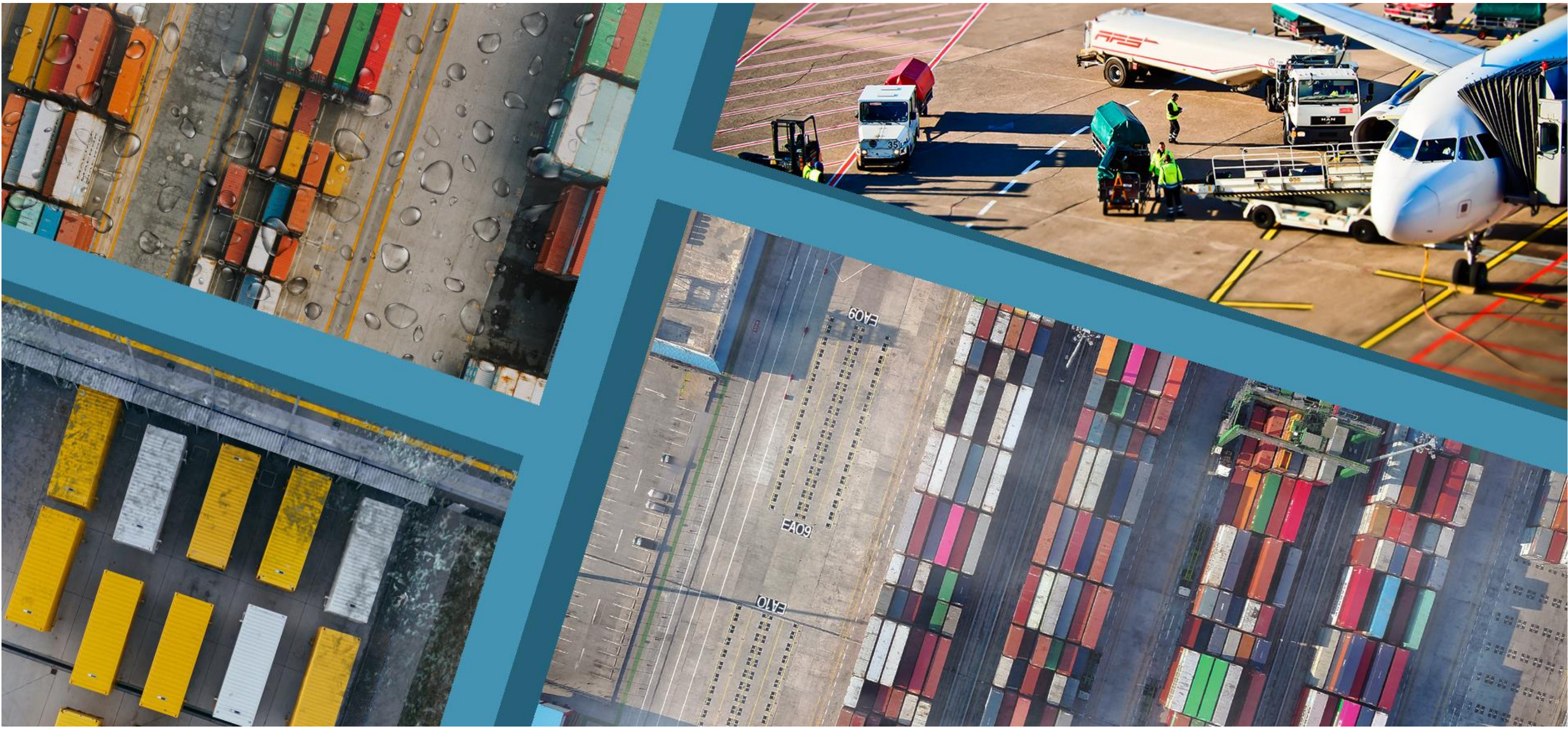

AWARD
Scaling autonomous logistics

D3.6
Public Report for measurement campaigns of ADS

Lead: EasyMile

Due date: January 2023

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LEGAL DISCLAIMER

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List of acronyms

ADS	Automated Driving System
ADV	Autonomous Driving Vehicle
AV	Automated Vehicle
ECA	Emergency Collision Avoidance
GNSS	Global Navigation Satellite System
IMU	Inertial Measurement Unit
RTK	Real-Time Kinematic
ROS	Robot Operating System
AWARD	All Weather Autonomous Real logistics operations and Demonstrations
API	Application Programming Interface
NTP	Network Time Protocol
UTM	Universal Transverse Mercator
MQTT	Message Queuing Telemetry Transport

1. Introduction

1.1. Purpose & scope

This report aims to evaluate the performance of AWARD's ADS and highlight preliminary actions made to integrate and test the AWARD sensor set into it. Going from the overview of the ADS, we bring attention to the specifications of each sensor equipped on a TractEasy (TLD vehicle).

Through a series of tests conducted in Toulouse at Francazal site, the performance of AWARD ADS is evaluated on a TractEasy under nominal conditions (sunny or cloudy weather without rain, fog, or snow).

The evaluations of both the ADS and each of the AWARD sensors are conducted by looking at two major topics: Localization and Perception.

1.2. Confidentiality

This document is public. The content of the report aims to be shared for external use, to all the partners of the AWARD consortium and extended to anyone else.

1.3. Platform applicability

The results of this report are only relevant for the TractEasy (baggage TLD tractor) use case. Knowing that the AWARD project involves other platforms, the description of the ADS and sensors is the same; however, the results would be different due to the difference in the sensors location, etc.

1.4. Overview

This report D3.6 is the public version of the D3.3 deliverable: Report for Measurement Campaign of ADS, presents the principles of the ADS on the inputs of EasyMile sensors only (Lidars) from one side, and the performance outcome of Award sensors: Continental radars, Foresight cameras, and Navtech radar.

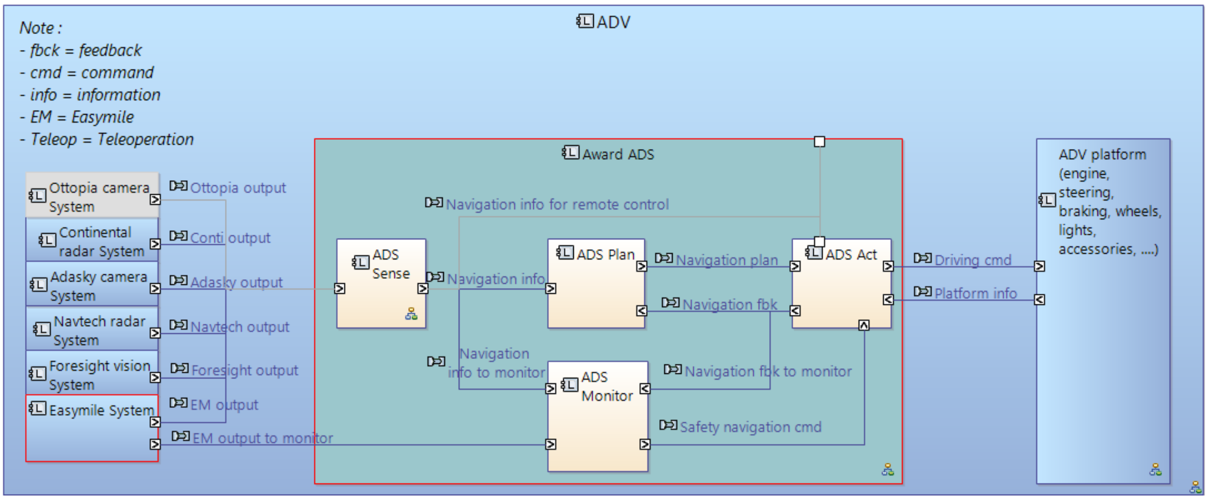

Figure 1: Final architecture of the ADS integrating both EasyMile and AWARD sensors

ADS Sense, Plan, Act, and Monitor are the pillars of the ADS as mentioned in Figure 1 above. In the architecture as it will be described in the further sections you will notice that Lidar data is the heart of the ADS Sense. The evaluation of this report is the description of the final reaction of the ADS Act module while executing the ADS Plan instructions in different scenarios. Furthermore, ADS-Monitor can override the decisions of ADS-Plan to intervene in case of unexpected objects detections in collision risk zones.

When evaluating the perception, if a decision of the ADS Act originated from the ADS Monitor by forcing an emergency stop, the test result is considered as failure. More details are described in the D3.5 document that highlights the different functionalities of each entity, not only in the EasyMile context but for the final AWARD ADS.

The final prototype would require the integration of each AWARD sensor signal into the existing legacy ADS. Before doing so, identifying the strengths and weaknesses that each provider must be considered which is a task which results are confidential.

2. AWARD ADS architecture description

This section aims to give a description of the hardware, including the field of view, range, position, and functionality of each sensor in the AWARD sensor set. Then a focus will be given on the distinct parts of the software that allow the vehicle to drive in autonomous mode and ensure the safety of the vehicle. Finally, two key functions of AWARD ADS will be introduced: Localization and Detection.

2.1. AWARD sensors

The TractEasy (TLD vehicle) is equipped with lidars, and a set of radars and cameras added in the context of the AWARD prototype:

- One 3D lidar, named VLP32, which uses 32 infrared (IR) lasers coupled with IR detectors to measure distances to objects. The set of laser/detector pairs rotates rapidly to scan the surrounding environment, firing laser pairs approximately 18,000 times per second, providing a 3D point data set. This sensor is located on the roof to scan the environment around it (Figure 2).

The software developed on it allows us to compare in real-time the scan results to a previously recorded map of the environment to locate the vehicle in space and to detect obstacles.

Figure 2: VLP32 Field of View

- One four-layer and one single-layer safety lidars, named respectively MRS1000 and Microscan3, that can detect low obstacles around the vehicle. These safety lidars each have a 275° detection angle and are located in the two front corners of the vehicle. The bottom of each lidar is located at approximately 15 cm (5.9 in) from the ground (Figure 3).

  The software uses these safety lidars to slow-down or stop the vehicle to avoid collision with potential obstacles, pedestrians, or vehicles inside a pre-defined detection area.

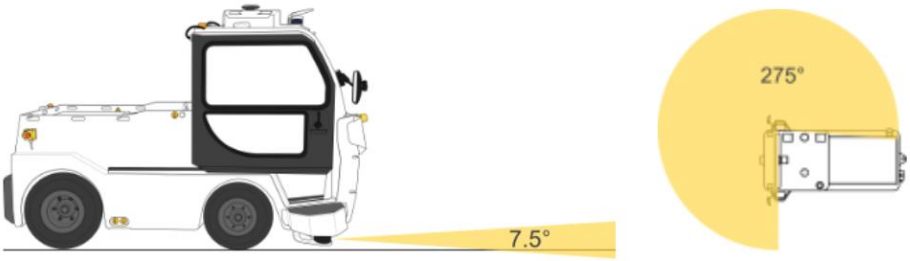

Figure 3: MRS1000 Field of View

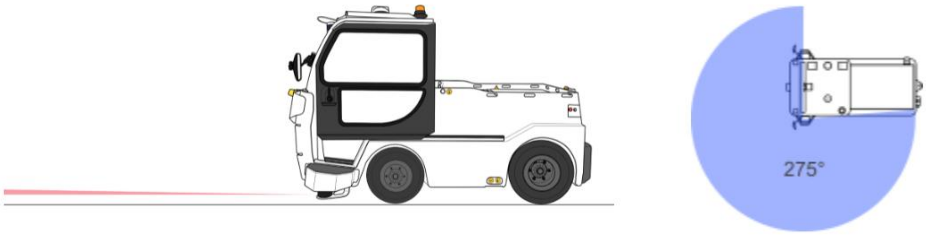

Figure 4: Microscan3 Field of View

- One optional 3D lidar, named VLP16, which uses an array of 16 infrared (IR) lasers coupled to IR detectors, located under the VLP32. It is slightly tilted towards the ground for better detection at close range. It is used to complement the VLP32 data in terms of close-range obstacle detection (Figure 5).

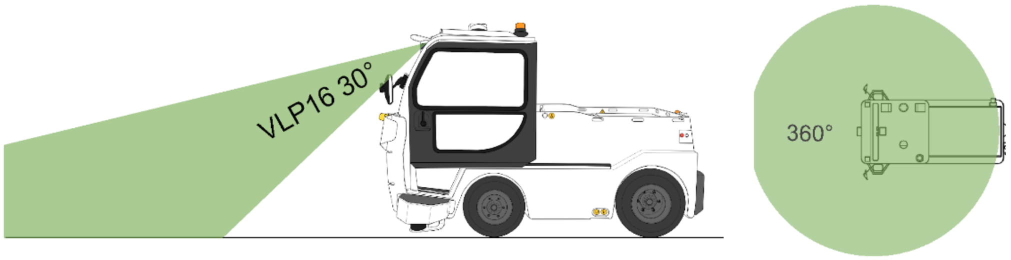

Figure 5: VLP16 Field of View

- One Navtech radar with a 360° field of view, with an adjustable rotation frequency from 3hz to 10hz. For AWARD, this radar was mounted on the roof of the TLD platform and raised to the highest position to provide a 360° view of the environment. The Navtech Radar is mainly used for localization using Navtech's localization solution, namely Terran360 (Figure 6).

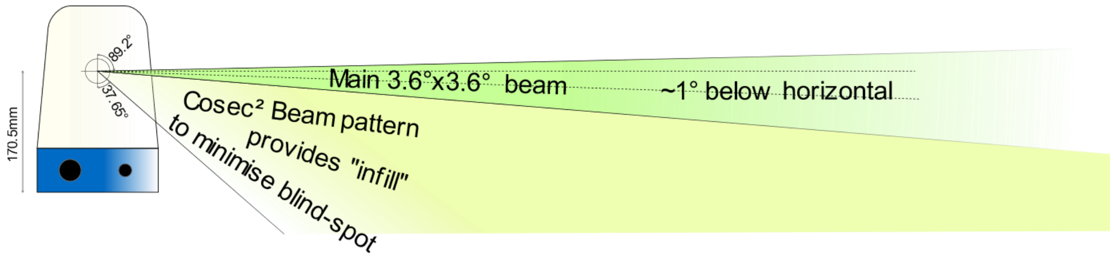

Figure 6: Terran 360 Localisation radar beam patterns

- Six Continental radar sensors equipped as a belt on the TractEasy covering a 360 degrees view. The radars equipped on the vehicle are the 77 GHz SRR520 with an operating range of nearly 100 meters (Figure 7).

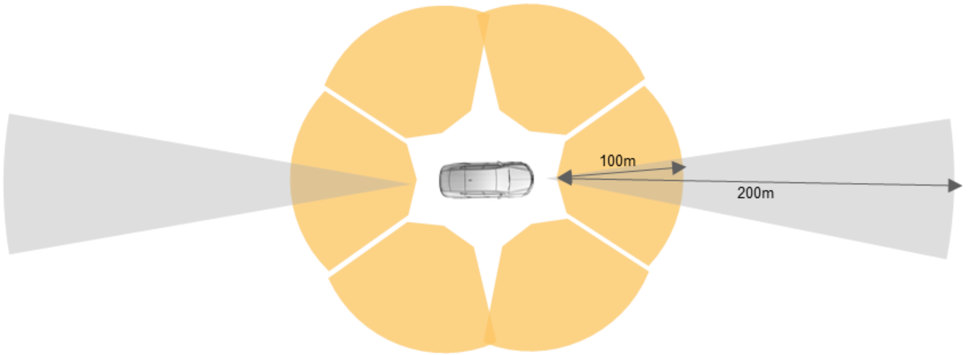

Figure 7: 360° Radar belt with SRR520 sensors

- The foresight rig is composed of two visible light cameras, and two infrared cameras. The operating range of these cameras is between 2.5m and 100m. The multiple lenses serve as stereo camera technology (Figure 8).

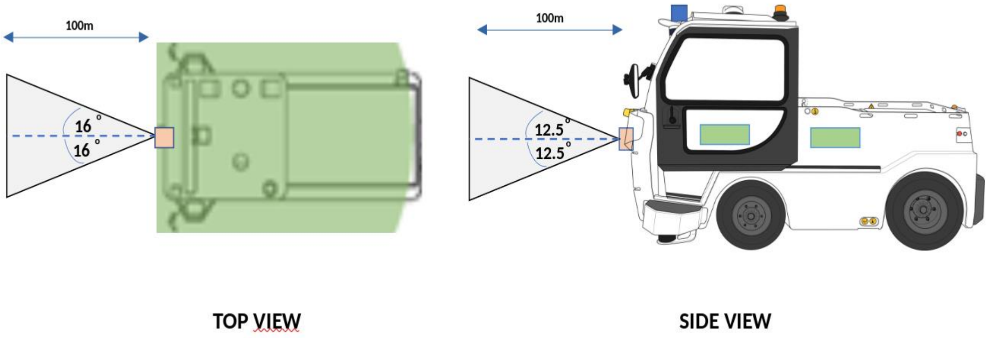

Figure 8: Camera foresight Field of View

2.2. AWARD ADS system description

The purpose of this section is to describe the ADS and its subcomponents as well as the main functions allowing the ADV to drive autonomously. The ADS is composed of four main parts: ADS Sense, Plan, Act, and Monitor which can be represented as follows:

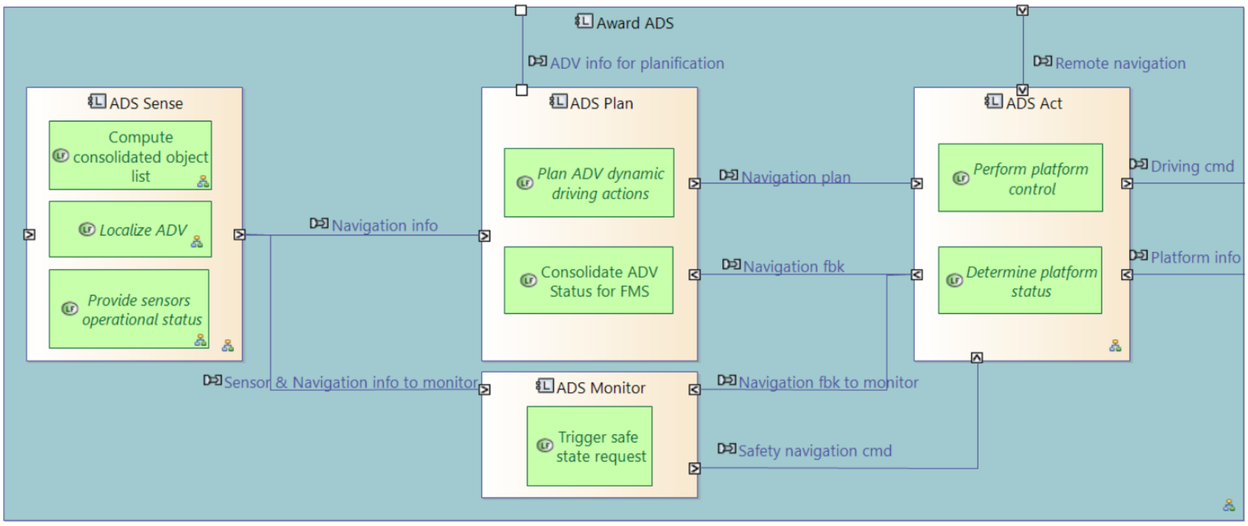

Figure 9: Award ADS and its main functions

2.2.1. ADS-Sense

ADS-Sense supports the environmental perception functions enabled by the different sensors. It also embeds additional sensors to estimate the autonomous vehicle's own position and orientation (GNSS and IMU respectively). The ADS-Sense exploits all data provided by the entire sensor-set to fulfil two main key functions: Localization and Perception.

2.2.2. ADS-Plan

ADS-Plan uses the outputs of the ADS-Sense to determine the optimal motion planning. The high-level functions performed by ADS-Plan in service of ADV can be divided into three sub-tasks:

- Follow a predefined trajectory stored in a map.
- Avoid collision with obstacles.
- Cross an intersection equipped with a connected traffic light.

ADS-Plan is also mainly involved in determining whether ADV is operational or not based on the operational status of the other subcomponents.

Nominally, ADS-Plan operates with a predefined path and a maximum speed limit along that path or subsets of the path. Other parameters can also be configured along the path and are used by the motion planning algorithm. Notable events such as traffic lights, intersections, and right-of-way are also included in the map and their position is predefined on the ADV trajectory to trigger specific behavior.

2.2.3. ADS-Act

ADS-Act translates the high-level planning commands into commands to take over the control of the actuators (propulsion, steering and braking systems). ADS-Act is also responsible for the control of vehicle accessories, such as low and high beams, automated platform systems, horn, etc.

2.2.4. ADS-Monitor

The ADS-Monitor is a backup safety system that triggers safety status requests that preempt nominal navigation commands. This system is designed to be triggered in the event of an ADS-Plan failure.
This system consists of performing the major monitoring actions that are necessary to cover most functional safety requirements.

2.3. ADS-Sense: Localization and Detection

2.3.1. Localization

The vehicle uses four localization modalities to locate itself in its environment. The selection of type and combination of these technologies is managed by ADS-Plan and can vary according to the site's configuration and the conditions of operation.

The various technologies are combined in real-time by legacy's proprietary software algorithm used by the vehicle's onboard computers. The vehicle uses the analysis of its environment to determine its location and to follow the path designed during the setup phase.

The available localization technologies are the following:

- **Odometry:** Wheel turn measurements are combined with an Inertial Measurement Unit (IMU) that measures acceleration on all axes to estimate changes in the vehicle's position and orientation over time.
- **Lidars:**
    - **Velodyne VLP32:** located on the roof to scan the environment around it. Lidar based localization modality using the VLP32 3D lidar to perceive features and landmarks of the ADV's surrounding. More specifically, a live comparison takes place between the actual detections during localization and the previously generated map using this same sensor contributing to the result of the lidar based localization.
- **GPS guidance:** One or two GPS antennas (depending on the type of GPS installed) located on the roof, coupled with corrections received by 3G/4G and Wi-Fi communication layers, provides direct coordinates (WGS 84) of its own position in the world.
- **Radar:**
    - **Navtech:** located on the roof to scan the environment around it and providing localization using Navtech's solution Terran360 (this solution is detailed in section 3.4.3.2).
    - **Continental:** The belt of radars provides a live localization output using Continental's solution.

2.3.2. Detection

Obstacle detection is provided at two levels:

- **ADS-Monitor** is the part of the software in charge of the exceptionally reliable low-level platform control and monitoring system. It includes an Emergency Collision Avoidance (ECA) function that triggers an emergency stop when an obstacle is detected in the monitored areas in vehicle’s vicinity, depending on the vehicle's speed and its distance to the obstacle.

- **ADS-Plan** is the high-level part of the system. If it detects an obstacle, ADS-Plan calculates the best way to apprehend it and makes the vehicle slow down, bypass the obstacle, or stop softly in a most comfortable way.

Several zones are defined around the vehicle by software, based on the distance that separates them from the vehicle. Depending on which zone the obstacle is in, the vehicle's computers determine the proper reaction to adopt.

The detection sensing technologies used by the ADS are the following:

- **Lidars:**
    - **MRS1000** and **Microscan3** perform obstacle detection around the vehicle. Their output is used by the safety software to slow-down or stop the vehicle to avoid collision with obstacles
    - **Velodyne VLP32** is used to detect on ground and overhanging objects, and to scan areas defined for the automatic validation of intersections.
- **Radar:**
    - **Continental** provides obstacle detection as the output of the fusion of the different radars. Detections are possible for dynamic objects only.
- **Camera:**
    - **Foresight** provides obstacle detection as the output of the fusion of the different cameras.

2.3.3. Localization and detection interdependencies

Adequate localization is a pre-requisite to perception evaluation. If localization is a given, we consider perception to be a success is ADS plan is able to perform obstacle detection and speed control to prevent collision. If an ADS-Monitor Emergency Stop is triggered, perception is considered to be a failure.
More details on the evaluation criteria of the localization and perception tests are presented in the following sections.

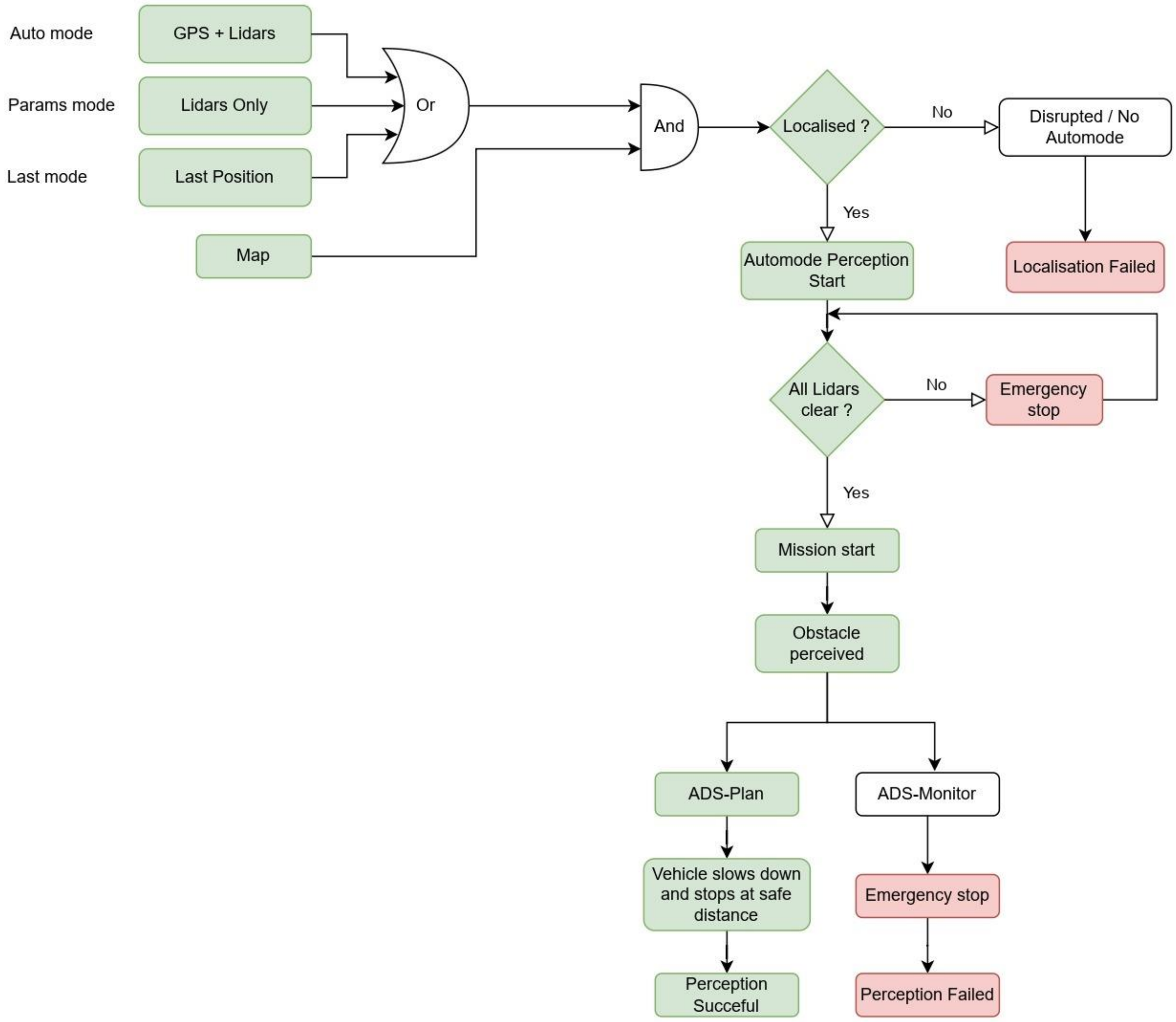

Figure 10: ADS evaluation flowchart

3. Performances evaluation of AWARD's ADS

3.1. Introduction – testing strategy

The evaluation of AWARD's ADS is established under two main categories: Localization tests and Detection tests. The prerequisites of these tests are to have the set of Lidar/Radar sensors operational alongside the GNSS data, and a predefined map in which the ego AV is supposed to operate. This operation will be described in Section 3.3.

Tests are conducted in autonomous mode only, aiming at evaluating the ADS's behavior. Results can be found in sections 3.4 and 3.5.

3.2. AWARD Sensor’s integration

In addition to the ADS that was described the AWARD sensors were integrated as follows:

- **Navtech:**

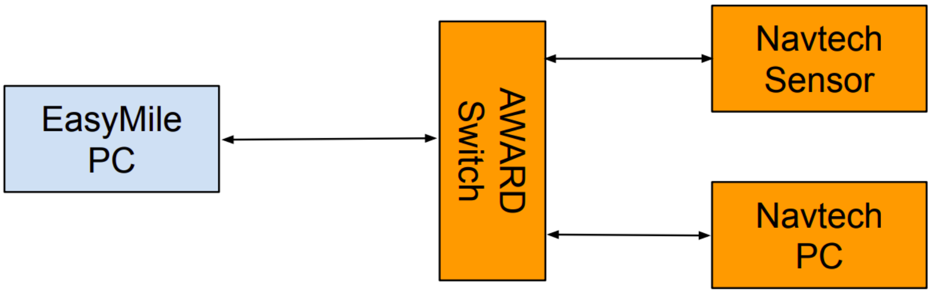

Figure 11 : Simplified schematic of Navtech-EasyMile PCs connection

The diagram above shows the hardware connection setup needed to use Navtech’s localization. The role of each PC is as follows:

- Navtech PC:
    - Acquisition of data from the radar
    - Data processing to build/generate a map
    - Live localization in the built map
- EasyMile PC:
    - Broadcasting of the NTP server on the network to synchronize the sensor data with EasyMile sensors
    - Broadcasting GPS data to the Navtech PC, enabling Terran360 to build the map in global (UTM) frame

- **Continental:**

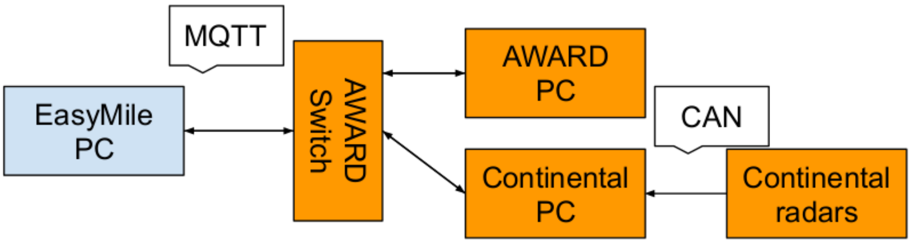

Figure 12: Simplified schematic of Continental-EasyMile PCs connection

The diagram above shows the hardware connection setup needed to use Continental’s perception and localization. The continental sensor set equipped on the TLD vehicle receives raw data from all six radars that are fed to their fusion algorithm (continental PC) through CAN connection. Then, via ethernet MQTT[1] network channels are set for data exchange between the Continental system and EasyMile's following Google Protocol Buffers serialization-deserialization method.[2]

The role of each PC is as follows:

- Continental PC:
    - Acquisition of data from the radars
    - Data fusion to get localization and perceptions outputs
- EasyMile PC:
    - Broadcasting of the NTP server on the network to synchronize the sensor data with EasyMile sensors
    - Broadcasting GPS data to the Navtech PC, enabling Terran360 to build the map in global (UTM) frame
    - Data acquisition of the different outputs

- **Foresight:**

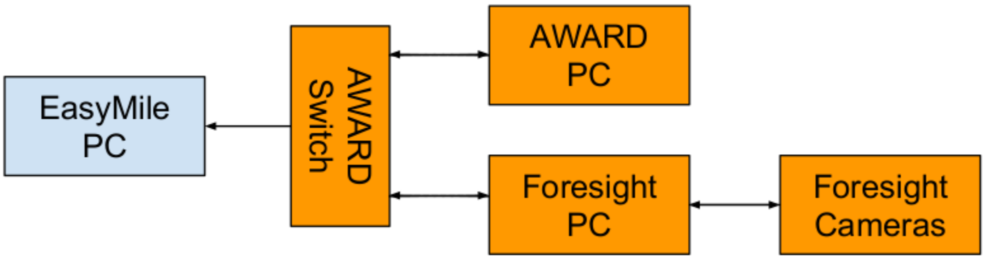

Figure 13: Simplified schematic of Foresight-EasyMile PCs connection

The diagram above shows the hardware connection setup needed to use Foresight's camera. The role of each PC is as follows:

- Foresight PC:
    - Acquisition of data from the camera
    - Data processing to generate an object output
- EasyMile PC:
    - Broadcasting of the NTP server on the network to synchronize the sensor data with EasyMile sensors
    - Data acquisition of detections

3.3. Mapping

In order for a vehicle to drive in autonomous mode, the ADS requires a map that represents the static environment, i.e., all the fixed and permanent elements of the site (buildings, trees, traffic signs etc.). Maps are generated by driving manually around a site following the potential paths that the ego AV would have to take in autonomous mode during a mission.

---

[1] https://mqtt.org/

[2] https://developers.google.com/protocol-buffers

3.3.1. Lidar mapping

Acquisition of point-cloud (every surface that causes a reflection of signals sent by a lidar would be visualized as a cloud of points) data from all three VLP32, MRS1000 and Microscan3 lidars is gathered and then transformed into a map file using the site generator tool (Figure 14). An auto-cleaning tool is available aiming to reduce the number of points present in a map due to noise such as signal reflections on some surfaces, etc. However, manual cleaning is usually necessary to remove temporary objects like parked cars, a moving object that entered the recording environment, etc.

Since the detection range and the number of layers of the VLP32 are much higher than the MRS and MCS, it is the main contributor to the map's creation. However, the latter two sensors provide more details at the ground level due to their close positioning to the ground compared to the VLP32.

The results from the different lidar point clouds generate the final map model seen in Figure 14, used as an input in the localization of the vehicle.

In order to give the ego AV a mission to execute in autonomous mode, the map should have stations that would serve as checkpoints that define the start/end of the path to follow.

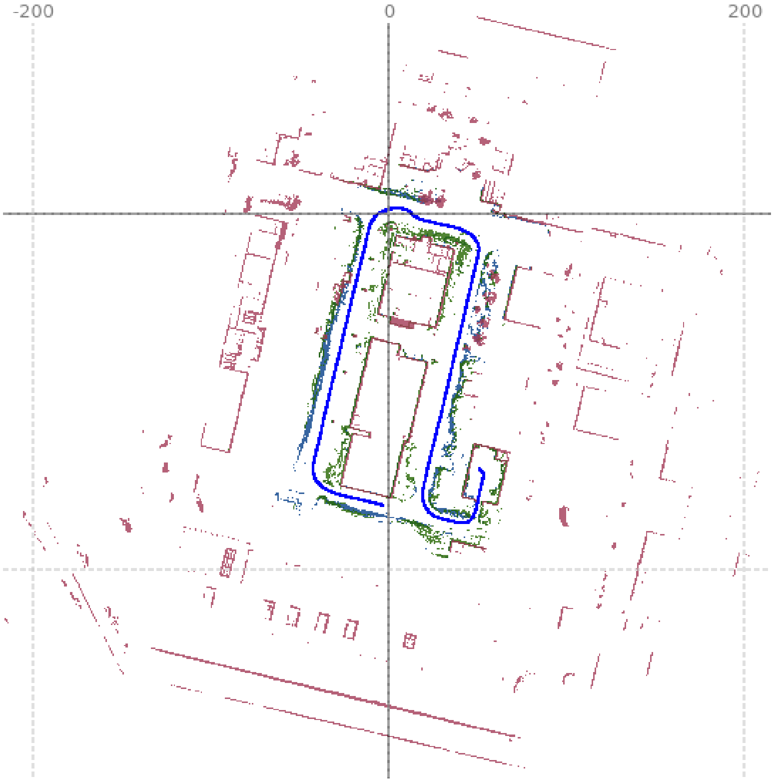

Figure 14: Map generated by Lidars following the blue trajectory, green points (MRS + MCS), red points (VLP32)

3.3.2. Navtech's mapping and calibration

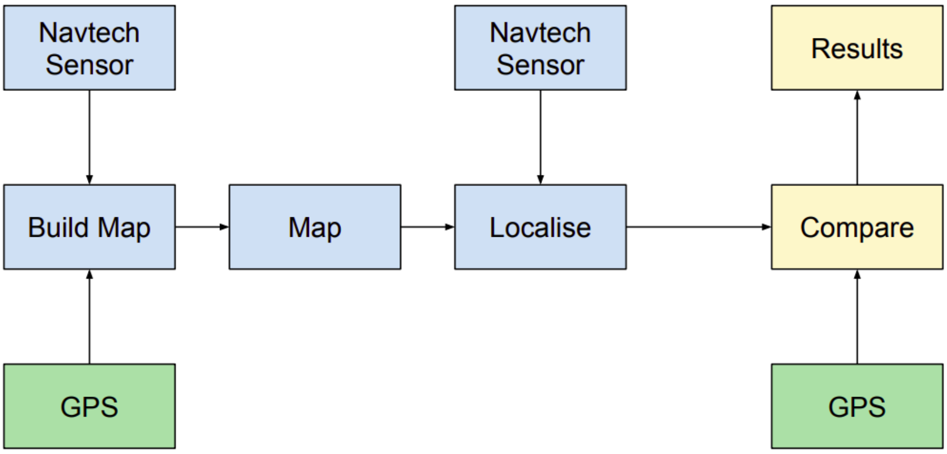

Figure 15: Schematic overview of the data analysis approach

The diagram above summarizes the approach to analyzing and comparing the Navtech radar localization data with the GPS output. Before starting data acquisition, a verification of the Navtech Radar odometry accuracy was performed following the procedure below:

Measure the distance between two points on the ground

Map Length: 154.00 Meters
Ground Length: 154.01
Heading: 193.32 degrees

☑ Mouse Navigation

lat 43.539978° lon 1.358769° elev 168 m eye alt 424 m

Figure 16: Overview of the site where odometry checking took place

First, the ADV drives on a straight line (the yellow line on the image above) of 154 meters distance according to the Google Maps tool (Figure 16).

Second, as soon as the ADV starts moving the Navtech radar odometry triggers the distance measurement process estimating a driving distance of 155.16 meters as shown in Figure 17 (the index metric is a unit used by the Navtech team to reflect time).

A margin of a couple of meters is accepted and respected when comparing the odometry's measured distance to the reference value taken from Google Maps.

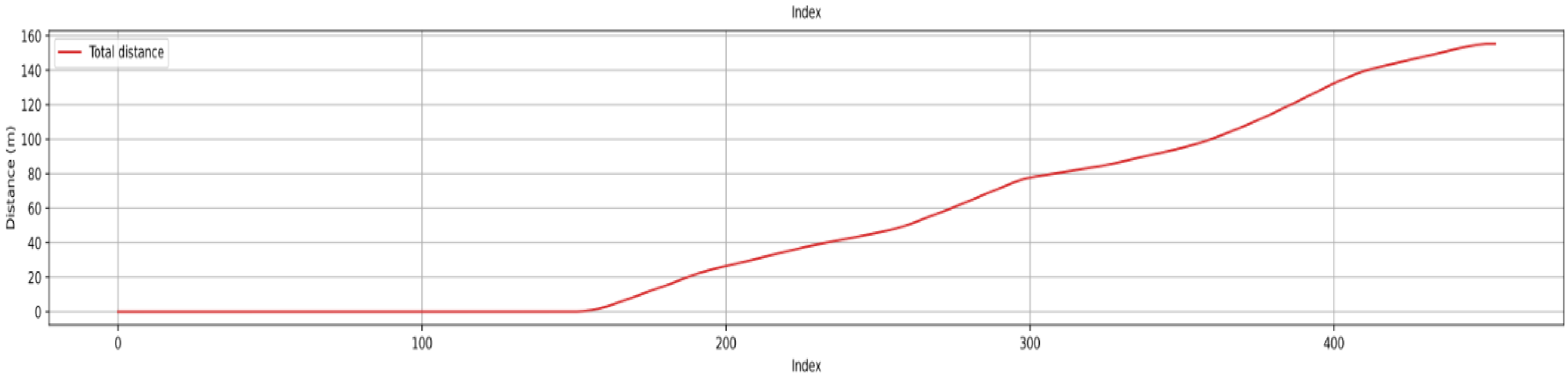

Figure 17: Plot of the distance according to the index made on the straight line driven by the TractEasy

Another test is necessary before starting the acquisition: check if the speed of the TractEasy estimated by the GPS agrees with the one estimated by the radar. The two speeds of radar and GPS reflect each other with a minor deviation in the graph of Figure 18 below:

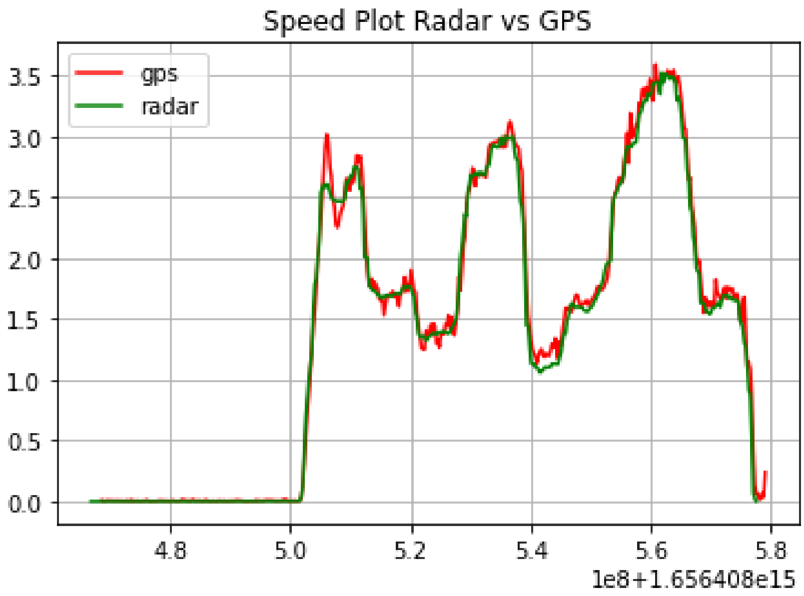

Figure 18: Speed plot of the radar versus GPSs over time (NAVTECH radar results in green)

After ensuring that the Navtech radar odometry is operating properly, the data acquisition can be started to build a map. It is preferrable to have a site rich with fixed landmarks. The testing conducted with the Navtech Localization was made at the Francazal Airport, Toulouse. The loop trajectory highlighted in blue was chosen by the project team to run the localization tests, since it circles solid constructions/landmarks and will allow testing the localization in both indoor and outdoor environments.

Figure 19: Overview of the acquisition route

The first step is to build the map as shown in Figure 15 using mainly radar data. The GPS data provided by EasyMile will be used as ground truth in order to make performance comparisons. Data acquisition is done on the above site by performing three similar loops of the route in manual mode.

After the acquisition of the radar data, a map construction tool based on radar point cloud is used to build the map. Using these point clouds, a first verification of the quality of the data can be done by observing the landmarks shown in the radar scans along the path shown in Figure 20.

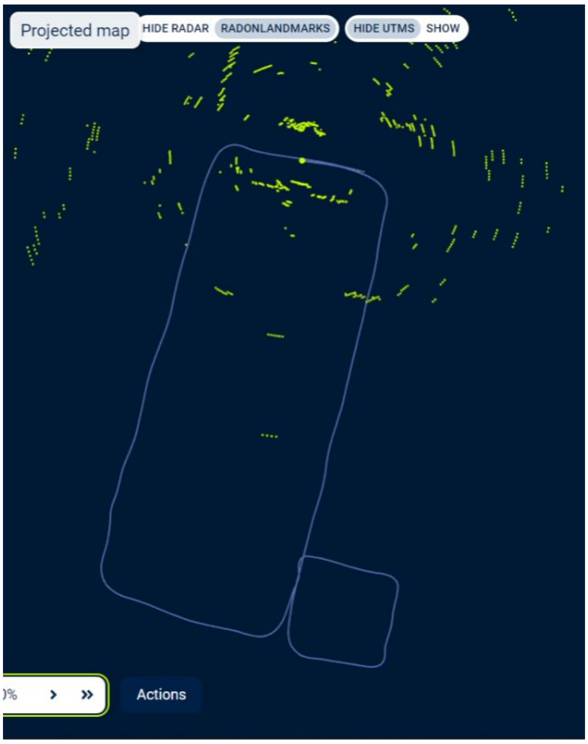

Figure 20: Navtech radar scan as seen from a given point on the path

3.4. Localization

3.4.1. Performance criteria

The performance criteria that were evaluated during those tests are the following:

- GPS age
- GPS mode
- Number of satellites caught (called GPS Nsat)
- Uncertainty of GPS (called GPS sigma)
- Uncertainty of each sensor (called Lidar sigma)
- Fusion uncertainty
- Number of emergency stops or slowdowns due to a localization uncertainty too high
- Error plots CTE/DTE
- Landmark association ratio

3.4.1.1. GPS age

The GPS age refers, in seconds, to the age of the differential corrections. The smaller the delay, the better.
This data is useful to detect erroneous position measures caused by outages in differential corrections.
Data interpretation of the GPS age is as follows:

- < 3 s: ideal
- > 3 s and < 10 s: tolerated
- > 10 s and < 30 s: suspicious
- > 30 s: invalid

3.4.1.2. GPS mode

The GPS mode is an indicator of the positioning performance. The higher, the better.
Data interpretation of the GPS mode is as follows:

- **50** stands for "narrow int." (integer narrow-lane ambiguity solution): In this mode, the standard deviation sigma is generally between 2 cm and 5 cm, and can reach up to 30 cm.
- **34** stands for "narrow float" (floating narrow-lane ambiguity solution): In this mode, the standard deviation sigma is generally between 10 cm and 50 cm.
- **17** stands for "PSR diff" (pseudo-range differential solution): In this mode, the differential corrections are used but they are not RTK (that is to say, the phase is not used in the computation). The standard deviation sigma is generally between 1 m and 3 m.
- **16** stands for "single" (single point position): In this mode, no correction is used. The standard deviation sigma is generally between 2 m and 8 m.

3.4.1.3. GPS Nsat

GPS Nsat indicates the number of satellites used for the position computation. The higher, the better. A large number of satellites leads to:

- an increased accuracy of the position computation,
- a smaller uncertainty ellipse, and
- a lower risk of no integrity of the measure.

3.4.1.4. GPS sigma

The GPS sigma refers, in meters, to the standard deviation of the position measure. It quantifies the expected dispersion of the data around the data point and scales the size of the uncertainty ellipsoid. Three sigmas are taken into account for lateral tolerance.
It is the main and preferred way of assessing the quality of the GPS localization on site. The other GPS-related measures presented in the previous chapters must only be used as diagnostic tools when the localization quality is not satisfactory to identify the cause of the problem.
The smaller the value is, the more precise the positioning is.
Data interpretation of the GPS sigma is as follows:

- < 3 cm: ideal values
- > 3 cm and < 10 cm: tolerated values

- > 10 cm: bad positioning, the GPS will not be used by the fusion. The maximum lateral tolerance is 30 cm, which corresponds to three times a 10 cm sigma.

3.4.1.5. Lidar sigma

The lidar sigma refers, in meters, to the standard deviation of the position measure. It quantifies the expected dispersion of the data around the data point and scales the size of the uncertainty ellipsoid. The lower the sigma, the better.
The minimal value of the lidar sigma is 5 cm and there is no threshold. All measures are used by the fusion and lead to a reduction of the uncertainty of the computed pose.

3.4.1.6. Fusion sigma

The fusion sigma refers, in meters, to the standard deviation of the position measure. It quantifies the expected dispersion of the data around the data point and scales the size of the uncertainty ellipsoid. The lower the sigma, the better.
The value is generally and ideally between 3 mm and 5 mm. The max (sigma_x, sigma_y) value is compared to a maximum threshold.
A value greater than 3 cm leads to a reduction of the vehicle's speed, and a value greater than 10 cm leads to a vehicle stop. These threshold values depend on the lateral_tolerance parameter values.

3.4.1.7. Error plots CTE/DTE

The purpose of this part is to evaluate the accuracy of the Navtech Radar localization. By estimating the differences of distance in orthogonal direction (E_{CT}) and longitudinal direction (E_{DT}) of the points estimated by the Navtech radar (Radon) compared to the GPS (ground truth).

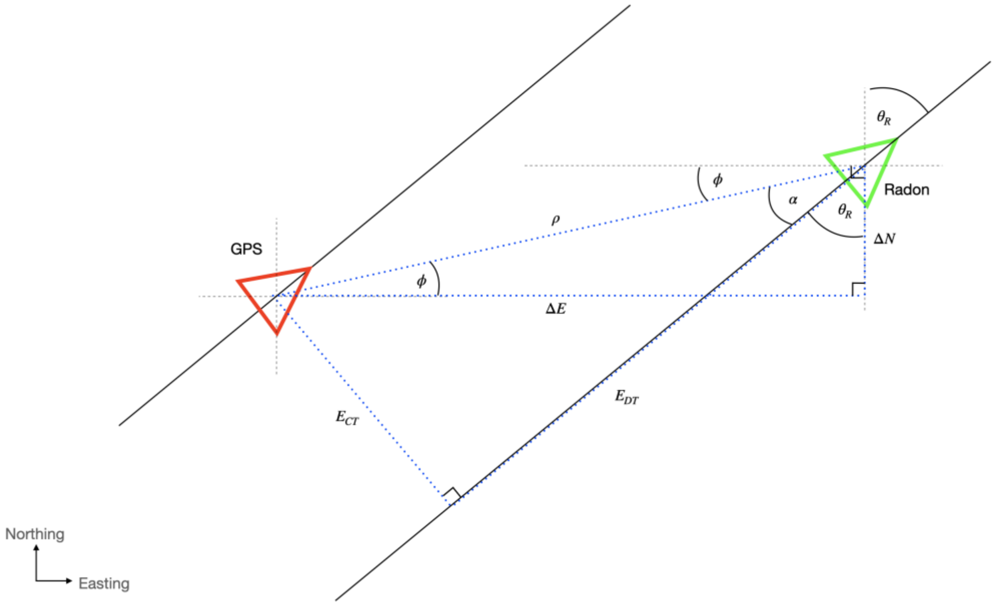

Figure 21: E_{CT} and E_{DT} geometrical definition

3.4.1.8. Landmark association ratio

This represents the ratio of identified landmarks by the radar while doing live localization compared to the expected number of landmarks. The higher the ratio the better the confidence of the localization for a given position.

3.4.2. Site initialization

There are three methods of localization initialization:

- **Auto**: The vehicle uses the GPS position and the lidars data to locate itself
- **Params**: The vehicle uses the lidars data only to locate itself on a particular initialization point defined in the site.
- **Last**: The vehicle uses the last position it monitored (only possible if the vehicle has not moved since the last use).

When launching a site, the operator can choose one of the three methods. Once the vehicle is well localized in its environment, it can start to move in autonomous mode.

The site used for localization tests is a site combining outdoor and indoor paths, in Francazal Toulouse (Figure 16) with stations that would serve as checkpoints that define the start/end of the path to follow as shown in (Figure 22).

Figure 22: Map generated by the fusion of the lidars for the given path

3.4.3. Localization tests results

3.4.3.1. Navtech localization assessment

This section aims to evaluate the localization performance of the Navtech radar. The localization performance depends on the maps created as explained in the mapping section.

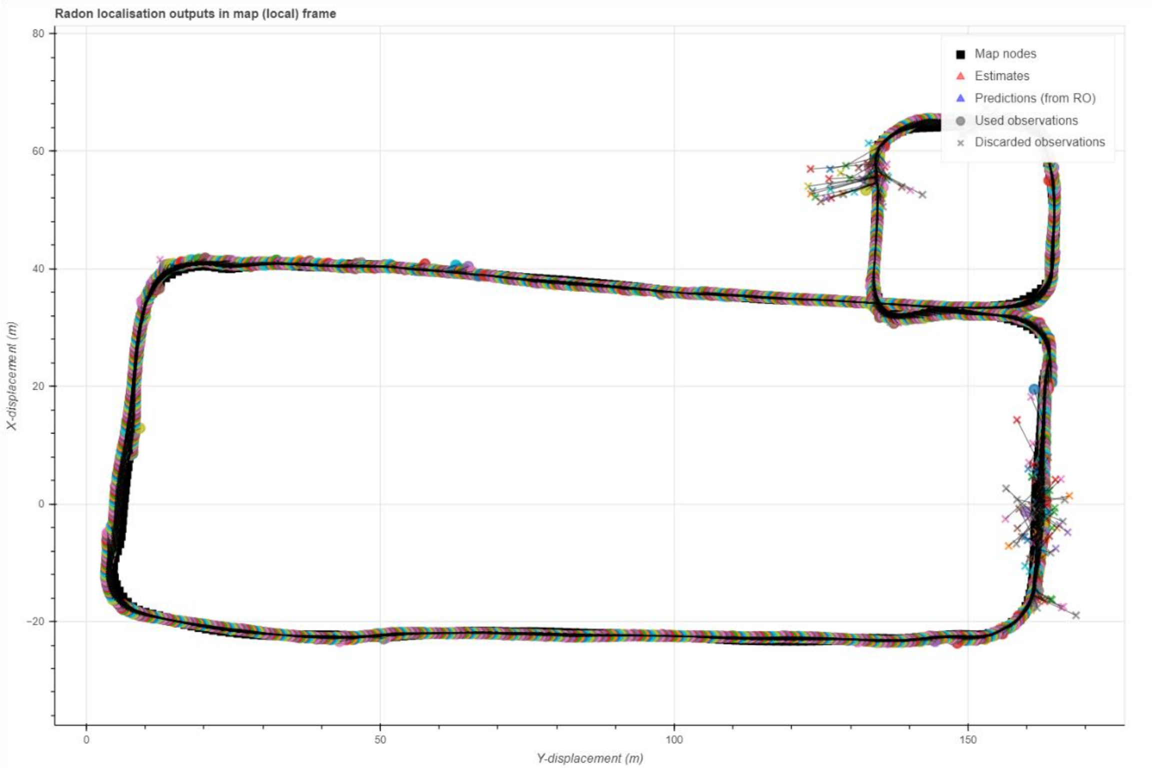

Figure 23: Navtech radar localization outputs in UTM reference

To give context to data points above, note the definitions of the legends shown on the trajectory plot while evaluating the outcome of the live localization:

- **Map nodes:** The map was built from an initial run aka mapping run; these nodes are based on this mapping run
- **Predictions:** x and y coordinates of predicted nodes based only on Odometry
- **Estimates:** Estimates are the final localization output
- **Used observations:** Observations represent estimates of position based on correlation of landmarks in live scan to a landmark on nodes.
- **Discarded observations:** These are the estimates deemed incorrect due to lack of correlation of live scan with map nodes

Referring to the definitions of the legends above, the localization starts by loading the map nodes considered as the original path that the TractEasy is supposed to follow while executing a localization test. Then, the actual localization starts by having predictions made by the Terran360 algorithm that uses the Navtech scans generating a predicted odometry for the vehicle. The next step is to transform these predictions into estimates by comparing the actual position in the scans to what is expected in the original map using landmark superposition. Finally, each node estimate (position) is either valid (Used observation) or invalid (Discarded observation).

A typical example to clarify a potential reason to why we have two zones of discarded observations as seen in Figure 23, is the presence of vehicles at the time of map generation and their absence while doing the live localization and vice versa which might confuse the algorithm's recognition when comparing scans.

We can see that the localization results are acceptable based on estimate and prediction nodes plotted against map nodes with some rejected observations at small portion of the run but maintain good localization overall (most of the nodes final outcome is used observation).

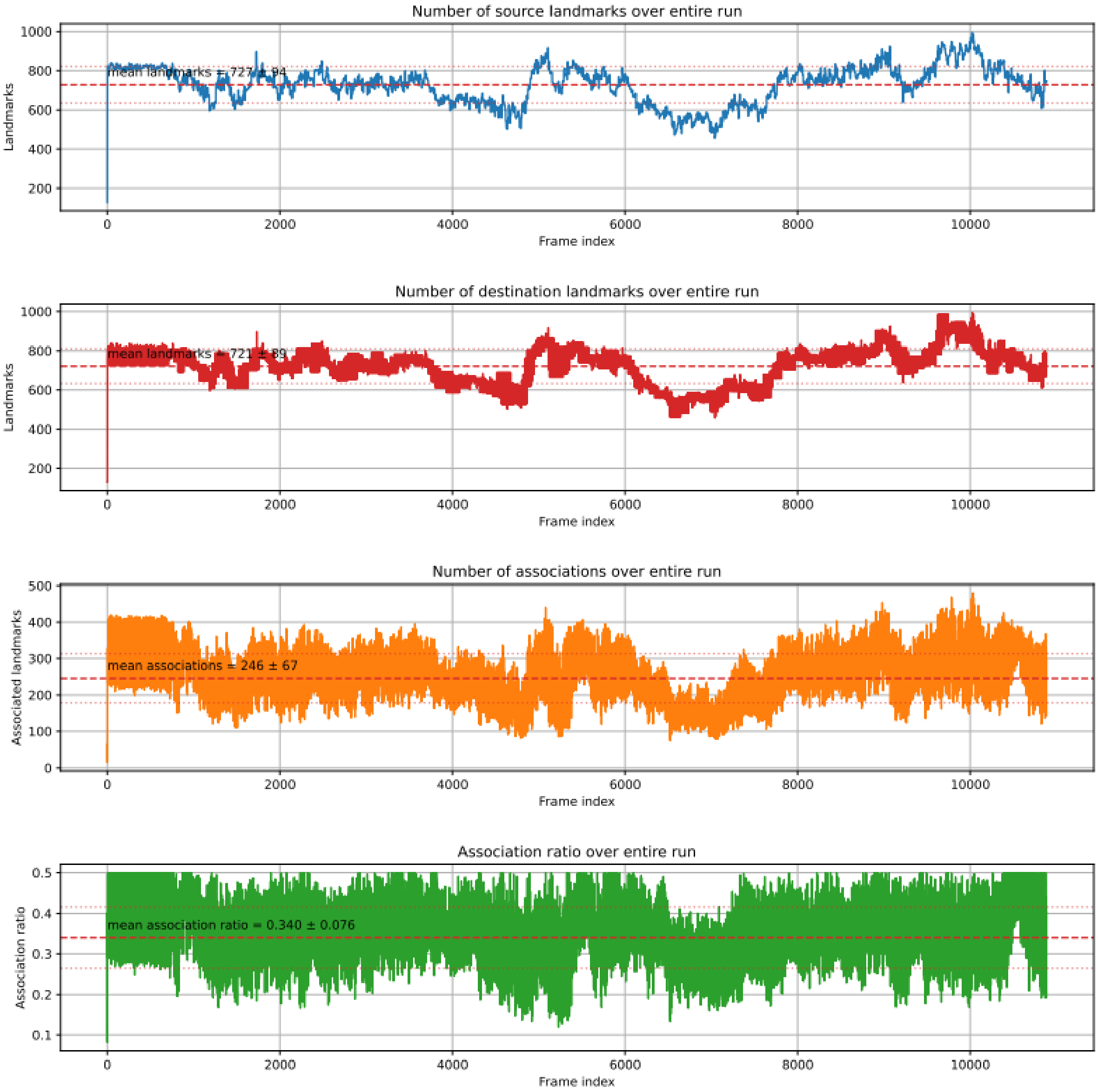

Figure 24: Mapping and localization landmark association

The four graphs displayed above, represent respectively the following:

- Source landmarks referring to the landmarks from mapping run
- Destination landmarks referring to the landmarks from the localization run
- The comparison of the first two landmark plots (source and destination) showing the number of the ones that matched (associations)
- The ratio of matched landmarks between localization and the mapping runs

As we can see in the above graphs, the average number of destination landmarks is 721 which is very acceptable when compared to the number of source landmarks, averaged at 727 detections. Over the entire localization run, around 246 landmarks match exactly with the source landmarks, resulting in an averaged association ratio of 0.34 (or 34% of matching).

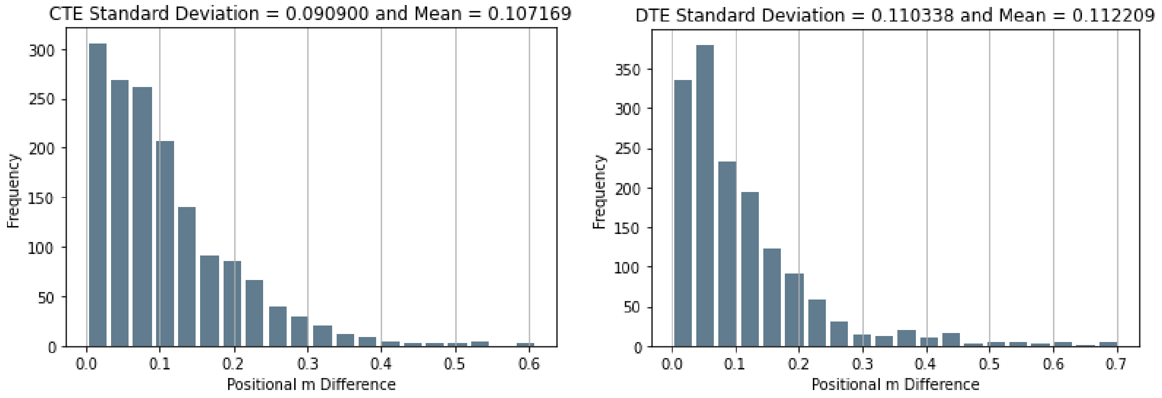

Figure 25: E_{CT} and E_{DT} estimation over the run

The two graphs above show the frequency of occurrence of Radon detected points according to the E_{CT} and E_{DT} in meters. We can see on the following curves the results of the stats obtained:

- E_{CT}: with an average of points on 0.107169 meters with a standard deviation of 0.090900 meters
- E_{DT}: with an average of points on 0.112209 meters with a standard deviation of 0.110338 meters

3.4.3.2. Continental Radar Localization Performance

Regarding the evaluation of Continental radar localization system, similar metrics such as the ones described by Navtech were used. The localization output has been compared to the corrected GPS 2D pose. The error has been decomposed in a longitudinal and a lateral component as seen in Figure 21. Moreover, the error on the vehicle heading (yaw angle in degrees) has been evaluated. In Figure 26 the distributions of the three errors have been shown.

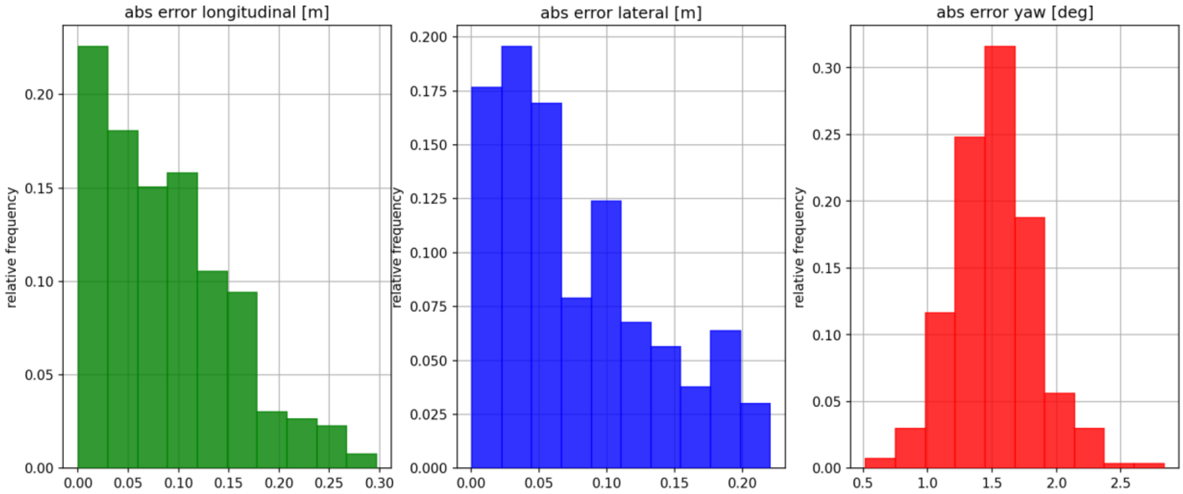

Figure 26: Longitudinal and lateral error distributions, heading error distribution

The average longitudinal error results in a value of 0.08250 m while the lateral error presents a mean value of 0.0769 m with a maximum error recorded of respectively 0.3233 m for the longitudinal component and 0.2275 m for the lateral. These values are also shown in a summary Table 1**Erreur ! Source du renvoi introuvable.**.

Table 1: Evaluation of Continental radar localization performance

avg_err_lon	avg_err_lat	avg_err_yaw
0.08250 m	0.0769 m	1.4954 deg
max_err_lon	**max_err_lat**	**max_err_yaw**
0.3233 m	0.2275 m	3.3174 deg

In addition, Figure 27 shows the test area and the localization output compared to the reference vehicle pose.

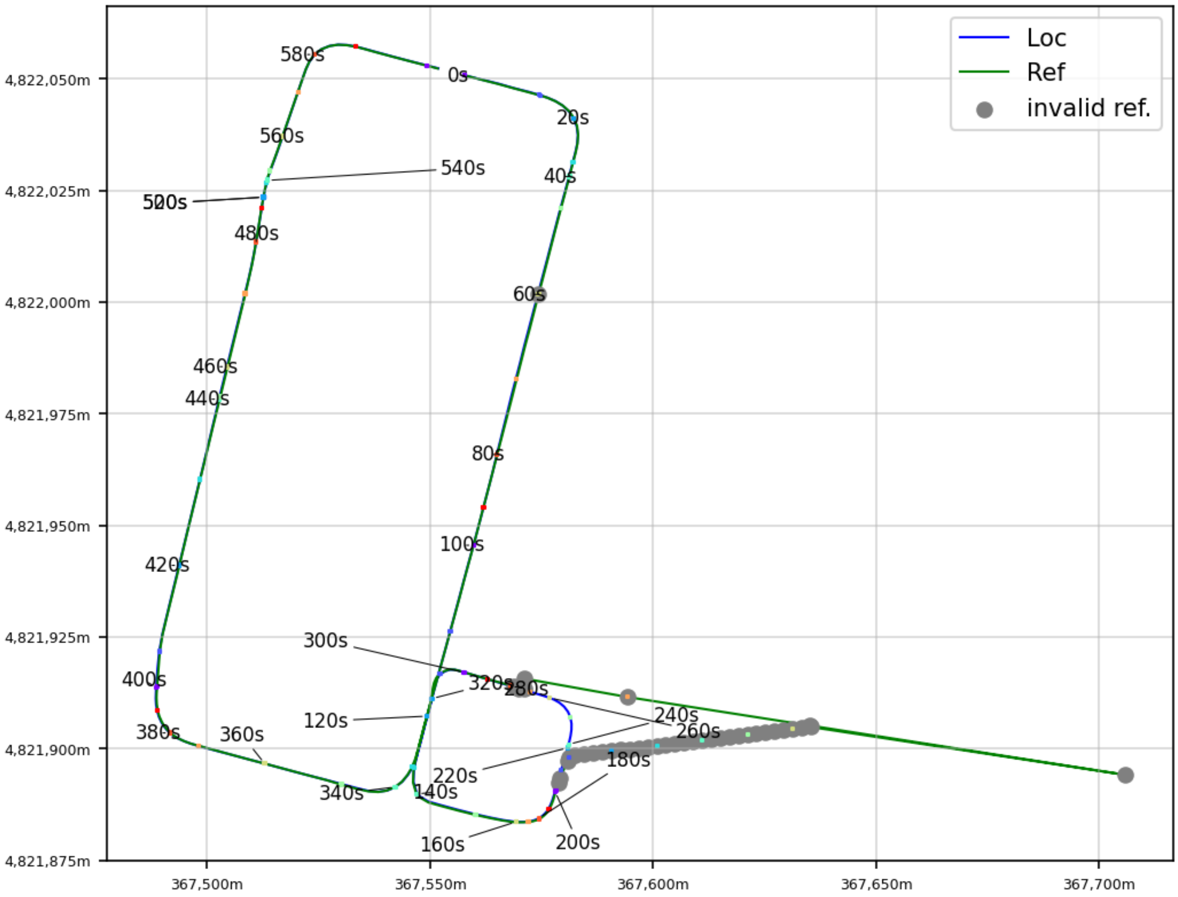

Figure 27: Localization and Reference poses on test area, UTM coordinates.

The map that has been used as a reference in the localization module was built offline based on the lidar data provided by EasyMile. In particular, the lidars sensors installed on the vehicle acquired the data used for mapping the test area.

During deployment, the framework is using Continental radar only data, performs localization using as a reference an occupancy map built as described above and eventually outputs a global pose in UTM coordinate frame that can be later compared with a precise GPS pose. The other input of the localization is the odometry provided by EasyMile.

A simplified diagram illustrates the mapping, deployment, and evaluation steps in Figure 28.

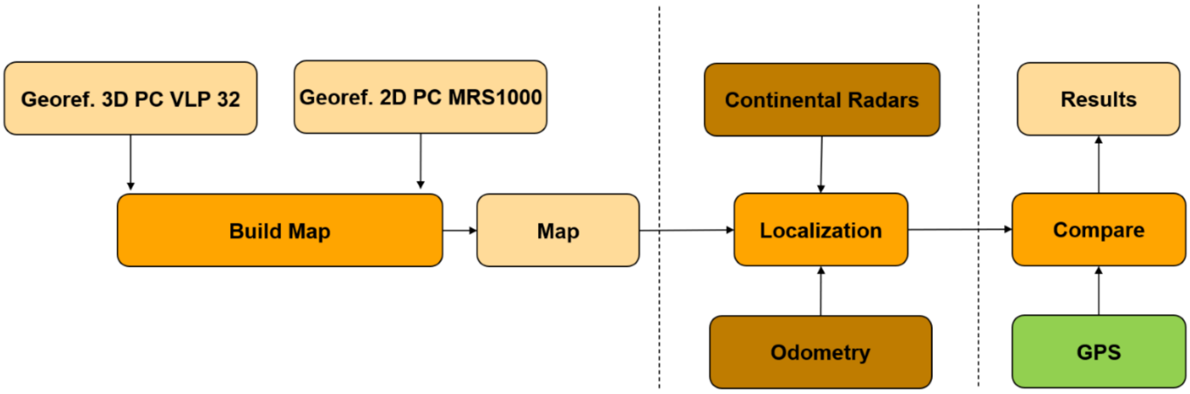

Figure 28: Simplified illustration of mapping, deployment, and evaluation steps

The evaluation excludes the time in which the vehicle was driving in the indoor area since the GPS does not work in this condition and therefore there is no reference to compare performance to. The time per area where the evaluation was not conducted can be seen in Figure 27 where the reference is marked as invalid by the gray markers. In particular, the GPS signal was considered valid only when the error on GPS provided in the covariance matrix presents a standard deviation less than 0.1m on the position and 0.5 degrees on the heading.

Continental localization framework shows not only good performances but also robustness of the system against environmental changes. For instance, there were changes in the static environment sensed in the measurements used for evaluation compared to the environment at the time of mapping due to different vegetation scenarios or different temporary parked vehicles.
The robustness of this system is also highlighted by the fact that the system is “cross-sensor,” considering that the mapping is only lidar based and the localization only radar based.
Moreover, the performances of Continental localization can be considered robust against different weather conditions since the radar sensors are mostly working in any weather condition and, in addiction, most differences in the sensed environment led by adverse weather conditions are tolerated within the localization framework. A specific evaluation can be conducted using specific measurements that contain challenging scenarios to quantify the performance loss if any.

3.5. Detection

In terms of perception, the final expected outcome of this section can be described as what we call an “objects list.” Each sensor set contributing to the perception stack would provide a list representing the summary of the objects detected by its technology through tracking algorithms. We currently have object detections generated by EasyMile, Continental radars, Foresight cameras, and we expect to have the same type of information for Adasky in the future.

3.5.1. Performance criteria

The performance criteria that were evaluated during those tests are the following:

- The final distance between the Ego AV and the static obstacles when the Ego AV reaches a full stop facing an obstacle.
- ADS-Monitor: Emergency stop triggered or not.
- Object detection and validity

3.5.2. Perception tests results

3.5.2.1. Continental and Foresight perception assessment

A visual representation in real-time was developed. This helps us have a clear idea of the performance of each solution revealing the strengths and weaknesses of each sensor/algorithm versus the other.
The representation of these objects lists consists of three-dimensional shapes (cylinders and boxes) representing an object's location and dimensions. This is done in an environment where we can display the lidar point cloud using a ground truth, namely RViz running on what we call "AWARD PC".

3.5.2.1.1. Continental

As previously mentioned in the network architecture represented in Figure 12, the MQTT server is responsible for the exchange of the data shown in the table below:

Table 2: MQTT channels between EasyMile and Continental

Message Name	From	To	Purpose	Status
Gps3d	EasyMile	Continental	GNSS signal: Required for Initialization of Localization	Activated
Velocity2d	EasyMile	Continental	Vehicle Dynamics information: Required for ego-vehicle speed compensation	Activated
EasyMilepose3d	EasyMile	Continental	Estimated Position of EasyMile; Currently not intended to be used; Just	Activated

			for reference and possibly for map creation	
RadarObjectList	Continental	EasyMile	Tracked Objects from Centralized Radar Tracking	Activated
PlfPose3d	Continental	EasyMile	Estimated Position of Continental Precise Localization Framework; Usage: Position-Fusion or Visualization or Evaluation	Activated
ParametricFreeSpaceMap	Continental	EasyMile	Parametric Free space Boundaries as Output of the Dynamic Grid	Not activated
IncidentsFromFHM	Continental	EasyMile	Consolidated Health Information from all Conti Modules	Note activated

The channel of interest for this section is the **RadarObjectList.** It consists of a list of all objects detected by the Continental radars updated frame by frame in real-time (see Appendix A).
A two-way data exchange between the Easy Mile and Continental system is required to create and transmit the RadarObjectList. EasyMile provides the vehicle dynamics data to Continental sensors need to receive and receives the object list in return.
For that, it is necessary to have a site in which the vehicle is localized. Once this is done, the AWARD Switch must start receiving the object detections from the radars in binary protocol buffer format that is decoded on the side of the EasyMile PC and formatted into a ROS message format. This gives the possibility to have a visual display of all incoming data from the different sensors alongside the lidar point cloud detections under RViz which is a visualization tool under the ROS middleware.
Also note that the RadarObjectList's timestamp on Continental radar system side is synchronized via the NTP server on the EasyMile system, which crucial when working with multiple sources of data in real time.

In terms of the positions and dimensions of objects detected, the algorithm provides a top view of the dynamic objects around it. Continental provides the following:

- Two-dimensional center position estimate of the detected object's location (missing the elevation of the center, which refers to our z-axis)
- Two-dimensional estimate of an object's dimensions (only the dimensions showing from the top, typically missing the height of an object)

Considering the above, Continental's detections are represented as bounding boxes with an assumed fixed elevation value. Same goes to the height dimension of these boxes.
The data available for the EasyMile PC is equally shared with the AWARD PC to achieve the visualization process.

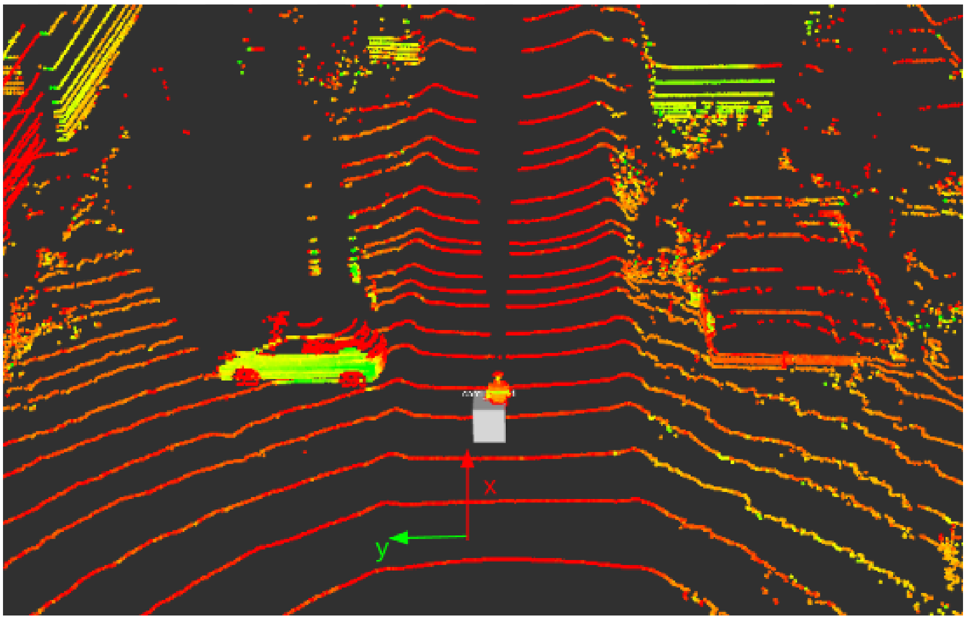

Figure 29: Walking pedestrian detection by Continental's tracking algorithm

Figure 29 is a screenshot from RViz showing a walking pedestrian. The x-y-plane is considered parallel to the ground.

The colored points represent the point cloud scans from the different layers of VLP32 lidar, and the white box represents the illustration of the pedestrian's detection by the Continental tracking algorithm. The point cloud can be considered as ground truth data to which can be visually compared to check if the detection's location is accurate.

Overall, results of the Continental detections perform very well in terms of locating a dynamic obstacle. However, dimensions of detected obstacles tend to be inaccurate.

3.5.2.1.2. Foresight

Foresight obstacle detection is based on machine vision, the algorithm analyses video imaging in real time. Footage from the visible light cameras is analyzed separately from the infrared footage. Foresight sends an object list where each list holds a label mentioning the source of the cameras that has detected it (see Appendix B).

Both static and dynamic obstacles are classified as: pedestrian, car, truck, and object (when unknown).

Foresight has two types of outputs in real time: video footage and object lists. However, only one of both can be acquired at the same time. The object lists output is the most significant for evaluation.

Referring to the simplified hardware architecture of Figure 13, and the defined objective as previously mentioned in the Continental detection chapter (Section 3.5.2.1.1), the data must be collected on the EasyMile PC for later data fusion and the AWARD PC for visualization purposes.

It will be achieved via an API provided by Foresight. This API is installed on the AWARD PC that allows:

- Launching the cameras
- Activating the tracking algorithm to start sending the object lists
- Stopping the cameras

The image processing algorithm runs on the side of the Foresight PC that collects live videos from the rig and sends them to AWARD switch making these data available to the other PCs. As seen in Appendix B, Foresight uses a Json format to send their objects. A MQTT server running on the Foresight PC keeps on updating and sending the lists of detections that are then formatted into ROS messages and stored on the EasyMile PC from one side and visualized on the AWARD PC from another.

Also, Foresight sensor timestamp is synchronized via the NTP server provided by the EasyMile system.

In terms of the positions and dimensions of objects detected, since the algorithm is based on machine vision, Foresight sensor provides the following:

- Three-dimensional center position estimate of the detected object's location
- Two-dimensional estimate of an object's dimensions (only the dimensions showing on the screen, typically missing the depth of an object)

Foresight's detections are represented as bounding cylinders having the 3D center positions provided and disregarding the depth factor since a cylinder only requires height and radius that represents the width in this case.

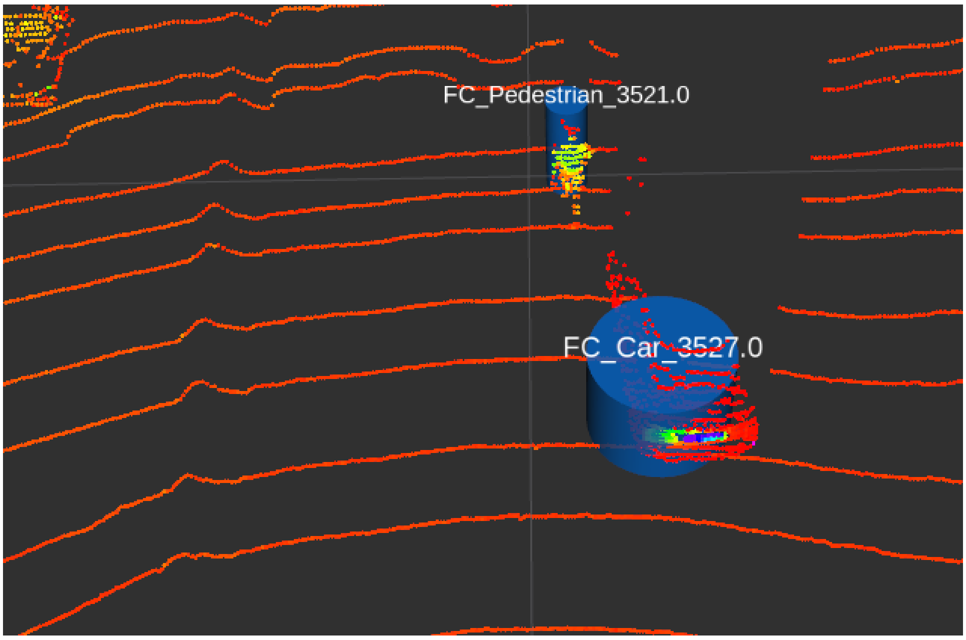

Figure 30: Car and pedestrian detection by Foresight tracking algorithm

Figure 30 is a screenshot from RViz showing a walking pedestrian and a static car.

The colored points represent the point cloud scans from the VLP32 lidar, and the blue cylinders represent the illustrations of both the car (labeled car) and pedestrian (labeled pedestrian) detection by the Foresight tracking algorithm. The point cloud can be considered as ground truth to which it can be visually compared to in order to check if the detection's location is accurate.

It is also important to mention that some object detections provided by Foresight tend to have some offsets with respect to their actual positions. This is particularly true for far objects.

3.5.2.1.3. Overview of all sensor's perception

Combined together, obstacle detections from Continental, Foresight and EasyMile can be visualized in the snapshot of car detection used in the example scenario below.

Figure 31: Image snapshot showing the vehicle tracked

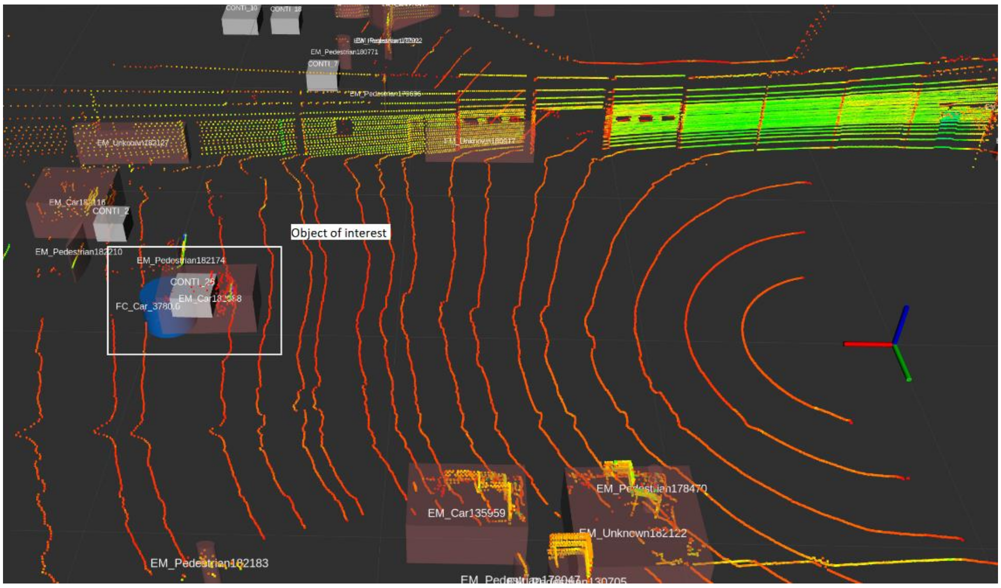

Figure 32: Image snapshot on RVIZ displaying the tracked objects

EasyMile's tracking algorithm is represented by the brown colored boxes, while for Continental it is the white boxes and for Foresight it is the blue cylinders. Highlighting the remark regarding the offset of Foresight's detections, one can notice that the position of the cylinder representing the car's location is slightly deviated from the actual position. Work is in progress to fix these offsets in cooperation with Foresight's engineers.
In Figure 32 the objects that are only detected by EasyMile's tracking to the bottom side of the screenshot are not detected by Continental because they are static objects, and not detected by Foresight because they are not covered by the view angle of the camera.

4. Conclusion

The assessment of the ADS showed a reliable performance in nominal weather conditions regarding localization and perception results. Most results match expectations. However, conducting the same scenarios in autonomous mode will be more challenging in harsh weather conditions.

For localization, the following modalities were studied: GPS + RTK corrections, Lidar, and Radar.
GPS + RTK corrections show particularly good precision as long as GPS reception quality is good and 4G available. This modality fails where GPS is not available (ex: in dense cities or covered areas such as tunnels) and where RTK corrections are not available (ex: indoor with no 4G reception) (see test 011 in 4.4.3 chapter).
Lidar modality needs landmarks to generate a map: it is very efficient when close to infrastructures. However, the created map needs post filtering of potential undesired detections, for instance, cars and other non-permanent objects, to have a better performance when used. This modality fails in desert areas (ex: areas with no infrastructure).
Radar and lidar modalities do have some similarities and are both compatible with autonomous driving (see chapter 4.4.3.). Making radars a workable solution to validate Lidar sensors localization.
Finally, the best results come when several modalities are combined (ex: GPS only + lidar, ex: GPS + RTK corrections...). The more different the modalities, the more situations the vehicle will be able to address. We would recommend at least GPS added to Lidar/Radar in order to address indoor and outdoor situations. However, in the absence of GPS coverage, lidar and radar localization are dependable in a standalone mode, and this was demonstrated in the indoor section of the track used at the Francazal airport site.

For perception, the following technologies were studied: Lidar, radar, and camera (IR & "classic").
Lidars allow high precision detection (capacity to detect small objects, static or dynamic). Radars allow only highly accurate dynamic obstacle detection. As a result, Lidar output is "richer" than radar output as all static elements are undetected. For lidars and radars, the use of a filtering algorithm is recommended to reduce the number of false positive detections.

Foresight cameras are a combination of infrared and visible cameras. Associated with detection algorithm they enable object detection & classification for static and dynamic objects.

Because those technologies are vastly different, a fusion of camera, radar and lidar will allow the autonomous vehicle to address a large panel of situations, especially when facing all weather situations.

One of the main challenges to tackle for the future for all those technologies is calibration: when one multiplies the sensors on the vehicle, calibration led errors by each sensor might result in a bigger overall error at system level.

Each of the object detection modalities has room for improvement that will take place in the upcoming platforms.