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RESEARCH ARTICLE

Connected and Intelligent Framework for Vehicle Automation in Smart-Ports

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ABSTRACT The increase in maritime traffic due to the globalization of trade has led to an exponential growth in logistics operations and port traffic management is becoming increasingly complicated. The need to improve the efficiency, safety, and sustainability of operations is leading to a strong demand for automation in port processes. A significant challenge is the optimization and automation of loading and unloading systems, given their complexity and repetitive nature. Advances in automated systems, through ongoing research and application in various transportation scenarios, are addressing these challenges. However, automating vehicles alone is insufficient; it is also important to have a connected, infrastructure-based collaborative framework to manage the complex logistics of port operations effectively and in a synchronized manner. In this sense, ESTIBA+ 2022, a Spanish-funded project, is addressing this challenge, aiming to develop strategic technologies for Smart-Ports. Its goal is to design and validate a scalable collaborative framework that meets the specifications and functions of port services using Industry 4.0 technologies and advanced wireless communications through Connected Intelligent Transportation Systems (C-ITS). This article presents the proposed architecture and its validation in the comprehensive use case of the project, focusing on communication from the supervision platform to Automated Guided Vehicles (AGVs) to ensure optimal traffic flow and management in ports. Specifically, the scenario involves three different forklifts equipped with an On-Board Unit (OBU) that interact with each other and the infrastructure via Roadside Units (RSU). The outcome of the project shows that the framework can meet the requirements for Smart-Port logistics, showing the feasibility of the implementation with a collaborative maneuver between three forklifts, a supervision station, and connected traffic lights.

INDEX TERMS Connected and automated vehicles (CAVs), smart-port, mobility, logistics, intelligent transportation systems, vehicle-to-everything communication (V2X).

I. INTRODUCTION

International maritime commerce carries over 80% of the volume of global trade [1]. The increase in traffic in this sector entails a strong demand for automation in terminal processes to improve operations' efficiency, safety, and sustainability, obtaining intelligent port warehouses. For this, it requires that the mechanical, electrical, and hydraulic equipment used to move the cargo in a terminal is manipulated remotely or completely autonomously by a software system that ensures control of the operations to be carried out.

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Nowadays, several seaports have incorporated technological tools that have made them automatic or semi-automatic. The container terminal at Qingdao Port (China) is the first fully automated terminal in Asia and started operations in May 2017. It works with two fully automated berths, seven ship-to-shore cranes, 38 automatic stacking cranes, and 38 Automated Guided Vehicles (AGV). Thus, the operators are in the control rooms and monitor all the processes from there [2]. The Yangshan Container Port is part of the Shanghai Port (China) and is fully managed by 130 AGVs, 26 bridge cranes, 120 rail-mounted gantry cranes, and a few workers in a control room [3]. The Victoria International Container Terminal in the Port of Melbourne (Australia) is the first fully automated terminal in Oceania, and it works with five automated STS neo-Panamax cranes and fully automated ship-to-dock operations, eight dock cranes stationed at the loading and unloading dock, 18 container carriers machines to transport containers to and from the container yard, and 32 automated stacking carriers in the yard [4]. The APM Terminal at the Port of Rotterdam Maasvlakte II facility started its automated operations in 2015. It remotely controls its ship-to-shore cranes to transport containers to and from ships and elevator AGVs. Guided by an onboard navigation system, these vehicles automatically transport these containers from the dock to the container yard. The 54 rail-mounted automatic gantry cranes take over the cargo, placing it at its designated locations [5]. The TEC II of Lázaro Cárdenas, in Mexico, was inaugurated in April 2017 and has become the first semi-automated port in Latin America. It is equipped with seven cranes, two fully automated Panamax docks, 20-yard cranes, and two cranes to move the merchandise to the railway lines that connect to the port [6]. But although we already find some examples, only 3% of the world terminals are semi or fully-automated. The low implementation of automation in ports is because of the capital-intensive investments [1] and social concerns about the automation of processes [7].

The ports, companies, and research centers of Spain aim to reach these great examples, so research in the automation of the maritime sector is a vital aspect [8]. The Strategic Program of National Business Research Consortiums (CIEN) supports research projects of an industrial nature and experimental development, which are generated in effective collaboration by business groups in strategic areas for the future and with international projection potential. One of the projects belonging to this program is the ESTIBA+ 2022 (where ESTIBA is the Spanish word for stowage), whose objective is to advance in the development of strategic technologies that bring us closer to the Smart-Port and meet the growing demand for efficiency, economy, safety, and environmental compatibility according to the Industry 4.0 concept and current socioeconomic situations [9]. The main contribution of this paper is the implementation of the framework developed in the ESTIBA+ 2022 project that covers the specifications and functions of port services using advanced technologies and wireless communications solutions through AGVs.

This article is divided as follows. In section II, it presents the state of the art in port management and the automation of the AGVs used. The description of the general framework of ESTIBA+ 2022 is presented in section III. Then, sections IV and V describe the details of implementation and specific use cases in which the project solutions were tested. The article finally ends by presenting the results and conclusions.

II. RELATED WORKS

Ports face a high volume of operations daily: cargo handling, mooring and unmooring of vessels, port towage, passenger handling, etc. Within these activities, cargo handling is particularly complex. When a loaded ship arrives in port, its cargo must first be unloaded ashore, then handled by forklifts and placed on trucks to be taken to the port warehouse or its final destination. The efficient organization of all these movements is vital, not only to prevent accidents but also to avoid congestion or unnecessary loss of time so that the port remains competitive in an increasingly globalized market. To meet these challenges, ports have relied on digital solutions for years [10], [11]. A large number of Port Management Systems (PMS) are now available to plan the movement of goods in a port [12], [13], [14]. These solutions have brought digital technologies such as the Internet of Things (IoT) [15] or Artificial Intelligence (AI) [16] closer to users with low digital literacy.

AGVs are the first type of self-guided internal transfer vehicle serving port terminals. It consists of a non-articulated platform for the transport of cargo whose transport speed ranges between 10 and 22 km/h for safety reasons. Due to its low speed and the enormous amount of traffic rules required to manage the system safely, delays can occur if an AGV vehicle is not available at the cargo unloading points. In [17], a simulation model was used to determine the optimal number of AGVs to deploy in common yard layouts and investigated the respective container terminals' operational performance. Normally the research objectives focus on the operational performance of the AGVs, such as [18] where the authors studied the Dublin Ferry port Terminal to optimize the time required by AGVs to process all tasks before the departure of a cargo vessel, and the routing of AGVs to minimize transportation times. In [19], the authors conducted a survey on AGVs focusing on their use in real-world applications, particularly in port automation for container handling and manufacturing systems for flexible material handling. The survey identified several key findings related to the usage, problem modeling, and solutions. Additionally, the authors highlighted several challenges for future research, such as simulation models, new AGV technologies within the context of Industry 4.0, dynamic vehicle routing strategies, etc. In [20], the authors introduce an intelligent container transportation system, which utilizes fully automated trucks to transport containers between inland ports and terminals and they simulated the proposed system with emphasis on the supervisory controller that synchronizes all the movements. The studies on the use of AGVs in real-world port terminals are limited, and the challenge of orchestrating real-time collaboration between the different systems is discarded due to the complexity of the process. In the ESTIBA+ 2022 project, we have sought to create a planning system that is adaptative and can be applied to the different AGVs, taking into account their dynamics and that is applicable efficiently in the real world.

On the other hand, for everything to work correctly, the systems are required to be connected and communicate with each other, so the importance of implementing a robust communications system is essential [21]. Vehicular communication (V2X) is a communication technology that allows vehicles to communicate with each other and with the surrounding road infrastructure, opening up access to a large amount of real-time traffic data aimed at ensuring safe and efficient mobility [22]. This information allows vehicles to make maneuvers with more accuracy and safety, such as lane changes [23], platooning [24], etc. A review of the developments of the Intelligent Transport System (ITS), the nature of port operations, and the potential effect of ITS on multimodal operations is presented in [25]. The authors discuss the objectives and research methodology used with ITS and analyze an industrial case study used to illustrate the role and contribution of ITS to multimodal logistics through wireless vehicular networks in the form of Dedicated Short Range Communication (DSRC). The case addressed involves examining the tipping operations of bulk material in a port terminal using event flow, mapping, and network simulation to demonstrate the feasibility of wireless vehicular networks to support data traffic in complex multimodal logistics operations.

However, the V2X standard does not cover the integration with management systems, focusing solely on the vehicle and its surrounding infrastructure. V2X thus joins together the complex ecosystem of a port, which networks together diverse systems of various manufacturers, each with its data formats and protocols. In these cases, there is a need for interoperability solutions enabling information exchange across heterogeneous systems that use different data format representations.

A gateway is a common and efficient interoperability solution in these circumstances, as this element assumes the role of protocol and format transformer from one communication endpoint to another, transparently. A gateway, which could be a piece of hardware or a software solution, is an intermediary between networks with different protocols and architectures to allow data exchange. In the ESTIBA+ 2022 project, one of the objectives was to develop a gateway-based solution that would enable seamless communication between vehicles and digital solutions in the port, i.e., a gateway-based solution able to transform V2X messages used by forklifts, to IoT data protocols that can be understood by standard PMS, and vice versa.

III. ESTIBA+ 2022 FRAMEWORK

The general framework and the description of each module corresponding to both the vehicle and the infrastructure are described in [9]. Figure 1 presents a summary structure focused on the main modules to take into account for forklift management, which is the main focus of this paper.

Forklifts are based on the six-block structure [26], [27]: acquisition, perception, communication, decision, control, and actuation. A Human Machine Interface (HMI) is added to supervise the correct vehicle operation or to display any alert.

- The acquisition handles the different sensors on board the vehicles. This sensory is what allows modeling and perceiving the environment. In this case, the sensors used are a Differential Global Positioning System (DGPS), an Inertial Measurement Unit (IMU), and a LiDAR (Light Detection and Ranging).
- Perception is in charge of processing the information obtained from the sensors and describing the environment. In this case, three submodules stand out that are used in the use cases: the recognition of the environment to detect everything around the vehicle; the detection of obstacles to classify what has been detected in the previous system, and if it is in the trajectory, define it as an obstacle; and the location of the vehicle itself.
- The communication module manages the information from the infrastructure (V2I) and the surrounding vehicles (V2V) to the decision module. The data obtained through an On-Board Unit (OBU) are messages based on the ETSI TS 102 637 standard: Cooperative Awareness Messages (CAM), Decentralized Environmental Notification Messages (DENM), MAP, Signal Phasing and Timing (SPAT), and messages sent by GeoNetworking (GN) protocol. This exchange of information allows the optimization of port traffic and reduces costs, time, and risks.
- The decision system creates, plans, and manages the optimal path to track by the automated vehicle based on the traffic rules, the environment, the trajectory to follow, communications, etc. The module is divided into three planners: the Global Planner performs a first approximation of the complete route with a list of waypoints; the Behavioral Planner handles unexpected situations or maneuvers and modifies the path; and the Local Planner smoothes the trajectory setting the final route the vehicle will follow.
- The control module focuses on achieving correct, safe, and reliable trajectory considering the vehicle's state.

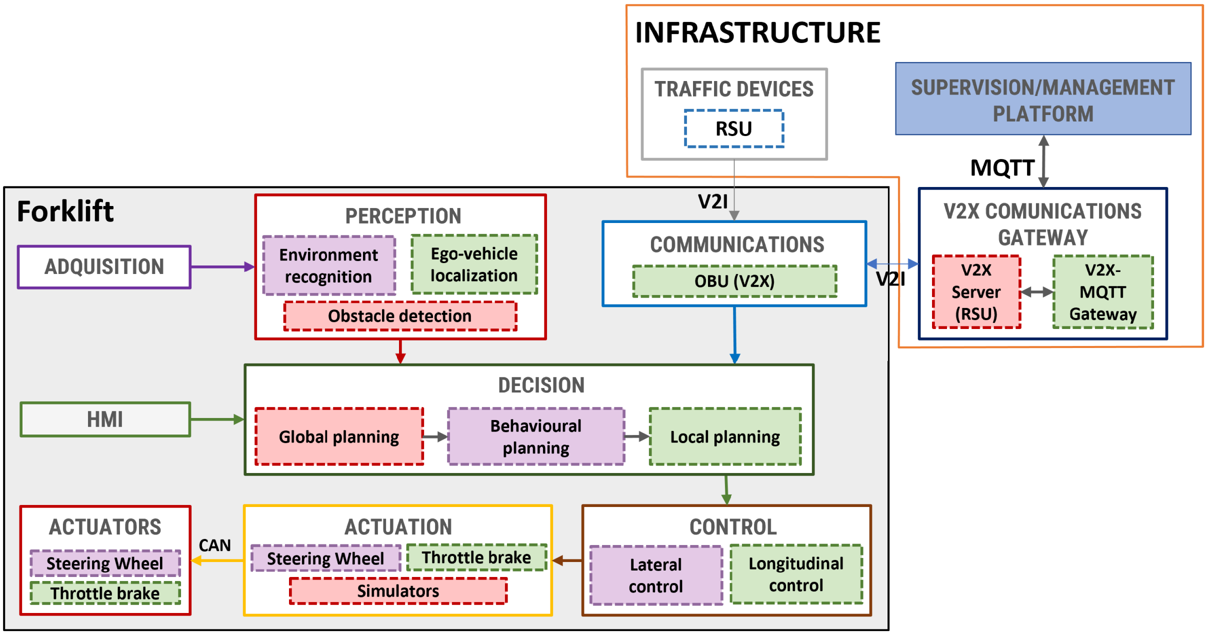


FIGURE 1. Summary structure of the ESTIBA+ 2022 general framework.

There are two controls: the lateral and the longitudinal. The first controls the movements of the steering wheel, and the second focuses on the accelerator and brake.

- The actuation is focused on the actuators (such as the steering wheel, the brake, the throttle, and its simulations) and correctly interprets the control signals by each one of the actuators to move the vehicle in both axes, lateral and longitudinal.
- The actuators include the mechanics necessary for the movement of the vehicle such as brake pedal/button, steering wheel, throttle, etc.

The infrastructure encompasses the different traffic devices, the communications gateway, and the supervision platform.

- The V2X communications gateway is the link bridge between the vehicle communications and the supervision platform. This module has two components: a V2X server and a V2X-MQTT (Message Queuing Telemetry Transport) gateway. Both systems exchange information bi-directionally. The first system is a RoadSide Unit (RSU) that receives information from both the vehicles and the infrastructure and sends them to the V2X-MQTT gateway via Transmission Control Protocol (TCP). On the other hand, the V2X-MQTT gateway manages the communications with the supervision platform. This module adapts the V2X frames to an MQTT format understandable by the supervision platform and vice versa, ensuring interoperability.
- The supervision/management platform mainly monitors the vehicles and manages them using the information obtained, enabling or not the actions and missions and indicating the destination points on the trajectories to carry out.

FIGURE 2. Pair of traffic lights for the crossing of two forklifts.

- The traffic devices are four traffic lights located along the track that indicate whether or not the movement of the forklift along that route is feasible. Each traffic light is placed in pairs (see Figure 2). Each pair communicates with an RSU which is in charge of sending the SPAT and MAP messages.

IV. ESTIBA+ 2022 IMPLEMENTATION

This section presents the implementation of the different modules described in the previous section. To do this, it describes, on the one hand, the communication infrastructure and, on the other, the test platforms used to validate automated driving in port environments.

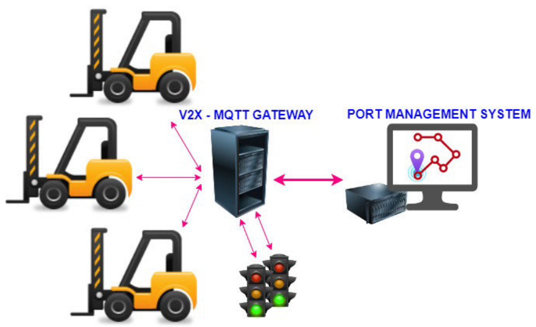


FIGURE 3. **V2X-MQTT gateway - A communication intermediary.**

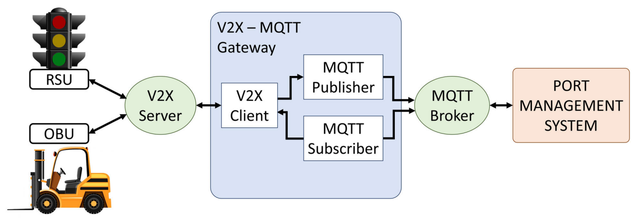


FIGURE 4. **Main components of vehicle-PMS communication.**

A. V2X-MQTT GATEWAY

As mentioned before, the V2X-MQTT Gateway is a component that acts as an intermediary enabling the communication and the exchange of information between the vehicles, intelligent devices in the port facilities, and the Port Management System (PMS) (see Figure 3). On the one hand, vehicles can transmit, at constant intervals, data related to their status, alarms, and failure notifications in real time. Also, intelligent devices, such as traffic lights, can send data related to their state. On the other hand, missions planned by operators in the PMS and events detected by the PMS are transmitted to the vehicles.

The gateway is composed of two submodules: a V2X-MQTT adapter and an MQTT publish-subscribe client (see Figure 4). The V2X-MQTT adapter is responsible for the formatting of the bidirectional messages exchanged between the vehicle and the PMS. The adapter transforms the data sent by the forklift about its status, the progress of the mission plan, and possible failures or alarms into the protocol and semantics comprehensible by the PMS. The state of intelligent devices (i.e., the color phase of a traffic light) is also adjusted to an intelligible format by the PMS. Besides, the adapter converts the messages (i.e., mission plans and commands) sent by the PMS into the ETSI TS 102 637 standard that is understandable at the vehicle level.

The MQTT publish-subscribe client manages lightweight, real-time communications with the PMS using the MQTT protocol. Different topics are used depending on the nature of the information being transmitted (i.e., status, mission plans, notifications, etc.).

As mentioned above, the messages exchanged between vehicles and intelligent devices and the V2X-MQTT gateway are formatted according to the ETSI TS 102 637 standards to guarantee interoperability with the vehicle Intelligent Transport System stations (ITS-Ss), in the communications between the vehicle's OBU with RSUs and with other OBUs. The V2X server enriches these messages by annotating them with additional metadata that is of interest to the PMS. The main messages managed by the V2X server are CAM, DENM, SPAT, and GN.

- CAM messages exchanged between ITS-Ss to create and maintain awareness of each other and to support the cooperative performance of vehicles [28]. These messages are sent periodically (10 Hz) while the vehicle is on and contain information about its status (e.g., time, position, motion state, activated systems, etc.). In addition, the messages are enriched with metadata describing the mission identifier and the driving mode (manual or automatic). These data allow the PMS to monitor the trajectories followed by the vehicles and compare them with the planned path to identify anomalies or incorrect situations. The PMS uses map-matching algorithms to correct the noise in GPS measurements and route-matching algorithms to calculate deviations between the planned and the actual track.
- DENM message contains information related to a road hazard or abnormal traffic conditions, such as its type and its position [29]. When this information is relevant to the driver, ITS-S applications present the details to the operator for appropriate action. Vehicles use this message to inform the PMS about alarms or malfunctions.
- SPaT message describes for each lane the current phase of an intelligent device at a signalized intersection, together with an estimate of the residual time of that phase [30].
- GN protocol provides packet routing in an ad hoc network. It makes use of geographical positions for packet transport. GeoNetworking supports the communication among individual ITS-Ss as well as the distribution of packets in geographical areas [31]. Vehicles in the project use these messages to report the progress in the execution of the commands for a given mission, whereas the PMS uses them to send new mission plans.

These types of messages are used to implement the following use cases:

- Communication with intelligent devices: traffic lights send SPaT messages to forklifts to inform them about their phases. Based on this information, the vehicles will need to make an action such as programming a stop, adjusting their speed, etc.
- Vehicle breakdown: a DENM message is transmitted from the vehicle describing the cause of the problem, e.g., a sensor or actuator failure.
- Obstacle detection on the way: every time an obstacle, either static or mobile, is detected on the trajectory,

the vehicle generates a DENM message to notify the situation.

- Brake warning: the vehicle sends a DENM message to inform about the stop executed.
- Forward collision warning: the vehicle sends a DENM message whenever another one is close to or approaching its trajectory.
- Mission management: the vehicle receives a new mission plan or updates on the ongoing mission through GN messages. Besides, it will also use CAM messages to inform periodically of its position so that the PMS can monitor possible deviations between the planned route and the actual route.
- Warning about change in driving mode: CAM messages notify about changes in the driving mode, i.e., from manual to automatic or vice versa.
- Emergency brake: DENM messages alarm of the need to brake.

In contrast, the messages exchanged between the V2X-MQTT gateway and the PMS use the MQTT protocol. They are grouped into three types of topics:

- Messages with information transmitted to the PMS related to the vehicle, follow the topic structure *"estiba/[scenario]/[vehicleID]/[topicName]"* where *scenario* describes the port or location where the vehicles are, *vehicleID* represents its identifier, and *topicName* provides more detail on the content of the data that is published.
- Messages with information from intelligent devices, such as traffic lights, follow the topic structure *"estiba/[scenario]/[deviceID]/trafficLight"* where *deviceID* identifies the traffic light.
- Messages with helpful information about the different types and codes that the system supports. These codes are related to alarms, events, and vehicle failures, and they can be retrieved by subscribing to the topics *"estiba/general/alarms"*, *"estiba/general/events"*, and *"estiba/general/failures"* respectively.

Under the first category of messages, there are six types of topics. The PMS uses the first four to subscribe to the information coming from the gateway. First, the PMS can subscribe to the topic name *status* to receive periodic information about the vehicle. The gateway extracts data from the received V2X CAM messages and publishes the relevant information to the PMS using the MQTT protocol. These data include the vehicle's device address (used as the vehicle identifier), the UTM coordinates, the driving mode, and the vehicle heading and speed. Besides, the mission identifier and a sequential number are used to avoid the redundancy of messages. Second, the gateway uses the topic name *missionReport* to publish information received through V2X GN messages containing the mission progress. The mission status is an integer whose value is 0 when the vehicle is waiting to be assigned a mission, 1 when it is currently carrying out the task, and 2 when it has finished executing the mission. Third, the topic name *vehicleNotification* is where the events, alarms, and vehicle failures are published. Next, we list the notifications supported by the system with their code identifier in brackets: emergency brake (10), stop due to obstacle (11), risk of collision with another vehicle (12), driver problem (13), inactive vehicle (20), vehicle in the manual (21) or auto (22) mode, stop - brake warning (23), steering wheel fault (30), throttle fault (31), brake fault (32), and positioning error (33). Finally, by subscribing to the topic name *trafficLight*, the PMS is aware of the changes in the phases of each traffic light, i.e., from unavailable to dark, red, green, or yellow.

The gateway uses the other two types of topics to subscribe to information coming from the PMS. First, the topic name *mission* is where the PMS publishes the actions that each vehicle is expected to carry out. A mission is defined as an ordered action list that a vehicle or a group needs to perform in a port in a given time (e.g., a day). Each mission has a unique identifier. The mission is composed of itineraries, and each itinerary has a stopping point where the vehicle must act. The gateway transforms the mission into V2X GN messages that the vehicle can interpret. Second, the topic name *platformEvent* is used to send commands to modify ongoing missions (i.e., stop, pause, resume) due to unexpected events such as an accident in the trajectory.

B. TEST PLATFORMS

Considering the complexity of the scenario, a mixed environment test was chosen, which is two real forklifts (Celsa and Dachser) and one simulated (Bergé forklift). Each vehicle has its respective onboard devices as shown in Figure 5.

1) BERGÉ FORKLIFT

The Bergé forklift is a Kalmar DCF250-12LB. It is the largest of the three ones used (5.500 × 3.050 × 5.000 mm) and weighs 35.650 kg. That is why its implementation is simulated. In addition, it is in charge of unloading the ship's cargo so it carries more weight. It has a load capacity of 25.000 kg and a driving speed between 25,5 and 29 km/h unloaded.

The control architecture for each of the three forklifts includes global, behavioral, and local planners to determine the reference trajectory, as well as lateral and longitudinal control methods to follow the specified reference trajectory. This architecture is designed for real-world scenarios in which a forklift travels from a designated starting location to a user-specified destination.

To simulate the implementation of this approach in actual scenarios, a software architecture is defined to verify the algorithms, which takes into account the real-time implementation structure of the proposed Decision and Control framework presented in [32] as shown in Figure 6.

This software architecture comprises three blocks that communicate with each other using the User Datagram Protocol (UDP) and different Local Ports (LP: A-F), enabling

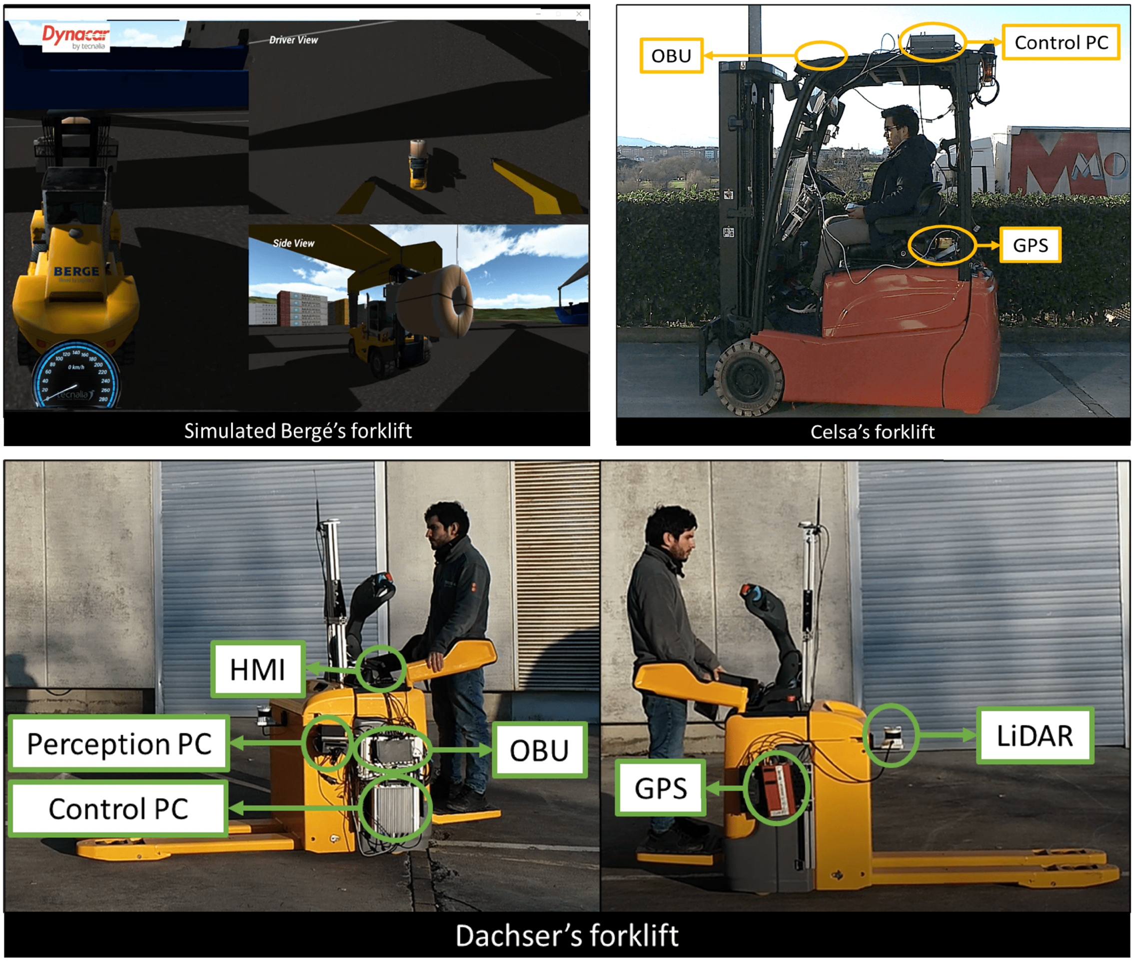


FIGURE 5. Test platforms - simulated Bergé forklift (top left image), Celsa forklift (top right image) and Dachser forklift (bottom image).

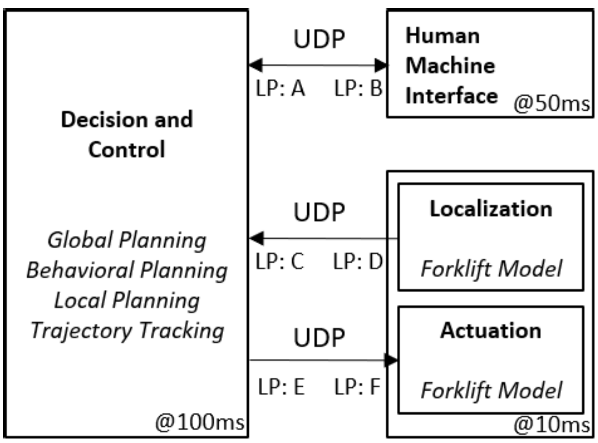


FIGURE 6. Software architecture for the verification of the algorithms [32].

them to be migrated to dedicated hardware with ease. Each block is programmed in Matlab, and three different scripts are executed concurrently in three separate instances. The results were obtained using a computer with an Intel® Core™ i7-10750H CPU @ 2.60GHz 2.59 GHz processor and 32.0GB RAM. Furthermore, the software Dynacar© + Visor3D was used to model and visualize the forklift.

The Decision and Control block, which is the main script, includes trajectory planning (global, behavioral, and local) and tracking algorithms that enable the forklift to travel autonomously. It shares data with the Human Machine Interface (HMI) to inform the current state of the forklift (e.g., behavior planner: *track speed*, *reduce speed*, *stop*, *change gear*; or the engaged gear: *drive*,*reverse* and *neutral*). It also sends the actuation commands to the forklift (accelerator and steering position) depending on the current driving scenario, and it executes these commands every 100 ms.

The Human Machine Interface block contains code that allows a user to interact with the automated forklift. It sends data to the Decision and Control block to specify a new destination when required (e.g., forklift stopped waiting for a mission). It also shares data to notify the current status (e.g., executing mission, final destination reached) or any error in communications (e.g., localization or destination

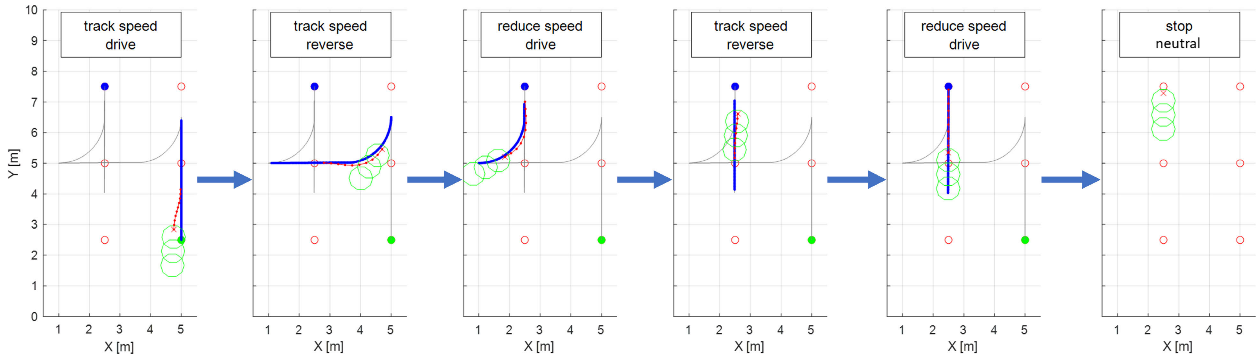


FIGURE 7. Path planning with a forward orientation at the beginning.

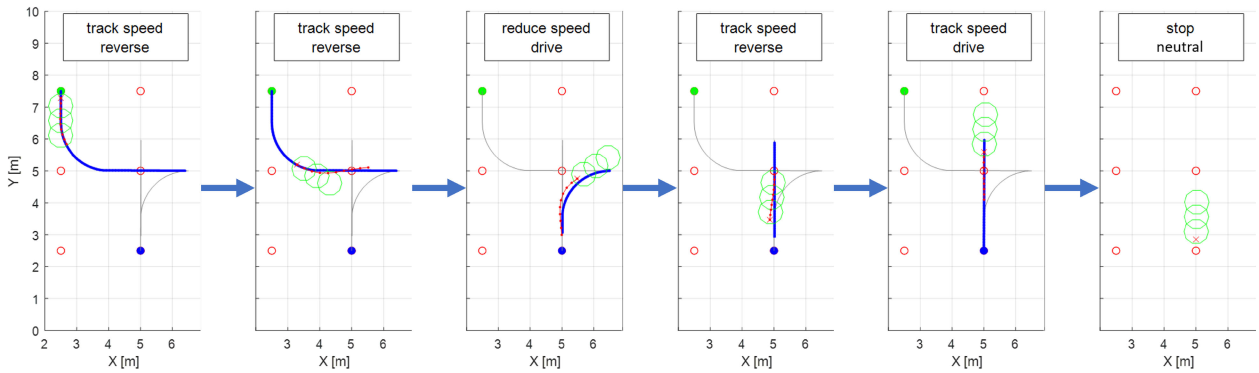


FIGURE 8. Path planning with a backward orientation at the beginning.

not received). This script runs faster than the Decision and Control block at 50 ms to ensure proper data sharing.

The Localization and Actuation block contains the test model for a virtual verification, handling both localization and actuation systems in the same script for simplicity, which is usually separated in real applications (the localization is executed by processing hardware, and the actuation is embedded in the forklift as an electronic control unit). This script runs every 10 ms to ensure proper data sharing.

To simulate this block, a forklift model based on a kinematic bicycle model is used, which allows for studying the lateral motion of the forklift. The equations can be defined by the kinematic bicycle model. The longitudinal motion of the forklift is modeled as an ideal particle, integrating the current acceleration from the speed tracking output to estimate the speed [33]. This simplification is reasonable as the main purpose of this study is to evaluate high-level planning. Furthermore, the simplicity of the trajectory planning enables the controllers to be tuned through an easy procedure when real implementation is required.

The proposed global and behavioral planning strategies and framework architecture were verified through two tests on a simulated environment. Both forward and backward initial orientations were tested on a real-time simulation, where polynomial-based local planners and trajectory trackers were coupled with the developed planners as per the proposed framework.

Figures 7-8 show the sequence of the two missions, where each frame demonstrates the planned path and behavioral states for each section. The forklift location is depicted by three green circles, with a red "x" indicating the front axle center point, whereas the forklift steering acts on the rear axle. Grid vertices are denoted by red circles, and solid green and blue circles denote the start and end vertices of the mission, respectively. The resulting path of the global planner is depicted by thin black lines, and the corresponding frame's global path section is highlighted by a heavy blue line. The active gear and behavioral state for each frame are indicated by a label at the top, and a thin red line with dots shows the corresponding instantaneous local planner trajectory.

The mission shown in Figure 7 involves starting the forklift near a grid vertex and finding a path to the target vertex using a graph-based approach according to the pre-programmed criteria. The planner chooses a forward gear as the angle between the vehicle heading and the desired path is less than $\pi/2$ rad. However, at the first opportunity, the planner changes the gear to maximize the reverse driving and improve the sensors' range. In the final approach, three sections are employed to ensure the proper frontal approach of the forklift to the target. The first section changes the gear so that the forklift can approach the target in drive gear. Then, the vehicle's alignment is adjusted by reversing on a straight path before finally approaching the target in a forward (drive) motion.

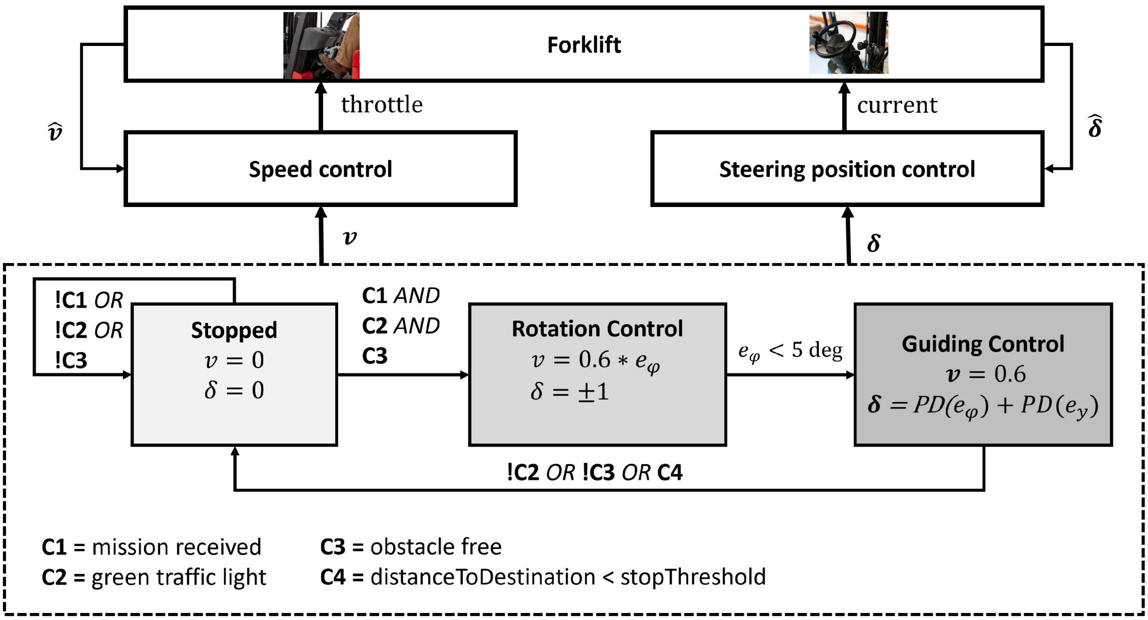


FIGURE 9. Control state machine of real forklifts.

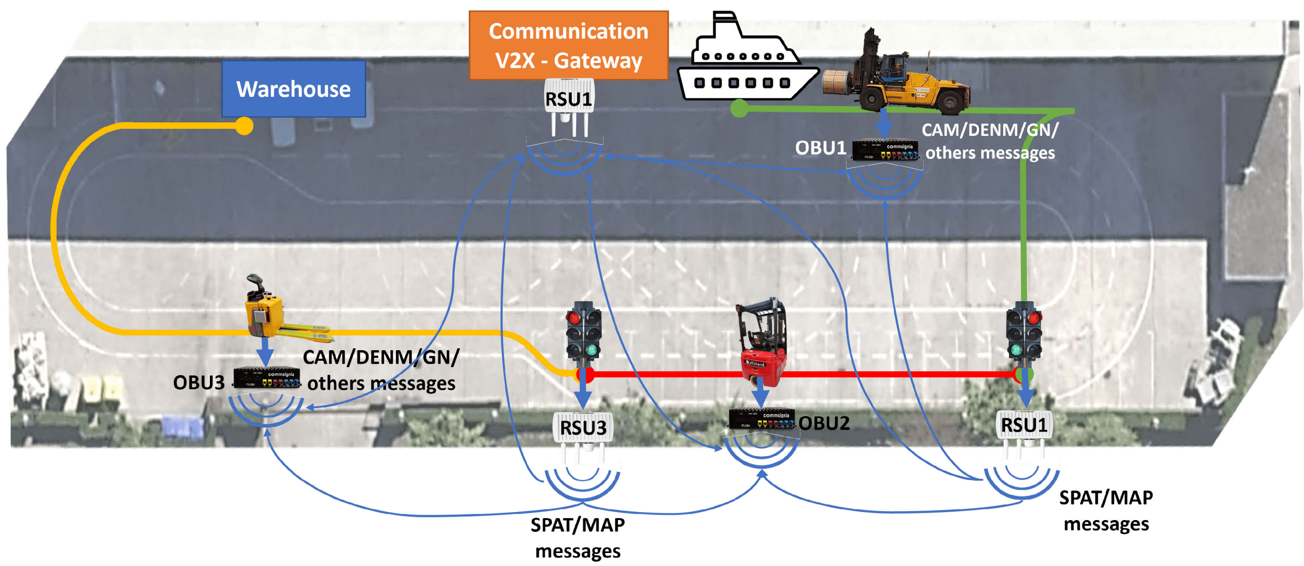


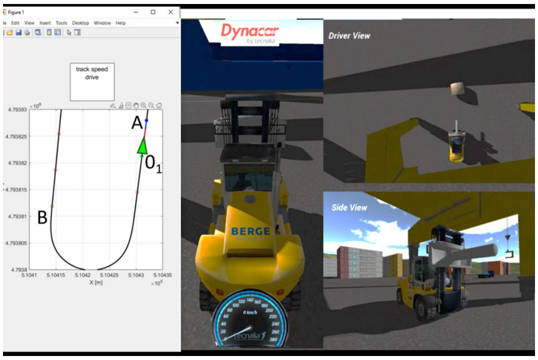
FIGURE 10. Main use case scheme.

The second mission, illustrated in Figure 8, is a reversal of the first mission. The starting point for this mission is the same as the ending point of the first mission, and the goal for this mission is the starting vertex of the first mission. Unlike the first mission, the forklift starts in reverse gear, eliminating the need to turn the forklift around at the first opportunity. The forklift follows the graph-based path in reverse gear from the starting point to the final approach maneuver. Afterward, the same gear change and alignment maneuvers are performed. The resulting path from the global planner is not symmetrical to the first mission.

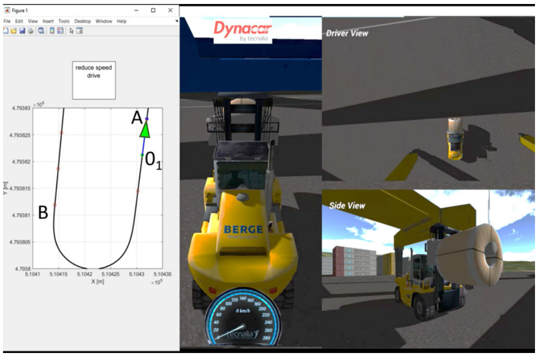
2) DACHSER AND CELSA FORKLIFT

The Celsa forklift is a HYSTER J1.6XNT MWB-type forklift. It is the medium-sized of the three (2.980 × 1.050 × 2.070 mm) and weighs 3.430 kg. Its load capacity is between 3.000 and 4.000 kg, and its driving speed is 16 km/h without load.

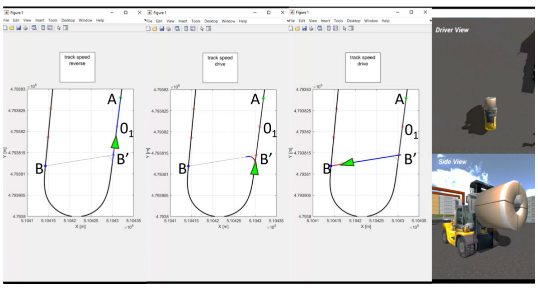
The Dachser forklift is a Jungheinrich ERE225-type forklift. It is the smallest of the three (1.847 × 770 x 1.419 mm)and weighs 404 kg. It has a load capacity of 2,500 kg and a driving speed of 12,5 km/h without load.



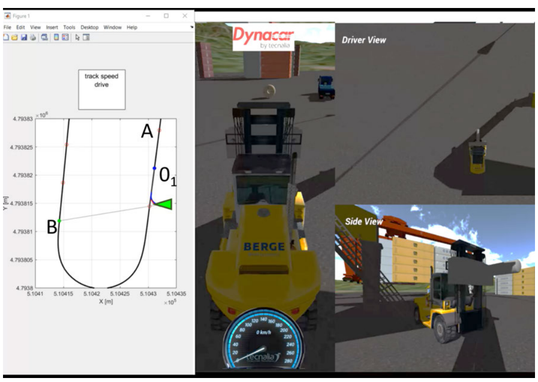
(a) Maneuver starts after receiving the mission



(b) Arrival at point A to take the load at 16 seconds since the maneuver began.

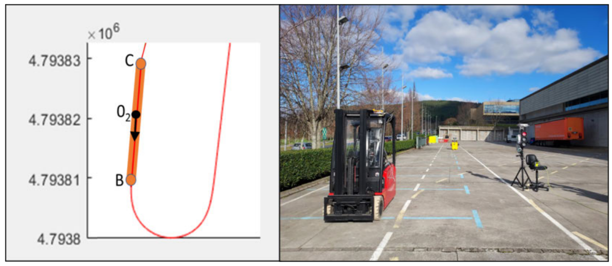


(c) Forklift path from point A to point B (at 2 minutes and 10 seconds) passing through point B' (at 56 seconds)

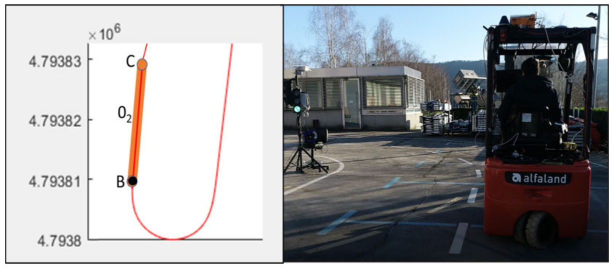


(d) Forklift path from point B to its starting point (at 2 minutes and 57 seconds).

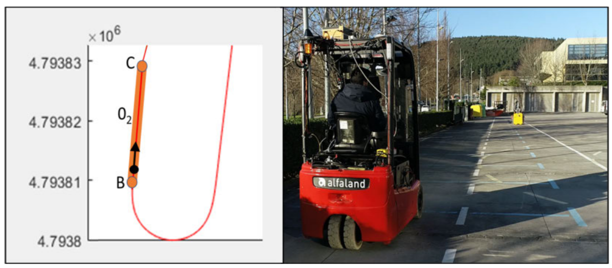
FIGURE 11. **Bergé's forklift regular service.**



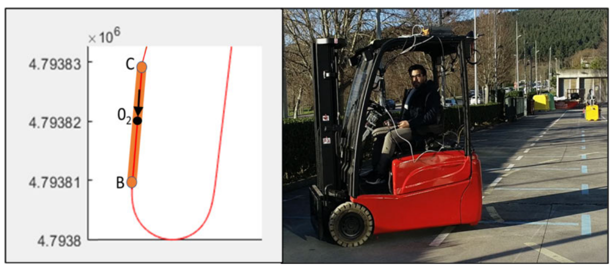
(a) Maneuver starts after Bergé's forklift finishes and its traffic light turns red (at 4 minutes and 3 seconds).



(b) Arrival at point B to take the load at 40 seconds since the maneuver began.



(c) Forklift path from point B to point C (at 5 minutes and 10 seconds).



(d) Forklift path from point B to its starting point and the forklift in this last point (at 6 minutes and 18 seconds).

FIGURE 12. **Celsa's forklift regular service.**

In real forklifts, the software architecture is similar (see Figure 1), despite using different sensors. Each forklift's sensors are listed in Table 1 with their respective protocols and operating systems. A LiDAR on the Dascher forklift detects obstacles in front and stops if collision risk exists. Linux (using C++ under ROS) and Windows (by using Matlab/Simulink code) were used to run the modules. A UDP socket is used to communicate between the computers running each operative system.

Through the OBU of each forklift, the V2X module receives and sends information. The device communicates with the management center to send vehicle data (CAM messages) and event data (DENM messages) and to receive command data, such as the mission, through GN messages.

TABLE 1. **Connections of the acquisition module on the Dascher and Celsa forklift.**

Forklift	Module	Sensor	Comm	PC
Dascher	Acquisition	GNSS - RT2002 OxTS	CAN	Windows
	Acquisition	Differential correction - Radio Base OxTS	SERIAL	Windows
	Acquisition	Lidar - Ouster	UDP	Linux
	V2X	OBU - Commsignia	TCP	Linux
Celsa	Acquisition	GNSS - DURO + Differential	TCP/IP	Linux
	Acquisition	NTRIP Differential correction	TCP	Linux
	V2X	OBU - Commsignia	TCP	Linux

The local planning module relies on a static map of the scenario to make decisions, while the behavior-based planning module uses a state machine to control the behavior of the forklift. This planning differs from that of the simulated forklift (Section 3.2.1) in that instead of moving backward to align with the trajectory, it performs full rotational control to orient to the desired heading angle of the trajectory and then performs the translational movements.

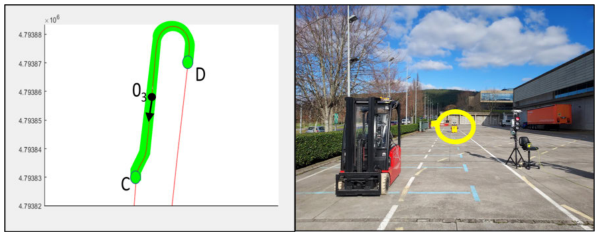
In this sense, the state machine comprises three main steps (refer to Figure 9). The first step is called the **stopped mode**, during which the forklift waits until certain conditions are met before it can start moving. These conditions include receiving a mission from the management center (C1), the traffic light being on green (C2), and no obstacles blocking the forklift's path (C3). If none of these conditions are satisfied, the system remains in stop mode. Once all these conditions are met, the system proceeds to the **rotation control** step, where the forklift aligns its heading with the route's heading using a proportional controller based on the wheels' speed while checking the angular error. To achieve this, the steering angle is set to the maximum value that allows the forklift to fully rotate without translating. Finally, the **guiding control** step is activated, which uses a double discrete PD controller based on the lateral and angular error to guide the forklift. The outputs of the state machine are both the reference speed (v) and the desired steering wheel angle (δ).

The control module operates using PD controllers during the guiding control phase and uses steering position control for the forklift actuator device. In addition, the control module incorporates a longitudinal control (speed control) for the forklift, which is a PI controller that relies on the velocity error ($v - \hat{v}$).

The actuator module is made up of the steering mechanism's automation devices, which consist of an electric motor and an electromagnet. Meanwhile, throttle control is achieved by communicating with the forklift's ECU. Both systems utilize the CAN protocol to communicate with the control module.

V. USE CASE

This section describes the major use case of the Estiba+ 2022 project. The goal is to demonstrate the system's capability to autonomously and efficiently manage the synchronized loading tasks typical of a port, involving three categories of logistics vehicles: heavy-duty, medium-duty, and small-duty forklifts. Each forklift category defines its operational role based on its characteristics. The Bergé forklift, the heaviest and most capable, handles the largest loads. Next, the Celsa forklift takes over, requiring two trips to transport the load equivalent to one trip by the Bergé forklift. Finally, the Dachser forklift completes the process, needing two trips to move the load equivalent to one trip by the Celsa forklift to the warehouse. For this, a loading-unloading scenario in ports was proposed in the Tecnalia test tracks.



(a) Maneuver starts after Celsa's forklift finishes and its traffic light turns red (at 6 minutes and 28 seconds).

(b) Arrival at point C to take the load (at 7 minutes and 23 seconds) and turns 180° to head to point D.

(c) Forklift goes from point C to point D and arrives at the destination at 9 minutes and 34 seconds.

(d) The Forklift turns to head its starting point and it arrives at 10 minutes and 48 seconds).

FIGURE 13. **Dachser's forklift regular service.**

As shown in Figure 10, it uses three forklifts with their work sections limited by traffic lights that indicate whether or not vehicles can circulate. Each forklift executes its *regular service* that is if the truck has received the mission from the supervision module through the GN message and its respective traffic light is green, it will go from its position to the collection point. When the load is already placed, it will

FIGURE 14. Obstacle detection.

go to the delivery point. Once it has reached its destination and the cargo is deposited, it returns to the starting point to wait for another mission. All routes are autonomous. The global execution of the scenario is carried out sequentially which means the Bergé forklift receives the mission and performs the service; when it finishes the tasks and has reached its waiting point, the next forklift (Celsa) receives its mission and executes it. Finally, when it has finished and is at its waiting point, the Dachser truck receives its mission and completes it. Throughout the execution of each service, the vehicles send their status via CAM messages, the mission status via GN unicast, and receive traffic light information (SPAT and MAP messages). On the other hand, all this information is collected by the supervision module through the V2X-MQTT Gateway system whose operation is explained in section IV-A.

VI. EXPERIMENTAL RESULTS

As described in section IV, the first forklift is virtually represented with the Dynacar® simulator, whereas others are real. The Supervision Platform generates the mission corresponding to each truck. Each of these messages consists of two legs: a starting point 0_x and two stopping points (points A and B for the first truck, points B and C for the second, and points C and D for the third). In the maps of Figures 11-13, it can be seen these points and the route made by each one of the forklifts. All vehicles move from point 0_x to the place of loading for their subsequent transfer to unloading point.

As shown in Figure 11, in the image 11a, the forklift has successfully received the mission and begins its movement. The image 11b represents its arrival at point A at 16 seconds since the maneuver began. Once the forklift has the load collected, it goes to point B (image 11c passing through point B' at 56 seconds). In this case, due to the dynamics of the vehicle, the first move from A to B' is in reverse to be able to turn and arrive with the load ahead. Finally, once the load has been deposited at point B (at 2 minutes and 10 seconds), the forklift returns to its starting point as shown in image 11d, and arrives at 3 minutes and 53 seconds to wait for a new mission. Throughout the process, the Mission Report message is sent by the vehicle to the supervision module.

When Bergé's forklift finishes, its traffic light turns red, then the one for Celsa's forklift turns green, so this forklift begins to carry out the mission as shown in Figure 12, where the same sequence of events is displayed.

This forklift begins its movement at 4 minutes and 3 seconds (image 12a) from the starting point to point B to pick up the load (it arrives 40 seconds after starting the maneuver, as shown in the image 12b). Once the load is collected, it begins its journey to destination point C (as seen in image 12c at 5 minutes and 10 seconds). In this case, the vehicle turns 180° to follow the path instead of going to an intermediate point as the first one. Upon reaching its destination and depositing the load, the forklift returns to its starting point to wait for the next mission received by V2X. He reaches this point at 6 minutes and 18 seconds as shown in the image 12d. As in the previous case, throughout the process, the Mission Report message is sent by the vehicle to the supervision module.

Finally, as in the previous case, when Celsa's forklift finishes its mission, its traffic light turns red, then the one for Dachser's forklift turns green to allow the service to proceed as shown in Figure 13, where the same sequence of events is displayed as in the Bergé's one. The forklift begins its movement at 6 minutes and 28 seconds (image 13a) from the starting point to point C to pick up the load (it arrives 42 seconds after starting the maneuver, as shown in the image 13b). Once the load is collected, it begins its journey to destination point D. Like the previous forklift, the vehicle rotates 180° to follow the path instead of going to an intermediate point as the first one. It reaches its destination at 9 minutes and 23 seconds as seen in the image 13c. Upon reaching its destination and depositing the load, the forklift returns to its starting point to wait for the next mission received by V2X. He reaches this point at 10 minutes and 36 seconds as shown in the image 13d. As in the previous case, throughout the process, the Mission Report message is sent by the vehicle to the supervision module.

During the route of the last forklift, an obstacle was detected on the road to validate the use case that an operator crosses or finds an object that interrupts the forklift (see Figure 14). While the vehicle executes the mission, it detects an obstacle in its trajectory through the LiDAR. The forklift stops and waits until the obstacle moves to continue with the task. The vehicle generates a DENM message to report the event (the cause code is 10, which means "obstacle on the road"). The V2X-MQTT Gateway transforms the message and forwards it to the supervision platform.

VII. CONCLUSION

The document has presented the framework developed for the ESTIBA+ 2022 project. The results validate the system as a possible and reliable solution to achieve the complex task of automating a port environment. The use case demonstrates the ease of the system implementation in different types of forklifts due to its modularity and adaptability to the dynamics of each one. Each forklift has successfully carried out its mission by accurately following the defined trajectories, reaching the expected points, and correctly reacting to unforeseen events, such as obstacles on the road.

The infrastructure environment developed allows fast and continuous communication, achieving easy and safe monitoring at all times. The versatility and adaptability of the V2X Communications Gateway ensure interoperability, meeting the different message and communication demands of both the vehicle and the supervision module.

From the social point of view, it is true that the use of automated systems reduces manpower but, in contrast, it eliminates eventualities and requires specialized and full-time port workers. Likewise, avoiding repetitive and high-effort tasks makes people's jobs easier and safer, reducing stress in the workplace. In addition, in the long term, technology ends up creating better jobs and improving productivity in an activity that has an impact on the economic development and foreign trade of a country.

The validation and the results in controlled laboratories bring closer the possibility of achieving a fully automated port soon. However, to fulfill this goal, there are remaining tasks to address, such as transferring this system to another type of forklift, evaluating the use case in more complex environments with more restrictive times or trajectories, or adding load placement to the automation so that it is no longer an activity of the operator.

As targets of future research, more messages, such as priority messages, can be added to consider emergency vehicles or transportation priorities between port vehicles in the scenario. Another appealing system to add is a security system that ensures the analyzed data protection and prevents cyberattacks. These will require a study of the risks of failure both at the vehicle and infrastructure levels.

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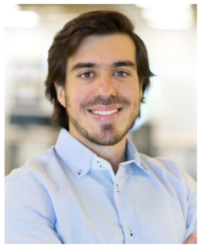

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