Toward the Deployment of an Autonomous Last-Mile Delivery Robot in Urban Areas

The Ona Prototype Platform

By Angel Santamaria-Navarro, Sergi Hernández, Fernando Herrero, Alejandro López, Iván del Pino, Nicolás Rodríguez-Linares, Carlos Fernández, Albert Baldó, Clément Lemardelé, Anaís Garrell, Joan Vallvé, Hafsa Taher, Ana M. Puig-Pey, Laia Pagès, and Alberto Sanfeliu

Nowadays, the skyrocketing last-mile freight transportation in urban areas is leading to very negative effects (e.g., pollution, noise or traffic congestion), which could be minimized by using autonomous electric vehicles. In this sense, this paper presents the first prototype of Ona, an autonomous last-mile delivery robot that, in contrast to existing platforms, has a medium-sized storage capacity with the capability of navigating in both street and pedestrian areas. Here, we describe the platform and position it with respect to other existing prototypes, providing its main Software modules and the first validation experiments, carried out in the Barcelona Robot Lab (Universitat Politècnica de Catalunya); Esplugues de Llobregat (next to Barcelona); and Debrecen (Hungary), which are

Digital Object Identifier 10.1109/MRA.2024.3487321
Date of publication 13 November 2024; date of current version 11 September 2025.

©SHUTTERSTOCK.COM/ANDREY SUSLOV

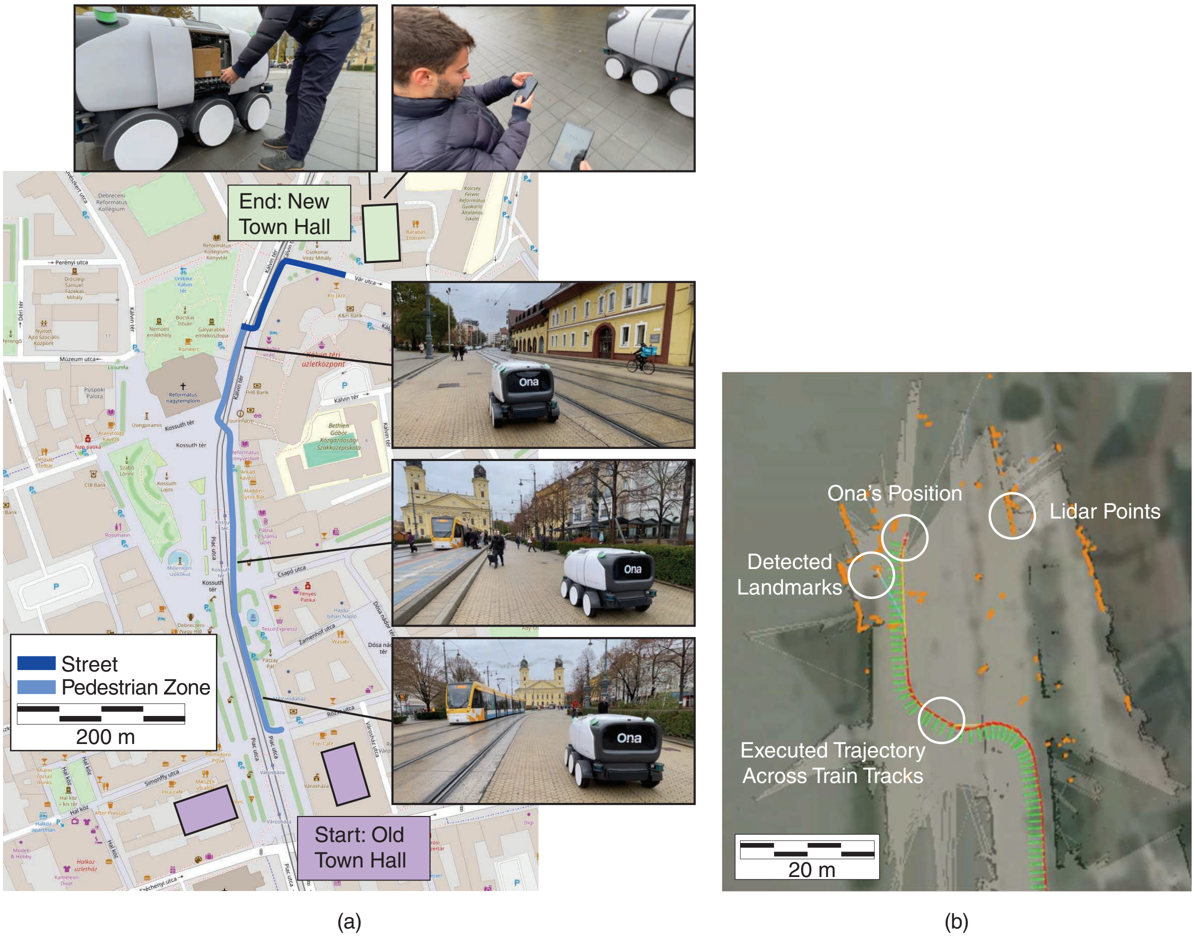


FIGURE 1. Pilot test at Debrecen (Hungary) in November 2022, using Ona, our autonomous last-mile delivery device. (a) Pilot site and mission details. (b) Perception of Ona, on top of its map, during the navigation across the tram tracks while sorting vulnerable road.

representative urban scenarios. In such validations, we focus our analysis on the key localization module, whose errors could cascade down the rest of the navigation pipeline (e.g., planning or control). Aside from robotic technical details, we also include the results of the technology acceptance by the public present in the Esplugues de Llobregat test, collected in situ through a survey.

INTRODUCTION

The logistics chain can be divided in two main transportation phases: 1) long-range transportation, where the package travels from one warehouse to another; and 2) short-range operation (referred to as *last-mile* hereafter), where the package is transported from/to the warehouse to/from the costumer. While in the long-range phases the focus is on developing efficient transportation systems or global coordination techniques (among others), the short-range operations may require precise maneuvering, interaction with people, or sorting semistructured terrains.

Regarding last-mile operations, there are several factors stressing the city logistics. For instance, urban population growth and rapid urbanization have generated an increase in freight transportation. Moreover, the appearance and rapid acceptance of e-commerce imply a high amount of goods to be delivered in metropolitan areas, which is expected to increase dramatically in the next few years with more frequent and fragmented deliveries [1], [2]. Today's logistics operations in city centers lead to very negative effects: increase in traffic congestion, air and noise pollution, or safety problems for pedestrians, bikers, and deliverers. Researchers and institutions are suggesting a more integrated logistics system, where shippers, carriers, and movements are coordinated, and the freight of different customers and carriers is consolidated into the same green vehicles, while avoiding some business models depending on unfair and low-cost labor (e.g., e-riders) [3]. In this sense, this article presents our first version of such a green vehicle: an autonomous last-mile delivery device named *Ona* (shown in Figure 1).

Autonomous city navigation (namely, *AutoNav*) is a hot topic [4], [5]. In particular, some examples of autonomous last-mile vehicles may include: The Kiwibot,[1] a four-wheeled device

[1]https://kiwibot.com

FIGURE 2. Examples of last-mile delivery robots under development.

TABLE 1. Main capabilities of the most famous prototype robots for urban last mile delivery.

	KIWIBOT	STARSHIP	SCOUT	SERVE	CAMELLO	ROXO	CLEVON 1	ONA	NURO
Pkg. cap.	↘	↘	↘	↘	→	→	↗	↗	↗
Road nav.	✗	✗	✗	✗	✗	✗	✓	✓	✓
Ped. zone	✓	✓	✓	✓	✓	✓	✓	✓	✗
Step size	<10 cm	<10 cm	<10 cm	<10 cm	<10 cm	<10 cm	<20 cm	<20 cm	<20 cm
Stairs	✗	✗	✗	✗	✗	✓	✗	✗	✗
HRI	↗	→	→	→	↘	↘	↘	↗	↗
Kinematics	Ack.	D.D.	D.D.	D.D.	D.D.	D.D.	Ack.	Ack. D.D.	Ack.
Bi-dir. nav.	✗	✗	✗	✗	✓	✗	✗	✓	✓
Lidar	✓	✗	✓	✓	✓	✓	✓	✓	✓

Ack.: Ackerman model; D.D.: differential drive. "Pkg. cap." is the storage capacity; "Road nav." is marked with a green check if the robot is enabled for street driving; "Ped. Zone" specifies if the robot is suited for accessing pedestrian-only areas, in contrast to road navigation; "Step size" shows (approximately) the height of a potential obstacle that a robot could be overcome by driving over it; "Stairs" refers to the ability of climbing several consecutive steps; "HRI" evaluates the interfaces of the robot that can enable a correct HRI (e.g., screen monitors); "Kinematics" shows the motion model of the robot; "Bi-dir. nav." refers to the capacity of the robot of driving either forward or backward, being related to the symmetry of the hardware design; "Lidar" exposes the usage of 3D lidars in their robotic solutions.

designed to deliver very small items; similarly, the Starship[2] platform, meant to drive on sidewalks; the Scout,[3] a small six-wheeled platform developed by Amazon; Serve,[4] by Postmates, which is also designed to carry small items but with a higher ground clearance; Camello,[5] a platform developed by OTSAW and also meant for sidewalk navigation; Roxo,[6] the FedEx SameDay Bot; Clevon 1,[7] with an adaptable, lightweight multi-purpose platform; and Nuro,[8] a high-capacity autonomous robot meant to navigate on the street or in wide pedestrian areas.

All of these robots have similar modules related to perception (to gather information of the surroundings), localization and mapping (to estimate the state of the vehicles and represent the environment), planning and decision making (to generate safe trajectories), control (to drive the platform); and human–robot interaction (HRI, to interact with the users or bystanders). However, from all of the mentioned (under development) platforms, shown in Figure 2 ordered by scale, Ona's design is closer to Clevon 1 or Nuro. Clevon 1 has been designed as an adaptable platform for different business cases related to goods' delivery and, similar to Ona and in contrast to Nuro, favoring the placement of the autonomy payload (e.g., sensors) on the lower level platform. In contrast to Clevon 1, Ona has been designed for its navigation in pedestrian areas, including, for example, top bright signaling colored lights or a large frontal screen for HRI. With respect to Nuro, Ona is also bit smaller. By design, both Clevon 1 and Nuro favor the street navigation, with Ona meant to navigate in both street and pedestrian zones, with a different navigation stack and a novel storage management concept. Aside from the technical details, Table 1 provides an overview of the capabilities related to the last-mile delivery challenges, related to the storage, navigation area types, main architectural barriers (e.g., steps or stairs), HRI, and motion models. Once again, Ona is close to the Nuro prototype, although Ona has two important extra features: the ability to navigate in pedestrian areas and a motion train based on an Ackerman model together with a differential drive, extending Ona's maneuverability.

Despite all of these efforts in terms of technological developments, prototyping, and algorithms [6], [7], the AutoNav solutions regarded as state of the art are still far from the

[2] https://starship.xyz
[3] https://bit.ly/scout_amazon
[4] https://www.jam3.com/work/postmates-serve
[5] https://otsaw.com/camello
[6] https://bit.ly/roxo-fedex
[7] https://clevon.com/clevon1/
[8] https://nuro.ai

maturity needed to safely operate in complex and highly uncertain intracity scenarios. With the aim at pushing toward a real deployment of our robot Ona, in this article we present and analyze the following key aspects:

- specialized hardware able to maneuver and drive at required speeds in both street and pedestrian areas
- localization and navigation using common sensors for urban delivery operations
- usage of virtual tools (i.e., simulation tools)
- validation in realistic scenarios
- study of technology acceptance.

In particular, the rest of the article is organized as follows. The "Ona: Our Autonomous Last-Mile Delivery Device" section presents our autonomous delivery device, Ona, with a particular emphasis on its design (e.g., the platform or its parcel locker) and localization and navigation software stack. The validation experiments and realistic scenarios are described in the "Validation and Experiments" section. The technology acceptance (i.e., feedback from bystanders during the experiments) is presented in the "Technology Acceptance" section. Finally, lessons learned and final remarks are drawn in the last section.

ONA: OUR AUTONOMOUS LAST-MILE DELIVERY DEVICE

Ona has a mobile platform featuring six-wheel drive with steering and Ackerman drive. In particular, it weighs around 200 kg and is roughly 1.8 × 1.1 × 1 m with the outer shell. Ona is an all-electric vehicle and has an autonomy of more than 5 h of continuous operation between charges, an autonomy more than enough for last-mile deliveries given the storage capacity shown hereafter. Ona has four front traction-only wheels and two rear traction and steering wheels. This type of architecture implies that some of the wheels will skid during its turns. Further, Ona has two (front and back) 22-inch and a lateral 7-inch screens, which are meant to interact with a potential costumer or pedestrians along the route.

Ona is equipped with a multitude of sensors, each type based on different physical phenomena to provide robustness, in particular:

- *Wheel encoders*.
- *Inertial measurement unit (IMU)*, providing an estimate of its angular velocity and linear acceleration.
- *Global navigation satellite system (GNSS)* to provide accurate global positioning. Even though Ona's GNSS receiver can work in real-time kinematic (RTK) mode together with a base station to improve accuracy, it is currently working in standalone mode.
- *Three-dimensional lidars:* Two 3D lasers of 16 beams are installed in the opposite corners of the robot (front-right and back-left corners). The information from these sensors is used to improve the odometry estimation and create a local map (i.e., point cloud). The "Navigation Stack" section details how this sensor works and how Ona uses it to obtain a robust localization.
- *Depth cameras:* There are three depth cameras on the front and sides, facing down. The field of view of these cameras include the immediate ground next to the robot (in the front and to the sides) and their usage is focused on high-resolution local traversability analysis. These operations run at the camera frame rates (individually processed) and we take advantage of our previous work [8]. To detect potential obstacles, we extract the dense point clouds from the ground surrounding the robot and filter the height inconsistencies by using an average filter (performing an integration approximation by observing each pixel in the point cloud at consecutive time intervals and keeping the z distance average). Then, we downsample the resulting point clouds and remove sparse outliers based on the computation of the distribution of point neighbor distances. Finally, we estimate the normal orientation of local planar patches at each point to classify between traversable or not traversable ground. Further, the area in front of the robot is divided into three regions, and the amount of data in each region is analyzed to evaluate the presence of a hole (negative obstacles). Notice that the average frame rate of this depth camera is 30 frames per second, thus this analysis is mainly used during local maneuvering (e.g., Figure 3). We refer the reader to [8] for further details. Additionally, a depth-color camera is placed in the front of Ona pointing forward. Here, after thorough outdoor experiments in urban settings, we decided not to use the depth information of the camera due to poor robustness and this camera is mainly used to aid in the teleoperation of Ona (notice how the navigation stack mainly relies on lidar readings).
- *Safety 2D lidar* used for hardware safety purposes.
- *Bumpers* as a hardware safety feature.
- *Sonars* placed in the front of the wheels and used to detect potential holes or obstacles next them.

Aside from these sensors, Ona has several emergency stop implementations (ranging from categories 0 to 2). Further, Ona is equipped with a novel pickup and delivery system to handle the storage, composed of: 1) automatic lateral doors, which will open/close upon request of the mission manager when the pickup/delivery and the costumer are ready; 2) automatic package manipulation system, with a belt that will move the packages in and out of Ona, and a two-axis manipulation device to place or pick the packages from the storage parcels; and 3) four storage parcels, designed to retain the packages during navigation phases. All of these elements can be seen in Figure 4.

To actuate and interact with the hardware mentioned above, we take advantage of the robot operating system[9] (ROS) middleware, which handles all internal communications. Further, we use Behavior Trees [9] as an internal robot task planner, managing the relationships between the mission management; remote control; parcel locker; navigation software stack; and the platform [see the action manager block in Figure 5(a)]. Externally, Ona needs Internet connection to communicate with the control center, to coordinate all logistic tasks (mission manager), and also to interface with a remote human operator

[9]https://www.ros.org

to monitor and assist it (monitoring and teleoperation) when it may get lost or stuck [see the blue arrow connections in Figure 5(a)]. The Ona solution consists of a communications' backpack, a commercially available device with parallel SIM cards (provided by a telecommunications service provider), supporting both 4G and 5G, and automatic roaming in almost 200 countries around the world, including Europe.

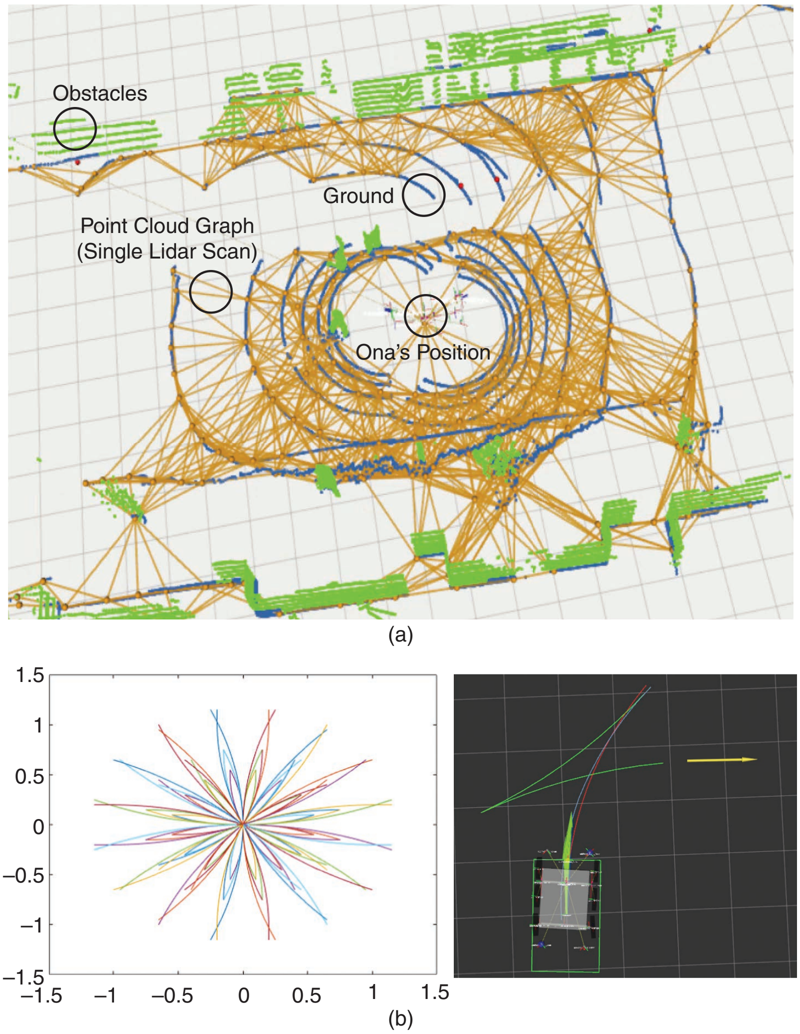


FIGURE 3. Perception and planning details of Ona. (a) Output sample of the ground segmentation algorithm used for traversability analysis, processing the merged instantaneous lidar readings of Ona, during an experiment in The Barcelona Robot Lab (North campus of the Universitat Politècnica de Catalunya). (b) Example of motion primitives (left) and a generated path (right) computed by the pedestrian area global planner (green lines: global path; blue line: current segment executed by the local planner; red line: actual motion command generated by the local planner).

Regarding Ona's integration in the urban setting, in the last-mile distribution using robots, there exist different categories of human roles and HRI tasks, investigated in our conference publication [10] and summarized with: the supervisors, who organize the logistics plans and tasks, optimizing the routes, the number of robots and the delivery of the goods; an operator, a skilled agent who manages the alarms and solves the navigation or deliveries in difficult cases (e.g., teleoperation of the robot from a remote site, in case it is needed); a mechanic/technician, in charge of the maintenance and repair tasks; a peer teammate, who could do cooperative tasks as for example, loading the robot, guiding and accompanying the robot, doing handover tasks, or recovering the robot in case of a problem; a peer end-user, which is the customer who receives the goods; and finally, bystanders. The bystander role is assumed by the citizens that coexist in the same environment of the robot and they can fall in different categories: citizens in good health condition; vulnerable citizens, as elderly, kids, and disabled people; urban services' workers; etc. The robot has to be aware of the type of citizens that it could meet and also of pets, bikes, etc. It could also interact with people following the social norms, be aware of them, and use communication methods and signs that people can understand. This HRI communication is done by Ona through screen monitors

FIGURE 4. Ona's storage management system with four internal compartments.

to show messages and drawings (e.g., icons or emojis) and using colored lights, following a standard coding with green, orange, and red to show the severity of the navigation status as nominal, warning, or fatal, respectively. The actual pickup/delivery system connecting the logistics operator and the peer end-user is based on a set of messages send to the latter with specific codes to validate its authenticity. The HRI interface of Ona is currently minimal for a nominal operation and this topic will be further investigated in the frame of the BotNet project[10] (23S06128-00), financed by the Barcelona city council and La Caixa foundation, which started in November 2023.

NAVIGATION STACK

SIMULTANEOUS LOCALIZATION AND MAPPING

To navigate autonomously, it is crucial to estimate the ego-motion of the robot and to create an accurate model of its surroundings by analyzing sensor observations [11]. These estimations are handled by the simultaneous localization and mapping (SLAM) module, shown in Figure 5(a), and detailed in Figure 5(b).

Each sensor has its own particularities, and a common visual sensor used in autonomous driving is lidar, which has a wide field of view but usually provides nondense information, requiring the concatenation of readings using the motion estimation to represent the surrounding scenario. Lidar measurements come at low frame rate; hence, its observations are usually fused with those from an IMU. In this sense, Ona fuses the IMU observations with those from the lidars with our own sensor fusion architecture, which draws inspiration from LIO-SAM (lidar inertial odometry via smoothing and mapping) [12] but includes an extra observability module as in our previous work [13]. The input of this module, named *LIO-SAM obs.* in Figure 5(a) leverages the lidar point clouds resulting from the traversability analysis (described in the next section) to fuse them with IMU measurements. The output of this initial lidar–IMU fusion is then combined with the wheel odometry using a well-known extended Kalman filter (EKF) [see the odometry estimation module in Figure 5(a)].

Even though this odometry estimation was providing fair ego-motion values, it is not globally consistent and subject to localization drift. As a common practice in robotics, a localization outer loop was set to: 1) localize with global consistency Ona (i.e., fusing the odometry estimation with reading of the GNSS module); and 2) obtain a local representation of the surroundings (i.e., a map) combining the estimated motion and the laser scans, obtaining a point cloud, to evaluate the required navigation plan and compute control commands. The approach used to compute the global localization and the local map was Cartographer [14], a system able to handle real-time SLAM. To give the map Universal Transverse Mercator (UTM) consistency, we added another EKF fusing the readings of the GNSS and the IMU heading estimation, namely a UTM calibration module. The connections of this module and the outer global localization loop using Cartographer are shown in Figure 5(b).

[10]https://www.iri.upc.edu/project/show/317

TRAVERSABILITY ANALYSIS

Ground segmentation is a crucial task for autonomous robots because the quality of its results conditions all of the subsequent higher-level processing stages, like obstacle detection, path planning, or localization, to name a few. Here, we take advantage of our probabilistic graph-based real-time ground segmentation algorithm [15] that, taking as input an instantaneous 3D point cloud, generates a probabilistic model representing the ground surface and its traversability in real time. The algorithm builds a graph while exploring the point cloud from its origin—where a solid prior of the ground level is available—to its limits. It does so by fitting small planes to the data in a probabilistic filter fashion: extract local data, use the prior to reject outliers, update the plane estimation with inliers, and explore new planes propagating the posterior as a prior for the new

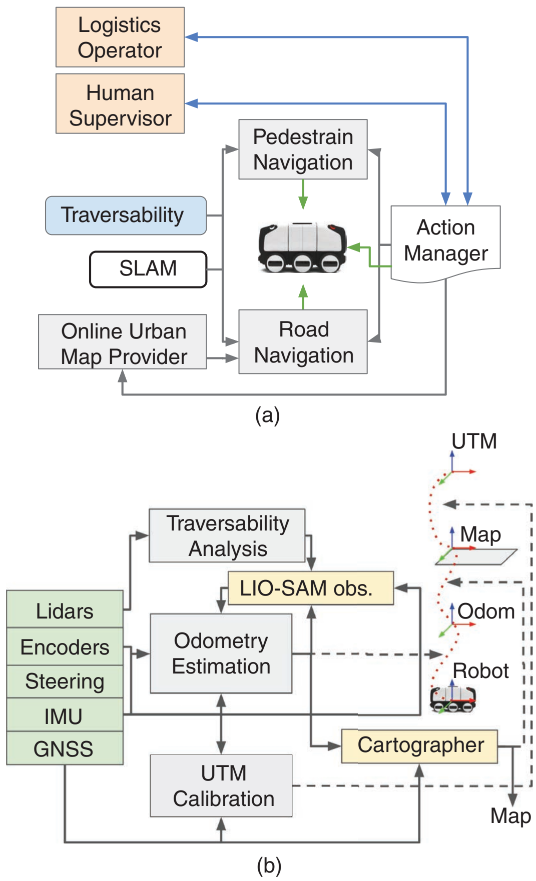


FIGURE 5. Main software modules of Ona's autonomous navigation pipeline: (a) operational and (b) localization. LIO-SAM: lidar inertial odometry via smoothing and mapping; SLAM: simultaneous localization and mapping; UTM: Universal Transverse Mercator.

nodes. This approach permits segmenting the point cloud taking into account the uncertainties of the model explicitly. Moreover, during the graph-building stage, we extract some statistic descriptors—including intensity information—to refine the traversability analysis by using a Random Forest model [16] to distinguish different types of surfaces, like roads, sidewalks, low vegetation areas, etc. For the sake of simplicity, we refer the reader to [15] for further details on this algorithm and its thorough evaluation. An example of this algorithm processing the ground segmentation in The Barcelona Robot Lab[11] (BRL, North campus of the Universitat Politècnica de Catalunya) is shown in Figure 3(a), where ground and obstacle points are depicted in blue and green, respectively. Vertices and edges of the roadmap are depicted in brown. The traversability analysis is leveraged by the planning modules [for both pedestrian and road navigation, shown in Figure 5(a)] and the segmented point cloud, including the static object above the ground, is fed into the lidar–IMU fusion algorithm [see Figure 5(b)].

GLOBAL MAP HANDLING AND PATH PLANNING

The mission manager, handling the business operation, provides Ona with the global UTM coordinates of the pickup and delivery points. Between these points, Ona extracts a global path by consulting a map service and running path planning algorithms [17]. Hence, with the robot state expressed with respect to a global reference frame, thanks to the global localization approach mentioned above, Ona needs to access a global map provider to compute the navigation trajectories [see the online urban map provider in Figure 5(a)].

In particular, to compute the global path, we take advantage of the Open Street Map (OSM) service.[12] Ona has a local copy of the OSM map of the region where the mission is expected to happen. Notice that OSM is an open source online map resource that can be edited by any user. Hence, to avoid incomplete or wrong data, we use this local copy of the OSM zone where Ona will navigate, allowing us to manually check the correctness of its information (or even complete it) before its usage. We consider this a bearable task as it is just required once in each area. With this OSM map, Ona has a ROS node to extract the routes from one point to another. The output of this node allows Ona to see if the route has pedestrian or road segment paths (a classification already existing in OSM maps), thus it can split the required route into parts (split path) to define different sequential trajectory goals to navigate considering the specifics of one type or the other (road or pedestrian areas). Thus, Ona can then select a path planner specialized for road or pedestrian area navigation [18]. This specialization arises from the fact that the pedestrian areas are less structured than conventional roads and, also, to consider potential vulnerable road users (VRUs) while computing the global path. Once the segments have been divided into road and pedestrian ones [shown in Figure 5(a)], we execute different planners to compute a global trajectory for the robot, which are briefly described in the following:

- *Road navigation:* It plans a shortest path/lane from a current location to the final parking spot following traffic rules defined in the map. The path is given as an array of the lane ID from the starting to the goal position. It notes that the global path is the center lane line and includes the path from/to the parking spot through the drivable area defined in the map.
- *Pedestrian area navigation:* This planner will generate a path from the robot's current position to a desired goal position. Paths are generated by combining a series of "motion primitives," which are short and kinematically feasible motions. The right panel of Figure 3(b) shows an example of these motion primitives. The plans result in smooth paths that consider the robot orientation. One of the main features of this planner is that it generates a set of maneuvers when a simple path cannot be found, as shown in the left panel of Figure 3(b).

The global path is only computed once for every mission and, to follow it, Ona has a local planner with reactive behaviors, especially suited for VRUs. This global-/local-planner relationship follows the ROS move-base architecture.[13]

The local planner, in contrast to the global one, replans several times per second to adapt to unexpected situations, for instance in the presence of VRUs. From the traversability analysis, Ona generates global and local cost maps as occupancy grids, where the local planner will search for a suitable local plan in every control cycle. The Ona motion model used in the local planner is an Ackerman design, with a custom modification to consider Spline trajectories to better smooth the paths and adapt to the real Ona motion. Apart from dealing with obstacles and VRUs, these planners have recovery behaviors defined to recover in the event of an unfeasible plan. These behaviors are mainly related to replanning tasks and, in the event that no valid plan is found, the task manager will trigger a flag to require assistance from the operator using the Behavior Trees' machinery [9].

REMOTE MONITORING AND TELEOPERATION

Ona is able to communicate bidirectionally to an external control center supporting ROS2 [Figure 5(a)]. In particular, this communication has been designed to minimize the effects of the following constraints:

- *Bandwidth:* We compress the data from the robot to upload a maximum of 1 Mbit/s (the upload bandwidth is usually the most constrained by the telecommunications companies), consisting of robot state messages and the front image for visual feedback purposes. The data downloaded in the robot have a rate of 8 Mbit/s and consist of control commands. These rates can be accomplished tuning the ROS2 quality-of-service network controller.

[11]http://www.iri.upc.edu/research/webprojects/pau/datasets/BRL
[12]https://openstreetmap.org
[13]http://wiki.ros.org/move_base

- *Latency:* To teleoperate Ona the latency should be (and is) less than 300 ms. This latency parameter can be tuned in the ROS2 throughput controller.

Notice that even though 4G is already present in all major and medium cities of Western countries, the usage of 5G signaling might not be a possibility nor distributed uniformly. Hence, an initial verification that the 4G network has no substantial shadows is required when deploying Ona in a new city.

LOGISTIC'S MISSION MANAGER

Ona can easily be integrated in any major logistics operator's software. Currently, Ona can send to the mission (business) manager any information related to its state, the state of the parcels, or the delivery/pickup status. In contrast to other existing last-mile robots, Ona has a unique compartment mechanism that fetches parcels and opens/closes doors automatically, thus the exchange of information between the mission manager and Ona can be reduced to the initial and final locations (UTM coordinates) and the pickup/delivery synchronization (i.e., operation trigger). Ona can also send live navigation data to the mission manager for tracking purposes.

POTENTIAL USE CASES

Ona has been designed with a set of initial use cases to guide its developments, in particular:

- *Follow-me mode:* Ona would follow a person or another vehicle at a given distance, increasing the weight that could normally be carried (i.e., Ona autonomously carrying heavy loads).
- *E-commerce parcel delivery and pick-up:* Ona receives parcels (pick up) and then finish the delivery (navigation) to an end customer (delivery).
- *Automated food deliveries from supermarkets/urban markets/restaurants:* Service to collect groceries from supermarkets in a city (i.e., employees of the markets could feed the Ona parcels with customer orders) and to deliver them to the end customers.
- *Autonomous vending machine (e.g., food, kiosk):* Ona would be loaded with groceries or other types of products and travels throughout the streets of a given service region. If a customer wants to buy something, he/she has to hail the robot.
- *Logistics on industrial site:* Similar to the above use cases but, instead of operating in open and public environments, Ona usage could be restrained to closed private industrial sites.
- *City mapping and cadastration:* Ona is constantly receiving information from its surroundings and using its local representation (i.e., a 3D map). Thus, if adequately treated, these data could provide useful insight to cities (potholes in roadway, obstacles on sidewalks, etc.).
- *Autonomous transport of recyclable material:* Automated garbage transportation with Ona to make waste management more flexible and efficient.
- *Passenger transport:* The Ona base platform could be used (with some modifications) as an autonomous individual pod for passenger transport.
- *Information point for tourists or tourist guide:* Information about the city and its monuments could be displayed in Ona's screens and shown to tourists, either statically or combined with the follow-me mode to act as a tourist guide.

All of these use cases take advantage of Ona's capabilities related to the autonomous navigation, its capacity to transport heavy packages, or to interact with surrounding pedestrians. During the first tests (see the following section), we focused on the e-commerce parcel delivery and pickup use case. This operation purpose is the most important one for the first implementation of Ona in real life and, even though the Ona capabilities will be validated with this e-commerce use case, they can be easily exported to most of the other use cases with minimal adaptations.

VALIDATION AND EXPERIMENTS

SIMULATION TOOLS

We developed two different simulations tools for Ona. On the one side, we have a simulated environment based on the Gazebo[14] simulator, already integrated with ROS. On the other side, we created a software layer to interact with the PTV Vissim traffic simulator[15] to test navigation conditions and interactions with the environment.

Regarding the PTV Vissim simulation, the navigation Software of Ona can virtually "move" the simulated Ona model in the PTV Vissim virtual environment and react accordingly to quickly and cost-effectively catch bugs and improve the code, while testing Ona in a traffic-based simulation, which allows the simulation of specific predefined urban areas and realities [see, for instance, the digital twin of the pilot site in Esplugues de Llobregat, shown in Figure 6(a)], easing the postanalysis and evaluation, for example, with more/less obstacles, more/less crowded, with/without traffic/bikes/scooters, with unexpected events, etc. An example of the semantic information that can be used in the PTV Vissim simulated environment is shown in Figure 6(b) and (c). The usage of these simulations are very useful to consider other vehicles and pedestrian flows while solving their interactions within the shared spaces or conflict areas.

REAL TESTS IN REPRESENTATIVE URBAN SCENARIOS

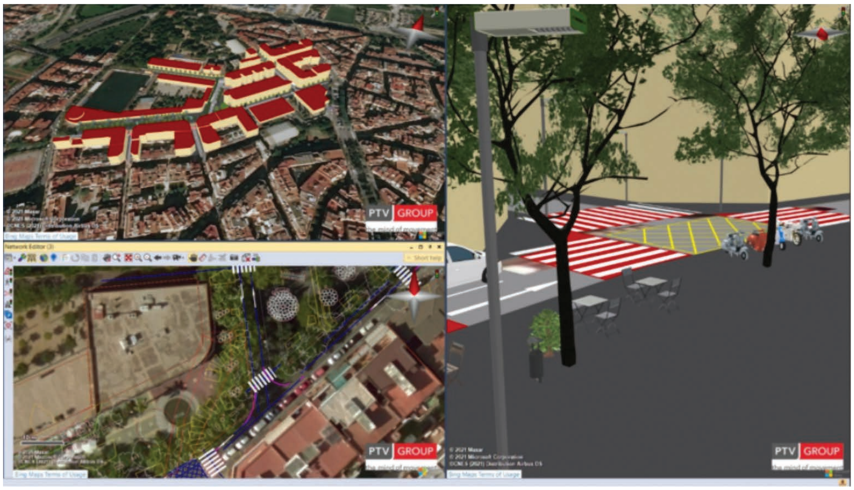
Moving autonomously in an urban setting presents several challenges and open problems. These are complex 3D scenarios and the space has to be safely shared with bystanders, animals, and other vehicles [19]. Among all of challenges, we find of paramount importance the following:

- *Presence of dynamic objects, people, animals, or vehicles:* As a dynamic vehicle, Ona navigates over a static urban setting

[14]https://gazebosim.org
[15]https://www.myptv.com/en/mobility-software/ptv-vissim

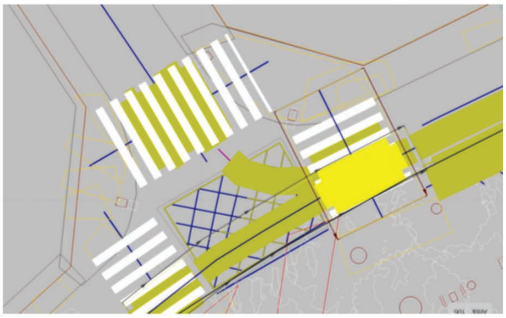
shared with others that may also have their own dynamic motion. In this case, we can remove them using Dynablox [20] from the data incoming to the SLAM approach that estimates the vehicle's location. By doing so, the respective observation models are simpler, faster, and can be processed as static scene landmarks. On the other hand, the segmented dynamic elements can be added to an occupancy grid map of the navigation stack, which is used by the planning modules to navigate safely and evade obstacles. Drawing inspiration from [21], this trajectory estimation of dynamic elements can be included in the occupancy grid map to better optimize the maneuvering path.

- *Weather conditions:* All robots perceive and represent their surroundings using sensors based on different physical phenomena. Such events can be affected by weather conditions, including, for instance, sunny or rainy days or the presence of fog. As time goes by, the scene might even differ between seasons. The robustness on processing such sensory data disturbed by the weather conditions is still an open challenge in robotics. Although we tested Ona in two different cities (Esplugues de Llobregat, Spain, and Debrecen, Hungary) Ona behaviors have shown no operational difference, as our focus has been in navigating in nominal weather conditions, during daylight without rain, nor snow or fog.
- *Existence of architectonic barriers:* Even though urban scenarios are quite structured, the presence of narrow corridors, steps, uneven floors, or stairs are common. This not only hinders the people's right to mobility (e.g., when using a wheelchair) but also affects the navigation of vehicles. Overcoming such obstacles commonly entails specific robotic designs (e.g., legged robots) and present a compromise between accessibility and mobility and strongly depends on the vehicle's hardware configuration.
- *People's curiosity:* A robot navigating among human beings attracts people's curiosity. Robotics is a relatively new discipline compared to the Western cultural developments and bystanders cannot have a clear interaction model while being next to Ona in the street. Such lack of prediction, together with inherent human's curiosity, produces an attraction effect on people, which usually surround the robot and automatically blind its perception. Even while Ona is moving, the public follow it, increasing the complexity of the localization approach as the ratio between dynamic and static obstacles is not in favor of properly solving the SLAM approach. Ona's current solution relies on stopping, advertising the situation to bystanders by using colored lighting, and then resuming the mission.



(a)

(b)



(c)

FIGURE 6. Virtual reality environment (a), and semantic information (b) and (c) codified in the virtual urban environment of the Esplugues de Llobregat pilot site (Spain) using PTV Vissim.

Overall, the development of Ona has been focused on solving its navigation tasks in urban nominal conditions (e.g., with a regular pavement or lane, and without big steps in the way of the robot), leaving as future work the study of edge cases, the effect of strong season differences, or unpredicted situations (e.g., sudden road blockades). In all of these situations, Ona can cancel its navigation status if the path is unfeasible, if the localization is unreliable, or if any other issue arises, asking for support and waiting for remote operation to overcome the main issue before resuming its mission.

Several integration and testing efforts took place in different locations, chosen aligned with the development and testing phases of Ona (reflected with dates):

- *Barcelona Robot Lab (Spain), January to March 2022:* The BRL encompasses an outdoor pedestrian area of 10.000 m^2, in the North Campus of the Universitat Politècnica de Catalunya. The area has moderate vegetation and intense cast shadows, challenging conditions for the computer vision algorithms.

- *Esplugues de Llobregat city center (Spain), May and June 2022:* Located in the busy Esplugues de Llobregat, with one of the highest population density in Europe.
- *Debrecen city center (Hungary), October and November 2022:* Located in Debrecen, this is the second place for open public tests.

It is worth mentioning that in all of these scenarios, gathering navigation (e.g., localization) ground-truth data was not possible. For instance, no GNSS signal was robust enough due to the nature of the scenes. In the BRL and the dense Esplugues de Llobregat (both in Spain), the GNSS had huge multipath interference and aliasing between tall buildings. In Debrecen there existed a poor signal reception, with a virtual reference station being created in Budapest (200 km away from the testing site), disabling our RTK GNSS solution as a ground truth of the global localization system.

Given the importance of the localization module, whose errors can cascade down the rest of the navigation pipeline (e.g., planning or control modules), and the lack of ground-truth data in the real scenarios, we focus the following in presenting the localization results of the "LIO-SAM obs. Module," being the most crucial approach within the SLAM scheme shown in Figure 5(b). The evaluations hereafter include comparisons of using the localization system with different onboard sensor means or algorithms (e.g., EKF-based odometry or LIO-SAM). In all of these experiments, the actual starting and end poses of the robot were equal, providing the drift error of our approach.

BARCELONA ROBOT LAB

The first experiments with Ona were conducted around the BRL, a controlled site, shown in Figure 7(a), where different robotic hardware configurations could be tested. The specific features and challenges of this site are shown in Table 2.

Among other tests, in the BRL we evaluated the differences between running LIO-SAM [12] (see the "Navigation Stack" section) with the front lidar sensor (LIO_SAM_front), the back lidar sensor (LIO_SAM_back), or with the merged point cloud from both sensors (LIO_SAM_fused), compared to a traditional fusion of the wheel inertial odometry (WIO) and IMU readings using an EKF (ekf_WIO). These comparisons pretend to assess the best strategy to estimate the ego-motion (i.e., odometry estimation) with the available Ona means and considering

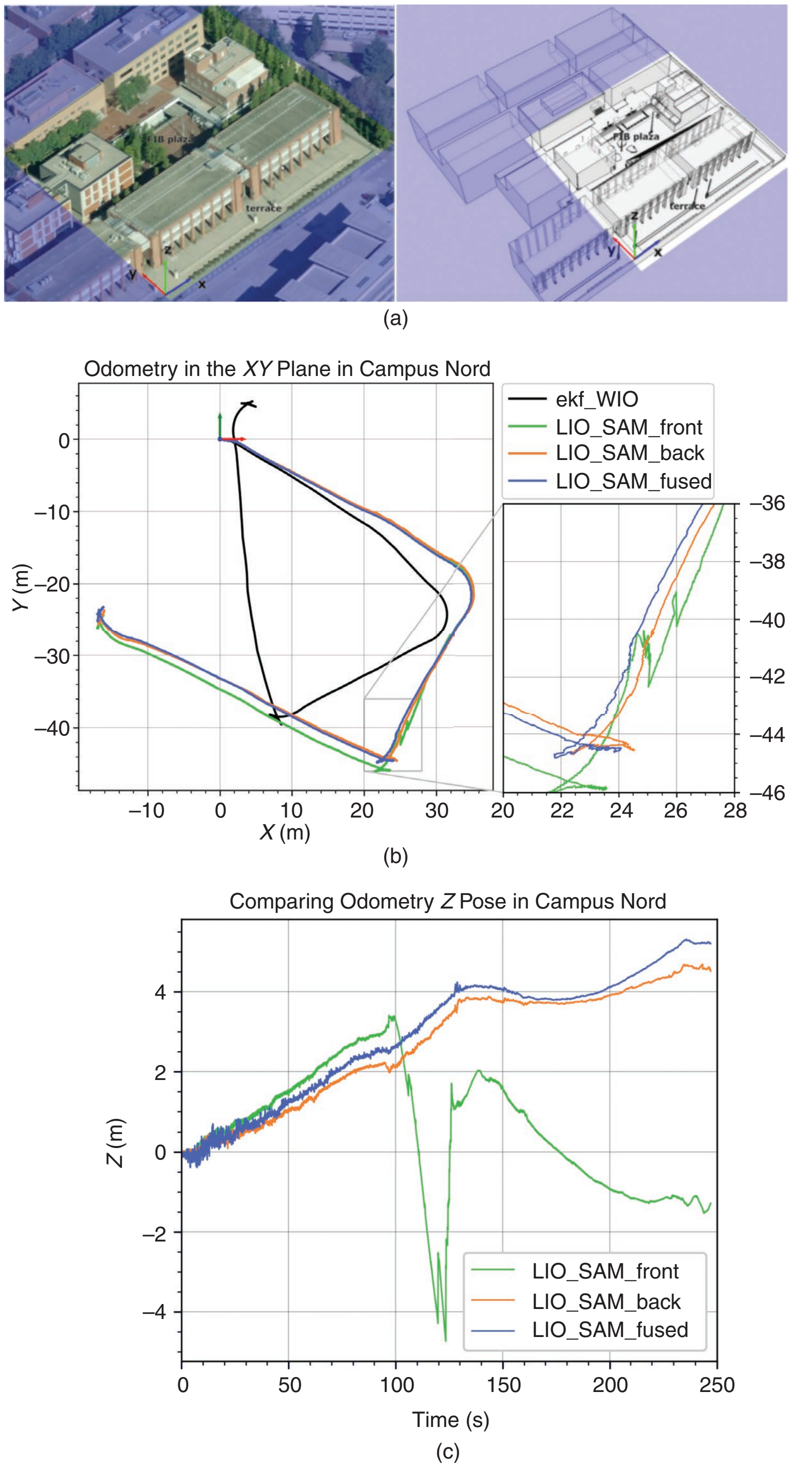


FIGURE 7. BRL experiments, Universitat Politècnica de Catalunya, Spain. (a) BRL test site. (b) Odometry estimations from three instances of "LIO-SAM obs." and an EKF-based wheel-inertial approach (WIO). (c) Odometry results in *z*.

TABLE 2. Main perception and navigation challenges of the test scenarios.

	BARCELONA ROBOT LAB	ESPLUGUES DE LLOBREGAT CITY CENTER (SPAIN)	DEBRECEN CITY CENTER (HUNGARY)
Pavement layout	Several levels and underpasses	Road and pedestrian areas	Mainly pedestrian areas
Vegetation	Mild	Moderate	Moderate
Architectonic barriers	Mild	Moderate	Severe (e.g., nonsegregated tram)
GNSS coverage	Intermittent	Intermittent and not reliable (aliasing)	Lack of precision (RTK virtual reference station 200 km away)
Sunlight exposure	Severe, existence of cast shadows	Severe dynamic range (direct sunlight and dark shadows between tall buildings)	Mild (cloudy)
Scene dynamics	Moderate, few bystanders	Severe, lots of bystanders	Severe, lots of bystanders, bicycle riders and shared tram route

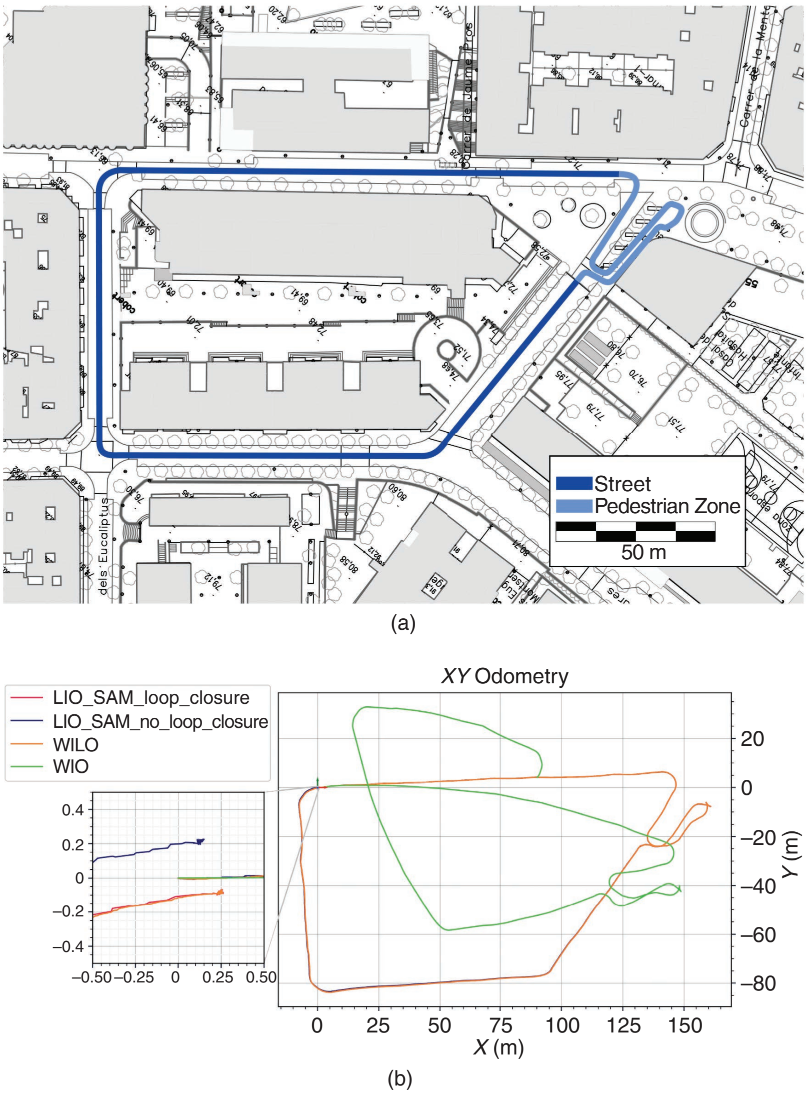


FIGURE 8. Esplugues de Llobregat experiments, Spain. (a) Map of the test site in the center of Esplugues de Llobregat (dark blue: road; light blue: pedestrian zone). (b) *XY* localization for different odometry estimators.

the tradeoff between computation and precision (e.g., ekf_WIO is lighter than processing a merged point cloud in LIO_SAM_fused).

Figure 7(b) plots the *xy*-odometry of the three LIO-SAM instances, alongside the ekf_WIO for reference. The zoomed region highlights the moment the robot is at the end of a long hallway, which has a slight upward incline. As a consequence, the front 3D lidar was only able to pick up the vertical walls. The degradation in the environment is responsible of the zigzag behavior in the LIO_SAM_front odometry, as well as the jumps in the *z*-estimate seen in Figure 7(c). The back lidar could still observe corners and columns outside of the hallway most of the way through. These features resulted in a better *xy*-odometry estimation. In addition, the upward slope meant that the back lidar could see the floor better than the front lidar, thus avoiding the large changes in *z*-estimate as seen with the front lidar LIO. By merging the point clouds, the robot can observe 360° surrounding it. And, as a result, the state estimation suffers less from the lidar-degraded environment compared to using a single lidar; hence, the extra computational burden is acceptable not to jeopardize a mission.

ESPLUGUES DE LLOBREGAT CITY CENTER

This test site covers a 750-m track that mixes roads and pedestrian areas. The chosen navigation route is depicted in the map shown in Figure 8(a). The initial tests in this site included open-street navigation in the streets marked with dark blue in Figure 8(a). As the previous tests in BRL already emulated a pedestrian area, our focus here was on street navigation.

In this scenario, the multitude of static features made the scene very observable for the lidar. As a result, the total localization error after 500 m was below 30 cm [left side of Figure 8(b)]. In this case, first, we compared the effect of enabling or disabling the loop closure factor in LIO-SAM. In theory, enabling the loop closure should decrease the final error, as the loop closure serves to eliminate drift accumulated when the same features are observed again. A disadvantage with loop closures is that we can no longer consider it an odometry estimation source and it loses its estimation smoothness. As shown in Figure 8(b), enabling or disabling the loop closure factor appears indistinguishable in the xy-odometry. The final error in the xy-plane for both cases is less than 30 cm. Second, we tested here a new fusion solution, WILO, as the results of a local EKF that fuses wheel, inertial, and laser odometry. The laser odometry for WILO will be from the LIO-SAM instance with the loop closure factor disabled. In addition, the WIO showcases, once again, the necessity of incorporating lidar odometry to the localization problem.

DEBRECEN CITY CENTER

In November 2022 we did a second pilot demonstration in the city center of Debrecen, Hungary. Here, the length of the pilot route was approximately 600 m and covered one of the most frequented areas in Debrecen. Most parts of the route were completely pedestrianized, with car traffic only affecting the last 150 m. One of the improvements with respect to Esplugues was on the consistency between the global (OSM with UTM coordinates) and local (SLAM) maps. For this, we included observations of external geolocalized landmarks to reduce the state estimation uncertainty in the SLAM solution. The landmarks at the starting location of Ona were of special importance (notice how we could normally add them in a robot hub were several Onas could be charging and waiting for a last-mile delivery mission). The main objective of this pilot test was to showcase a full-delivery mission, delivering an actual package. The route and some of the mission stages are shown in Figure 1(a).

Overall, the Debrecen tests and demonstration were a success. Ona performed as expected conducting the last-mile delivery mission. Figure 1(b) shows an example of the Ona perception system while sorting VRUs in the middle of the delivery route. Notice the VRUs as orange dots in Figure 1(b), next to the Ona trajectory (depicted as a yellow line with a sequence of 2D coordinate frames, with red x-forward and green y-left axis) and how Ona modified its route to keep a safe distance from them while moving forward. This exact case happened in the middle of the route when a tram vehicle did bring several pedestrians to a tram station just in front of Ona. See in Figure 1 how Ona is sharing the route with the city tram and several pedestrians. The satisfaction of VRU was already assessed in the Esplugues pilot test thorough surveys, as described in the following section.

TECHNOLOGY ACCEPTANCE

During the tests in the city center of Esplugues de Llobregat, we distributed a survey to the bystanders to assess the technology and human acceptance of Ona. The details of such technology acceptance can be seen in [10]. This survey was distributed in Catalan and Spanish print version to the bystanders. The English version was made for the online survey through an online form. Further, we added supporting material to the attending public in the form of videos and images (videos and images can be found in the supplementary material, available at https://doi.org/10.1109/MRA.2024.3487321).

The statistics of bystander types are shown in Figure 9 and the complete survey and analysis of each answer can be found at https://bit.ly/survey-ona. As a summary, the analysis leads to the following:

- There is a high acceptance on the use of robots for last-mile deliveries.
- The public suggests a first integration in industrial or university sites.
- These robots might cause some degree of interference in the city daily life; thus, they prefer scheduled daily autonomous deliveries.
- There is a high confidence in the autonomy of the delivery devices and high confidence in the delivery success of robots like Ona.

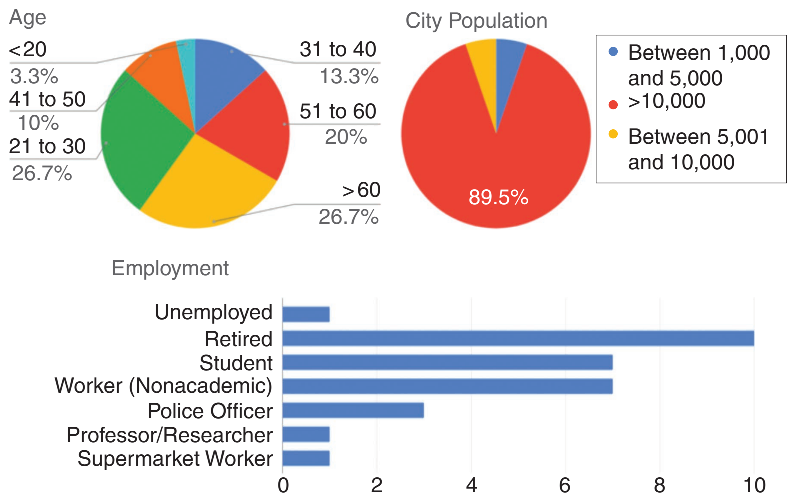


FIGURE 9. Classification of bystanders that fulfilled the technology acceptance survey during the pilot test in Esplugues de Llobregat.

- A free navigation of the robot is clearly preferred.
- The general public believes the cities require some architectonic modifications to allocate for these types of robots, and they would prefer to integrate the new infrastructure in the current urban furniture.
- Overall, these delivery robots are not seen as annoying (e.g., considering noise or sharing the space) and the public highly values the ecological benefits of the possibility of returning the packaging waste inside the robot right after the delivery.

As general comments, there is a clear acceptance on the usage of these robots, although there is also a clear worry about unemployment generated by its integration in our daily lives during the initial phases. Interestingly enough, looking at the conclusions of our previous work [10], senior individuals tend to exhibit reluctance when it comes to the introduction of new technology in the urban public space.

Overall, the acceptance of robotic last-mile distribution is notably high in urban public spaces, particularly in areas with lower population density. However, this existing public space is not fully equipped to seamlessly incorporate this emerging technology and requires adaptation. The survey indicates a significant willingness to allow the robot's free navigation, as opposed to confining it to a segregated route, as long as safety measures are assured. Essential infrastructure elements, such as charging points, cameras, and sensors, could be seamlessly integrated into the current street furniture.

On the whole, Ona has not caused a sense of insecurity among pedestrians in open spaces like public squares. However, in more confined areas, such as sidewalks, there is a heightened perception of insecurity. It is also important to remark that the tests with Ona have not disrupted the tasks performed by other entities in the public space. The circulation of the distribution robot has not resulted in noise or visual pollution within the public space and the peer teammate is acknowledged not as a separate entity from the robot, but as a companion in its vicinity, overseeing multiple units and promoting integration.

LESSONS LEARNED AND FINAL REMARKS

This article presents Ona, our last-mile delivery robot. Aside from describing the hardware and sensors, we provided insights on the navigation software stack, related to SLAM, traversability, planning, and global map handling. In contrast to other existing delivery robots, Ona is meant to navigate in both street and pedestrian areas, incorporating a midsized storage system that can automatically pick up or deliver packages.

Regarding the SLAM system, we leveraged a state-of-the-art approach (i.e., LIO-SAM [12]) fused with measurements of the wheel odometers (i.e., WILO). This integration has shown to be crucial, as the WILO final drift was lower than 30 cm after 500 m. The reduction in drift in the local odometry means that a fast and accurate GNSS signal becomes less important when navigating, as the global corrections can occur less frequently. This is especially critical in the urban environments where Ona will make deliveries, as the city buildings often block or degrade the GNSS signal.

The use of the Ona simulator was crucial in the initial development phases, especially the Gazebo-ROS simulation, to test and debug the navigation algorithms. The initial viable tests of Ona navigating in a representative scenario could also be tested thanks to the digital twin of Esplugues de Llobregat programmed in the PTV Vissim software. These virtual tools are very valuable and will also be for future tests. Thanks to their compatibility with the real robot software, these considerably reduce the development time of new capabilities.

We validated Ona in three different scenarios. First, initial tests were conducted at the BRL (Universitat Politècnica de Catalunya), to prepare the Ona platform and test the initial sensor configurations and methods. Then, the official Ona presentation was in Esplugues de Llobregat (June 2022), an event attended by Spanish national authorities like the Minister of Transportation. Considering that Esplugues de Llobregat has one of the highest population densities in Europe, the test results were very satisfactory toward the deployment of autonomous last-mile delivery robots. A second pilot demonstration was carried out in Debrecen (Hungary) in November 2022. This time, the city mayor attended the event and a complete delivery mission was carried out. In this case, Ona shared the route with tram vehicles as well as a considerable number of pedestrians.

As future work, all modules mentioned in this document have room for improvement, especially in the direction of providing robustness. The main expected change in the near future is to improve the mobility of the Ona platform. A second version of the Ona prototype has already been built and the software stack will be migrated shortly. The new Ona not only improves the maneuverability by using a double Ackerman six-wheel system but also has a better locker system. Additionally, it is worth mentioning that we are working with the Spanish Dirección General de Tráfico to obtain a certification for Ona, which is the first vehicle of its kind in Spain, and still there is no legislation for this type of robots.

ACKNOWLEDGMENT

This work has been partially supported by the European Union project LogiSmile (EIT-UM-2020-22140); by Horizon Europe under Grant agreement 101168042 [auTonomous Robotic aId For increasing FIrst responDers efficiency TRIFFID]; by the Spanish Ministry of Science and Innovation under the projects Autonomous package delivery in urban areas (AUDEL) (TED2021-131759A-I00, funded by MCIN/AEI/10.13039/501100011033 and by the" European Union NextGenerationEU/PRTR") and Lifelong navigation learning using human-robot interaction (LENA) (PID2022-142039NA-I00, funded by MCIN/AEI/10.13039/501100011033 and by "ERDF A way of making Europe"); by the Nou model de repartiment de paquets en superilles urbanes mitjançant una xarxa de vehicles elèctrics autònoms (BotNet) project (23S06128-00), funded by the Ajuntament de Barcelona and Fundació la Caixa; and by the Consolidated Research Group RAIG (Mobile Robotics and Artificial Intelligence Group, 2021 SGR 00510) of the Departament de Recerca i Universitats de la Generalitat de Catalunya. We thank the Spanish Ministerio de Universidades, the European Union-Next Generation and the University of Alicante for the financial support (Margarita Salas, MARSALAS21-08). This article has supplementary downloadable material available at https://doi.org/10.1109/MRA.2024.3487321, provided by the authors.

AUTHORS

Angel Santamaria-Navarro, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, Universitat Politècnica de Catalunya, 08028 Barcelona, Spain. E-mail: asantamaria@iri.upc.edu.

Sergi Hernández, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, 08028 Barcelona, Spain. E-mail: shernand@iri.upc.edu.

Fernando Herrero, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, Universitat Politècnica de Catalunya, 08028 Barcelona, Spain. E-mail: fherrero@iri.upc.edu.

Alejandro López, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, Consejo Superior de Investigaciones Científicas, 08028 Barcelona, Spain. E-mail: alopez@iri.upc.edu.

Iván del Pino, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, 08028 Barcelona, Spain; and the departamento de Física, Ingeniería de Sistemas i Teoría del Señal, Universidad de Alicante, 03690 San Vicente del Raspeig (Alicante), Spain. E-mail: idelpino@iri.upc.edu.

Nicolás Rodríguez-Linares, Instituto de Astrofísica de Canarias, 38205 La Laguna, Santa Cruz de Tenerife, Spain. E-mail: nicolas.linares@iac.es.

Carlos Fernández, Urbiotica, 08028 Barcelona, Spain. E-mail: carlos.fernandez@urbiotica.com.

Albert Baldó, CARNET and Vaivé Logistics, s.l., 08034 Barcelona, Spain. E-mail: albert.baldo@carnetbarcelona.com; albert.baldo@vaivelogistics.com

Clément Lemardelé, CARNET and Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya, 08034 Barcelona, Spain. E-mail: clement.lemardele@carnetbarcelona.com; clement.lemardele@upc.edu.

Anaís Garrell, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, Universitat Politècnica de Catalunya, 08028 Barcelona, Spain. E-mail: agarrell@iri.upc.edu.

Joan Vallvé, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, Consejo Superior de Investigaciones Científicas, 08028 Barcelona, Spain. E-mail: jvallve@iri.upc.edu.

Hafsa Taher, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, Universitat Politècnica de Catalunya, 08028 Barcelona, Spain. E-mail: htaher@iri.upc.edu.

Ana M. Puig-Pey, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, Universitat Politècnica de Catalunya, 08028 Barcelona, Spain. E-mail: apuigpey@iri.upc.edu.

Laia Pagès, CARNET, 08034 Barcelona, Spain. E-mail: laia.pages@carnetbarcelona.com.

Alberto Sanfeliu, Institut de Robòtica i Informàtica Industrial, CSIC-UPC, Universitat Politècnica de Catalunya, 08028 Barcelona, Spain. E-mail: sanfeliu@iri.upc.edu.

REFERENCES

[1] A. Sharma, P. Zanotti, and L. P. Musunur, "Drive through robotics: Robotic automation for last mile distribution of food and essentials during pandemics," *IEEE Access*, vol. 8, pp. 127,190–127,219, 2020, doi: 10.1109/ACCESS.2020.3007064.

[2] M. Viu-Roig and E. J. Alvarez-Palau, "The impact of e-commerce-related last-mile logistics on cities: A systematic literature review," *Sustainability*, vol. 12, no. 16, 2020, Art. no. 6492, doi: 10.3390/su12166492.

[3] C. Lemardelé, M. Estrada, L. Pagès, and M. Bachofner, "Potentialities of drones and ground autonomous delivery devices for last-mile logistics," *Transp. Res. E: Logistics Transp. Rev.*, vol. 149, May 2021, Art. no. 102325, doi: 10.1016/j.tre.2021.102325.

[4] E. Yurtsever, J. Lambert, A. Carballo, and K. Takeda, "A survey of autonomous driving: Common practices and emerging technologies," *IEEE Access*, vol. 8, pp. 58,443–58,469, 2019, doi: 10.1109/ACCESS.2020.2983149.

[5] N. Boysen, S. Fedtke, and S. Schwerdfeger, "Last-mile delivery concepts: A survey from an operational research perspective," *OR Spectr.*, vol. 43, no. 1, pp. 1–58, 2021, doi: 10.1007/s00291-020-00607-8.

[6] F. Ingrand and M. Ghallab, "Deliberation for autonomous robots: A survey," *Artif. Intell.*, vol. 247, pp. 10–44, Jun. 2017, doi: 10.1016/j.artint.2014.11.003.

[7] S. Fakoorian, A. Santamaria-Navarro, B. T. Lopez, D. Simon, and A-a Agha-Mohammadi, "Towards robust state estimation by boosting the maximum correntropy criterion Kalman filter with adaptive behaviors," *IEEE Robot. Autom. Lett.*, vol. 6, no. 3, pp. 5469–5476, Jul. 2021, doi: 10.1109/LRA.2021.3073646.

[8] A. Santamaria-Navarro, E. H. T. Avilés, M. Morta, and J. Andrade-Cetto, "Terrain classification in complex three-dimensional outdoor environments," *J. Field Rob.*, vol. 32, no. 1, pp. 42–60, 2015, doi: 10.1002/rob.21521.

[9] M. Colledanchise and P. Ogren, *Behavior Trees in Robotics and AI: An Introduction*, 1st ed. Boca Raton, FL, USA: CRC, 2018.

[10] A. Puig-Pey et al., "Human acceptance in the human-robot interaction scenario for last-mile goods delivery," in *Proc. IEEE Int. Conf. Adv. Robot. Social Impacts*, 2023, pp. 32–29, doi: 10.1109/ARSO56563.2023.10187432.

[11] C. Cadena et al., "Past, present, and future of simultaneous localization and mapping: Toward the robust-perception age," *IEEE Trans. Robot.*, vol. 32, no. 6, pp. 1309–1332, Dec. 2016, doi: 10.1109/TRO.2016.2624754.

[12] T. Shan, B. Englot, D. Meyers, W. Wang, C. Ratti, and D. Rus, "LIO-SAM: Tightly-coupled lidar inertial odometry via smoothing and mapping," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, 2020, pp. 5135–5142, doi: 10.1109/IROS45743.2020.9341176.

[13] A. Tagliabue et al., "Lion: Lidar-inertial observability-aware navigator for vision-denied environments," in *Experimental Robotics*, B. Siciliano, C. Laschi, and O. Khatib, Eds., Cham, Switzerland: Springer-Verlag, 2021, pp. 380–390.

[14] W. Hess, D. Kohler, H. Rapp, and D. Andor, "Real-time loop closure in 2D LIDAR slam," in *Proc. IEEE Int. Conf. Robot. Automat. (ICRA)*, pp. 1271–1278, 2016, doi: 10.1109/ICRA.2016.7487258.

[15] I. d Pino, A. Santamaria-Navarro, A. G. Zulueta, F. Torres, and J. Andrade-Cetto, "Probabilistic graph-based real-time ground segmentation for urban robotics," *IEEE Trans. Intell. Veh.*, vol. 9, no. 5, pp. 1–14, May 2024, doi: 10.1109/TIV.2024.3383599.

[16] L. Breiman, "Random forests," *Mach. Learn.*, vol. 45, no. 1, pp. 5–32, 2001, doi: 10.1023/A:1010933404324.

[17] R. L. Guimarães, A. S. de Oliveira, J. A. Fabro, T. Becker, and V. A. Brenner, *ROS Navigation: Concepts and Tutorial*. Cham, Switzerland: Springer-Verlag, 2016.

[18] G. Ferrer and A. Sanfeliu, "Bayesian human motion intentionality prediction in urban environments," *Pattern Recognit. Lett.*, vol. 44, pp. 134–140, Jul. 2014, doi: 10.1016/j.patrec.2013.08.013.

[19] R. Kümmerle, M. Ruhnke, B. Steder, C. Stachniss, and W. Burgard, "Autonomous robot navigation in highly populated pedestrian zones," *J. Field Rob.*, vol. 32, no. 4, pp. 565–589, 2015, doi: 10.1002/rob.21534.

[20] L. Schmid, O. Andersson, A. Sulser, P. Pfreundschuh, and R. Siegwart, "Dynablox: Real-time detection of diverse dynamic objects in complex environments, *IEEE Robot. Autom. Lett.*, vol. 8, no. 10, pp. 6259–6266, 2023, doi: 10.1109/LRA.2023.3305239.

[21] G. Ferrer and A. Sanfeliu, "Proactive kinodynamic planning using the extended social force model and human motion prediction in urban environments," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2014, pp. 1730–1735, doi: 10.1109/IROS.2014.6942788.