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Unified Travel Solutions: Bridging Outdoor Route Planning with Intelligent Indoor Navigation

Benjamin Molina[1,*], **Carlos E. Palau**[1] **and Jaime Calvo-Gallego**[2]

[1]*Communication Department, Universitat Politècnica de València, Spain*

[2]*Department of Computing and Automatics, Universidad de Salamanca, Spain*

Abstract: Indoor navigation, an innovative service built on indoor localization, is a game-changer for travelers. This paper introduces a unique multimodal, dynamic indoor navigation service for indoor spaces. The novelty of this service lies in its seamless integration with outdoor routers, paving the way for a comprehensive door-to-door trip planner. The service's indoor multimodality is a key focus, considering accessibility options profiling and incorporating limited vehicular paths (e.g., internal buses in airports). The service's indoor dynamism is another standout feature involving real-time monitoring of events within the navigation path. The integration with outdoor routers is a significant achievement, primarily through the establishment of common interconnection points (shared points where indoor and outdoor navigation systems can exchange data) and a common data format structure (a standardized way of representing and exchanging navigation data). The proposed navigation service was put to the test in three real deployments at Berlin Tegel, Berlin Schönefeld, and Palma International airports. Users traveling between these cities experienced the system's rapid detection of mechanical problems (e.g., travelators or elevators out of order) and incidents (e.g., temporarily non-navigable areas). The service's integration with other travel assistants and services, such as evaluating waiting times at check-in counters and security checkpoints, provided more accurate estimations of indoor navigation travel time and helped avoid agglomeration. These successful real-world validations underscore the service's effectiveness and reliability. The findings indicate that this innovative service significantly improves the travel experience by enhancing the planning and scheduling of movements from origin to destination. The validation showed an increase in travel efficiency, reduced wait times, and better accessibility options for travelers, underscoring the practical benefits of the proposed door-to-door navigation system.

Keywords: indoor routing, indoor navigation, indoor positioning, multimodal routing

1. Introduction

People are used to carrying out most of their activities indoors in modern cities. Whatever the activity is, a plethora of related services help users fulfill special tasks thanks to mobile devices and sensors connecting user context with service context. From a broad perspective, this is typically called the Internet of Things (IoT), where smart objects connect together and build from ad hoc to remote services covering user and industry requirements. Industry, government, and users converge at a wide scale level in the framework of smart cities [1] to fulfill their inhabitants' needs efficiently and sustainably.

A smart city encompasses multiple dimensions, and this paper primarily focuses on smart mobility in indoor spaces. Information and communication technologies are applied to transportation as intelligent transportation systems for outdoor spaces. Outdoor routers can provide an efficient route for travelers from one place to another, even with the possibility of performing real-time tracking along the route using the Global Positioning System (GPS). Multimodal outdoor routers are commonly used by travelers in the form of desktop and mobile services. However, the transfer of such services to indoor spaces is quite limited, and it remains a hot research topic of growing interest in the commercial sector. Several difficulties still need to be fixed to provide the indoor traveler with a successful quality of experience. As an illustration, indoor navigation primarily relies on indoor location, which is still not accurate enough for buildings in a cost-effective way. Commercial-off-the-shelf (COTS) technologies such as Wi-Fi and Bluetooth Low Energy (BLE) are being widely deployed for indoor positioning in open spaces such as airports, universities, hospitals, etc. Still, specific ad hoc fine-tuning is typically required to offer good accuracy. Turn-by-turn indications similar to outdoor navigation are also a big challenge.

The main novelties coming from this paper are:

- Seamless integration of indoor and outdoor navigation services to provide a real door-to-door journey to the user; interconnection points acting as gateways between outdoor and indoor spaces are defined to facilitate transitions. The technical contribution

*Corresponding author: Benjamin Molina, Communication Department, Universitat Politècnica de València, Spain. Email: benmomo@upvnet.upv.es

consists of defining these points and establishing a margin area in case of different background cartography maps (e.g., Google Maps, OpenStreetMaps (OSM), etc.).

- Dynamic navigation of the indoor service, as a real-time navigation graph that is continuously generated, providing accurate estimations in terms of trip distance plus duration. Mechanical POIs (elevators, escalators, and travelators) are constantly monitored to guide travelers through the fastest route and avoid point of interest (POI) failures. The technical contribution refers to the continuous graph generation, which can update with changes in mechanical POIs.
- Indoor navigation through integration with airport real-time services. This involves, for instance, the last updates of boarding gates to guide the traveler properly without panic. Moreover, the indoor navigation service seamlessly integrates with Waiting Time Detection services at queues (e.g., check-in counters and security checkpoints) to provide a more precise time estimation of the trip. The technical contribution does not encapsulate the graph as an isolated standalone service. It incorporates external interaction with other services, providing relevant information about the (real-time) status of the physical area conceptualized by the graph. Therefore, it can be easily enriched.
- Step-by-step built-in indoor navigation support, as the traveler defines intermediate navigation route points according to planned operations (check-in, luggage belts, rental car stations, etc.). The technical contribution defines and develops a composed output format in which the global navigation route can be split into different intermediate routes according to predefined features (e.g., level changes) or particular actions travelers take (e.g., luggage check-in).
- Accessibility support, as the indoor routing algorithm can avoid special POIs (e.g., stairs) according to the traveler's settings. The technical contribution deals with various simultaneous graphs representing a different routing perspective according to accessibility constraints (e.g., a blind person will never use the stairs).
- Easy design for a fast deployment. Graphs are easily generated with web drag-and-drop tools, and multiple edge weights can be assigned, potentially supporting multimodality. Technical contribution refers to the administration user interface that allows for the easy addition, editing, and deletion of nodes and edges compounding the graph. The UI (user interface) is intuitive and web-based, not requiring special skills or training.

This paper is structured as follows: Section 2 presents related work considering different technologies and techniques for indoor positioning and indoor navigation. Section 3 introduces the architecture of the system. The performance evaluation is presented, providing results for both offline and online (real-time) navigation modes. Finally, this paper ends with the conclusions and further work.

2. Related Work

Some studies [2–4] have shown that the market for outdoor location-based services (LBS) has increased over the last decades, with GPS being the prime technology used for these applications (e.g., car navigation). LBS allows online navigation and service information, on-the-spot advertisement, notifications possibilities, plus other spatial-related information. Nevertheless, it has primarily been targeting outdoor scenarios, while Indoor Positioning Systems (IPSs) have only widely attracted attention during the last five years with the introduction of Bluetooth.

Although there are various taxonomies for indoor localization in the literature, there is a general classification in two separate groups: those based on Radio Frequency (RF) and those using another kind of technology. One may cite wireless local area networks, such as Wi-Fi, BLE, and radio-frequency identification localization among RF-based techniques. Researchers have explored several alternatives using Wi-Fi signal intensity to estimate position [5–7], Bluetooth [8–10], ultra-wideband [11, 12], and RFID [13, 14]. Non-RF-based techniques may include alternative technologies based on audio, visual, ultrasonic, infrared, and laser sensors. This paper will focus on combining Wi-Fi and BLE technologies for indoor service implementation based on location fingerprinting, as it provides good results. A complete overview of IPS technologies is outside the scope of this paper. It has already been targeted in a recently published paper by the authors [15], where a multimodal indoor localization system is described and evaluated in terms of accuracy. Since this paper continues with the previous one, indoor localization accuracy will mostly affect overall accuracy.

Navigation services rely on two crucial factors: (i) how the routing graph or route database is built and managed and (ii) the route calculation module using the route database plus some algorithm. The algorithm optimizes a particular aspect of the graph to ensure finding the shortest, fastest, or cheapest route, which is linked to the weight associated with the edges (the navigable space is converted to a graph consisting of nodes and edges in a certain topology). The algorithm published by Dijkstra in 1959 [16] belongs to the family of greedy algorithms and is widely used to solve shortest-path problems [17] due to its simplicity and robustness. Recent publications on BLE indoor navigation still use the Dijkstra algorithm [18, 19] for route planning.

Other algorithms, such as Bellman–Ford and Floyd–Warshall, are also used in route optimization problems [20]. Another common algorithm is the A-star, a widely used pathfinding and graph traversal algorithm known for its efficiency and accuracy. It combines the strengths of Dijkstra's algorithm and Greedy Best-First Search using a heuristic to estimate the shortest path from the start node to the goal node. A-star is quite efficient and adopted in outdoor environments for trip planning [21] but also in indoor environments [22]. Our research paper builds a directed graph and evaluates it both for Dijkstra and A-star.

Considering how graphs are built and managed for indoor navigation, there is limited effort to generate and consolidate a standard. IndoorGML, specified by the Open Geospatial Consortium, is probably the best candidate. It describes indoor spaces and their relationships, but not architectural features; this is provided by CityGML or Industry Foundation Classes – IFC data models. The standard realizes the complexity of modeling indoor spaces due to consumer's freedom compared to outdoor scenarios: whereas vehicles are supposed to drive only along streets, people can walk freely across different floors and use different transportation modes such as lifts, escalators, etc. Unfortunately, IndoorGML has not gained much attention from the market, and tools for edition and management are very limited. Several articles have been published about it [23, 24] with reduced scopes. The i-locate project [25] tried to produce a data model that bridges IndoorGML and OSM using the lessons learned from the deprecated IndoorOSM tagging schema and extensions. Unfortunately, the proposed architecture was quite complex and had no significant impact on the community.

It is difficult to analyze and compare current solutions from commercial entities, as many technology aspects are not disclosed, and only a few publications are available, such as indoo.rs CaLibre [26]. Regarding open approaches, AnyPlace is a recent Internet-based Indoor Navigation system [27]. The architecture is similar to the one proposed in this paper; however, the map service, called Architect, is limited to rasterized images instead of the vectorial formats employed in this paper, providing better quality. AnyPlace is also oriented to crowdsourcing [28], whereas this paper does not target such a feature, which is considered further work. On the contrary, this paper integrates real-time data and services by building a real-time navigation graph to provide the best (fastest) route. Finally, in Kumrai et al. [29], a new method using smartphone camera images with received Wi-Fi signal strength indicators is proposed to automatically construct a Wi-Fi-based indoor logical location classifier for commercial complexes. However, this method is not real-time oriented. On the other hand, as stated in Kumrai et al. [29], indoor logical location classifiers using data collected by sensors embedded in smartphones and handheld devices have been actively studied due to recent advances in smartphone technologies. The latter reference summarizes the characteristics of the most relevant recent related studies ([29] page 4, Table 1).

3. System Architecture

Indoor navigation relies on three associated modules required to provide a successful independent service.

The first module is the map service, which shows the route on a georeferenced map and makes the user experience more attractive. When they are being built, indoor spaces rely on the construction sector that uses architectural (CAD, computer-aided design) maps. Unfortunately, no valid indoor maps are usually created for indoor navigation. Converting an architectural map (e.g., AutoCAD's DWG, MicroStation's DGN) to a valid indoor map (Esri's shapefile – SHP) is difficult. It should be guided by an expert to obtain a professional output.

The second component refers to the POI service, being a relevant piece of information for the user at the presentation level because they are typically the starting, end, and intermediate spots in the route. Considering mainly mobility issues, 20 categories have been selected: toilets, elevators, escalators, travelators, boarding gates, entrances, security checkpoints, check-in points, stairs, catering, shops, information points, luggage belts, meeting points, shuttle bus stations, car rental places, taxis, public buses, car sharing stations, and bike sharing stations.

The third component is the indoor positioning service, which displays the customer's position in real time. Fingerprinting was selected as the mechanism to use for indoor positioning. It consists of two steps. During the first phase, the offline phase, measurements are taken in special spots of the buildings (terminals), forming a fingerprinting grid. In the second phase of the fingerprinting process, called the online phase, travelers take measurements from their smartphones (via Wi-Fi and BLE) and send them to a server, which compares them with the fingerprinting database and returns a location estimation based on a concrete criterion (typically distance in the signal space). The algorithm principally employs a weighted K-nearest neighbor to calculate the location, so the result is a smart interpolation of the three closest ones; therefore, the algorithm can estimate any intermediate place among fingerprints. The detailed description of this positioning service is outside the scope of this paper and was subject to a previous publication [15].

Moreover, the navigation service makes proactive and/or reactive decisions according to the traveler's context (e.g., the user changes route or gets lost).

3.1. Indoor navigation

Indoor navigation involves a series of actions that are typically performed on the client and server side. Though several different architectures are possible and valid, Figure 1 depicts the main building blocks, and their interactions with the architectural approach followed in this paper:

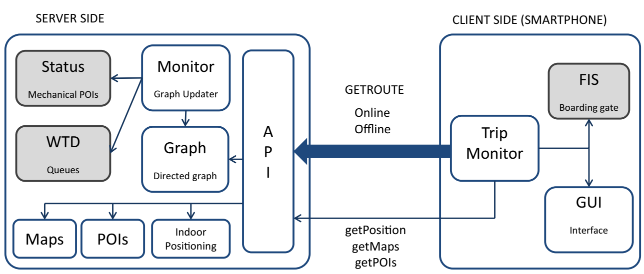
- Server side: it is responsible for generating a valid graph and updating it periodically according to external services (in gray): either status information of mechanical POIs or Waiting Time Detection services at specific places of the graph. The server side exposes an Application Programming Interface (API) to invoke the service, including access to complimentary services such as maps, POIs, and indoor positioning. Note that the server never contacts the client directly; the client periodically requests the server for updated information.
- Client side: it is in charge of displaying the routes to the user via a GUI (graphical user interface) and monitoring the indoor route (trip). Changes in the route may be obtained from external services (in gray), such as the flight information service (FIS), or directly from the server if the navigation graph changes. This triggers some action (e.g., an alert) notifying the user. The client-side module accesses the complimentary services (maps, POIs, and indoor positioning) to display the related information. Note also that the service invocation can be either offline or online. Neither indoor positioning nor monitoring is required by offline routing. Such a service is useful for planning the route in advance, broadly estimating the path to follow, the involved distance, and the predicted duration.

In fact, this connects with the offline outdoor router, outside the scope of this paper, to have an overall view of the whole route in terms of time and distance. For online routing, online monitoring is mandatory to check that the path is correctly followed by the traveler (not getting lost) and that it has not changed since the routing request. Obviously, this involves interacting with external services and using the indoor positioning service.

3.2. Graph manager

As the related work section commented, no common or consolidated standard exists for building indoor navigation graphs. The approach of using some extension of outdoor routing (e.g., OSM) introducing additional tags describing indoor functionalities was initially investigated because it would directly provide seamless integration with outdoor routers (e.g., OpenTripPlanner). However, initial contact with researchers in this line did not provide enough support and confidence, so we opted for our own

Figure 1
General architecture of the indoor navigation system



approach. The approach is based on simplicity (easy to manage and export) and flexibility (supporting different navigation modes, easily extensible).

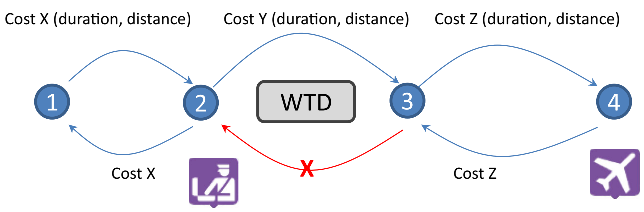
Independently of the opted approach, graph calculations from a mathematical perspective are always reduced to nodes and edges interconnecting them. Therefore, we started from these basics and modeled an airport, considering three aspects: (i) what type of graph is needed, (ii) what different types of nodes have to be modeled, and (iii) what different types of edges are required.

The first aspect is relatively easy to find out. A dual-weighted directed graph is required. The situation is depicted in Figure 2 as a sample scenario where a traveler goes to a boarding gate. In this case, the path is divided into different sections modeled by starting node (node 1), intermediate nodes (nodes 2 and 3), and end node (node 4). The transitions between nodes represent the edges, including the cost of going from one node to another. As the target application for such a graph is (indoor) navigation, the cost in terms of duration and distance is of particular interest. The distance can be easily (automatically) calculated if the nodes are georeferenced, which is the case if we deal with georeferenced maps served by a maps service. Duration cost depends on several, but it can be statically calculated based on distance and an average walking speed (e.g., cost X-duration) or dynamically based on an external service (e.g., cost Y-duration), which will be the case of a security checkpoint in an airport (see Figure 2) where the duration value is obtained from a Waiting Time Detection service. The security checkpoint is also a good example to justify why the graph has to be directed, as it is only possible to go in one way and has no sense to go in the other way. Therefore, whereas a traveler can walk from node 1 to node 2 and vice versa, it makes no sense to go from node 3 to node 2. The option of a directed graph assigning different weights between two nodes depending on the direction is even more flexible. It allows "cutting" one direction (e.g., for security checkpoints) and allows for discrimination in certain situations where the cost (in terms of duration) between two nodes is different. This could be the case of a travelator in an airport facilitating fast access to the boarding gate (e.g., from node 3 to node 4 in Figure 2) but with no travelator in the opposite direction (from node 4 to node 3).

The second aspect to analyze refers to the different nodes to be considered in the graph. In terms of navigation, four main categories have been identified:

- *Simple*: this is a typical base node that allows the basic building and representation of the graph. The remaining nodes could also be considered as an extension of this category.
- *AnchorFloor*: this node can connect two or more floors within a building. Typically, this will be the case with airport stairs, escalators, and lifts.

Figure 2
Dual-weighted directed graph for airports



- *AnchorBuilding*: this node can connect two or more buildings (terminals) within an airport. Commonly, this will be a corridor or a gate connecting the nearby terminals.
- *AnchorOut*: this node can connect to an outdoor environment and allows the transition from indoor to outdoor routing. Generally, this refers to main entrances at airports and determines the tracking switching mechanism (e.g., from GPS to indoor positioning).

Besides category, graph nodes may also be associated with POIs. In fact, the normal procedure when building the graph starts with importing the POIs (from the POI service) and generates automatically the associated nodes depending on the location. Afterward, intermediate (simple) nodes are generated, which allow walking from one POI to another. Thus, some nodes of the graph will refer to a shop, a restaurant, a toilet, etc., and the traveler will always be able to walk across POIs as they have a representation in the graph.

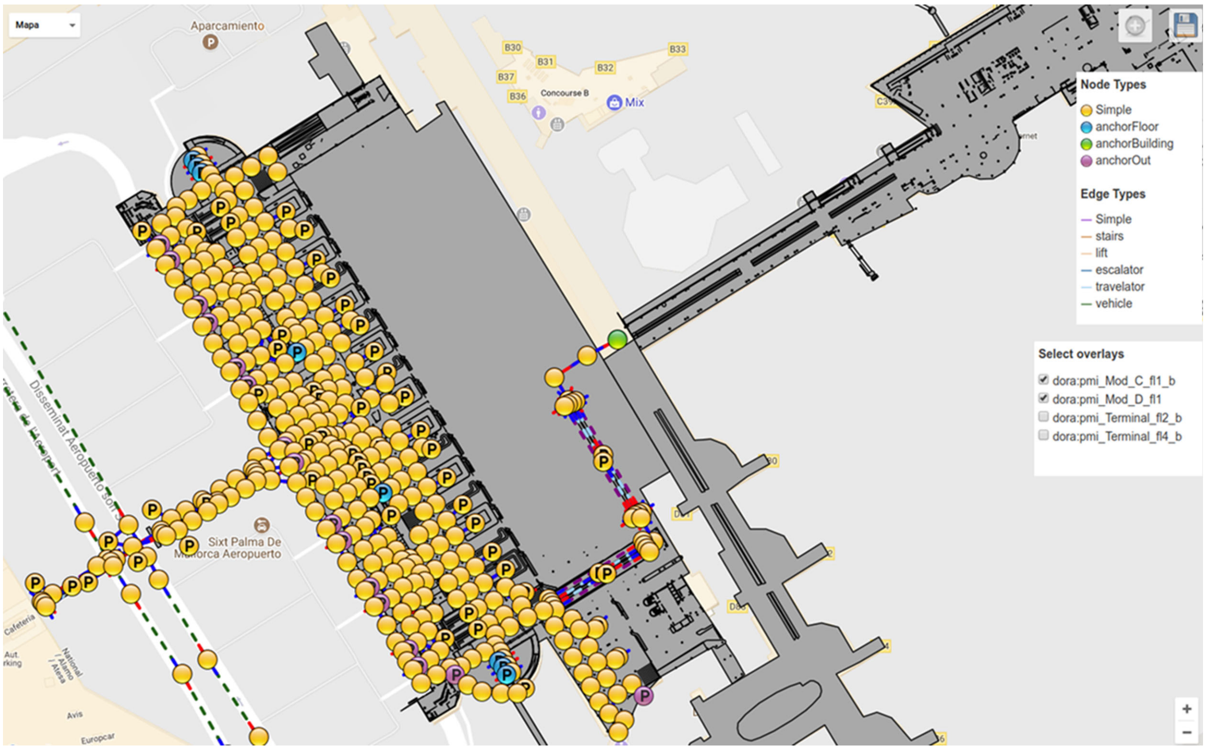
A web, visual, and intuitive tool has been developed to generate the graph. Some functionality is automatically available, such as visualizing georeferenced maps and generating the nodes representing the available POIs for each floor. After that, the manager only has to click on a particular point on the map representing a specific location to create a node. The zoom-in functionality of the georeferenced map provides as much accuracy in the location as possible.

An example of the Palma International (PMI) airport is depicted in Figure 3 for the main terminal (Floor 0). Simple nodes (in yellow) represent the majority of the graph, which encompasses not only indoor areas but also external areas to build connections to outdoor connection points (bus stations, taxis, etc.) or even other buildings (e.g., parking spots). *AnchorFloor* nodes (blue nodes) correspond to lifts connecting Floor 0 to Floor 2 and Floor 4 (there are only even floors in the main terminal). They are mostly located in the north or south part of the building. There is one *AnchorBuilding* node (green node) on the east connecting to Terminal C and Terminal D. *AnchorOut* nodes (purple nodes) are located on the west part of the building corresponding to entrances. As Floor 0 is associated with arrivals (luggage belts), travelers leave the building to take the bus, taxi, shuttle, etc., to go to the city.

The third aspect to cover relates to edges connecting nodes. Here, six categories have been identified:

- *Simple*: relates to the basic edge. Distance cost can be automatically calculated from the distance between nodes, and duration cost is calculated by considering an average speed of 3.6 km/h.
- *Stairs*: it models the usage of stairs. Distance cost can be automatically calculated from the distance between nodes, considering an average slope of 35 degrees. Duration cost is calculated similarly to the simple node but adds a factor of 1.2, as walking on a flat floor is easier and faster than going upstairs.
- *Lift*: it models the usage of lifts (elevators). Distance cost cannot be automatically calculated from the distance between nodes because they have the same latitude and longitude values. Altitude values are not used, but floor levels are. A default value can be associated (e.g., 5 meters), but it is preferable to insert the distance between floors manually. Duration cost is calculated similarly to the simple node, but a factor of 0.6 is added, as it should be faster than just walking. Besides, this approach prioritizes using lifts instead of stairs, which is the common case for people in airports.
- *Escalator*: it models the usage of escalators. Distance cost can be automatically calculated from the distance between nodes

Figure 3
Navigation graph (PMI airport, main terminal, Floor 0)



considering an average slope of 35 degrees (as for stairs). Duration cost is calculated similarly to the simple node but adds a factor of 0.8, establishing priority in front of stairs.

- *Travelator*: it models the usage of travelators. Distance cost can be automatically calculated from the distance between nodes. Duration cost is calculated similarly to the simple node, but a factor of 0.8 is added, as it should be faster than just walking.
- *Vehicle*: it models the usage of vehicles. Obviously, vehicles do not drive inside the terminals, but there are airport shuttles that connect distant terminals and park sites. Distance cost can be automatically calculated from the distance between nodes. Duration cost is calculated similarly to the simple node but adds a factor of 0.4 (faster access).

Average speed and associated factors have been empirically established and obtained from consulting airport operators. Nevertheless, they can be changed or adjusted if required. From a practical perspective, the most relevant aspect is the assignment of priorities according to travelers' behavior so that lifts and escalators are prioritized before stairs and travelators before simple walks. It is obviously more comfortable, above all, if one has to carry luggage. Note that airport operators are also concerned with facilitating mobility for travelers and avoiding bottlenecks.

4. Performance Evaluation

4.1. Initial data analysis and preparation

Before starting any testing scenario, it is important to summarize the amount of data available for the generated graphs in the airports. Table 1 depicts the number of nodes and edges involved. Several floors are concerned for PMI, and the total number rises to 1.526 nodes plus 4.374 edges. Berlin Tegel (TXL) airport has several terminals, but all actions concerning travelers involve only the ground floor; thus, solely one (aggregated) georeferenced image was built. For Berlin Schönefeld (SXF) airport, two floors are affected. As can be observed, the graph size is significant. Even if the navigation graph can be split into different floors, it is impossible to anticipate such behavior of the traveler, who will typically traverse several floors. Therefore, the whole airport graph must be taken for the routing path calculation.

Table 1
Graph size for PMI, TXL, and SXF airports

Airport floor	Nodes	Edges
PMI – Main terminal – Floor 0	453	1187
PMI – Main terminal – Floor 2	523	1498
PMI – Main terminal – Floor 4	157	395
PMI – Terminal C – Floor 1	393	1294
TXL – All terminals – Floor 0	1018	2741
SXF – All terminals – Floor 0	334	863
SXF – All terminals –Floor 1	103	247

As the graph size is considerable and building it for every routing request would be inefficient, the graph structure should be generated and stored (cached) in memory at service start-up. Note that there is a different graph for the routing calculation depending on the request parameters; hence, a multi-cached structure has been designed. It is updated every 2 min, and basically, the structure considers two scenarios and four possible graph modes:

- *Possible graph modes relate to the associated weight assigned to graph edges*. Regarding mobility, we need duration (time) and distance (space). For both cases (duration and distance), a special graph considers accessibility options where some nodes are removed (e.g., stairs).

- *Possible scenarios relate to real-time or non-real-time situations*. In real-time situations, the traveler is present at the airport, and the graph must be updated with the latest information according to the available external services: (i) status for mechanical POIs, (ii) Waiting Time Detection (WTD) for queues, and (iii) incidents for non-accessible areas.

For non-real-time situations, the traveler is not present at the airport and may typically be planning the route. Therefore, no real-time information is required, and average values can be used to provide standard estimations to the user. However, the non-real-time structure can also be refreshed depending on the availability of two external services. The non-real-time graph can be updated if the WTD service can create usage models and support future values. Besides, if some envisaged incidents are active when the traveler requests the route, the graph is also refreshed, removing the concerned areas. The whole process is called projection of the non-real-time graph in the future, but it depends on the external services supporting such a feature. In our case, they were available for the TXL airport.

Before starting a trip, travelers may plan the route to the airport several days in advance, including the outdoor and indoor parts. There is no highly accurate response requirement here, as the traveler may only want to know the shortest or fastest route to the destination. Consequently, the indoor route concerning airports, the corresponding check-in counters, plus boarding gates may not be available, and some default values should be accepted for calculation purposes.

A desktop demo application has been developed to easily test the offline indoor routing service. Thus, the customer can select the target airport (PMI or TXL) and the involved flight operation (arrival or departure) to load the corresponding maps and POIs automatically. The response provided by the demo application is depicted in Figure 4, where a traveler arrives at Terminal C and uses a default gate (with finger support). S/he has to walk to the main terminal (green path section), then to the luggage belt (blue path section), and finally to the bus station (orange path section). The whole navigation path is split into parts according to: (i) there is a floor or terminal change, and (ii) there is an intermediate operation to perform (luggage belt). For each part, the guiding points of the path are displayed with a different color on top of the georeferenced map. Also, a series of turn-by-turn indications are given in the selected language (left area in Figure 4). The covered distance (884 meters) and duration (31 min) are also provided. The duration is significant because an average default waiting time of 15 min was set for the luggage belt.

The routing algorithm was implemented in Java, so the JGraphT library was used (http://jgrapht.org/). It supports various kinds of graphs and routing algorithms. For the scenarios, weighted directed graphs were implemented using routing algorithm A*, which is compared with basic Dijkstra in Table 2. Fifty different requests (altering origin and destination nodes) were established for each operation (arrival, departure) and each airport, obtaining the numerical mean response time and the time employed by the algorithms.

A* outperforms Dijkstra as expected, but the user will perceive no significant relevance. As the overall response time is around or below one second in all cases, there was no need to improve the algorithms according to user expectations. Furthermore, to the authors' knowledge, no improved (shortest path) algorithm specifically targeting indoor spaces can be compared.

Besides average response times, the impact of external services was also successfully tested to check for graph responsiveness. For example, supposing an incident scenario (TXL, Terminal B), we have issued a routing request for a

Figure 4
Arrival at PMI. Indoor response

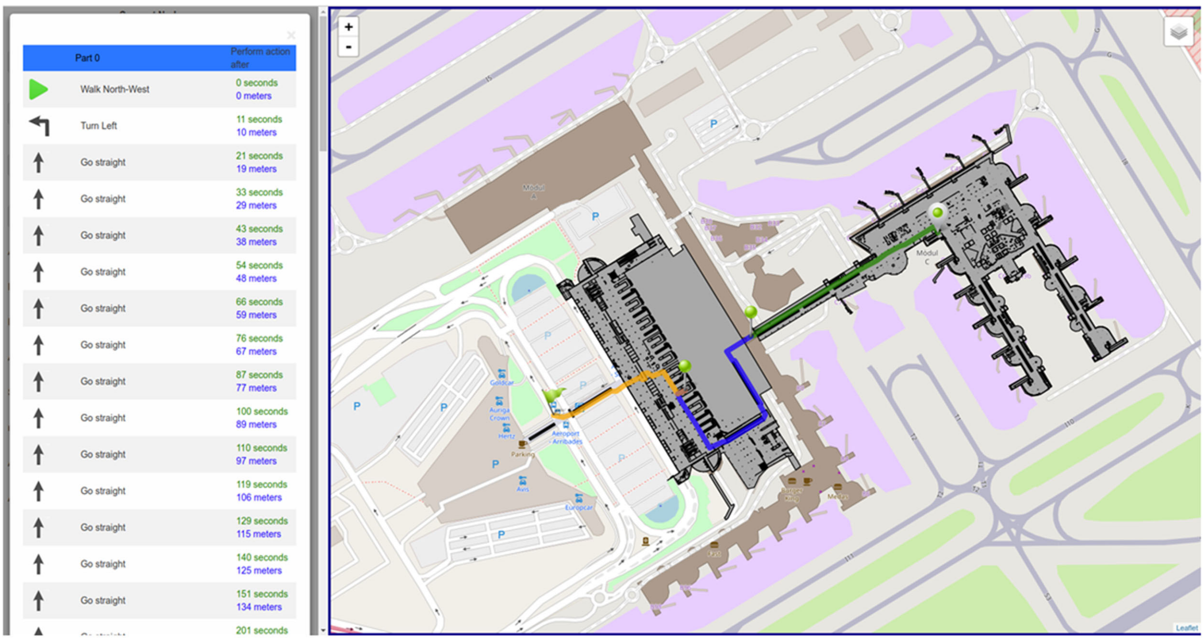


Table 2
Average response times for indoor routing

Scenario	Average response time (ms)	Dijkstra (ms)	A* (ms)
PMI. Arrival	1213/1105	476	368
PMI. Departure	1190/1064	528	402
TXL. Arrival	720/669	308	257
TXL. Departure	754/668	387	301

traveler using Terminal B for check-in. Here, the affected navigation nodes were successfully disabled in real time, and the traveler was rerouted accordingly.

Another performance test comprehends responsiveness to requesting parameters. Here, the scenario to consider refers to accessibility options combined with status information. For example, the mechanical POIs (lifts and escalators) for the north area of the main terminal in PMI are unavailable (red nodes). The external service is providing such status information either because they are really out of order or because their status is unknown. Considering such a situation, we can analyze two scenarios:

- *Traveler with no accessibility options*: the obtained routing graph is depicted in Figure 5. It corresponds to a departure operation where the user arrives by bus at the airport and makes the check-in at the north area of the main terminal – Floor 2 (green segment), and then s/he takes the stairs to get into Floor 4 (blue segment). There, the traveler goes to the security check (orange segment) and traverses the main terminal to Terminal C (yellow segment). Note that the orange and yellow segments correspond to Floor 4, whose map is not depicted (only Floor 2 is depicted to prevent confusion).
- *Traveler with accessibility options:* the obtained routing graph is depicted in Figure 6. The situation is similar to the previous example, but now the traveler cannot take the stairs. Therefore, s/he has to walk to the nearest available lift in the middle of the main terminal (blue segment) to reach Floor 4. Once there, the traveler walks to the north security checkpoint and then to Terminal C (yellow segments equal in both use cases).

Figure 5
Departure operation (no accessibility options) and status information (PMI airport)

Figure 6
Departure operation (accessibility options) and status information (PMI airport)

4.2. Online routing

When designing the online indoor navigation service, it is important to consider the target audience, the technological limitations, and how users should utilize this service within airports. The target audience is as broad as any traveler with a smartphone, which will be used as a sensor device for scanning networks (RSSI values), as a communication device with the backend indoor server, and as an interface to the user. Though it would be nice to perform a navigation system alike outdoor systems (onboard GPS with real-time travel instructions on screen), it turns out that some remarks for indoor spaces should be considered:

- *Indoor navigation highly depends on indoor positioning to check whether the traveler follows the path.* The relevant parameters for indoor positioning affecting navigation are (average) accuracy and refresh interval. In our tests, and for the existing available technology (Wi-Fi and BLE), (average) accuracy ranges from 1 to 8 meters, adequate for getting a rough estimation of the user's location. If placed on a georeferenced map with nearby POIs, travelers can probably "fine-tune" the estimation. The refresh interval for determining the position has been set to 10 s due to BLE limitations, reduced energy consumption, and network traffic.
- *Indoor travelers may follow a different path than originally suggested but still go in the right direction.* Considering only the segment between two nodes, the suggested path would be a direct line between both. Nevertheless, for large distances, the traveler may choose alternative paths because there are people in between them or because there are nearby unplanned POIs to visit (shops, toilets). This situation appears seldom in outdoor scenarios because all lanes go in the same direction, and it is less comfortable to make stops while driving than by walking.
- *Indoor travelers may be typically busy when they move through the airport.* They may be carrying (heavy) luggage or even taking care of children; it reduces (i) the availability of a free hand to hold the smartphone during navigation and (ii) the available time gap to watch the smartphone and understand the navigation instructions.

Under previous assumptions, turn-by-turn navigation in indoor spaces does not seem possible or even practical. Even if the indoor routing service indicates where to turn left or right, the positioning accuracy will not be able to establish when exactly the traveler has to turn, leading to confusion. Furthermore, if the traveler takes alternative paths between nodes, the calculated turn indications can make no sense, provoking confusion. An alarm-based design has been established to simplify the user's service usage. Consequently, travelers can always see the planned route and their current position on the airport map. As s/he will not be continuously watching the smartphone, two alarms have been defined to notify the user: (i) when the user is clearly not following the path and is getting lost (time interval to the destination increases instead of reducing) and (ii) when the user will not be able to arrive in time to the destination, and s/he must hurry up. Besides, the smartphone navigation app has been extended to support smartwatches as an innovative add-on. It would be easier to carry and check for a traveler, but its description is beyond this paper's scope.

Online routing can be considered an extension of offline routing with real-time monitoring of the indoor trip. An overview of the monitoring algorithm is depicted in Figure 7. Before starting, an initial route is obtained to know the starting and destination points, distance, and duration. When the navigation starts, the indoor position estimation is obtained periodically.

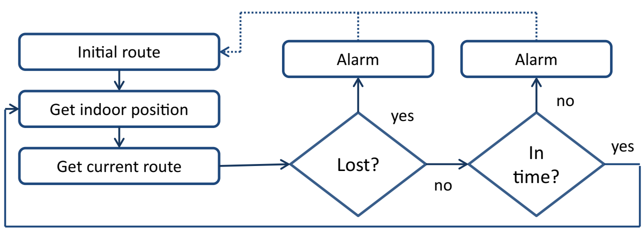
Once obtained, a new route is generated using this estimation as a starting point. Comparing both routes, two decisions have to be made. First, if the user is getting lost, considering a buffer of previous positions, an alarm notifies the user (smartphone screen with vibration mode), which may result in the generation of a new navigation process from this current position. Second, if the user is not going to get to the destination on time, an alarm is also generated.

An example of real-time navigation is depicted in Figure 8 for PMI airport (Terminal D). It represents three snapshots of the mobile app that guides the traveler from gate D83 (departure) to gate D98 (arrival). The routing path is depicted by an orange path, and the indoor positioning estimation is provided by our DORA algorithm and the internal (Google) plugin for a better comparison. As can be observed, our proposed estimation algorithm outperforms the internal plugin by more than 5–10 meters on average. This also means our navigation algorithm can better track the user along the path.

For every refresh interval (10 s), the remaining distance and time are calculated and shown to the user. By comparing the planned route and the current route (calculated from the current position), DORA can make some deductions, such as whether the traveler is following the path correctly, whether the traveler will arrive on time or not, etc.

For this specific scenario, there is only one single part (0) in the route as there is no intermediate operation (floor change, check-in, security check); thus, this aspect is not considered here. However, the concept of "projection" is important and useful as it acts as a basic filtering mechanism to prevent oscillations in the behavior. When the indoor location is estimated by the DORA algorithm, the projection on the planned route is calculated. This refers to the

Figure 7
Indoor navigation monitoring



nearest waypoint of the planned route. Showing this point provides a friendlier navigation progress experience rather than oscillating lines caused by (i) a real trace of the traveler not being able to follow a strict line and/or (ii) oscillations in the location estimation originated by signal strength variability. This latter scenario is depicted in Figure 8, which shows real traces for the internal (Google) plugin (blue), DORA algorithm (green), and projected path (yellow). The yellow path is much friendlier and less confusing for a traveler. Moreover, our DORA algorithm outperforms the internal (Google) plugin in two observable aspects:

- The internal plugin does not always detect the arrival point as it does not have real knowledge of the extension of the airport map.
- The internal plugin sometimes "loses" fine-grained accuracy and defaults to Cell-ID (see the blue line going outside the building in Figure 9), placing the traveler far away from the airport for a certain timeframe (15–20 s). Even if it recovers, it bewilders and upsets the user.

4.3. Integration of indoor routing and outdoor routing

An important aspect to evaluate is the degree of integration with external routers to provide seamless integration in a complete door-to-door journey planner. Basically, outdoor and indoor routers have to agree on a common list of interconnection points, which typically refer to some mobility POIs (e.g., taxi stands, bus stops, train stations, etc.). An example is provided in Table 3.

In fact, several outdoor routers may be potentially used by the door-to-door journey planner; therefore, the coordinates of the outdoor destination (or arrival) points at airports may differ depending on the different maps or cartography they work with. To tackle such a problem, the indoor graph manager can easily set (by dragging and dropping) its internal POI in a close location, where the matching indoor algorithm will look for nearby POIs in the vicinity. This is why latitude and longitude values are not the same in Table 3; ideally, they should be identical, but due to flexibility issues, interconnected POIs are mapped so that each router (indoor or outdoor) can independently manage its own POIs.

4.4. Aware versus unaware traveler

Finally, besides alerting travelers for real-time modifications along the route, estimating how much time and distance travelers would save using our navigation system is interesting. Hence, a comparison between an aware traveler (AT) versus an unaware traveler (UT) was made. The former uses our navigation system and knows where to go. In contrast, the latter may not know the airport and will typically go to the information point, ask for instructions, and observe the signs during the walk, reducing the speed. We have, therefore, experimented with 50 random starting and destination points (using Terminal C in PMI and TXL) to compare ATs and UTs. The result is presented in Table 4.

As can be observed, the reduction in distance is significant because there are few information points, and travelers have to go there, wait, and ask, even if it is not their optimal initial route. Time savings may not appear significant depending on intermediate actions taken by travelers. Check-in counters and other long waiting times might subjectively "absorb" such differences. It is also important to highlight that these values may serve to assess a well-designed airport and minimize traveling time.

Figure 8
Real-time indoor navigation at PMI (Terminal D)

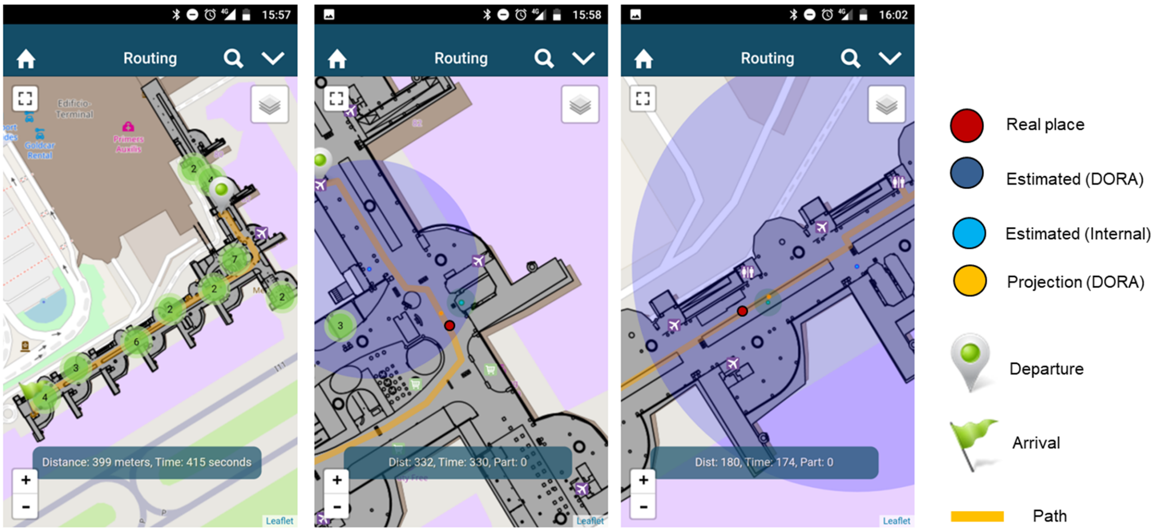


Figure 9
Indoor navigation trace at PMI (Terminal D)

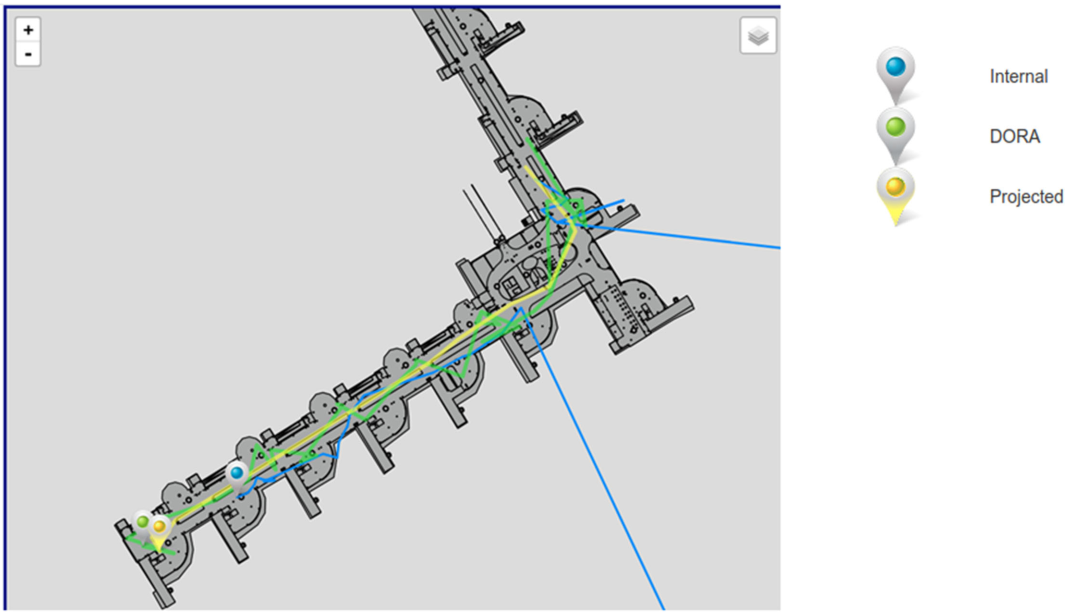


Table 3
Example of interconnection points indoor-outdoor (TXL)

Category	Lat/lon (indoor)	Lat/lon (outdoor)
Taxi stands	52.554372, 13.289331	52.55445862114559, 13.289363980293274
Taxi stands2	52.555240, 13.295760	52.55522672220549, 13.295838832855225
Public transport station	52.554210, 13.292844	52.554069, 13.292837
Car sharing stations	52.550140044716, 13.297904133796	52.55014004471609, 13.297904133796692

Table 4
Average response times and distances for indoor routing

Scenario	AT average distance (m)	UT average distance (m)	AT average time (s)	UT average time (s)
PMI. Arrival	1039	1147	1997	2318
PMI. Departure	905	1204	1871	2212
TXL. Arrival	418	539	1439	1742
TXL. Departure	421	504	1420	1620

5. Conclusion

Indoor navigation as an extension of indoor location is a trendy topic and is expected to grow in the coming years. It will assist in integrating buildings as part of complete door-to-door journeys, plus encompassing outdoor and indoor spaces, even in a multimodal approach. Some of the first target indoor areas are airports and shopping malls, which are open, public, and crowded spaces where mobility issues and potential business arise.

This paper provides results in this direction, where the indoor navigation service is applied to open public areas (airports) and integrates with outdoor routes to provide a complete door-to-door route. Moreover, the indoor navigation service has been developed from a general approach and is easily extensible to other indoor spaces. The proposed navigation service is decomposed into various components and integrates smoothly with other related services (maps, POIs, indoor positioning). An HTTP REST interface has been developed and exposed via Swagger to facilitate easy integration with other software components (e.g., outdoor routers). Even the response format has been harmonized with the outdoor routers for seamless integration with the door-to-door journey planner.

Not only are the functionalities important, but they are also an easy way to manage the whole proposed service. The developed service included both a server-side component plus a client side, in the form of a desktop application for offline routing while planning the indoor trip and a test mobile app to target online routing, capable of notifying alarms to the traveler when getting lost or not arriving on time.

Indoor maps are vital for travelers to display POIs, routes, and locations in a friendly way so that the user's spatial intuition can correct slight deviations. This task is intended for a professional designer worker from the airport who can react if changes appear.

The obtained indoor location accuracy in real live conditions outperforms the internal (Google) plugin and ranges from 1 to 8 meters when using Wi-Fi and BLE technology, which can be considered a COTS approach; it depends on several factors, such as the fingerprinting grid and signal strength stability, among others. Considering such accuracy, refresh intervals of about 10 s, and travelers' behavior, an easy online navigation approach has been developed. It warns the user merely when the path is clearly not being followed (potential lost situation) or when it will not reach the destination on time. It is also fundamental to have an updated graph during the navigation process which relies on integrated external services: (i) mechanical POIs (elevators, travelators, and escalators) are periodically checked in case they run out of service, and (ii) Waiting Time Detection services at security checkpoints and at some check-in counters also provide accurate time estimations and (iii) incident management. This process is seamless for the user, who always receives an updated response. However, it may also consult additional services (such as the FIS) in case of specific changes (boarding gate changes).

Offline routing is also available for the traveler planning the trip in advance and checking the indoor path across the airport. If the boarding gate or check-in counter is unknown, default values are established to estimate the average. If known, the routing graph can be quite accurate because it can be "projected" in the future, considering planned incidents and predicted values from Waiting Time Detection services, if available.

POIs have not only been defined for indoor spaces but also the nearby outdoor spaces acting as transition points between outdoor and indoor routers concerning mobility.

Future research opportunities include several directions. First, enhancing user experience while navigating is a key area of focus, which can be achieved by (i) improving accuracy during the refresh intervals by using inertial sensors in the smartphone for temporal indoor positioning (and optionally checking for turns) and (ii) providing a smartwatch app that facilitates the interactive process including voice messages, guiding instructions, or alarms. Additionally, exploring integration with more advanced AI and machine learning techniques to predict and adapt to real-time changes in the environment can further enhance the service. Finally, expanding the service to other types of buildings, such as hospitals, universities, and large corporate campuses, could broaden its applicability and benefit a wider range of users.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Benjamin Molina: Conceptualization, Methodology, Software, Validation, Writing – original draft, Writing – review &

editing, Visualization. **Carlos E. Palau:** Conceptualization, Investigation, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Jaime Calvo-Gallego:** Conceptualization, Investigation, Writing – original draft, Writing – review & editing.

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