real-time Communication, and Replicability). These principles ensure that the resulting digital twins are not merely functional, but are designed for long-term sustainability and community adoption.
- **Iterative Design:** Unlike linear development models, the framework incorporates explicit feedback loops that acknowledge the iterative nature of digital twin development. This design recognises that achieving high fidelity often requires multiple refinement cycles.

5.1.3 Validation Use Cases

Three use cases were designed to validate the framework and provided crucial insights into its practical applicability:

- **Versatility:** The successful application of the framework to three different vehicle platforms; a custom-built research platform, an upgraded RoboRacer vehicle and a full-scale vehicle demonstrate its scalability and adaptability across different hardware configurations and complexity levels. In addition, the framework has intentional been described as generic as possible since it can potentially be used for the creation of DTs for other types of vehicles.

- **Sim2Real Gap:** The validation results showed measurable improvements in the correspondence between physical and digital systems, particularly evident in the sensor data comparisons and SLAM mapping results. While perfect correspondence remains elusive, the framework provides a structured path toward continuous improvement by exploiting the power of digital twins to bridge this gap.
- **Ecosystem Availability:** All tests leveraged open-source (ROS, Gazebo, CARLA) or widely available (Matlab/Simulink) tools and rendered all results publicly available, demonstrating the framework's alignment with collaborative research principles and its potential for community adoption.

5.2 Impact

This dissertation has a two-fold impact to the community; both in academic and industrial domain. As far as the academic community is concerned, this work offers a comprehensive conceptual methodology specifically designed for the development of digital twins in autonomous vehicles. By providing a structured framework, it equips researchers with a clear and systematic approach that is expected to enhance the quality and comparability of future research efforts in this domain. Furthermore, the work serves as a bridge across multiple disciplines, integrating insights from robotics, simulation, Internet of Things (IoT), and systems engineering. This interdisciplinary perspective demonstrates how combining diverse fields can effectively address complex technological challenges inherent in autonomous vehicle development. Additionally, the framework emphasises its replicability by promoting the use of open-source tools and publicly sharing the software used in the validation use cases. This focus directly tackles a common challenge in autonomous systems research, i.e. the ability to reliably replicate and build upon previous work, thus fostering cumulative knowledge and progress.

From an industry standpoint, this work offers substantial practical benefits for practitioners engaged in autonomous vehicle development. The structured methodological framework helps to reduce risk and uncertainty typically associated with implementing digital twins. By clearly defining development phases and validation criteria, it supports more predictable and controlled project execution. Moreover, by prioritizing open-source tools and a systematic development approach, the framework significantly lowers financial barriers to adopt DTs. This is particularly advantageous for smaller companies and startups that may face resource constraints. Lastly, if such a standardised framework is broadly adopted across the industry, it could drive greater interoperability among digital twin implementations and streamline development processes, resulting in reduced overall costs throughout the autonomous vehicle ecosystem.

5.3 Limitation and Challenges

During this research, several technical limitations were identified. High-fidelity digital twins require substantial computational resources to operate in real time. Although the framework addresses this challenge through its modularity principle, practical constraints related to hardware capabilities remain. Additionally, perfect sensor simulation continues to be an extremely difficult task, particularly under complex environmental conditions such as varying weather, lighting, and material properties. These sensor fidelity challenges ultimately affect the achievable accuracy of the digital twin. Furthermore, real-time synchronisation between the physical system and its digital counterpart is hindered by communication latency, network reliability issues, and bandwidth constraints. While acknowledged within the framework, such communication challenges persist as significant obstacles during deployment in real-life scenarios.

From a methodological perspective, the framework demonstrates scalability principles; however, physical validation use cases were confined to 1:10 scale vehicles while scale-up was performed on a simulated vehicle acting as the physical system. Conducting full-scale physical validation remains a significant effort that exceeded the scope of this research. Although the framework is designed to be vehicle-agnostic, the validation use cases predominantly focused on land vehicles. Application of the framework to aerial and marine vehicle domains, while conceptually supported, requires further validation to confirm its effectiveness. Moreover, the current validation effort concentrated on proof-of-concept demonstrations rather than extended operational testing. Longer-term validation is necessary to provide deeper insights into the framework's robustness and future maintenance needs.

5.4 Future Work

While the validation use cases have demonstrated the applicability and validity of the developed four-phase application framework for digital twins in autonomous vehicles, several areas remain open for deeper investigation.

In the short term, expanding the validation is a clear priority. This expansion should include implementations involving physical full-scale vehicles and applications beyond land vehicles, extending to aerial and marine platforms, as DT applications are significant for these domains too. It should also encompass extended operational periods and more complicated testing and validation not only in environments but also in hardware and controls. This will lead to the refinement of the framework with the addition of further feedback loops or even new phases that emerge through experience gained from framework application for its intended purpose.

The development of a comprehensive ecosystem of tools to support framework implementation would also be beneficial. This effort may involve creating automated tools for vehicle characterisation, utilities for sensor calibration and validation, and performance benchmarking and comparison tools to facilitate evaluation across different implementations.

For medium-term research opportunities, integration of artificial intelligence and machine learning techniques may offer significant potential. These technologies can automate fidelity optimisation based on specific application requirements, enable digital twins that adapt and improve over time, and develop predictive models for system behaviour and failure modes. Extending the framework's applicability to adjacent domains such as industrial automation, robotics, smart city infrastructure, healthcare, medical robotics, and space exploration systems represents another promising avenue that can be achieved by leveraging the existing framework. Establishing formal standardisation and certification processes in collaboration with industry partners and standards organisations would be worth investigating; published work such as ISO 23247 - Digital Twin Framework for Manufacturing can act as an implementation guide. Such efforts should focus on developing clear standards based on this framework, creating certification processes for digital twin fidelity, and setting interoperability requirements to accommodate multi-vendor systems.

Looking further ahead, the long-term vision is to create comprehensive digital twins of entire autonomous vehicle ecosystems. This would include multi-modal transportation networks, infrastructure-vehicle interactions, human-machine interfaces with social acceptance considerations, and environmental impact as well as sustainability factors. Future digital twins should go beyond merely mirroring their physical counterparts and actively optimize system performance through continuous learning and adaptation, predictive maintenance and health monitoring, and dynamic reconfiguration in response to mission demands. Integration with smart infrastructure and broader IoT ecosystems will be vital to enable such capabilities. Additionally, societal integration must be addressed as autonomous vehicles become more widespread, encompassing public acceptance and trust fostered through transparent digital twin representations, ethical considerations in decision-making, privacy and security implications, and educational and training applications for preparing the next generation of engineers.

5.5 Closing Remarks

This dissertation presents a comprehensive investigation into the integration of digital twins within the domain of autonomous vehicles. It emphasises the increasing importance and transformative potential of DT technology in the design, development, testing, and operation of autonomous systems. A detailed literature review revealed fragmentation and the lack of a standardised approach for DT deployment in AVs, a gap which the proposed conceptual framework addresses by providing a clear, modular and scalable methodology focusing on real-time synchronisation, high-fidelity modelling, and replicability to reduce the sim2real gap. This work further validates the practical applicability of this framework through validation on scaled and full-size autonomous platforms, demonstrating its adaptability across various vehicle types. It aims to bridge theoretical research with practical application, promote the use of open-source and widely available tools to foster replicability, thereby supporting community-driven innovation.

In further detail, this doctoral research represents a significant step forward in bridging the gap between digital twins technology and autonomous vehicle development. This systematic approach demonstrates that standardised methodological frameworks can indeed advance this rapidly evolving field. As the autonomous vehicle industry continues to mature, the need for rigorous, systematic approaches to digital twins development will only increase. The framework developed in this research provides a solid foundation for future endeavours, offering both the theoretical foundations and the practical guidance necessary to transform digital twins from an interesting research concept to an essential engineering tool. The journey from simulation to reality — closing the sim2real gap — requires exactly this type of systematic, principled and well-structured approaches. While challenges remain and future work is definitely required to fully realize the potential of digital twins in autonomous vehicles, this research demonstrates that the path forward is not only clear but very promising too. The convergence of digital twins and autonomous vehicles represents not just a technological opportunity, but a fundamental shift in how intelligent autonomous vehicles are designed, developed, and deployed in the physical world. In conclusion, this research delivers a foundational methodology that enhances the autonomous systems development lifecycle and accelerates the broader adoption and reliability of digital twin technology in autonomous vehicle applications, paving the way for safer, more efficient, and resilient autonomous mobility solutions.

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Appendices

Appendix A

Land Vehicles Publications Analysis

Table A.1: Analysis of land vehicle publications under study.

Ref	Work Description	Tools / Technologies	Vehicle Type
[141]	A digital twin prototype for a learning-enabled self-driving vehicle, focusing on traffic sign recognition and lane keeping.	PAVE360	Vehicle Agnostic
[142]	A sim2real method that leverages an executable digital twin (xDT) to automatically tune and adapt autonomous vehicle control systems.	NMPC	Vehicle Agnostic
[91]	A DT framework designed to enhance the capabilities of traditional radar systems.	N/A	Vehicle Agnostic
[111]	A mobility digital twin framework, aiming to enhance CAVs with edge computing.	NeRF	Vehicle Agnostic
[163]	A traffic safety detection system that leverages DT and VR technologies.	Gaussian Process - Background Subtraction	Vehicle Agnostic
[143]	A microscopic agent-based simulation environment integrated with a digital twin to assess dispatching methods for AMRs.	SMP-LSAP	AMRs
[340]	Use of overhead camera views and vehicle sensor data to create a network of distributed digital twins on fog machines, continuously updated with vehicle locations.	ML Forecaster	Vehicle Agnostic
[8]	A standardised framework for vehicular digital twins to facilitate data collection, processing, and analysis, crucial for identifying and mitigating cyber threats and operational failures.	N/A	Vehicle Agnostic
[112]	Exploring how increasing vehicle autonomy through DTs can alleviate urban traffic congestion, which is primarily caused by human driving decisions and reaction times.	SUMO software	Vehicle Agnostic
[164]	Combined safety and cybersecurity testing methodology for autonomous driving algorithms, addressing the common issue of these crucial evaluations being conducted in isolation with the use of DTs.	N/A	Vehicle Agnostic
[113]	Creation of realistic LiDAR simulations for testing autonomous vehicles, aiming for ”zero domain gap” where simulated performance perfectly mirrors real-world behaviour.	N/A	Vehicle Agnostic
[92]	Exploring the application of digital twins to the product lifecycle management of battery packs in electric vehicles.	N/A	Vehicle Agnostic
[114]	Advanced methods for creating efficient virtual models of complex systems, specifically focusing on off-road vehicles.	Dynamic Reduction Techniques	Off-Road Vehicles

[115]	Application of digital twin theory and parallel intelligence to enhance the testing of autonomous vehicles.	N/A	Vehicle Agnostic
[144]	Visual Simultaneous Localisation and Mapping (VSLAM) technique aligning the sparse 3D point cloud generated by VSLAM to a pre-existing digital twin of the environment.	N/A	Vehicle Agnostic
[116]	Design and development of a digital twin platform for scenario-based testing of road vehicles.	CARLA	Vehicle Agnostic
[145]	Introduction of ”Swarm Metaverse”, a novel approach to control robot swarms by integrating physical robots with their digital twins.	N/A	UGV
[117]	A framework that uses digital twins alongside V2X communication technology to enable realistic testing in virtual complex road scenarios.	N/A	Vehicle Agnostic
[98]	An optimised delivery system for automated vehicles, particularly focusing on car-sharing services, by leveraging a digital twin-based method.	N/A	Cars
[93]	Reverse-engineering vehicle suspension characteristics to create highly accurate digital twins for autonomous vehicle development and testing.	IPG Carmaker / Unity 3D	Vehicle Agnostic
[146]	Prototyping of a VR digital twin designed to train autonomous vehicle lane detection systems, specifically addressing the challenging conditions of snowy environments.	Virtual Reality	Vehicle Agnostic
[118]	Miniature autonomous vehicle environment designed to bridge the sim-to-real gap in reinforcement learning for autonomous driving by leveraging digital twins.	TD3	Vehicle Agnostic
[119]	Addressing the critical need for reliable validation and verification of artificial intelligence components in autonomous vehicles with the help of DTs.	N/A	Self-Driving Shuttle
[99]	Integrate digital twin technology into Software Defined Vehicles, highlighting the benefits of decoupling hardware and software.	SDV	Vehicle Agnostic
[185]	A Digital Twin based Internet of Vehicles framework designed to enhance smart transportation systems.	CoAP protocol	Vehicle Agnostic
[88]	Digital Twin technology that revolutionise EV battery management, significantly enhancing sustainability and efficiency.	AI / ML	EV
[89]	Design and implementation of a digital twin for predicting failures in automobiles using machine learning algorithms.	Eclipse Hono,Kura and Ditto / Gradient Boost Regressor	Vehicle Agnostic
[186]	Real-Time Communication and Data Acquisition methodology for designing electric autonomous vehicles by integrating Model-Based Systems Engineering with digital twin technology.	MBSE/SysML	EVs
[6]	Digital Twin technology to optimise the electric propulsion drive systems of autonomous electric vehicles.	AI/ML	Autonomous Shuttle
[341]	Developing a system for evaluating EV performance through Digital Twins.	N/A	Autonomous Shuttle
[147]	DT platform designed to efficiently schedule shared autonomous electric vehicles by integrating both transportation and power networks.	N/A	Shared Autonomous Vehicles
[95]	A parametric Digital Twin for the transmission system of an autonomous electric vehicle.	N/A	Autonomous Shuttle
[120]	A co-simulation framework designed to create a digital twin of an urban 3D environment for autonomous vehicles operating in mixed traffic.	SUMO	Vehicle Agnostic

[187]	Utilize digital twin technology to enhance the reliability of multi-hop millimeter wave V2X communication.	N/A	Vehicle Agnostic
[100]	Integration of digital twin and blockchain technologies to revolutionise future transportation systems.	Blockchain	Vehicle Agnostic
[121]	AutoDRIVE, a sophisticated digital twin ecosystem specifically designed for research and education in autonomous driving.	N/A	Vehicle Agnostic
[122]	A digital twin ecosystem designed to streamline the development, simulation, and deployment of autonomous driving solutions.	N?A	Vehicle Agnostic
[123]	An immersive digital twin framework designed to facilitate the safe co-existence and interaction between human-driven and autonomous vehicles in urban environments.	N/A	Vehicle Agnostic
[124]	Validation through DTs of off-road autonomous systems which are inherently complicated by the unpredictable nature of these environments.	HPC	Off-Road Vehicle
[125]	A unified digital twin framework called AutoDRIVE Ecosystem, designed to streamline the development and validation of autonomous vehicles across various scales and operational environments.	Autoware	Off-Road Vehicle
[15]	Design and implementation of a ROS testbed for research into autonomous vehicles, particularly within the IoV concept and the integration of Digital Twins.	ROS	Research Scale Vehicles
[188]	A simulation-based Digital Twin designed for 5G connected automated and autonomous vehicles, focusing on cross-border scenarios.	SVL simulator	5G-Enabled Vehicles
[165]	A Safety Toolkit for Automated Vehicle Shuttles, with a DT in its core, detailing a practical approach to evaluating the safety of autonomous vehicles before their widespread deployment.	N/A	Autonomous Shuttle
[166]	Investigate the crucial role of digital twin technology in validating the safety of Autonomous Vehicles within the framework of Industry 5.0.	MaaS/TaaS	Vehicle Agnostic
[126]	Explore how digital twin technology can be used to improve the safety and reliability of connected autonomous vehicles, particularly in complex, mixed-traffic environments.	N/A	Vehicle Agnostic
[43]	Investigate how digital twin technology can revolutionise the testing of autonomous vehicles.	N/A	Vehicle Agnostic
[127]	Look into how digital twin technology combined with Artificial Intelligence can revolutionise the testing and development of self-driving cars.	AI	Vehicle Agnostic
[148]	How Digital Twin technology can significantly improve the operational environment for Autonomous Mobile Robots, particularly within challenging industrial settings like production halls.	N/A	AMRs
[101]	A digitalisation concept, involving a DT to create a virtual, real-time representation of both user and car, for the emerging "Car-as-a-Service" model.	N/A	Cars
[149]	Development and validation of a digital twin for an Automated Guided Vehicle to optimise its operation in industrial settings.	PID / Fuzzy	AGV
[342]	How Digital Twin technology and Deep Reinforcement Learning can enhance collaborative autonomous driving systems.	DRL	Vehicle Agnostic
[167]	A Time-Sensitive Local Differential Privacy-Based Federated Learning framework specifically designed for Vehicular Digital Twin Networks.	Federated Learning	Vehicle Agnostic

[128]	Exploring Scenario-in-the-Loop a novel simulation concept designed to enhance the development and validation of autonomous vehicle technology through DTs.	N/A	Vehicle Agnostic
[150]	Digital Twins-assisted multi-autonomous vehicle distributed collaborative path planning algorithm.	LSTM / DFRL	Vehicle Agnostic
[189]	Digital Twins and the Internet of Vehicles can enhance smart driving by tackling data synchronisation and resource constraints.	Swarm Learning	Vehicle Agnostic
[129]	Development of a digital twin for the F1TENTH race car using the INTO-CPS tool-chain.	N/A	Scale Research Platform
[130]	Development of a Virtual Simulation Environment and a Digital Twin of an autonomous driving truck, specifically for use within a distribution centre.	IBM Rhapsody/MATLAB Simulink/Unity	Trucks
[131]	an emulation tool designed to help agrifood producers integrate advanced digital technologies, specifically intelligent and autonomous unmanned ground vehicles into real-world farming operations.	ROS	UGVs
[7]	Digital Twins that significantly improve the dependability of autonomous driving by enhancing safety and security.	IoT/CPS	Vehicle Agnostic
[132]	A transfer learning approach, specifically tackling the sim2real challenge. The core of this solution lies in leveraging digital twin technology, which creates a high-fidelity virtual representation of a physical system.	RL	Vehicle Agnostic
[190]	Introduces a Digital Twin-assisted cooperative driving system designed to enhance traffic flow and safety at non-signalised intersections.	AR	Vehicle Agnostic
[168]	A Digital Twin approach to real-time hazard prediction for Connected Autonomous Vehicles, aiming to significantly enhance safety, particularly for pedestrians.	CARLA/CORTEX Cognitive architecture	Vehicle Agnostic
[67]	A DT framework for autonomous driving, focusing on its comprehensive real-world implementation and demonstration.	N/A	Vehicle Agnostic
[169]	Evaluating Autonomous Emergency Braking systems through digital twin-based simulation framework that accurately replicates vehicle dynamics, sensor performance, and diverse road and weather conditions.	N/A	Vehicle Agnostic
[170]	Digital twin vehicle stability monitoring system designed to enhance the active safety of intelligent electric vehicles.	PSOLSTM	Vehicle Agnostic
[151]	Smart mobility digital twin platform designed to enhance connected and automated vehicle navigation, focusing on improving traffic efficiency and road safety.	RSUs/V2X	Vehicle Agnostic
[102]	Digital twin-enabled reinforcement learning approach for autonomous driving, aiming to enhance the efficiency of training self-driving policies.	MBRL	Vehicle Agnostic
[171]	An intelligent driving system that utilises V2X communication within a digital twin framework to enhance testing and validation of autonomous vehicles.	V2X	Vehicle Agnostic
[172]	Digital twin-assisted simulation method for autonomous vehicles, specifically focusing on car-following scenarios.	N/A	Vehicle Agnostic
[343]	A vehicular digital twin framework designed to enhance autonomous vehicle performance by offloading intense real-time sensing, computing, and communication tasks to virtual digital twins in the cloud.	N/A	Vehicle Agnostic
[173]	A VR-enabled digital twin platform designed to monitor and reduce on-road vehicle emissions in urban areas.	N/A	Vehicle Agnostic

[191]	Intelligent network architecture for the Internet of Vehicles, leveraging edge intelligence and digital twin technology to enhance autonomous unmanned vehicle operation.	DL/SCCS	Vehicle Agnostic
[133]	Introduction of an Autonomous Driving Digital Twin simulation system designed to enhance the efficiency and reliability of autonomous driving system development.	N/A	Vehicle Agnostic
[152]	Digital Twin Vehicle Platooning Simulation System that innovatively applies digital twin technology to vehicle queue simulations within a Virtual Reality environment.	N/A	Vehicle Agnostic
[134]	Simulating self-driving car systems by repurposing, Grand Theft Auto V as a cost-effective and realistic testing environment.	OpenCV/YOLO /TensorFlow	Vehicle Agnostic
[135]	Explores the virtualisation of self-driving algorithms through a novel approach by integrating embedded controllers with a popular video game engine.	OpenCV/YOLO	Research Scale Platform
[103]	Hybrid terminating strategy for Particle Swarm Optimization, specifically applied to digital twin modelling of electrified vehicles.	PSO	Vehicle Agnostic
[104]	An intelligent driving school vehicle system utilising digital twin technology to revolutionise driver education.	N/A	Driving School Cars
[136]	Autoware-based digital twin simulator designed to advance autonomous agricultural vehicles.	Autoware	Agriculture Vehicle
[230]	Optimising the repair and recovery process for autonomous vehicles within an intelligent transportation system through a DT-enabled framework to efficiently manage post-accident maintenance.	N/A	Vehicle Agnostic
[192]	Prioritising communication between digital representations of vehicles in order to significantly improve the efficiency and safety of autonomous transportation systems.	N/A	N/A
[153]	A DT framework for the remote control of Autonomous Guided Vehicles within a Network Control System that leverages Integrated Sensing and Communications to achieve simultaneously monitor and control.	RL	AGVs
[193]	A virtual counterpart of a physical vehicle, deployed at the network edge, which continuously synchronises with the real vehicle to monitor, predict, and enhance its safety and driving experience.	OMA-LwM2M	Vehicle Agnostic
[174]	Integration of Artificial Intelligence, specifically deep learning with DT technology, to enhance the safety and efficiency of autonomous vehicles within smart city transportation systems.	STGCN	Vehicle Agnostic
[344]	Automated driving simulation test system that leverages digital twin technology to enhance the safety and efficiency of autonomous vehicle development.	N/A	Vehicle Agnostic
[137]	A privacy-preserving authentication scheme specifically designed for digital twin-enabled autonomous vehicle environments.	BAN logic/ROR models	Vehicle Agnostic
[154]	A fuzzy shared-control system designed to improve teleoperated driving, particularly when experiencing network delay, by integrating a real-time digital twin of the vehicle with human operator input.	N/A	Vehicle Agnostic
[194]	Application of digital twins in programmable vehicular networks to significantly enhance wireless Quality of Service, particularly in challenging non-line-of-sight scenarios.	N/A	Vehicle Agnostic
[138]	Digital twin-based system designed to rigorously test and collect data for autonomous driving systems, specifically focusing on extreme traffic scenarios.	Unreal Engine/CARLA	Vehicle Agnostic

[155]	A framework for connected autonomous vehicles to prevent collisions, particularly with unexpected obstacles by deploying a DT system within a vehicle platoon significantly reducing communication overheads and decision-making delays.	RRI/ULTP	Vehicle Agnostic
[175]	Digital twin test method for assessing the safety of autonomous vehicles, addressing the challenges of ensuring real vehicle dynamic performance and generating a sufficient number of critical safety scenarios.	V2X	Vehicle Agnostic
[105]	A digital twin of an autonomous agricultural vehicle. The research focuses on creating a three-dimensional dynamic model of the vehicle.	Chrono/FMU	AGVs
[106]	An application of digital twins within connected, cooperative, and automated mobility, highlighting their crucial role in advancing autonomous vehicle systems.	N/A	Vehicle Agnostic
[176]	DT-assisted decision-making framework for the Internet of Vehicles, aiming to enhance transport safety and efficiency by overcoming the limitations of individual vehicles' sensing and computing capabilities.	RL/IoV/V2X	Vehicle Agnostic
[139]	Test method for autonomous driving systems leveraging the concept of a DT by linking a digital representation of a physical driving environment and vehicle with real-world sensor data and vehicle behaviour.	LTE-V2X	Vehicle Agnostic
[107]	Digital twin framework for connected vehicles, aiming to enhance communication and coordination within the Internet of Vehicles.	N/A	Vehicle Agnostic
[177]	Anomaly detection model to enhance the security of Vehicular Internet of Things tackling with issues like high latency and privacy leakage with the use of DTs.	HFL	Vehicle Agnostic
[140]	Advancing Artificial Intelligence research within autonomous vehicle networks by highlighting how DTs offer a superior platform for designing, deploying, and testing AI techniques.	AERPAW Platform	Vehicle Agnostic
[90]	A distributed intelligent digital twin-based architecture designed to enhance the diagnosis and prognostic health management of autonomous electric vehicle powertrains.	IoT	Vehicle Agnostic
[178]	The authors propose a system that uses Generative Adversarial Networks to predict future visual frames within a Digital Twin environment to enhance autonomous vehicle safety.	N/A	Vehicle Agnostic
[195]	Vehicular digital twin networks designed to enhance autonomous vehicles by creating virtual replicas that synchronise with physical cars in real-time.	N/A	Vehicle Agnostic
[97]	A sensor-less control model for hub motors by integrating sliding mode control with digital twin technology.	N/A	Vehicle Agnostic
[179]	A quantitative assessment algorithm for Safety of the Intended Functionality in autonomous driving systems leveraging digital twin technology in order to build realistic driving scenarios.	CARLA	Vehicle Agnostic
[196]	vehicular intelligence within vehicular networks (VNs), aiming to create a vehicular network digital twin. The core challenge addressed is maintaining stable connectivity and rapid information flow in highly dynamic vehicular environments,	N/A	Vehicle Agnostic
[180]	Proposing a digital twin-driven asymmetric driving aggressiveness assessment model for connected autonomous vehicles in mixed traffic environments, moving beyond traditional methods that primarily focus on collision probability.	N/A	Vehicle Agnostic

[181]	An innovative trajectory tracking system for autonomous vehicles that significantly enhances driving safety and stability through a digital twin which accurately calculates the real vehicle's projection point on the expected trajectory.	MPC/LQR/PID	Vehicle Agnostic
[108]	Proposing a DT-enabled framework to optimise collaborative and distributed driving for the concept of Collaboration as a Service.	Game Theory	Vehicle Agnostic
[197]	DT-enabled edge collaboration scheme for composite services within autonomous vehicular networks, aiming to enhance efficiency and user experience.	Coalition / Stackelberg Game	Vehicle Agnostic
[156]	Digital Twin Network designed to enhance the capabilities of Connected and Automated Vehicles through a three-layered system — physical, virtual, and application— that facilitates ubiquitous perception, adaptive path planning, and precise motion control.	N/A	Vehicle Agnostic
[157]	A teleoperated driving system integrated with digital twin technology, designed to serve as a reliable backup for autonomous vehicles.	N/A	Vehicle Agnostic
[182]	A digital twin architecture for the validation and verification of autonomous driving systems, aiming to significantly reduce development time and costs.	N/A	Vehicle Agnostic
[109]	A highly accurate digital twin of a vehicle's design and production processes which is crucial for integrating disparate domains, enabling early verification and validation through simulation, and enhancing manufacturing efficiency.	N/A	Vehicle Agnostic
[158]	A digital twin to enhance teleoperated driving in urban settings, particularly addressing the challenge of limited network bandwidth.	N/A	Vehicle Agnostic
[159]	A digital twin technology to enhance teleoperated driving, addressing significant challenges like network latency and bandwidth limitations.	Kalman Filters	Vehicle Agnostic
[110]	Integration of Robot Operating System as a middle-layer within Unity3D for simulating propulsion drives in autonomous vehicles.	ROS / Unity-3D	Vehicle Agnostic
[160]	An approach to human-robot teaming for mobile robot navigation, addressing challenges in unpredictable environments where traditional autonomous systems often fail such as shared control.	N/A	AMRs
[161]	A digital twin-empowered approach to autonomous driving specifically tailored for electric mobility and the sustainable use of power in EVs.	N/A	Vehicle Agnostic
[162]	A digital twin-based traffic guidance scheme for autonomous vehicles, aiming to alleviate persistent urban traffic congestion.	Inverse RL / Social Value Orientation (SVO)	Vehicle Agnostic
[183]	A honeypot system designed to address security challenges intrinsic to Autonomous Vehicles leveraging Digital Twin technology to accurately emulate AV components.	N/A	Vehicle Agnostic
[184]	A DT-powered adaptive traffic signal control in an environment where both autonomous and traditional vehicles coexist.	N/A	Vehicle Agnostic

Appendix B

Air Vehicles Publications Analysis

Table B.1: Analysis of publications under study.

Ref	Work Description	Tools / Platforms	Utilized Technology	UAV Type
[203]	Evaluating sensors layouts for damage detection with the help of a calibrated DT	FBG sensors	FEM	Fixed Wing
[204]	Installation of FBG sensors for the creation of a monitoring DT	FBG sensors	FEM	Fixed Wing
[205]	Definition of a structural Digital Twin for predictive maintenance	N/S	N/S	Fixed Wing
[206]	Sensors placement and dynamic sensor scheduling decisions through DTs	N/S	OCT	Fixed Wing
[207]	Design of an IVHM system for condition-based maintenance	ROS 2	N/S	Quadrotor
[208]	Creation of a hardware testbed and experimental setup for a DT-enabled UAV	N/S	N/S	Fixed Wing
[209]	System for fault diagnosis on VTOL Fixed Wing UAVs	Matlab, ROS, Gazebo	N/S	VTOL Fixed Wing
[210]	A strain detection DT for UAV wings	N/S	N/S	VTOL Fixed Wing
[211]	Using optimization through digital twins for the early stages of product development across various components	Amesim, Noesis Optimus	PLM, MBSE	Fixed Wing
[212]	Applying optimization as an enabler for product development through DTs	Amesim, Matlab	ODPD, MBSE	Fixed Wing
[213]	Development of a DT for the design of propulsion systems	Matlab, Unity, GIZMOS	DL	Single Rotor & Fixed Wing
[214]	Design of a power plant DT using anomaly detection algorithms	N/S	DL	Fixed Wing
[215]	A two-level DT for UAV landing	AERO, Matlab, Python	N/S	Fixed Wing
[216]	DT of a common turbo-shaft engine	N/S	Kalman Filter	Single Rotor
[217]	DT integration into UAV product development using semantic modelling techniques	N/S	HLA	N/S

[218]	Development of a DT framework for large-scale military UAVs	N/S	CC	Fixed Wing
[219]	A barebones DT simulator for Parrot AR Drone 2.0	Matlab, Simulink	N/S	Quadrotor
[220]	Simulation of a Multi-Rotor UAV through the combination of multiple tools	Matlab, SimulIDE, ROS, Unity	N/S	Quadrotor
[221]	A DT platform architecture for multi-rotor UAVs focusing on the communication interface	ROS, Unity	N/S	Quadrotor
[222]	A DT modelling method for military multi-rotor UAVs	QGC, ROS, Gazebo	N/S	Quadrotor
[223]	A DT-enabled MBSE testbed for multi-UAV swarms	Python	MBSE	Quadrotor
[224]	A trust-building exercise among autonomous drones with the support of DTs	N/S	PNs	Quadrotor
[225]	Airspace discretization for reduced energy consumption through DT simulations	Python, C#, Rhinoceros	N/S	Quadrotor
[226]	UAV inspection process supported by DTs	Blender, AirSim, UE	GIS	Quadrotor
[227]	A DT framework for emulating AR assisted ground and aerial systems	Ardupilot FCS, Gazebo	AR	N/S
[228]	An architecture and environment of a DT supporting rapid prototyping and testing of multi-agent solutions	AirSim, Cesium, UE, Python	N/S	N/S
[229]	A VR verification platform utilising DT technology	AirSim, UE	VR	Quadrotor
[230]	A DT systems enabling mixed-reality tests for autonomous operations	AirSim, Cesium, UE	MR	Quadrotor
[231]	An application framework for DTs in the UAV domain; definition and testing	ROS, Matlab, Unity, Maya	CC	Quadrotor
[232]	A DT-based intelligent cooperation framework for UAV swarm	Python, Tensorflow	ML	N/S
[233]	A training framework for multi-UAV path planning	Python, PyTorch	DRL	N/S
[234]	Teaching flocking motion on multi-UAV systems through a DT	Python, PyTorch	DRL	N/S
[235]	Automatic application of flight plan for forest fire monitoring	Gazebo	N/S	Quadrotor
[236]	VR based system for remote control of UAVs through DTs	Unity, ROS	VR	Quadrotor
[237]	Design and testing of a visual navigation system based on DTs	N/S	DNN	Quadrotor
[238]	A novel framework to minimize time and energy consumption on mobile targets visitation	Python, PyTorch, Gazebo	DRL	Quadrotor
[239]	A training framework for multi-UAV cooperative search of stationary targets	Python, PyTorch	DRL	N/S
[240]	A DT for take-off, hovering and landing in varied wind conditions	ROS, Gazebo	N/S	VTOL Fixed Wing
[241]	A federated DT framework supporting the imitation of mobile systems and a multimodal DT-based inspection algorithm	ROS, Gazebo	FL	Quadrotor
[242]	A hierarchical decision-making DT framework to enhance resource-efficient utilization and facilitate real-time mission planning	N/S	DQN	N/S

[243]	Development of an imperfect DT for assisted training of multi-UAV networks	N/S	DRL	N/S
[244]	A DT platform for UAV path planning and trajectory tracking control	Matlab, Simulink, Simscape	N/S	Quadrotor
[245]	A DT used to support and accelerate the design, testing and deployment of aerial swarms	Python	N/S	Fixed Wing
[246]	Design, test and improvement of UAV vision-based precision landing system supported by DTs	ROS, Gazebo, RViz, OpenCV	N/S	Quadrotor
[247]	Development of a novel teleoperation system through DTs for aerial manipulation	Abaqus, Matlab, ROS, Unity	VR	Quadrotor
[248]	Development of a 5G DT communication channel to study and simulate the interference suppression	Matlab, Python	5G and Beyond-5G	N/S
[249]	Identification of real-time intrusions and anomalies in UAVs	Python	ML & DRL	N/S
[250]	Introduction of DT combined with CNN in order to explore the airspace structure and safety performance	Matlab, Python	CNN	N/S
[251]	A DT network assisting the intrusion detection in UAV networks	Python	FL & Stacked Broad Learning	N/S
[252]	Development of a generic non-stationery channel model with time-variant channel parameters for dynamic UAVs	FPGA	RT	N/S
[253] [254]	An end-to-end latency minimisation problem of DT-aided offloading in edge networks	N/S	Ultra Reliable Low Latency Communications	N/S
[255]	An integrated sensing, communication and computation network powered by DTs	N/S	DRL & PPO	N/S
[256]	Utilization of a framework for DT-based UAV applications in the realm of green IoT	N/S	mmWave Radar Imaging, RT, AI	Quadrotor
[257]	A DT integrated approach of software-defined UAV networks with a routing flow adjustment algorithm	Matlab	M/M/1 Queuing Model	N/S
[258]	Investigating a UAV data transmission method for rapid medical resource delivery in epidemics	AlexNet	DL	N/S
[259]	A dynamic DT of air-assisted IoV is established to capture the time-varying resource supply and demands	N/S	Alternating Direction Multiplier Method	N/S
[260]	Intelligent task offloading in UAV-enabled MEC	N/S	DQN	N/S
[261]	A DT-based multi-agent Deep Q Network for network resource allocation and load balancing	N/S	DRL	N/S
[262]	Establishing DTs of UAVs and targets in order to enable accurate decision guidance for dynamic task assignment	N/S	Particle Swarm Optimization	N/S
[263]	A distributed deep reinforcement learning approach for computation offloading in DT-based UAV networks	N/S	DRL, FL, DDPG	N/S
[264]	Resource allocation strategy based on online training with low communication overhead supported by DT	N/S	DRL, Multi-Task Learning	N/S
[265]	Study the problem of intelligent UAV deployment and resource allocation through DTs in aerial computing networks	N/S	DQN	N/S
[266]	Optimizing the offloading decision under uncertainty with the use of DTs	N/S	Upper Confidence Bound Stable Matching Problem	N/S

[267]	Energy efficient offloading supported by DTs in Aerial Edge Networks	N/S	Markov Decision Process, PPO	N/S
[268]	A DT assisted approach to improve the resource-intensive utilization and efficiency of task assignment	N/S	Genetic Algorithm, DQN	N/S
[269]	Intelligent offloading in UAV-assisted vehicular networks by DT utilization	N/S	DRL, PPO	N/S
[270]	A service orchestration scheme for selecting the most suitable domain to offload processing task in post-disaster situations	Matlab	N/S	N/S
[271]	A scheme jointly considering bandwidth allocation and trajectory design in a UAV scenario involving power-consumption Outage	N/S	Echo State Network	DRL
[272]	Communication and computing resource allocation in a DT-assisted and UAV-enabled mobile edge computing	N/S	N/S	N/S

Appendix C

Surface & Underwater Vehicles Publications Analysis

Table C.1: Analysis of publications under study.

Ref	Work Description	Tools / Technologies	Vehicle Type
[294]	Explores the vital role of Distributed Simulation in enhancing Digital Twin technology, particularly for complex systems like autonomous underwater vehicles in maritime applications.	IEEE 156 HLA	UUVs - SPARUS II
[275]	A survey of existing DT-based applications, such as smart shipping, autonomous surface vehicles, and vessel life cycle management, while also examining emerging trends like AI integration and smart port compatibility.	N/A	N/A
[283]	Development and testing of an autonomous pilotage system for an Unmanned Surface Vessel (USV), designed to navigate complex port entries and narrow channels.	MarineSIM	ASVs - Scale Vehicle
[277]	A multi-layered VTS that leverages AI, IoT, and advanced communication platforms to enable safe and efficient navigation for uncrewed ships.	N/A	ASVs - Scale Vehicle
[284]	Development of a digital twin for an Autonomous Underwater Vehicle, primarily focused on assessing the effectiveness of searching for objects on the seabed.	Monte Carlo methodology	AUVs
[296]	A Digital Twin enabling comprehensive modelling and simulation offering faster time-to-market, improved product quality and efficiency, and crucial predictive maintenance capabilities.	N/A	ASVs
[303]	An advanced DT framework for Autonomous Surface Vessels, enhancing safe maritime navigation through a virtual replica of a physical ASV that can predict future states and make optimal decisions.	RL	ASVs
[298]	A novel fuel cell power supply system designed for underwater applications, specifically autonomous underwater vehicles and the corresponding digital twin.	CFD	AUV
[297]	Application of reinforcement learning and imitation learning algorithms to autonomous sailboats within digital twin simulations.	RL/IL	ASVs - Sailboats
[285]	A SemDT, specifically tailored for marine robotics, particularly in the challenging environment of subsea station inspection.	Knowledge Graphs	AUVs

[304]	Explores the crucial need for rigorous simulation-based testing to ensure the safe deployment of autonomous navigation systems in maritime transport.	N/A	ASVs
[276]	This survey highlights how DTs, as digital representations mirroring real-world attributes and behaviours, can overcome the cost and risk limitations of traditional maritime exploration.	N/A	USVs
[286]	Digital twin infrastructure for the navigation, guidance, and control of Remotely Operated Vehicles, during underwater inspection	N/A	ROVs - BlueROV2
[278]	A novel autonomous path-planning solution for vessels, addressing the complexities of the marine environment compared to land-based autonomous vehicles.	Supervised Learning	ASVs
[279]	A multi-target tracking system for Autonomous Surface Vessels, crucial for safe navigation in complex maritime environments.	Kalman Filter / NSDLS / DBSCAN	USVs
[280]	An innovative anti-disturbance parallel control architecture, leveraging a digital twin model to tackle the complex challenge of automatic berthing, especially considering the tricky, low-speed manoeuvres required in busy ports.	N/A	ASVs
[300]	A digital twin-driven fault diagnosis approach specifically designed for autonomous surface vehicles.	AEKF	ASVs - Otter
[291]	A novel approach to digital twin motion modelling for an Autonomous Surface Vehicle, particularly when its dynamic behaviour is initially unknown..	Meta-Learning/DNN	ASVs
[299]	Outlines how digital twin technology can revolutionise the industrialisation and development of underwater gliders.	N/A	AUVs - Petrel Glider
[287]	A path planning system for autonomous underwater vehicles, aiming to overcome the challenges of complex and unpredictable ocean environments.	Edge Computing	AUVs
[292]	Development and implementation of a DT for an Autonomous Surface Vehicle, specifically focusing on its use for environmental monitoring and operational efficiency.	N/A	ASVs
[281]	A data-driven digital twin system for CDVs, a novel marine apparatus capable of operating on both water surfaces and underwater.	LSTM/MPC	CDVs
[306]	Explores how digital twins can enhance operator confidence in autonomous unmanned underwater vehicles, especially given the challenges of intermittent underwater communication.	N/A	AUVs
[295]	Introduces the MAS-DT project, an initiative aiming to enhance the efficiency and value of oceanographic research using autonomous platforms.	N/A	AUVs - Gliders
[288]	Identifying crucial self-propulsion parameters for the Maritime Research Institute's Autonomous Underwater Vehicle. The primary goal is to enhance the accuracy of its control system.	N/A	AUVs
[289]	An underwater DT system designed to enhance the teleoperation of Remotely Operated Vehicles, addressing critical challenges in subsea environments such as reduced situational awareness and heightened operator workload.	VR	ROVs
[282]	Developing a cost-effective and modular autonomous ship model to analyse steering dynamics and design control systems.	IoT	ASVs
[290]	An Autonomous Terrain-Aided Navigation system for AUVs, which significantly reduces reliance on external reference systems and data.	MBES / Particle Filter	AUVs

[301]	Predictive digital twins to enhance the safety and reliability of autonomous surface vessels.	AXKF	ASVs
[302]	A method for diagnosing faults in the propulsion systems of autonomous ships by leveraging digital twin technology.	Adaptove Extended Kalman Filter (AEKF)	ASVs - Otter
[293]	A preliminary study for developing digital twin ship technology, which involves creating a virtual replica of a physical vessel to simulate its behaviour and environment in real-time.	N/A	ASVs - Scale Vehicle
[305]	A connectivity manager designed to ensure robust connections for autonomous ships, which rely on multiple radio technologies leveraging digital twins.	N/A	ASVs

Appendix D

Software Description of RoboRacer Digital Model

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<sdf version="1.8">

<model name="roboracer" canonical_link="base">

<static>false</static>

<link name="base">
 <inertial>
  <pose>0 0 0 0 0 0</pose>
   <mass>3.5</mass>
   <inertia>
    <ixx>0.021262</ixx>
    <iyy>0.072917</iyy>
    <izz>0.094179</izz>
   </inertia>
 </inertial>

 <visual name="baseVisual">
  <pose>.1371 0 -.0115 -0.018 0 1.5707</pose>
  <geometry>
   <mesh>
    <uri>package://roboracer_description/models/roboracer/
    meshes/base.dae</uri>
   </mesh>
  </geometry>
 </visual>

 <visual name="topVisual">
  <pose>.1371 0 -.0115 -0.018 0 1.5707</pose>
  <geometry>
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```
  <mesh>
   <uri>package://roboracer_description/models/roboracer/
   meshes/top.dae</uri>
  </mesh>
 </geometry>
</visual>

<collision name="baseCollision">
 <pose>0 0 .06 0 0 0</pose>
 <geometry>
  <box>
   <size>.3 .09 .12</size>
  </box>
 </geometry>
</collision>

<visual name='zedVisual'>
 <pose>0.075 0 0.091 1.5707 0 1.5707</pose>
 <geometry>
  <mesh>
   <scale>0.007 0.007 0.007</scale>
   <uri>package://roboracer_description/models/roboracer/
   meshes/zed.dae</uri>
  </mesh>
 </geometry>
</visual>

<visual name='hokuyoVisual'>
 <pose>0.085 0 0.07 0 0 1.5707</pose>
 <geometry>
  <mesh>
   <scale>0.001 0.001 0.001</scale>
   <uri>package://roboracer_description/models/roboracer/
   meshes/hokuyo.dae</uri>
  </mesh>
 </geometry>
</visual>

<visual name='vescVisual'>
 <pose>-0.09 -0.025 0.0475 0 0 1.5707</pose>
 <geometry>
  <mesh>
   <scale>0.7 0.7 0.7</scale>
   <uri>package://roboracer_description/models/roboracer/
   meshes/vesc6.dae</uri>
  </mesh>
 </geometry>
</visual>

```

```
<visual name='orinNanoVisual'>
 <pose>-0.025 -0.03 0.06 1.5707 3.14 -1.5707</pose>
 <geometry>
  <mesh>
   <scale>0.008 0.008 0.008</scale>
   <uri>package://roboracer_description/models/roboracer/
   meshes/orin.dae</uri>
  </mesh>
 </geometry>
</visual>

<sensor name='hokuyo' type='gpu_lidar'>
 <pose relative_to="lidar_frame">0 0 0.03 0 0 0</pose>
 <topic>scan</topic>
 <update_rate>15</update_rate>
 <ray>
  <scan>
   <horizontal>
    <samples>1080</samples>
    <resolution>1</resolution>
    <min_angle>-2.3562</min_angle>
    <max_angle>2.3562</max_angle>
   </horizontal>
  </scan>
  <range>
   <min>0.06</min>
   <max>10.0</max>
   <resolution>0.004</resolution>
  </range>
 </ray>
 <always_on>1</always_on>
 <visualize>1</visualize>
</sensor>

<sensor name='zed' type='camera'>
 <pose relative_to="camera_frame">0.05 -0.05 0 0 0 0</pose>
 <topic>camera</topic>
 <frame>camera_frame</frame>
 <update_rate>15</update_rate>
 <visualize>1</visualize>
 <camera name='front_camera'>
  <horizontal_fov>1.5708</horizontal_fov>
  <image>
   <width>1920</width>
   <height>1080</height>
   <format>RGB_INT8</format>
  </image>
  <clip>
   <near>0.02</near>
```

```
      <far>100</far>
    </clip>
  </camera>
</sensor>

<sensor name="zed_depth" type="depth_camera" >
  <pose relative_to="camera_frame">0.05 -0.05 0 0 0 0</pose>
  <topic>depth_camera</topic>
  <frame>camera_frame</frame>
  <update_rate>15</update_rate>
  <visualize>1</visualize>
  <camera name="front_depth_camera">
    <horizontal_fov>1.5708</horizontal_fov>
    <image>
      <width>1280</width>
      <height>720</height>
      <format>R_FLOAT32</format>
    </image>
    <clip>
      <near>0.1</near>
      <far>10.0</far>
    </clip>
  </camera>
</sensor>

</link>

<link name="frontRightWheel">

 <pose relative_to="frontRightWheelJoint">0 0 0 0 0 0</pose>

 <inertial>
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  <inertia>
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   <ixz>0</ixz>
   <iyy>0.0000204</iyy>
   <iyz>0</iyz>
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  </inertia>
 </inertial>
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 <velocity_decay/>

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  <pose>0 0 0 0 0 0</pose>
  <geometry>
   <mesh>
```

```
    <uri>package://roboracer_description/models/roboracer/
    meshes/wheel.dae</uri>
   </mesh>
  </geometry>
 </visual>

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  <pose>0 .015 0 -1.5707 0 0</pose>
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    <radius>0.0365</radius>
   </cylinder>
  </geometry>
  <surface>
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    <ode>
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   </friction>
  </surface>
 </collision>

</link>

<link name="frontRightWheelSteering">

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</link>

<link name="frontLeftWheel">

 <pose relative_to="frontLeftWheelJoint">0 0 0 0 0 0</pose>

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  <mass>.05</mass>
  <inertia>
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  </inertial>
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     meshes/wheel.dae</uri>
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  </visual>

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   <iyy>0.0000204</iyy>
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    <radius>0.0365</radius>
   </cylinder>
  </geometry>
  <surface>
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<link name="rearLeftWheel">

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  </geometry>
  <surface>
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   </friction>
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<joint name="frontRightWheelSteeringJoint" type="revolute">

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 <child>frontRightWheelSteering</child>
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   <upper>0.6</upper>
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  </limit>
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</joint>

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 <child>frontRightWheel</child>
 <pose relative_to="frontRightWheelSteeringJoint">0 0 0 0 0 0</pose>
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  <limit>
   <lower>-1.79769e+308</lower>
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<joint name="frontLeftWheelSteeringJoint" type="revolute">

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   <effort>25</effort>
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  </limit>
  <dynamics>
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</joint>

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 <child>rearRightWheel</child>
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  <limit>
   <lower>-1.79769e+308</lower>
   <upper>1.79769e+308</upper>
  </limit>
  <dynamics>
   <spring_reference>0</spring_reference>
   <spring_stiffness>0</spring_stiffness>
```

```
   </dynamics>
   <use_parent_model_frame>1</use_parent_model_frame>
  </axis>

</joint>

<joint name="rearLeftWheelJoint" type="revolute">

  <parent>base</parent>
  <child>rearLeftWheel</child>
  <pose relative_to="base">-.1135 .10 0 0 0 0</pose>
  <axis>
   <xyz>0 1 0</xyz>
   <limit>
    <lower>-1.79769e+308</lower>
    <upper>1.79769e+308</upper>
   </limit>
   <dynamics>
    <spring_reference>0</spring_reference>
    <spring_stiffness>0</spring_stiffness>
   </dynamics>
   <use_parent_model_frame>1</use_parent_model_frame>
  </axis>

</joint>

<plugin filename="ignition-gazebo-ackermann-steering-system"
name="ignition::gazebo::systems::AckermannSteering">
  <left_joint>frontLeftWheelJoint</left_joint>
  <left_joint>rearLeftWheelJoint</left_joint>
  <right_joint>frontRightWheelJoint</right_joint>
  <right_joint>rearRightWheelJoint</right_joint>
  <left_steering_joint>frontLeftWheelSteeringJoint</left_steering_joint>
  <right_steering_joint>frontRightWheelSteeringJoint</right_steering_joint>
  <wheel_base>.325</wheel_base>
  <wheel_separation>.23</wheel_separation>
  <kingpin_width>.19</kingpin_width>
  <wheel_radius>0.05</wheel_radius>
  <steering_limit>0.5</steering_limit>
  <min_velocity>-100</min_velocity>
  <max_velocity>100</max_velocity>
  <min_acceleration>-5</min_acceleration>
  <max_acceleration>5</max_acceleration>
  <topic>cmd_vel</topic>
  <odom_topic>ackermann_odom</odom_topic>

</plugin>

<frame name='base_chassis' attached_to='base'/>
```

```

<frame name='lidar_frame' attached_to='base_chassis'>
 <pose>0.0875 0 0.07 0 0 0</pose>
</frame>

<frame name='camera_frame' attached_to='base_chassis'>
 <pose>0.11 0 0.091 0 0 0</pose>
</frame>

</model>
</sdf>
```

Appendix E

Supplementary Material

Table E.1: Supplementary Material Table

File Names	Description	Link
Gazebo & RViz	A video presenting the functionality of the Gazebo simulator and the visualization of the simulated sensors in RViz.	Gazebo & RViz Video Link
Gazebo Simulator	A video showcasing the simulated testing environment build to replicate the Unmanned Systems and Robotics Lab obstacle course.	Gazebo Simulator Video Link
Physical Data Visualization (USRL Test Area)	Visualization through RViz of the physical test in USRL testing facility; RGB, depth, LiDAR and odometry visualizations can be seen.	Physical Data Visualization (USRL) Video Link
Simulated Data Visualization (USRL Test Area)	Visualization through RViz of the digital twin test in USRL testing facility; RGB, depth, LiDAR and odometry visualizations can be seen.	Simulated Data Visualization (USRL) Video Link

Physical Data Mapping (USRL Test Area)	Utilization of SLAM to create a map of the USRL test environment from physical data.	Physical Data Mapping (USRL) Video Link
Simulated Data Mapping (USRL Test Area)	Utilization of SLAM to create a map of the USRL test environment from simulated data.	Simulated Data Mapping (USRL) Video Link
Physical Data Visualization (McNair Aerospace Centre)	Visualization through RViz of the physical test in McNair Aerospace Centre; RGB, depth, LiDAR and odometry visualizations can be seen.	Physical Data Visualization (McNair) Video Link
Physical Data Mapping (McNair Aerospace Centre)	Utilization of SLAM to create a map of the McNair Aerospace Centre from physical data.	Physical Data Mapping (McNair) Video Link
Physical Testing Dataset (USRL Test Area)	The dataset in ROS2 bag format of the physical test in USRL test area. It includes all recorded topics.	Physical Test (USRL) Dataset Link
Simulated Testing Dataset (USRL Test Area)	The dataset in ROS2 bag format of the simulated test in USRL test area. It includes all recorded topics.	Simulated Test (USRL) Dataset Link
Physical Testing Dataset (McNair Aerospace Centre)	The dataset in ROS2 bag format of the physical test in McNair Aerospace Centre. It includes all recorded topics.	Physical Test (McNair) Dataset Link
Framework Validation Experiment - Upstream Test	Validation of sensor data stream towards the digital twin.	Upstream Test Video Link
Framework Validation Experiment - Downstream Test	Validation of digital twin ability to control the physical system.	Downstream Test Video Link
Framework Validation Experiment - Object Detection Test	Testing the digital twin real-time processing of sensor data.	Object Detection Video Link

Framework Validation Experiment - Lane Detection Test	Testing the digital twin real-time processing of sensor data in external processor.	Lane Detection Video Link
Framework Validation Experiment - Emergency Braking Test	Validating the bidirectional communication and control of the physical system by a digital twin trigger.	Emergency Braking Test Video Link