Appendix A

DATASETS

This appendix introduces the resources with which the proposed perception framework has been evaluated. Since the AUTOPIA research group has an autonomous vehicle prototype, the perception framework proposed in this thesis has been primarily tested using datasets gathered using this prototype. Additionally, for the cases where a quantitative evaluation is needed, the publicly available dataset nuScenes [14] is used, as it provides reliable ground truth data. Both datasets are presented in the following sections.

A.1. AUTOPIA resources

The present thesis is conducted within the context of the activities of the AUTOPIA group at the Centre for Automation and Robotics (CSIC-UPM). AUTOPIA is a pioneering research group that possesses a fleet of autonomous vehicles and other resources that facilitate research activities in the field of autonomous driving. In the following, the key resources used in this thesis are introduced.

A.1.1. Main autonomous vehicle prototype

The main autonomous vehicle prototype from AUTOPIA used in this thesis is a conventional Citröen DS3 modified by including several actuators and sensors. Figure A.1 displays a general view of this prototype highlighting the main devices used in this work: (i) three LiDAR sensors for perception of the environment, (ii) a camera sensor for reference images, (iii) on-board units to enable V2X communications and (iv) a Real-Time Kinematic (RTK) Global Navigation Satellite System (GNSS) for localization and time synchronization (the localization system is based on an EKF that fuses information from the RTK GNSS receiver and CAN bus sensors, see [4] for more details).

An example of the LiDAR point cloud obtained from the three on-board LiDAR sensors—one IBEO-Lux and two VLP-16 sensors—is also shown. The main characteristics of these sensors, under the configurations used, are provided in Table A.1. It is noteworthy that the data density of the

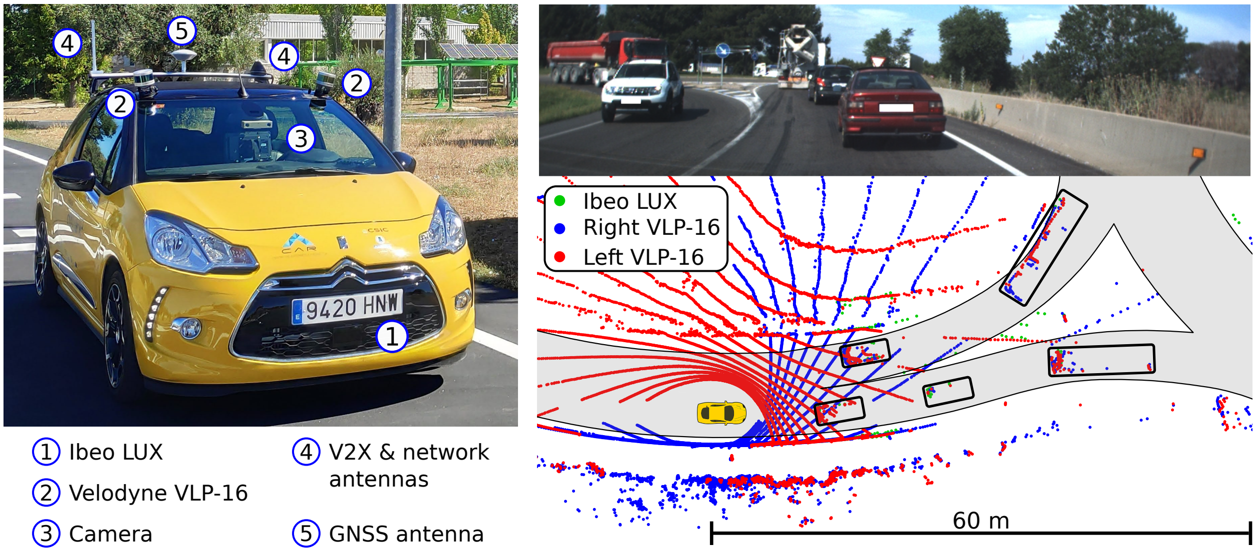


Figure A.1: AUTOPIA's autonomous vehicle prototype. The main components used in this thesis are highlighted and an example of the LiDAR data gathered by the three on-board sensors is provided. Vehicles, denoted in black, have been manually labeled.

obtained point cloud is reduced in comparison to other vehicle prototypes' sensor setups used in popular open datasets, such as KITTI [38] or Waymo [145] (see Figure A.5). This influences aspects such as the development of a point cloud classification approach for sparse LiDAR data—Chapter 2.

Table A.1: Main characteristics of the LiDAR of the datasets used.

	N. layers	Horizontal FoV	Vertical FoV	Horizontal res.	Vertical res.
Ibeo LUX	4	$[-50, 50]^\circ$	$[-1.2, 1.2]^\circ$	0.25°	0.8°
VLP-16	16	360°	$[-15, 15]^\circ$	$\sim 0.2^\circ$	2°
nuScenes	32	360°	$[-30, 10]^\circ$	$\sim 0.33^\circ$	1.25°

A.1.2. Scenes recorded, other prototypes and digital maps

AUTOPIA's dataset is conformed by multiple driving scenes recorded in the test track of the Centre for Automation and Robotics (CAR), in Arganda del Rey, Madrid, Spain, and in its vicinities, in urban real scenarios with real traffic. These scenes contain multiple scenarios—e.g. multi-lane roads, intersections and roundabouts—and different types and densities of obstacles—vehicles, pedestrians, vegetation, roadworks, etc. Figure A.2 displays four examples of different scenes recorded.

The AUTOPIA research group has other automated vehicle prototypes that, although not equipped with exteroceptive sensors to perceive the environment, have proprioceptive sensors to estimate their dynamic state (position, orientation, velocity and acceleration). Thanks to the high precision with which this state is estimated, these vehicles can be used as ground truth for vehicle tracking evaluations—the data between vehicles is correlated by time synchronization using the

Figure A.2: AUTOPIA's dataset scene examples.

GNSS receivers.

Additionally, the road and its corresponding regulatory elements have been mapped with high accuracy for both the CAR's test tracks and the nearby urban area. Indeed, high-definition digital maps of both are available including features such as road limits, lane markings, traffic signals, regulatory elements, etc. Figure A.3 shows an example of the digital map of the centre's test tracks.

A.1.3. Vehicle-to-Everything communications

In some scenarios, V2X communications are available to provide additional information about the obstacles in the environment. For example, Figure A.4 shows a setup that reports the area in which roadworks are to be carried out.

In order to enable these communications, the autonomous vehicle prototypes are equipped with Commsignia on-board units ITS-OB4 and certain infrastructures with Commsignia roadside units ITS-RS4. These devices comply with the standard IEEE 802.11p and offer a high-level V2X software development kit. The service used is the Collective Perception Service (CPS), a novel system that allows to receive and inform about the environment perceived, through CPMs [1].

A.2. nuScenes dataset

NuScenes [14] is a public dataset for autonomous driving that addresses urban scenarios. In this thesis, it is used for evaluations that require a quantitative evaluation.

This dataset incorporates multiple sensors among which a top-mounted LiDAR is included. The specifications are detailed in the third row of Table A.1. Additionally, it provides ground truth

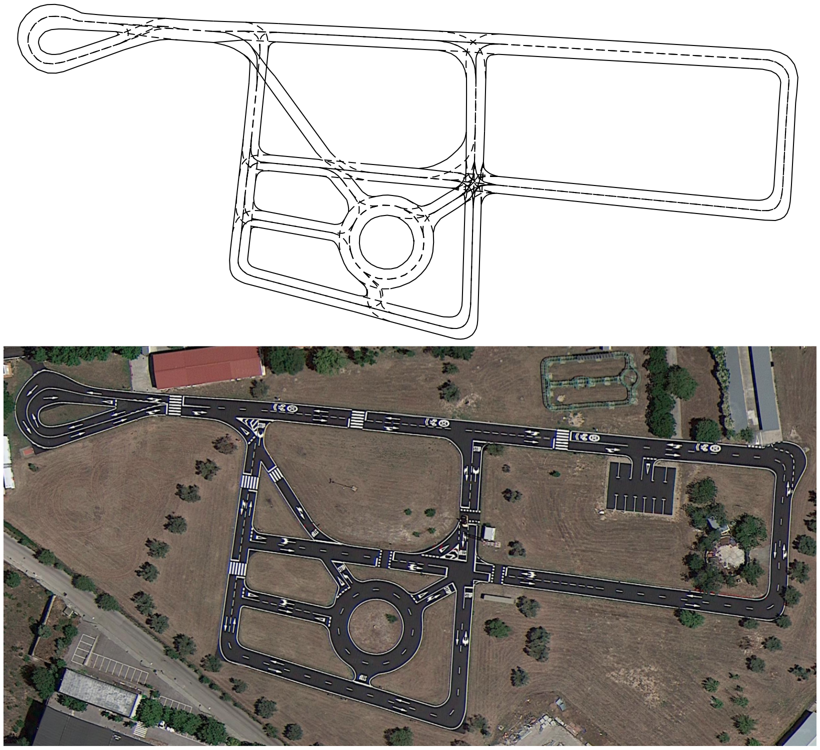


Figure A.3: Top: Digital map of AUTOPIA's test tracks. **Bottom:** Aerial view (source: Google ©2022 CNES/Airbus, Maxar technologies).

labels for road users in the scene and semantic labels for points of the point cloud, e.g. points corresponding to cars, sidewalks, etc.

Other public datasets are available, for example [38, 145], but nuScenes has a LiDAR point cloud density similar to AUTOPIA's dataset. As a result, the conclusions drawn from nuScenes-based

Figure A.4: Example of roadworks area reported through V2X communications [41]. The area covered by the roadworks is delimited by fences and estimated using Ultra-wideband (UWB) sensors installed on the road infrastructures.

evaluations are more readily transferable when compared to other datasets using sensors with higher capacities.

Figure A.5 provides an example of the information used from nuScenes dataset. Additionally, to illustrate the difference in the point cloud density compared to other datasets, an example of a LiDAR point cloud from the Waymo dataset is also included.

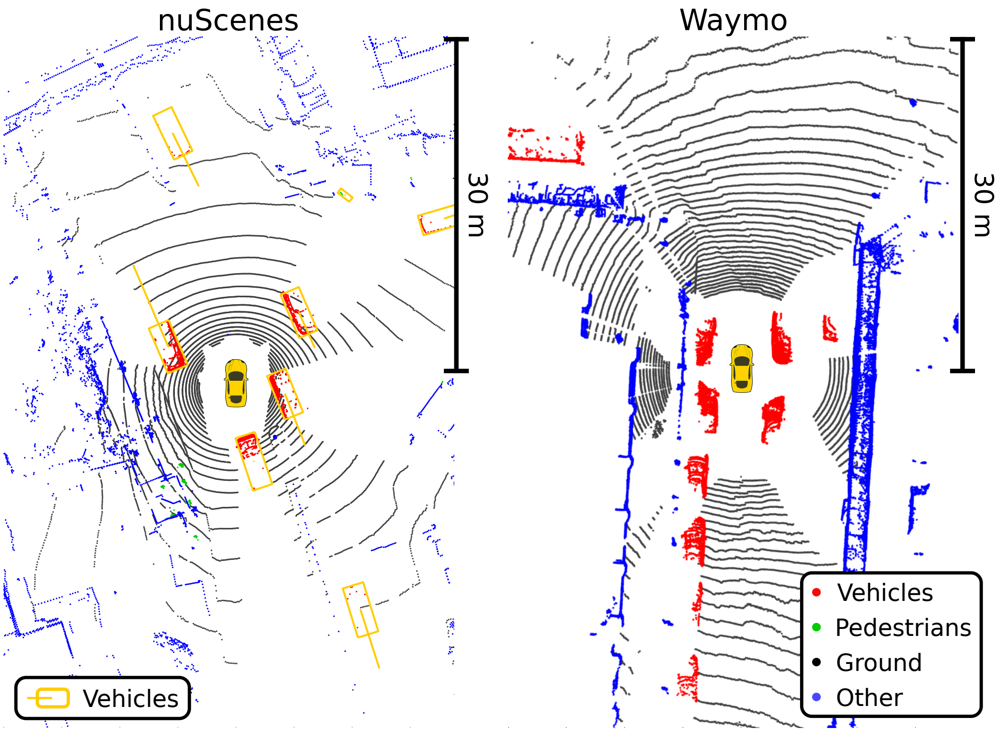


Figure A.5: Examples of nuScenes and Waymo dataset. The point cloud is colored based on a summarized set of the points' ground truth labels. Waymo dataset includes five LiDAR sensors, only the one with the highest point density is shown.

Appendix B

PERCEPTION FRAMEWORK INTEGRATION AND DEMONSTRATIONS

During the development of this thesis, the AUTOPIA research group has actively participated in various projects and activities that required an autonomous vehicle prototype with specific capabilities, including perception of the environment. This appendix briefly outlines the real-time integrated tasks within AUTOPIA's main prototype (see Appendix A.1) and presents an overview of the results of some of the demonstrations conducted.

B.1. Real-time realization

Figure B.1 shows the scheme of the perception framework integrated into AUTOPIA's prototype architecture. This framework has been tested in different real-scenarios yielding an average execution time of 0.055 s with an approximate possible variation of ±0.020 s.

To achieve real-time execution, the code is programmed to run on both CPU and GPU. For the point cloud processing module and grid-based module, parallel programming of GPUs with Nvidia CUDA has been employed. In contrast, the object-level module has been implemented in CPU using C++11. Moreover, certain steps have been simplified:

- **Obstacle–ground classification:** The LBP algorithm of the CB-MRF strategy presented in Chapter 2 is computationally expensive. Instead, the CB-MF strategy has been employed as, in comparison, its computational demands are lower.
- **Measurement Occupancy Grid:** In Section 3.4.1.1, the *weighted angular sector-based* scan rendering method has been introduced seeking to obtain a more reliable representation of the LiDAR data. Nevertheless, this higher accuracy implies a higher computational cost. To

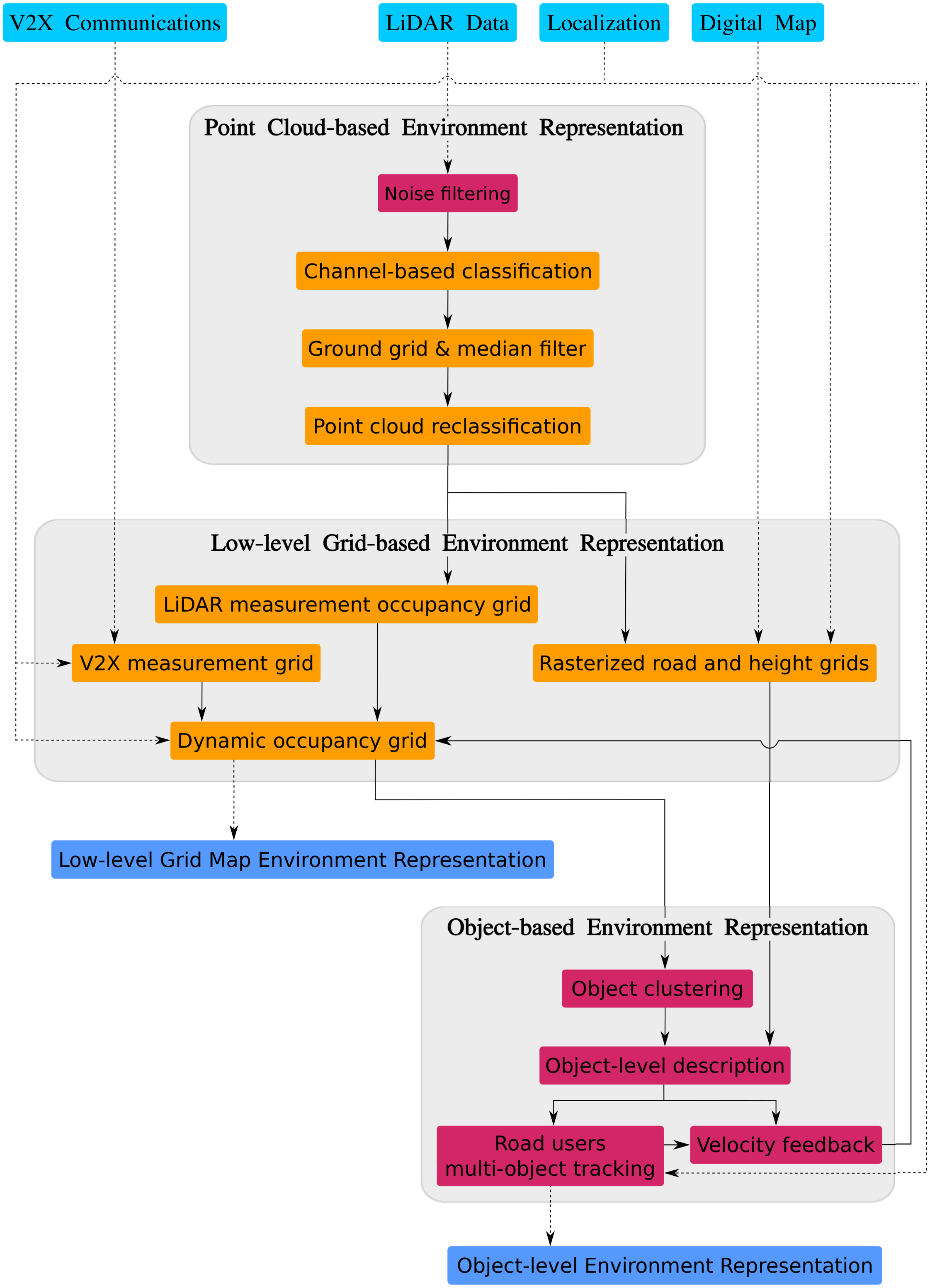


Figure B.1: Scheme of the real-time implemented perception framework. Steps implemented in CPU are denoted in garnet red and steps implemented in GPU in orange.

enable real-time implementation, the approach used considers only the influence of the two adjacent laser beams instead of computing the influence of every laser angularly close to the cell.

- **Classified Occupancy Grid:** The COG presented in Section 4.5 is real-time realizable. However, at the moment of the deployment and integration in the vehicle, it was not yet fully developed. In order to avoid wrong object-level track initializations, a strategy based on checking the road area was used, i.e., vehicle tracks can only be initialized inside the road.

Tests were executed on an HP ZBook Studio G5 with an Intel(R) Core(TM) i7-8750H CPU @ 2.20 GHz, 16 GB RAM DDR4 2667 MHz and a Nvidia Quadro P1000 Mobile with 4 GB VRAM.

B.2. Project demonstrations

To showcase that the proposed perception framework satisfactorily interacts with the other modules that comprise the complete autonomous vehicle system, this section overviews some of the results obtained during project demonstrators.

The PRYSTINE project [105] (2018-2021) was a project funded by the European Union that aimed to bring safe automated driving to urban and rural environments. The AUTOPIA group participated in this project focusing on the domains of automated prototypes, V2X communications, and decision-making. Figure B.2 illustrates a demonstrator conducted during this project, where these three domains were applied. The ego-vehicle is located at an intersection with a car, a bus and a pedestrian. In order to proceed with the route, it must yield to both vehicles and wait for the pedestrian to cross the road. Therefore, the perception framework must be capable of detecting the three road users, fusing the other agents' detections received through V2X communications, and conveying this information to the motion prediction, motion planning, and maneuver planning modules. The outputs of the perception framework are displayed with a human-machine interface used by the AUTOPIA research group to report information to the driver. The detected obstacles

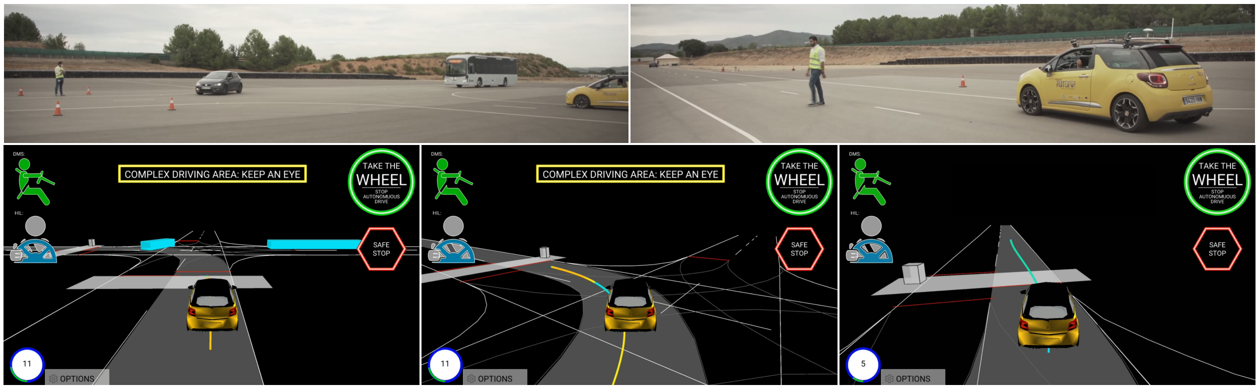


Figure B.2: PRYSTINE project demonstrator. **Top:** reference images. **Bottom:** output of the perception framework.

are visualized with the bounding boxes estimated, blue for the vehicles and gray for the pedestrian. The interaction with the motion planning module is partially reflected by the planned trajectory, represented by a blue/yellow line being blue positive acceleration and yellow deceleration.

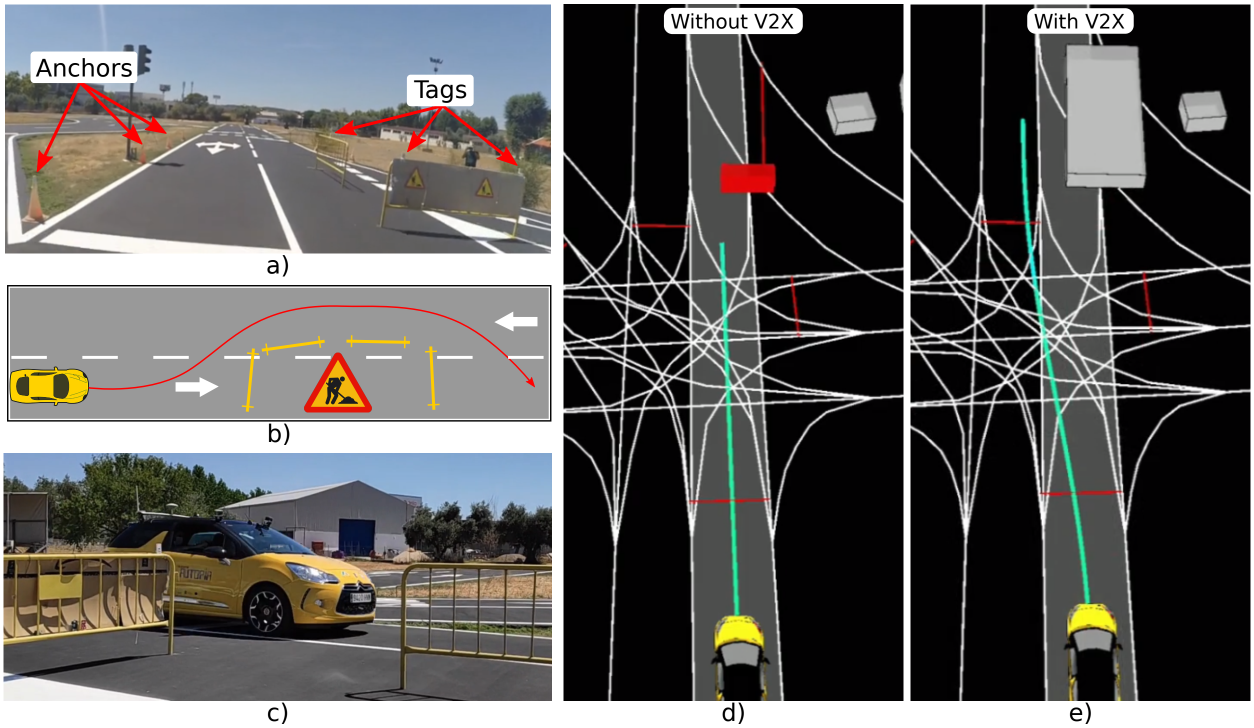
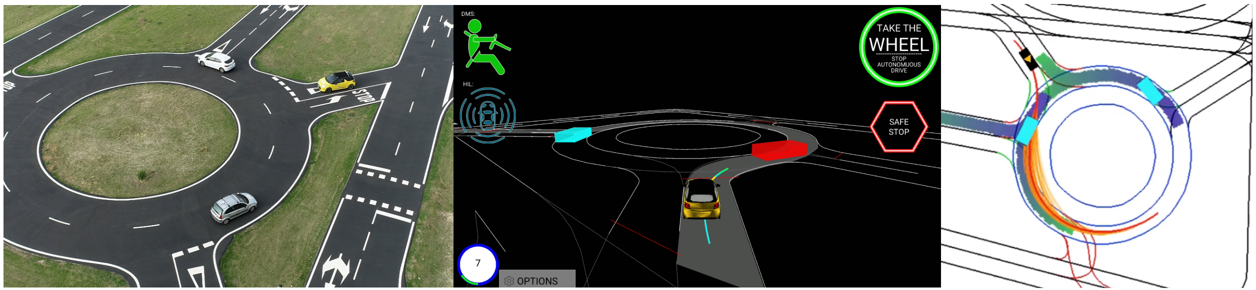


Figure B.3: SECREDAS project demonstrator. a) Roadworks area and UWB setup. b) Example of the desired maneuver. c) AUTOPIA's prototype performing the desired maneuver. d) Outcome of perception framework, both without and with V2X communications, respectively.

The SECREDAS EU-funded project [135] (2018-2021) was intended to advance the field of automated and autonomous systems by integrating high security and privacy protection while preserving functional safety and operational performance. The AUTOPIA group contributed to this project through the domains of Collective Perception and decision-making. In this context, Figure B.3 illustrates a demonstration where V2X communications are applied to address low-visibility situations. In the depicted scenario, roadworks are simulated using fences and traffic cones in a manner that the autonomous vehicle cannot fully perceive the total covered area using only onboard sensors. A UWB setup is installed to detect the boundaries of the roadworks and transmit them using V2X communications. It can be clearly seen that the inclusion of V2X data enhances the estimation of the roadworks area. When relying solely on onboard sensors, only the first fence is perceived. In contrast, when fusing the information received through V2X communications, the entire extent is correctly modeled.

Lastly, the EU-funded project NewControl [88] (2019-2023), aimed to enable mobility-as-a-service for next-generation highly automated vehicles. The AUTOPIA group was involved in this project through the development of automated vehicles capable of addressing complex scenarios. For



a) b) c)

Figure B.4: NewControl project demonstrator. a) Aerial reference view. b) Perception framework real-time outcome. c) Motion prediction and motion planning modules outcome.

example, Figure B.4 shows a demonstrator where the ego-vehicle has to merge into a roundabout in between two other vehicles. In this experiment, the perception framework must estimate accurately the state of both vehicles and send this information to the motion prediction, motion planning, and maneuver planning modules. Notice that, in addition to the results of the object-based module, the outputs of the motion prediction module—predicted occupied space denoted in shades of blue and green—and the outputs of the motion planning— trajectory candidates denoted in orange—are also displayed (see [80] for details about these modules).

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