

# Robotic delivery service in combined outdoor-indoor environments: technical analysis and user evaluation

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## Abstract

Robotic solutions for delivery tasks in urban and unstructured areas have represented a solid and considerable field of research in recent years. The aim of the proposed paper is to present the technical feasibility and usability of a robotic solution able to carry items from outdoor areas up to the user's apartment and vice-versa. The proposed solution is based on three heterogeneous mobile platforms, working in three different environments (domestic, condominium, outdoor), able to cooperate among themselves and with other machines in the framework (i.e. the elevator of the condominium). The evaluation was performed in realistic environments involving 30 end-users.

*Keywords:* service robotics, cooperative robotics, delivery, user centered design

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## 1. Introduction

In recent years, research progress in robotics has heavily driven the spread of robotic solutions in different fields of applications, including defense, rescue, security, healthcare, and agriculture. In particular, logistic applications have  
5 been investigated thoroughly and have resulted relevant success cases such as the

Kiva robots used in Amazon’s warehouses <sup>1</sup> <sup>2</sup>. Furthermore, service robotics for logistic applications have been successfully installed in hospitals. These devices are based on mobile platforms that can navigate and move safely in a human populated environment. A survey of the current state of the art of these systems is proposed in [? ]. Moving the focus to the urban context, in 2016, DHL, the global market leader in the logistics industry, conducted an extensive analysis of robotics in logistics, proposing futuristic scenarios where the supply chains will be strongly automated and the door-to-door delivery will be performed by a system of coordinated robots <sup>3</sup>. In this direction, new innovative start-ups have been founded aiming to perform robotic delivery, such as Dispatch Robotics <sup>4</sup> and Starship Technologies <sup>5</sup>. In addition, service robotics in urban environments have increased importance in assisted living applications, such as assistance to elderly or disabled individuals, by enabling independent living and autonomy.

This paper present the results, in terms of technical feasibility and usability, of two developed services in the context of real urban environments: shopping delivery and garbage collection service. These two services were considered useful by 75% and 62% of individuals, respectively, out of more than 100 people who participated in the end-users’ needs analysis [? ].

These experimental scenarios, described in Sec. 4, were implemented using a system composed of three heterogeneous mobile platforms and common agents (i.e. elevator) able to cooperate among themselves and in three different environments [? ]: domestic, condominium, and outdoor (Sec. 3). As introduced, the implemented solution has been tested extensively to understand its reliability and the usability experienced by the involved end-users (Sec. 5).

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<sup>1</sup><http://www.dailymail.co.uk/sciencetech/article-2855570/Amazons-new-robot-army-ready-ship.html>, visited on April 2016

<sup>2</sup><http://www.seattletimes.com/business/amazon/at-amazon-warehouses-humans-and-robots-are-in-sync/>, visited on April 2016

<sup>3</sup>[http://www.dhl.com/content/dam/downloads/g0/about\\_us/logistics\\_insights/dhl\\_trendreport\\_robotics.pdf](http://www.dhl.com/content/dam/downloads/g0/about_us/logistics_insights/dhl_trendreport_robotics.pdf), visited on April 2016

<sup>4</sup><http://dispatch.ai/>, visited on April 2016

<sup>5</sup><https://www.starship.xyz/>

30 To conclude, the feasibility of the described solution is presented and explained through analysis of both technical and usability aspects.

The paper is structured as follows:

- Sec. 2 features an overview of the current state of the art is provided.
- Sec. 3 contains a description of the system, while Sec. 4 presents details of  
35 the scenario and describes the strategy to provide the proposed services.
- Results of the performed technical tests and the usability evaluation by end users are shown in Sec. 5.
- Sec. 6 contains a discussion of the work performed.

## 2. Related Works

40 In the current state of the art, the use of mobile robots for transportation of goods has been explored extensively. Actually, starting from the navigation capabilities of mobile platforms, transportation of objects can be considered one of the first tasks investigated in service robotics. Several examples can be found in current literature. In the work described in [? ], a system consisting of a  
45 fleet of robot vehicles, automatic stations and smart containers for automation of transportation of goods in hospitals is presented. Furthermore, in the work described in [? ], the issue of transporting a certain number of goods by a team of mobile robots was considered, with the aim to minimize the total transportation time. Other examples can be found in [? ], where a modified Q-learning  
50 approach for object transportation using cooperative and autonomous multiple mobile robots was investigated, and in [? ], where a cooperating team of two vehicles with complementary capabilities, a truck restricted to travel along a street network, and a quadrotor micro-aerial vehicle that can be deployed from the truck to perform deliveries, is presented.

55 The urban services implemented in this paper (i.e. shopping delivery and garbage collection) are realized using a set of both indoor and outdoor mobile platforms including also an elevator. These machines must cooperate together to

transport goods from outdoor to indoor and vice versa. In literature, examples of robotic cooperation are multi-robot localization [? ], multi-robot exploration [? ], multi-robot search and rescue [? ], and multi-robot collaboration specifically for urban pedestrians [? ][? ]. The topic of using a multi-robot system for transportation was investigated in [? ], where a general approach for the control of a large fleet of autonomous mobile robots involved in transshipment tasks was explained. More recently, in [? ], task-allocation strategies for a multi-robot transportation system were studied.

The main characteristic of the proposed system is a “robot relay” strategy where, to link the carriages in outdoor and indoor environments, items are physically exchanged between mobile platforms, as typically performed in production chains in industrial and structured environments. To the best of the authors’ knowledge, the relay strategy has been already used in robotics for telecommunication purposes, as explained in [? ], but this is the first time that this strategy has been employed in transportation tasks.

Regarding the indoor carriage, the proposed solution involved the use of an elevator already present in the environment to perform multi-floor navigation. This aspect was investigated also in [? ], where the CoBots platform has the functionality of riding elevators with human help, and in [? ], where the recognition method of the buttons and path planning algorithms for navigating in the elevator were studied.

Going beyond the current state of the art, the work described in the paper aimed to develop a feasible solution to provide delivery services from outdoor to indoor environments (and vice versa) based on heterogeneous mobile platforms working in heterogeneous environments, focusing on analysis of the reliability and usability of the system.

### 3. Description of the System

The proposed system implements two services that involve three different environments: outdoor, condominium, and indoor [? ]. The agents involved

in this system are the DOMestic RObot (DoRo); the CONdominium RObot (CoRo); the Outdoor RObot (ORO), the lift, which can be considered as another kind of robot; and a Control PC.

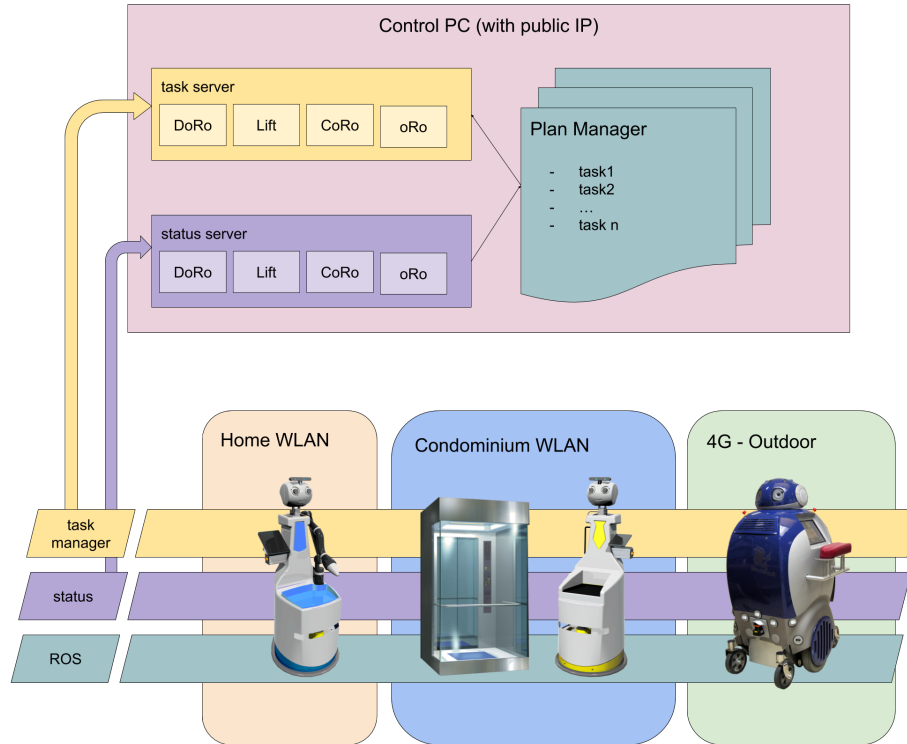


Figure 1: The system consists of five agents operating on four different networks. Each agent communicates with the control PC, continuously sending its internal status and asking for the task that must be done. All the communications are implemented via the Client/Server TCP mechanism.

90 *3.1. General Architecture*

To develop the multi-agent system described above, one of the first problems to address is the communication issue. In our case, we have five agents with four different networks: DoRo operates on a domestic WLAN, CoRo and the Lift on a condominium WLAN, ORO on a 4G outdoor connection, and

95 the Control PC is connected on a public IP. The communication issue across  
different networks is outside the scope of this work. Therefore, for our exper-  
iments, we implemented a basic communication system using the Control PC  
as a task coordinator. It sends and receives data from all the agents to deploy  
the requested service, running two servers to handle the communication. Each  
100 agent sends continuously (1 Hz) its internal status to the status server, including  
robot identifier, position, and status of the current task. Moreover, it requests  
(at 1 Hz) from it the action that must be performed (see Fig. 1). All the agents  
have the same high-level communication interface, and they are distinguishable  
from the Control PC by specific string identifiers. All the communications are  
105 implemented by means of a Client/Server TCP mechanism.

### 3.2. Agents

As mentioned, three mobile robots were used in the system. They here  
briefly described in this section.

**DoRo:** The domestic robot DoRo was implemented over the SCITOS G5 mo-  
110 bile platform (developed by Metralabs <sup>6</sup>), and can safely navigate in do-  
mestic environments through the use of a front (SICK S300) and a rear  
(Hokuyo URG-04LX) laser. Speakers and multicolor LEDs are used to  
provide feedbacks to the user. The navigation stack relies on CogniDrive,  
a proprietary software of MetraLabs, and it is linked to ROS middleware  
115 [? ], used for the development of all the software. In the case of these  
two services, the DoRo robot represents the gateway to the system for  
the user: a removable tablet, mounted on the platform, can be used for  
service requests, as well as a dialog manager for speech interaction [? ].

Even if the use of a domestic robot can be considered inordinate compared  
120 to its role in the described services, its employment is justified by different  
aspects:

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<sup>6</sup><http://www.metralabs.com/en/research>, visited on April 2016

- It provides a mobile interface that is able to autonomously navigate toward users to facilitate the provision services and information, specifically with cognitively frail people [? ]
- 125 • In the role of providing services and information, physical embodiment enhances trustworthiness experienced by users [? ] [? ].

**CoRo:** The condominium robot CoRo shares most of the hardware with Doro. However, a set of rollers was mounted, enabling the movement of item towards and from the outdoor robot.

130 **ORo:** The outdoor robot ORo is based on the resultant DustCart platform of DustBot project<sup>7</sup> [? ]. The mobile base consists of a mechanical chassis with two central actuated wheels (Swissdrive 400 T hub motor) and four passive wheels: the six wheels are linked by joints and shock absorbers allowing the robot to adapt to and compensate for road disconnections. The navigation sensors consist of wheel encoders (Hall effect, 352 pulses per turn); laser scanner (Hokuyo UTM-30LX) positioned on the front of the robot; lasers and ultrasonic sensors to detect common obstacles in urban environment such as sidewalks, steps, and gaps; and two GPS units and antennas (Novatel FLEX6-D2L-R0G-TTR and FLEX6-D2S-Z00-00N  
140 as align unit) mounted on the back of the robot. GPS units provide not only the position but also the orientation of the robot with accurate resolution if enough satellites are visible and Real Time Kinematic (RTK) correction is applied. GPS data acquired by the robot are transmitted in real time through the Internet to a RTK service provider (SmartNet in the case of this experiment), which applies real-time corrections to the data  
145 on the base of its differential ground reference station or virtual reference stations. In these conditions, accuracy achieved by the application of RTK correction is less than 5 cm in positioning and 0.5 degree in orientation depending on the GPS distance from the reference station. Navigation is

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<sup>7</sup>Networked and Cooperating Robots for Urban Hygiene, FP6-045299, 2006-2009

150 achieved using the navigation stack of ROS, and localization makes use of  
both GPS and AMCL (Adaptive Monte Carlo Localization) to provide the  
better position and orientation estimates of the robot in almost all urban  
environment conditions. It relies on the information provided by the GPS  
in wide or open areas, where satellites are visible, and on the information  
155 provided by AMCL in narrow environments, where walls are well detected  
by the laser scanner and a map can be easily built and matched with laser  
readings. A solution in ROS for combining GPS and AMCL and that can  
automatically switch between them, depending on their estimates, has  
been implemented.

160 **Elevator:** The elevator, already present in the environment, is embedded in  
the system, and is controlled remotely using the Phidget Input/Output  
digital board. ROS nodes are used to implement its functionalities, such  
as move to a specific floor, open/close the door, and keep the door open.

**Control PC:** The Control PC is reachable from all agents of the system. It  
165 runs a status server, which collects all the status data of the agents, and  
a task server, which waits for agent requests, sending back the task that  
a specific agent has to accomplish. This module also has a Plan Manager,  
which stores the sequence of tasks (plan) to execute in order to accomplish  
the shopping or the garbage service. The Control PC receives a service  
170 request from the speech or the tablet interface of the DoRo robot. When a  
service starts, the Plan Manager sends the tasks to the task server module.  
When a task is requested of a robot, the robot starts to execute the task.  
The Plan Manager waits until the robot finishes, looks at the status server,  
and then requests the next task. Some tasks could also run also in parallel  
175 (e.g. lift and robot control).



## 4. Methodology

The aim of the work conducted and described in the paper was to demonstrate the maturity of a developed system both from a technical point of view and the usability of end users point of view.

180 For this reason, the proposed services were tested in realistic environments and tried by end-users to evaluate them thoroughly.

### 4.1. Experimental Scenarios

The system implements robotic services for shop delivery and garbage collection. Therefore, items have to be delivered from outdoors (a shop) to indoors (user apartment) in the first case and from indoors to outdoors (discharge area) in the latter case.

The overall strategy for the shopping service is shown in Fig. 2, where steps of the process are depicted. The steps are actions generated by the Scenario Plan Manager:

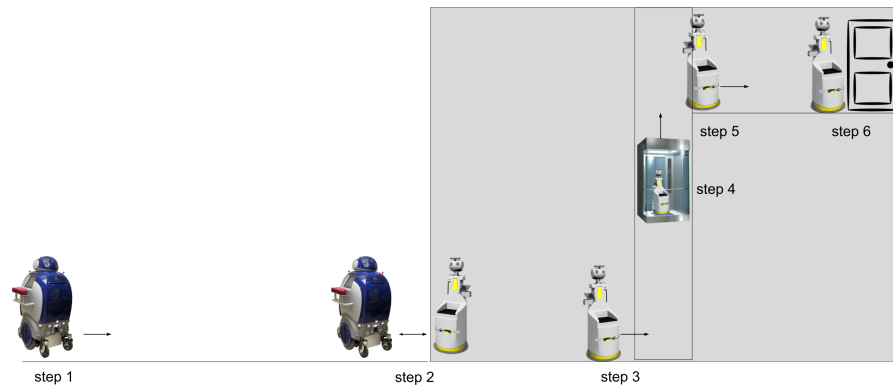


Figure 2: Schematization of the shopping scenario. The outdoor robot exchanges the good with the condominium robot. Then, it goes to the user’s apartment using the elevator. Steps are actions generated by the Plan Manager. See text for step details.

190 **step 0** The service is requested by the user through voice command and/or using a tablet application. Voice interaction is provided by the domestic

robot in the house environment; the outdoor robot moves to the shop, and the grocer puts selected items inside the platform.

**step 1** The outdoor robot moves from the shop to the entrance of the user's building, carrying the object.

**step 2** At the entrance of the building, the item is physically moved from outdoor mobile platform to an indoor mobile platform, acting in the condominium areas.

**step 3-5** The condominium robot uses the elevator to reach the user's home floor, and the elevator is moved to the right floor.

**step 6** The condominium robot reaches the user's house while he/she is informed by the domestic robot.

The same protocol can be performed from the user's apartment to the outdoor environment to provide garbage collection.

#### 4.2. Technical Evaluation

From a technical point of view, the crucial points of the services were identified at particular sub-tasks of the procedure:

- In outdoor navigation, in areas close to buildings due to degradation of quality of GPS signal
- In the link between outdoor and indoor navigation, where the carried item is moved from outdoor robot to condominium platform (or vice versa)
- In multi-floor navigation, where the condominium platform uses the elevator to move from one floor to another.

*Outdoor navigation in areas close to buildings.* In outdoor navigation, the localization is commonly based on GPS data. However, the degradation of the quality of this signal in areas close to buildings is well-known and has to be faced

in the described outdoor navigation task, which has the goal of the entrance of the building.

For these reasons, a solution that combines GPS and AMCL to provide  
220 position and orientation of the robot by switching automatically in real time  
between these two systems, depending on their estimates, was investigated.  
Tests were performed in the outdoor environment, where the robot navigated in  
an environment comprising both a narrow street surrounded by high buildings  
and open areas. The goal of the test was to demonstrate that the system  
225 can select the system which guarantees the better position estimate during the  
complete navigation of the robot.

During the tests, the position estimates of GPS and AMCL were evaluated in  
terms of standard deviation along the  $x$  and  $y$  coordinates; the robot selected the  
localization system with lower standard deviations. GPS standard deviations  
230 are provided by the GPS itself after the application of RTK correction. AMCL  
standard deviations are computed from the covariance matrix provided by the  
AMCL node of ROS. Priority is always given to GPS since it is the most accurate  
and reliable system: if RTK correction is applied and the solution computed and  
fixed, the system uses GPS to localize itself, otherwise, it switches to AMCL.

235 *Robot Cooperation.* To perform a continuous carriage from outdoor and indoor  
environments, a mechanism of haulage, crossing the edge of heterogeneous areas,  
was implemented (see Fig. 3). This is mechanically based on sets of rollers  
mounted on both outdoor and condominium platform.

Platforms, and therefore rollers, can be aligned using a *docking* strategy  
240 by which the condominium robot is able to move closely and precisely toward  
the outdoor robot. The *docking* strategy was developed based on the docking  
function provided by MetraLabs and was used to move the platform over its  
recharging station. Differently from the recharging purpose, with the case of  
alignment with another mobile platform, the goal position is not fixed, but  
245 dynamically defined according to the final position of the outdoor platform.

Due to stochastic errors in the docking procedure, resulting in slight mis-

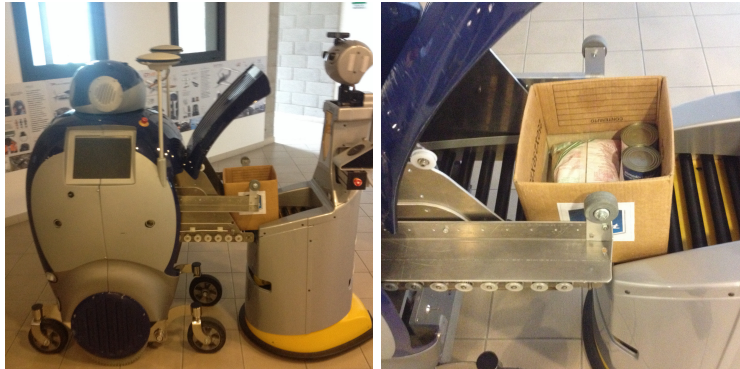


Figure 3: On the left, docking procedure performed by condominium platform on outdoor platform. On the right, close up of aligned rollers.

alignments, failures could occur during the movement of items from one platform to the other. Considering the direct consequences of errors, such as items stacked between rollers, a deeper analysis was performed. In particular, variability in the procedure could occur from two main causes:

250

- Intrinsic variability of the procedure
- Variability introduced by the operator during the teaching operation of the docking procedure

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Indeed, the desired final position of the docking procedure is taught by moving the condominium robot in front of the outdoor robot. After that, the laser template is recorded as reference to navigate to the desired position. For these reasons, additional tests were performed, focused on evaluating the variability of the procedure, which was measured as introduced offset and deviation standard on relative pose  $[x, y, yaw]$ . This was measured based on data retrieved by condominium laser sensor; elements of the shape of the outdoor robot were identified as landmarks and used to compute the relative position.

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*Use of elevator and multi-floor navigation.* The condominium platform was conceived to perform multi-floor navigation in modern building through the use of elevators already in the environment. Instead of focusing on mechanical activation of the panel elevator through robotic manipulator, the lift is controlled

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through an ad-hoc PC and therefore modeled in the architecture as another machine activated by the Control PC.

During the operations of entering and exiting from the elevator, specific navigation parameters, such as the maximum speed, yaw goal tolerance, preferred  
270 direction of navigation, and minimum distance from obstacles, are dynamically adjusted by the local control system of the robot.

To prove the repeatability and robustness of this sub-task, a focused evaluation was performed: current position of condominium robot during navigation on different floors and final position inside the elevator were logged on to demon-  
275 strate the high repeatability and stability achieved in the sub-task.

#### 4.3. User Evaluation

To evaluate the usability of the proposed Robot-Era services, the System Usability Scale (SUS) [?] was administered to participants at the end of the experiments (Tab. 6). SUS provides a subjective view of usability, and it  
280 consists of 10 items with five response options for respondents: from 1=Strongly disagree to 5=Strongly agree. The SUS is easy and quick to administer, and for this reason it is used to evaluate a wide range of products and services such as websites [?], mobile applications [?], medical systems [?], and robotics systems [?] [?] [?]. Processing results of the SUS include the Cronbachs  
285 Alpha calculation to verify the reliability of the survey. Then, a basic set of descriptive statistics (minimum, maximum, mode, and median) is calculated to obtain a general overview on the scores of each item. Afterward, the score contribution of each item is determined from 0 to 4. For positively worded items (1, 3, 5, 7, and 9), the score contribution is the scale position minus 1.  
290 For negatively worded items (2, 4, 6, 8, and 10), the score contribution is 5 minus the scale position. To obtain the overall SUS score, the sum of the item scores is multiplied by 2.5. Thus, SUS scores range from 0 to 100. The interpretation of the score is: not usable (0-59 points), usable (60-79 points), and excellent (80-100 points), as used in [?]. Finally, to investigate if socio-demographic factors,  
295 such as gender, age and marital status, and technology knowledge impact on the

usability, non-parametric tests, such as Wilcoxon rank test and Kruskal-Wallis rank test, were applied.

## 5. Results

Experiments were run in a realistic scenario at the DomoCasaLab of the  
300 BioRobotic Institute, part of the Echord++ Rif. <sup>8</sup>.

### 5.1. Technical Results

*Outdoor navigation in areas close to buildings.* Fig. 5 shows the map of the testing area, where buildings are represented in cyan, and free navigation space for the robot is represented in white. Black edges represent both building walls and other elements relevant for the navigation and for the planner such as  
305 sidewalks, walk paths, and urban furniture: these latest particular elements are not detectable by the laser because of the height and therefore cannot be used by AMCL for matching map and laser readings.

Resolution of the map is 0.05 m per pixel. Total length of the testing path  
310 was 60 m; navigation lasted 145 seconds; and robot average speed was 0.4 m/s. During the testing, standard deviations of GPS and AMCL have been sampled at 1 Hz for a total of about 200 data. Fig. 4 displays data of standard deviations  $\sigma_x$  and  $\sigma_y$ , respectively, along the  $x$  coordinate and along the  $y$  coordinate for GPS and AMCL. Lower values indicate a better estimation of the position: GPS  
315 values are more precise at the beginning of the path and degrade quickly when the robot enters the narrow passage between buildings, and improve again when the robot exits from the passage. On the contrary, AMCL values are poor at the beginning of the path, when the robot is in the large square and few features are available for matching, and are more precise when the robot enters the narrow  
320 passage, degrading again when the robot exits from the passage.

The path is divided into three sections, A, B, and C. Sections are defined corresponding to the change of localization system. In Fig. 5, the path of the

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<sup>8</sup><http://echord.eu/the-peccioli-rif/>, visited on April 2016

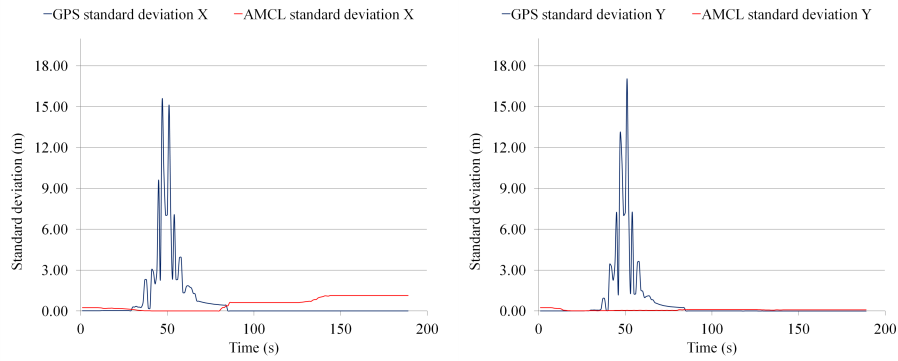


Figure 4: Standard deviations of coordinates x and y for GPS and AMCL on the whole path.

robot is blue when GPS is selected and used, and red when AMCL is selected and used.

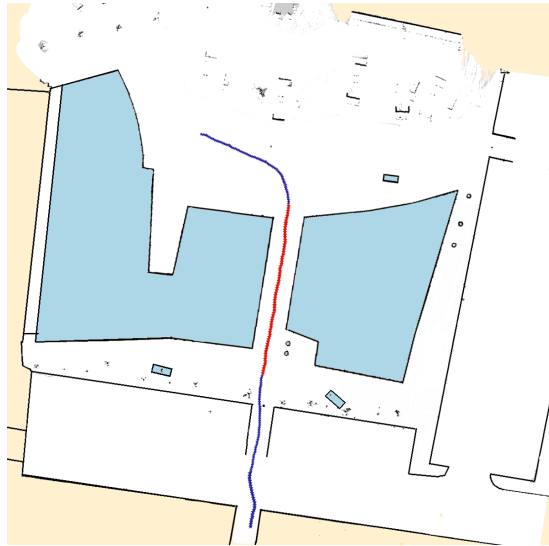


Figure 5: Navigation paths of Outdoor Robot in outdoor trials.

325 Tab. 1 reports averages, standard deviations, and maximum of GPS and AMCL values on the complete path and on the three different sections of path during a test.

In Fig. 6, the combination of GPS and AMCL  $\sigma$  standard deviations along the whole path is represented. Two peaks can be identified, corresponding with

Table 1: Average and standard deviation of GPS and AMCL  $\sigma$  values along  $x$  and  $y$  axis.

		Whole Path		Section A		Section B		Section C	
		x[m]	y[m]	x[m]	y[m]	x[m]	y[m]	x[m]	y[m]
GPS	Mean	0.73	0.64	0.04	0.01	2.52	2.22	0.01	0.00
	Std. dev.	2.17	2.13	0.05	0.01	3.48	3.54	0.00	0.00
	Max	15.39	17.05	0.29	0.29	15.39	17.05	0.01	0.01
AMCL	Mean	0.53	0.08	0.20	0.11	0.03	0.04	0.88	0.09
	Std. dev.	0.15	0.07	0.04	0.10	0.07	0.02	0.25	0.01
	Max	1.14	0.24	0.24	0.24	0.39	0.10	1.14	0.09

330 the changes of sections in which both systems had good performances, although not the best. Tab. 2 reports average and standard deviation of the combination of GPS and AMCL  $\sigma$  values for the  $x$  and  $y$  coordinates on the whole path.

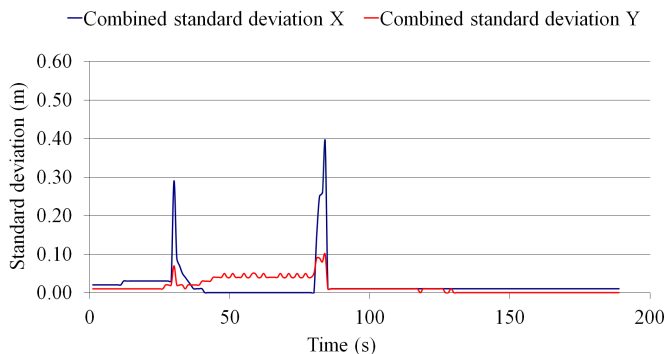


Figure 6: Standard deviations of the combination of GPS and AMCL.

*Robot Cooperation.* The success rate of the sub-task was measured equal to 96% on 60 tests (58 success, 2 failure).

335 However, to achieve a complete reliability on this task, a deeper analysis was performed to implement a recognition of the error mechanism.

The variability due to the manual teaching process was evaluated in 15 different trials, in which the procedure was repeated by the same operator.



Table 2: Average and standard deviation of combined GPS and AMCL  $\sigma$  values.

	Whole Path	
	x[m]	y[m]
Mean	0.02	0.02
Standard deviation	0.04	0.02
Max	0.39	0.10

Table 3: Standard deviation of the final positions of the robot in the teaching phase. Mean offset measured is referred to the desired relative position [ $x = 0.52, y = 0, yaw = 0$ ] between mobile platforms

	x[m]	y[m]	yaw[deg]
Standard deviation	0.0159	0.0159	1.476
Max value	0.5494	0.0255	5.1474
Min value	0.4918	-0.0256	0.1426
Mean offset introduced	0.0043	0.0082	1.651

Standard deviation in the  $x, y$  position and orientation was computed (Tab. 3).

340 The intrinsic variability of the procedure was evaluated in 30 additional trials, related to three different processes of the docking procedure. In Tab. 4, data are reported divided, for each sub-session and related to the global evaluation, considering all three trials as a whole. The resulting data confirm the contributions of both cited factors in the final variability of the docking  
345 procedure.

Considering the data retrieved from the analysis described earlier, two strategies were added to manage the appearance and resolution of misalignments:

1. To reduce the variability introduced by the operator, reference of the outdoor robot was provided online to aid the operator during the teaching  
350 phase.
2. To avoid failures during the transfer of items between outdoor and condo-

Table 4: Mean and standard deviation of the final positions at the end of docking phase during trial 1 (n = 10, success = 10, failure = 0), trial 2 (n = 10, success = 9, failure = 1) and trial 3 (n = 10, success = 10, failure = 0). Desired relative pose is defined as:  $x = 0.52, y = 0.0, yaw = 0.0$

		Test 1	Test 2	Test 3	Global
x[m]	Mean	0.5226	0.5163	0.5079	0.5156
	Standard deviation	0.0129	0.0157	0.0110	0.0142
	Max value	0.5520	0.5376	0.5297	0.5520
	Min value	0.5053	0.4895	0.4914	0.4895
y[m]	Mean	-0.0304	-0.0267	0.0171	-0.0133
	Standard deviation	0.0114	0.0111	0.0095	0.0243
	Max value	-0.0092	-0.0075	0.0314	0.0314
	Min value	-0.0483	-0.0451	0.0036	-0.0483
yaw[deg]	Mean	-0.3518	1.8459	1.1312	0.8751
	Standard deviation	0.8500	1.2673	0.6152	1.3065
	Max value	0.7301	4.1960	2.3368	4.1960
	Min value	-1.6483	0.4538	0.4821	-1.6483

minium platforms, a simple failure recovery system was used. Whenever a docking process was performed, resulting in a final position where the reference point and relative orientation were identified out of a “region of confidence”, empirically measured as  $\pm 0.04$  tolerance on  $x$  and  $y$  axis and  $\pm 2$  deg on orientation, the procedure was simply restarted before the activation of rollers. In this way, even if there was a hypercorrection of the procedure, namely the correction of right performances, the probability of a failure occurring was reduced. In other words, each navigation task is characterized by a balance among accepted tolerance and requested precision that the navigation planner must respect. Using a simple failure recovery enhances the success rate of the operation, without changing the navigation planner which would cause a loss of generality.

*Use of elevator and multi-floor navigation.* The success rate of the sub-tasks  
365 was measured as 100% on 30 tests.

As mentioned, to prove the repeatability and robustness of this sub-task, a focused evaluation was performed. On 30 tests performed, current position of condominium robot was logged. Positions are plotted in Fig. 7, while in Fig. 8 the same paths are referred to the relative maps.

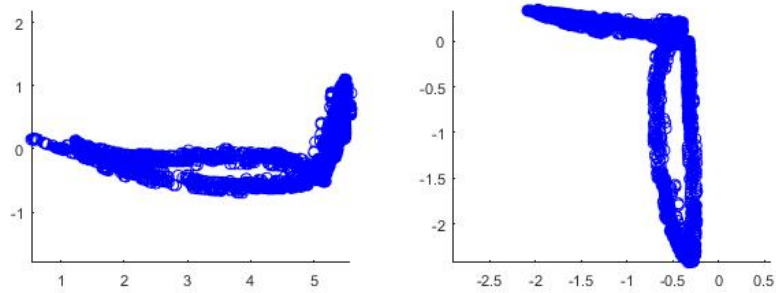


Figure 7: Navigation paths of the elevator trials (First floor - left side, Ground floor - right side).

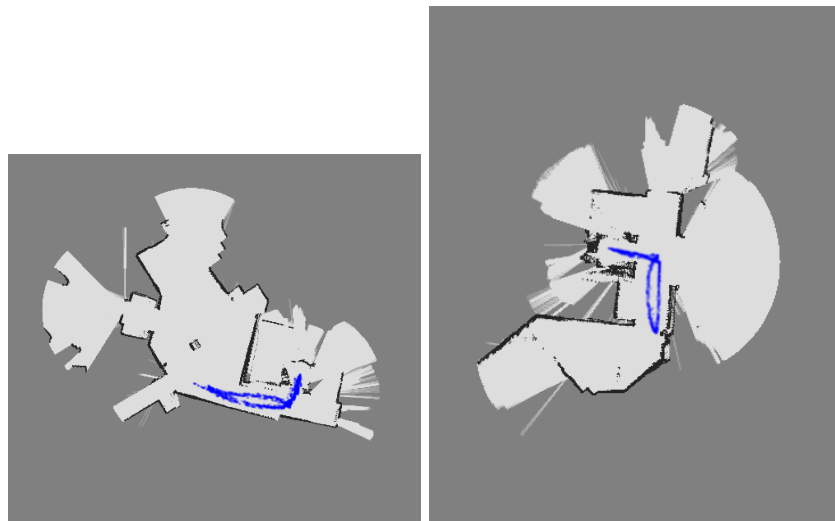


Figure 8: Navigation paths of the elevator trials matched with the maps (First floor - left side, Ground floor - right side).

In Fig. 9, the scatter plots of the final position of the mobile platform inside the elevator at the first floor and ground floor are depicted, respectively. Mean and standard deviation of resulted values are reported in Tab. 5, showing the high repeatability and stability achieved on the sub-task.

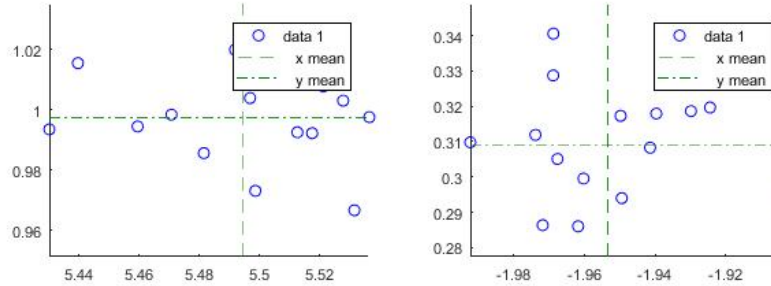


Figure 9: Scatter plots of the final positions of the robot inside the elevator (First floor - left side, Ground floor - right side).

Table 5: Mean and standard deviation of the final positions of the robot inside the elevator on the first and ground floor.

	Mean and standard deviation		
	x[m]	y[m]	yaw[deg]
First Floor point (5.5 1.1 84)	$5.495 \pm 0.033$	$0.997 \pm 0.015$	$76.9 \pm 3.5$
Ground Floor point (-2.07 0.33 165)	$-1.953 \pm 0.023$	$0.309 \pm 0.015$	$170.6 \pm 3.3$

## 5.2. Results of user evaluation

Thirty elderly people, who signed a written informed consent for the research, were involved in the Robot-Era experimentation. Participants ages ranged from 65 to 84 years old (Age:  $71.00 \pm 5.45$ ) and the sample was composed of 15 men (Age:  $70.60 \pm 4.84$ ) and 15 women (Age:  $71.40 \pm 6.14$ ).

According to The Assistive Technology Device Predisposition Assessment, [? ], the Mini-Mental State Examination [? ] and Instrumental Activities of

Daily Living (IADL) [? ], the sample was composed of 7 participants with a low level of autonomy, 7 with a middle level, and 16 with a high level of autonomy.

Regarding the socio-demographic characteristics, 12 participants lived with their own partner and 18 lived alone. Regarding educational level, the sample was balanced because 15 subjects had a low educational level and 15 subjects had a high one. Finally, concerning user skills regarding technology, 13 individuals out of 30 were able to use a PC and internet for entertainment or information. Nevertheless, the most technological devices and software were used by a few members of the sample, such as Smartphone (8 users), Tablet (6 users), and Skype (8 users).

First of all, the reliability of participants' answers was verified using the Cronbachs Alpha calculation [? ], and the cut-off value for being acceptable is .7 [? ]. In this study, the Cronbachs Alpha of the SUS was .862.

Tab.7 presents the results of the SUS questionnaire and gives a first impression on how participants perceived the interaction with Robot-Era system in terms of usability. According to the overall values of SUS Score, the Robot-Era system was evaluated as excellent ( $81.94 \pm 3.49$ ) by nine elderly people. Eleven participants perceived it as usable ( $70.91 \pm 6.73$ ), and the proposed system was not usable ( $39.75 \pm 11.81$ ) for ten older adults.

Furthermore, to identify if personal and cultural factors had influenced the users' answers, nonparametric tests, such as Wilcoxon rank test and Kruskal-Wallis rank test, were applied because the variables were not normally distributed. In particular, the level of autonomy; socio-demographic data such as gender, age, educational level, and marital status; and the technology knowledge factors did not influence statistically the overall SUS scores.

## 6. Discussion and conclusion

Even if not quantitatively investigated in the current state of the art, the user experience can be affected by the reliability of the system. In other words, particularly in new and innovative solutions as the one proposed, failure that

410 occurred in the system during the services can be self-attributed by the end-users, decreasing their perception of usability of the system.

Furthermore, differently from other technological solutions (as logistics or industrial), the analysis of technology readiness level of innovative systems addressed to be used by non-expert end users has to include not only technical  
415 aspects but also more user-related factors.

For these reasons, the analysis performed and presented in this paper has been focused on both aspects to provide a complete evaluation of the system developed.

To better understand the process, a deeper analysis was performed of the  
420 most difficult sub-tasks: outdoor navigation in areas close to buildings, docking process for transport of items between outdoor and indoor environment (and vice versa), and navigation inside the elevator for multi-floor navigation. The results obtained showed the repeatability and robustness of the system.

From the user's point of view, considering the overall SUS scores, the proposed system was evaluated positively from the usability perspective by twenty  
425 elderly participants. The level of autonomy as well as the technology skills variables did not impact the perceived usability significantly. Moreover, the overall usability of the system is not related to age, gender, and educational level. These results suggest that the proposed system was developed to be usable for a wide  
430 segment of the elderly population.

Concerning the 10 items of the SUS questionnaire, the results are positive because the positively phrased items have a mode value equal to 4, while the negatively phrased items have a mode value equal to 2 (excepted for Item4). In particular, Item1 indicates that participants would like to use the proposed  
435 system frequently and assessed a positive rating (Mode:4). In effect, 15 elderly people agreed and strongly agreed with Item1. Moreover, most older volunteers (19 of 30) felt very confident using the system during the experimentation (Item9, Mode:4) and only 9 of them found the robotics system very cumbersome to use (Item8, Mode:2). These results suggest that the elderly users were  
440 satisfied by the evaluated system.

Moreover, the proposed services (shopping delivery and garbage collection) were accomplished by all participants, and this could indicate enough efficiency of the solutions tested. In confirmation of this, the perceived ease of use was judged positive by 21 elderly people (Item3, Mode:4) and the system was not  
445 unnecessarily complex (Item2, Mode:2).

Furthermore, according to users' answers, the system is characterized by a high learnability because only 4 elderly people reported the need to learn a lot of things before using the proposed solution (Item10, Mode:2), while most of them (19 of 30) would imagine that most people would learn to use this system  
450 very quickly (Item7, Mode:4). However, elderly users asserted a neutral score regarding a needed support of a technical person to be able to use it (Item4, Mode:3).

Finally, 15 participants found the various functions to be well integrated (Item5, Mode:4), and only 2 users thought there was too much inconsistency  
455 in the robotic services (Item6, Mode:2). These results suggest that the elderly volunteers had enough trust in the capabilities of the described system.

As a final result, the developed solution could be considered usable by end-users for of the developed services.

The choice of SUS was made because this evaluation tool is a quick as-  
460 sessment of the usability of a product. The tool is easy for participants to administer and to complete, giving a global view of subjective assessments of usability. However, the SUS is not an objective measure of a systems usability, but it is a measure of perceived usability. For these reasons, the assessment of perceived usability has some limitations because participants could be in-  
465 consistent and prone to bias while rating their own usability experience after interacting with a system. Moreover, an evaluation tool based on a Likert scale could be subject to distortion such as the central tendency bias, in which the user avoids the use of extreme response categories, or the acquiescence bias, in which the user always agrees with statements. However, developing survey in-  
470 struments with positively and negatively worded items, such as the SUS, could avoid response bias [? ]. Keeping in mind these limitations, in this study the

Cronbachs Alpha test was applied to verify the internal consistency of the SUS survey. The Cronbachs Alpha of the SUS was .862, above the threshold of .7 for being acceptable [? ], so the outcome of the survey can be considered reliable.

475 However, for future work, the usability of the robotics system will be evaluated with a mixed method based both on quantitative approaches, such as SUS, and qualitative ones, such as the interview, to avoid distortion or bias. Furthermore, an objective measure of a systems usability will be done by calculating metrics such as the success rate, the time required to complete a task, or the error rate.

480 In conclusion, in both the shopping delivery and the garbage collection services proposed, a high technology readiness level was achieved together with a high usability perceived by the end-users involved in the experiments. Considering the main important characteristic, which is the capability of carrying items from outdoor areas to the users' homes through heterogeneous environments, 485 the proposed solution provides the starting point of the development of new delivery services based on automation and cooperation between different mobile platforms.

## 7. Acknowledgement

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## References



Table 6: Questionnaire results

<b>Item 1: I think that I would like to use Robot-Era system frequently.</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
5	3	7	8	7
16.67%	10.00%	23.33%	26.67%	23.33%
<b>Item 2: I found Robot-Era system unnecessarily complex.</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
10	10	6	3	1
33.33%	33.33%	20.00%	10.00%	3.33%
<b>Item 3: I thought Robot-Era system was easy to use.</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
1	2	6	14	7
3.33%	6.67%	20.00%	46.67%	23.33%
<b>Item 4: I think that I would need the support of a technical person to be able to use Robot-Era system.</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
6	6	9	4	5
20.00%	20.00%	30.00%	13.33%	16.67%
<b>Item 5: I found the various functions in Robot-Era system were well integrated</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
2	3	10	12	3
6.67%	10.00%	33.33%	40.00%	10.00%
<b>Item 6: I thought there was too much inconsistency</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
6	13	9	1	1
20.00%	43.33%	30.00%	3.33%	3.33%
<b>Item 7: I would imagine that most people would learn</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
3	2	6	13	6
10.00%	6.67%	20.00%	43.33%	20.00%
<b>Item 8: I found Robot-Era system very cumbersome to use.</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
9	10	5	3	3
30.00%	33.33%	16.67%	10.00%	10.00%
<b>Item 9: I felt very confident using Robot-Era system.</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
2	1	8	13	6
6.67%	3.33%	26.67%	43.33%	20.00%
<b>Item 10: I needed to learn a lot of things before I could get going with Robot-Era system</b>				
Strongly disagree	Disagree	Neither agree nor disagree	Agree	Strongly Agree
6	11	9	0	4
20.00%	36.67%	30.00%	0.00%	13.33%

Table 7: Minimum, maximum, mode, and median values of users' answers to questionnaire

	Item1	Item2	Item3	Item4	Item5	Item6	Item7	Item8	Item9	Item10
Min	1	1	1	1	1	1	1	1	1	1
Max	5	5	5	5	5	5	5	5	5	5
Mode	4	2	4	3	4	2	4	2	4	2
Median	3,5	2	4	3	3,5	2	4	2	4	2