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INTEGRATING BIM-BASED PATH PLANNING WITH AUDIO AUGMENTED REALITY NAVIGATION ASSISTANT FOR BLIND AND VISUALLY IMPAIRED PEOPLE

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Abstract

Statistics of blindness and visual impairments reported by the World Health Organization (WHO) stress the urgent need for navigation assistants supporting Blind and Visually Impaired People (BVIPs). Despite progress in systems aimed at enhancing BVIPs' independence, a navigation assistant integrating path planning functionalities for applicability in unprepared environments is still missing. Hence, this study proposes an Audio Augmented Reality (AAR) navigation assistant that integrates a path planning engine. It leverages spatial information provided by Building Information Models (BIM) for the computation of the reference path. The proposed solution has been tested on a real university campus case study showing very promising results.

Introduction

According to the World Health Organization (WHO), approximately 2.2 billion people worldwide experience visual impairment or low vision, with at least 1 billion affected by vision impairment (Zafar et al., 2022). Vision is recognized as one of the most important human senses since it plays an essential role in allowing people to understand the environment, finding a desired goal, and determining the correct path in unknown environments. This is why Blind and Visually Impaired People (BVIPs) frequently encounter a multitude of challenges in their routine activities in both indoor and outdoor environments (Abidi et al., 2024). Orientation in familiar environments is manageable for BVIPs, but navigating unfamiliar or dynamic settings – such as shopping malls, train stations, and airports – remains highly challenging due to frequent layout changes and numerous distractions. (Messaoudi et al., 2022). In this context, navigation systems hold a pivotal role in enhancing the independence of BVIPs by supporting both orientation and mobility (Messaoudi et al., 2022). The capacity to identify one's personal current location and the destination to which someone desires to navigate is known as orientation, whereas the capacity of an individual to get from one location to another one in a safe and well-organized manner is referred to as mobility (Abidi et al., 2024).

Numerous studies have explored navigation systems for BVIPs, leading to the development of solutions that integrate sensing and feedback technologies to enhance autonomy and environmental awareness. Among them, our recent study (Messi, Vaccarini, et al., 2024) proposes an Audio Augmented Reality (AAR) navigation assistant for BVIPs. It applies Computer Vision (CV) technologies to enable high-accuracy user localization seamlessly in (i) mixed and (ii) unprepared environments. Although this study aligns the two key criteria suggested by literature for developing BVIPs navigation assistants (Messaoudi et al., 2022), some features are still missing. In fact, to the best of the author's knowledge, none of the existing studies integrates BVIPs navigation assistants with pathfinding functionalities for applicability in unprepared environments. These environments include spaces the user cannot control because not enough skilled or not allowed to (Azuma et al., 1999; Kuriakose et al., 2022). If a navigation assistant could be initialized without the need to carefully prepare the environment in advance (e.g., by installing infrastructures or providing reference paths), that would be a major step in reducing the difficulty of application among BVIPs.

In order to cover this gap, the current study further develops the AAR navigation assistant proposed in (Messi, Vaccarini, et al., 2024) by integrating a path planning engine based on spatial information provided by Building Information Models (BIM). The remainder of this paper is structured as follows. A Literature review section introduces existing path planning solutions supporting navigation assistants for BVIPs. The Research questions section formalizes the objectives of the study. Then, the Methodology section presents the proposed technological solution. The Experiments and results section describes tests carried out for a real university campus case study, followed by the Conclusions section that closes the paper.

Literature review

Navigation assistants can be grouped into the two categories of Electronic Travel Aids (ETAs), and Electronic Orientation Aids (EOAs), supporting mobility and orientation respectively (Kim, 2024; Kuriakose et al., 2022). ETAs assist users with exploring their surroundings safely by providing obstacle detection support. EOAs, instead, assists users by finding a path and providing directions to navigate their surroundings. This study, mainly focusing on orientation of BVIPs, falls within the domain of EOA navigation assistants. They include key functionalities such as tracking the user pose, planning and following the path, and communicating directions to the user (Fernando et al., 2023). Since the objective of this study is integrating the AAR navigation assistant proposed in (Messi, Vaccarini, et al., 2024) with path planning functionalities, existing solutions will be discussed hereon. Path planning is based on the definition of (i) optimizing factors, (ii) procedures and algorithmic approaches, and (iii) spatial information (Fernando et al., 2023). The most common optimizing factor is travelling distance that leads to calculating the route with the least distance to travel (Fernando et al., 2023).

Among procedures and algorithmic approaches, A*, is the most popular across existing literature (Bai et al., 2017, 2018; Fernando et al., 2023; Kim, 2024; Martinez-Sala et al., 2015; Zhang et al., 2019). A* is a graph traversal and pathfinding algorithm that, given a weighted graph with source and goal nodes, finds the shortest path from source to goal.

Path planning is strongly coupled with the way spatial information is represented (Fernando et al., 2023). Among existing studies, some navigation assistants rely on ready-made routes, whereas others ensure near real-time path planning. In the first group, all possible routes connecting rooms inside a building are defined ex-ante (Chaccour & Badr, 2015; Croce et al., 2019). These systems require a preliminary learning phase (Chaccour & Badr, 2015) or, in case of vision-based approaches, the installation of markers on the ground useful to identify the followed path (Croce et al., 2019). These approaches, despite their ease of use, suffer from a limited path adaptability to contextual scenarios and the effort to manually input all the possible routes. Studies in the second group apply different technologies for describing space and computing routes in near real-time. Spatial information is provided by a dedicated infrastructure installed across the facility based on UWB (Martinez-Sala et al., 2015) and BLE (Ahmetovic et al., 2016) technologies. These solutions suffer from the need of preliminary preparing the target environment by installing an infrastructure. This limitation is overcome by the possibility of using the spatial mapping generated by HoloLens through Simultaneous Localization and Mapping (SLAM) (Yamashita et al., 2017). This spatial mapping is provided as an input to a local route search module. Alternatively, a 2D probabilistic grid map is computed based on RGB-D data for dynamic path planning (Lee & Medioni, 2016). Similarly, a virtual-blind-road is generated using visual SLAM and a stereo camera (Bai et al., 2017, 2018). The route model can be obtained also based on collected photos processed using Structure from Motion (SfM) (Jonas et al., 2015). A limitation of these approaches lies in the necessity to preliminary scan the target environment to initialize the path planning process. In addition, BVIPs are often required to use cumbersome wearable systems, comprising cameras and onboard processing units. To alleviate this burden, spatial information may be sourced from existing 2D CAD map, thereby enabling a more lightweight and accessible configuration (Zhang et al., 2019). More detailed spatial information is ensured by 3D models. In this perspective, BIM models providing semantic and topological information together are strongly recommended (Fernando et al., 2023). These models are typically structured using the open exchange format Industry Foundation Classes (IFC) regulated by (ISO 16739-1:2024, 2024). Given these premises, the next section will introduce the Research Questions (RQs) addressed by the current study.

Research questions

This study originates from the need to integrate the AAR navigation assistant proposed in (Messi, Vaccarini, et al., 2024) with path planning for applicability in unprepared environments. Leveraging spatial information provided by BIM models enables the computation of the reference path without the need to carefully prepare the environment in advance. In fact, this methodological approach obviates the need for preliminary data collection or manual environment mapping, as the spatial configuration is directly retrieved from BIM models, while path computation is performed dynamically. Consequently, this paradigm enhances the system's adaptability and scalability across diverse built environments. In light of these considerations, this study formulates the following RQs to systematically investigate the proposed integration:

RQ.1. What system architecture would facilitate the integration of a BIM-based path planning module with an AAR navigation assistant for BVIPs operating in unprepared environments?

RQ.2. What technical solution are most suitable for such an integration?

Methodology

The system architecture, reported in Figure 1, contextualizes the integration of the BIM-based path planner into the broader navigation framework for BVIPs presented in (Messi, Vaccarini, et al., 2024). The proposed system architecture is built on top of (i) a custom cloud platform, and (ii) the Google cloud platform, both interfaced with (iii) the AAR navigation assistant (hereinafter for brevity called also "assistant"). Both the custom cloud platform and the Google cloud platform rely on CV for registration purposes. Whereas Google cloud platform exploits outdoor Street View images collected by Google, the custom cloud platform uses custom image datasets collected by users and stored by the same platform. Registering an image to a reference dataset allows for the estimation of the user pose. In addition to image registration, the custom cloud platform performs BIM-based path planning thanks to a dedicated engine. Results from image registration and path planning are provided to the assistant for navigation purposes. While the proposed methodology is compatible with any connected device featuring basic sensors, the assistant has been deployed as a smartphone application in this study.

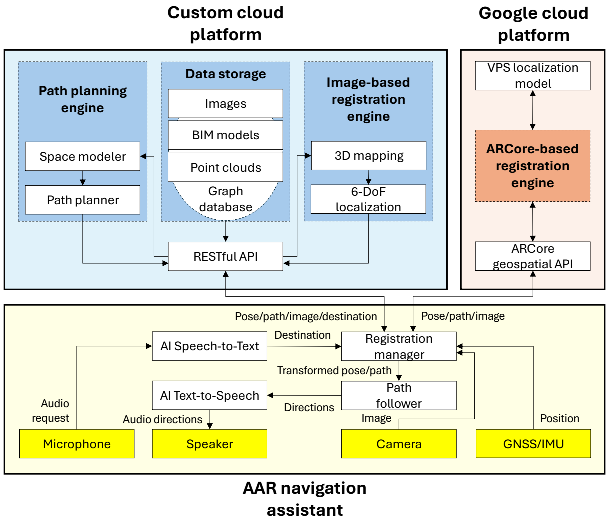

Figure 1: System architecture of the proposed system integrating a BIM-based path planning engine with the Audio Augmented Reality (AAR) navigation assistant.

Custom cloud platform

The proposed custom cloud platform operates as a decentralized hub for computational resources, enabling data processing, storage, and distribution through a RESTful API. This API acts as a standardized, web-based communication interface, facilitating interoperability with multiple AAR navigation assistant clients distributed across the internet. The custom cloud platform is centered around two core computational modules: (i) the image-based registration engine, that tacks the user position and orientation, and (ii) the path planning engine, that computes the reference path in real-time. These components are supported by a centralized data storage system (Figure 1). The data storage layer is designed to manage both structured data – such as BIM models – and unstructured data – including images and point clouds – thus providing rich contextual geolocated information to support image registration, path planning, and navigation. The image-based registration engine is specifically engineered to support localization in environments characterized by limited or absent GNSS signal availability. Leveraging CV techniques, this engine utilizes image and point cloud data to compute precise device positioning. The operation of this engine is articulated in two main phases: 3D mapping and 6-DoF localization (Figure 1). The 3D mapping involves the generation of a 3D reference model (i.e., a point cloud) from an input image dataset via SfM algorithms (Schönberger & Frahm, 2016). This model is constructed once per environment and serves as the spatial reference for subsequent localization. The 6-DoF localization consists in estimating the pose of the device from a query image by applying the Perspective-n-Point (PnP) algorithm (OpenCV, 2023). In both phases, key points extraction and matching are performed by implementing the Hierarchical Feature Network (HF-Net) (Sarlin et al., 2018).

The path planning engine includes the space modeler and the path planner (Figure 1). It has been implemented as a headless simulation environment capable of dynamically computing the shortest route to the target destination, hence addressing RQ.1. Game engines are adopted as simulation frameworks for their native support of physical interactions and event-based dynamics, enabling realistic path generation (Naticchia et al., 2019). The space modeler provides the path computation context by importing georeferenced BIM models from the cloud, selected based on the user's position estimated via GNSS and vision-based localization. The path planner, instead, implements the A* graph traversal and pathfinding algorithm – widely recognized in the scientific literature for its effectiveness and computational efficiency.

Google cloud platform

The Google cloud platform improves user pose estimation outdoor over GNSS accuracy. In dense urban environments, a geographic location can be hardly pinpointed due to low visibility to the sky and signals reflecting off buildings. Another technical shortcoming of GNSS is the possibility to determine the location of the device and not the orientation (Reinhardt, 2019). In addition, even if the image-based registration engine can be potentially applied outdoors, it is hard to collect reference images on large scale environments. To cover these gaps, the Google cloud platform has been integrated within the system architecture to estimate the device pose based on CV technology. The Google cloud platform includes three blocks: (i) the ARCore geospatial API, (ii) an ARCore-based registration engine, and (iii) the Visual Positioning System (VPS) localization model (Figure 1). A client makes a registration request for the ARCore-based registration engine through the AR Geospatial API, which makes this platform accessible to clients. This action consists in sending to the Google cloud platform the GNSS-based user position along with a query image). CV algorithms within the ARCore-based registration engine process the input image to match visual features from the VPS model, based on Street View data, and estimate the device pose (Reinhardt, 2019).

AAR navigation assistant

The AAR navigation assistant is deployed as a smartphone-based application. The functioning of the assistant is based on a set of hardware (yellow boxes) and software modules (white boxes) (Figure 1). Basic hardware components included in every smartphone commercially available in the market (i.e., camera, GNSS/IMU sensors, microphone, and speaker) along with internet connection are required. The smartphone microphone and speaker define the communication interface with BVIPs, whereas the smartphone camera and GNSS/IMU sensors collects data required by the two platforms for registration purposes. The proposed assistant is activated when the user pronounces a vocal request for instructions to reach a specific destination. The vocal request is picked by the microphone and processed by an AI Speech-to-Text module that can convert voice into text in a matter of seconds and extract the destination (Messaoudi et al., 2022). To compute the path and provide spatial guidance to that destination, the user needs to be localized first. To this purpose, the registration manager gets an image from the camera and positional and inertial data from GNSS/IMU sensors of the smartphone. The registration manager is responsible for delegating the registration task to one of the two registration platforms and, hence, to the embedded image-based registration engine or the ARCore-based registration engine. Whereas the first one has a centimeter-level accuracy (Messi, Corneli, et al., 2024), the second one is affected by errors in the order of the meter (Google for Developers, 2024). For this reason, the first one has priority over the second one. The registration manager regularly queries the custom cloud platform the existence of any image dataset in the vicinity of the user's position, provided by the smartphone GNSS/IMU sensors. If any image dataset exists near the user, the registration manager delegates the custom cloud platform and then, the image-based registration engine to retrieve the pose of the user; otherwise, the Google cloud platform is activated, along with the ARCore-based registration engine. Given the user starting position and the destination, the registration manager delegates the pathfinding task to the path planner engine hosted by the custom cloud platform. This further answers RQ.1. Once both the registration and pathfinding tasks are completed, the device pose, and the path are returned to the registration manager and transformed into the local coordinate system of the device. While the registration task is regularly repeated to track the position of the user during the navigation task, the pathfinding task is triggered only if the destination changes. At this point, the path follower component has all the information required to steer the user to the target destination. The path follower can provide the user spatial guidance to minimize to zero the distance between the user and the path and the angle between the user direction and the tangent to the path (Hung et al., 2023). Practically, the path follower regularly computes the steering angle to guide the user. In this study, the path follower has been developed by implementing the Line-Of-Sight (LOS) path following algorithm (Hung et al., 2023).

Such spatial guidance is provided in the form of text to the AI Text-to-Speech component, which is in charge to convert it into an audio message. Finally, the audio message is delivered to the user by speakers. To provide BVIPs with an AAR experience, the AI text-to-speech module includes head-related transfer functions (HRTFs) as spatial sound synthesis (Yang et al., 2022). This enables a spatial contextualization of turn-by-turn instructions with cues that, being emitted from the same direction of the followed trajectory, avoid disturbance when the information is over-flooded.

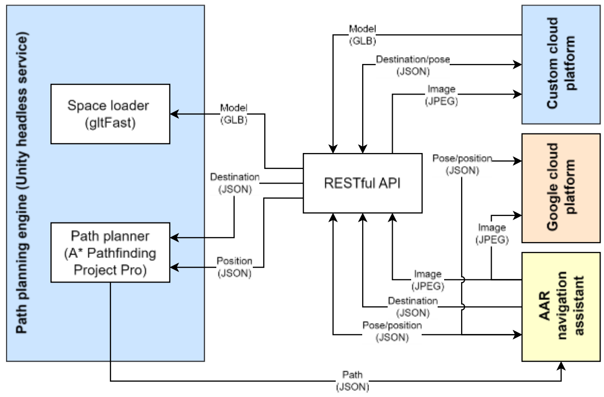

Figure 2: Information model of the integrated path planning engine.

Implementation of the path planning engine

The path planning engine has been developed as a headless service using Unity3D (Figure 2). The choice of a game engine is due to its embedded physics and event dynamics engine. When the assistant receives a path planning request, an executable Unity3D instance is initialized on a server. A RESTful API has been implemented to enable internal communication, among the components of the custom cloud platform, and external communication between the same platform and the assistant. The functioning of the path planning engine can be described through the registration and the pathfinding tasks. The first one esteems the user position and orientation, whereas the second one computes the reference path. In the registration task, the assistant acquires a JPEG image from the smartphone camera and the GNSS position as a JSON document (Figure 2). These data are delivered to the custom or Google cloud platform for the registration task. The GNSS data are utilized to query the availability of image datasets (i.e., custom or Google) in the surrounding area, thereby determining the appropriate platform to engage. Priority is given to the custom platform due to its superior localization accuracy. In the pathfinding task, the assistant acquires the GNSS position as a JSON document (Figure 2). It is applied to identify the nearest BIM model to the user to be loaded within the path planning engine. The custom cloud platform is in charge to store BIM models as IFC files but also to extract the corresponding GLB files that, being more compact in size, ensure a higher computation efficiency. The GLB file corresponding to the identified BIM model is delivered to the path planning engine. At the same time, the assistant delivers, as JSON documents, the estimated user position to the path planning engine and the required destination to the custom cloud platform. The latter can query the IfcSpace and return the corresponding geometric center to the path planning engine. The JSON string indicating the destination is extracted from the user vocal request by the AI Speech-to-Text module included within the assistant. For the experimental purposes of this study, the JSON string indicating the destination can be also manually inputted to the assistant. Hence, each pathfinding call can be formalized as a function that provides BIM model, user position, and destination as arguments to the path planning engine (Figure 2). The path planning engine includes the space loader and the path planner modules. The first one loads the GLB model using the gltFast library (Unity Technologies, 2025) that is the de facto standard for importing large scene, like the ones related to BIM models, within Unity3D serious game engine. Hence, the path planner receives as inputs the destination array from the custom cloud platform and the position array from the assistant. The pathfinding task is ensured by the A* algorithm implemented within Unity3D using the A* Pathfinding Project Pro (Granberg, 2020). As a result, the shortest path connecting the user position and the destination is computed and returned to the assistant as a JSON document. During the navigation task, this will be used as the reference path by the path follower module included within the assistant. This answers RQ.2.

Experiments and results

Experiment design

The developed assistant was tested in a university campus, namely the Polo Monte Dago of the Università Politecnica delle Marche in Ancona, Italy. Polo Monte Dago includes the faculties of Engineering, Agriculture, and Sciences dislocated in several building blocks including classrooms, offices, and laboratories. In the main building, hosting the faculty of Engineering venue, each floor takes its name according to its elevation above sea level; thus, the lowest floor is named 140 elevation (140 m above sea level) and the highest floor, at the top of the tower, is elevation 195. Each floor is 5-m-high, and the faculty is spread over eleven floors. In this paper, experiments consist in carrying out three pathfinding tasks for a user, initially located outdoor, who is looking for directions to reach three different destinations. Table 1 reports data required for each pathfinding task formatted as JSON objects. Selected destinations are three classrooms at elevation 140 defined by the following strings: “Classroom 140/1”, “Classroom 140/2”, and “Classroom 140/3” (Table 1). For the experimental purpose of this study, destination strings have been manually inputted into the assistant. Other data, like for example starting and destination points, are automatically retrieved by the proposed system (Table 1). For the three pathfinding tasks, the starting point is the same because it has been assumed the user launches the assistant in the same position outdoors. The destination points, instead, corresponding to the geometric center of the classroom assumed as a destination, varies according to it. The assistant delivers theese data to the path planning engine, embedded within the custom cloud platform. As a result, the shortest paths connecting the user and the destinations are returned to the assistant and applied as reference paths to provide turn-by-turn audio instructions to the user during navigation tasks.

Table 1: Experiment overview and results.

Pathfinding task	1	2	3
Destination string	{“destination”: “Classroom 140/1”}	{“destination”: “Classroom 140/2”}	{“destination”: “Classroom 140/3”}
Starting point	{"P1": [-35.05, -10.20, -80.95]}	{"P1": [-35.05, -10.20, -80.95]}	{"P1": [-35.05, -10.20, -80.95]}
Destination point	{"P1": [-76.24, -5.00, -55.46]}	{"P1": [-67.33, -5.00, -55.47]}	{"P1": [-31.46, -5.00, -56.99]}
Points no.	24	20	22
Length [m]	138.16	126.02	123.00
Computing time [ms]	11.00	11.00	12.00
Points coordinates	{"P1": [-35.05, -10.20, -80.95], "P2": [-36.70, -10.20, -81.20], "P3": [-48.20, -9.86, -81.20], "P4": [-61.00, -9.41, -81.20], "P5": [-73.80, -8.97, -81.20], "P6": [-77.40, -8.83, -81.10], "P7": [-77.80, -8.79, -80.40], "P8": [-77.30, -8.75, -79.90], "P9": [-48.20, -6.51, -79.20], "P10": [-45.00, -6.26, -79.00], "P11": [-42.40, -6.03, -78.00], "P12": [-39.80, -5.77, -75.90], "P13": [-38.40, -5.57, -73.80], "P14": [-37.40, -5.34, -71.10], "P15": [-37.30, -5.06, -67.60], "P16": [-37.50, -5.00, -66.50], "P17": [-42.00, -5.00, -64.60], "P18": [-45.00, -5.00, -59.60], "P19": [-53.40, -5.00, -58.70], "P20": [-61.00, -5.00, -61.00], "P21": [-62.70, -5.00, -61.50],	{"P1": [-35.05, -10.20, -80.95], "P2": [-36.70, -10.20, -81.20], "P3": [-48.20, -9.86, -81.20], "P4": [-61.00, -9.41, -81.20], "P5": [-73.80, -8.97, -81.20], "P6": [-77.40, -8.83, -81.10], "P7": [-77.80, -8.79, -80.40], "P8": [-77.30, -8.75, -79.90], "P9": [-48.20, -6.51, -79.20], "P10": [-45.00, -6.26, -79.00], "P11": [-42.40, -6.03, -78.00], "P12": [-39.80, -5.77, -75.90], "P13": [-38.40, -5.57, -73.80], "P14": [-37.40, -5.34, -71.10], "P15": [-37.30, -5.06, -67.60], "P16": [-37.50, -5.00, -66.50], "P17": [-42.00, -5.00, -64.60], "P18": [-45.00, -5.00, -59.60], "P19": [-63.00, -5.00, -57.00], "P20": [-67.33, -5.00, -55.47]}	{"P1": [-35.05, -10.20, -80.95], "P2": [-36.70, -10.20, -81.20], "P3": [-48.20, -9.86, -81.20], "P4": [-61.00, -9.41, -81.20], "P5": [-73.80, -8.97, -81.20], "P6": [-77.40, -8.83, -81.10], "P7": [-77.80, -8.79, -80.40], "P8": [-77.30, -8.75, -79.90], "P9": [-48.20, -6.51, -79.20], "P10": [-45.00, -6.26, -79.00], "P11": [-42.40, -6.03, -78.00], "P12": [-39.80, -5.77, -75.90], "P13": [-38.40, -5.57, -73.80], "P14": [-37.40, -5.34, -71.10], "P15": [-37.30, -5.06, -67.60], "P16": [-37.50, -5.00, -66.50], "P17": [-39.70, -5.00, -65.20], "P18": [-39.90, -5.00, -64.60], "P19": [-39.20, -5.00, -49.50], "P20": [-38.20, -5.00, -49.40], "P21": [-35.40, -5.00, -49.60],

"P22": [-63.20, -5.00, -61.60], "P23": [-71.80, -5.00, -61.70], "P24": [-76.24, -5.00, -55.46]}	"P22": [-31.46, -5.00, -56.99]}

Table 2: RQs answers overview.

Research question	Answer
RQ.1.	The proposed system architecture is built on top of (i) a custom cloud platform, and (ii) the Google cloud platform, both interfaced with (iii) the AAR navigation assistant (Figure 1). Both the platforms include specific engines that apply CV for registration purposes. The custom cloud platform includes also a BIM-based path planning engine for computing the reference path. The path planning engine consists in a headless simulation environment able to provide the shortest path connecting the user and the destination.
RQ.2.	The path planning engine has been developed as a headless service using Unity3D game engine, since it embeds a physics and event dynamics engine (Figure 2). The path planning engine includes the space loader and the pathfinder modules. The first one loads the geometry of the BIM model as a GLB file within Unity3D using the gltFast library (Unity Technologies, 2025). The custom cloud platform ensures the extraction of the GLB file from the IFC file collected by the data storage. The path planner module, instead, receives as inputs the destination from the custom cloud platform and the user position from the assistant. Hence, the pathfinder module runs the A* algorithm implemented using the A* Pathfinding Project Pro (Granberg, 2020).

Results and discussion

The shortest paths connecting the user and the three selected destinations are returned by the path planning engine to the assistant. Table 1 reports, for each pathfinding task, the following data about the computed shortest path: the number of points defining the path, the path length, the computing time, and the list of point coordinates formatted in JSON format. These coordinates, related to the local coordinate reference system of the BIM model, are delivered by the path planning engine to the assistant for navigation purposes. Figure 3 depicts in green the graphical representations of the computed paths related to the three classrooms. They can be potentially accessed across several doors highlighted in orange. It must be noted that, for each pathfinding task, the computed path crosses the door that ensures the shortest path. In addition, a path planning engine that leverages spatial information from BIM models eliminates the necessity for preliminary on-site surveys aimed at manually defining navigable paths. This approach also obviates the need for prior environment preparation or the use of cumbersome technological setups for environmental scanning and data processing during navigation tasks. The proposed system architecture makes it possible by integrating such a path planning engine with the assistant for BVIPs, hence answering RQ.1 (Table 2). Since reference paths can be computed according to the building topology, any BIM model update can be easily considered by pathfinding tasks with no efforts. This is enabled by the choice of modelling the space within a Unity3D headless instance based on BIM models, hence answering RQ.2 (Table 2). The pathfinding task is achieved by delegating the computation to a path planning engine embedded within the custom cloud platform, rather than running that computation locally within the smartphone-based assistant. The path planning engine processes the request and returns a simple list of vectors including point coordinates as reported in Table 1. Computing times, in the order of milliseconds, have been

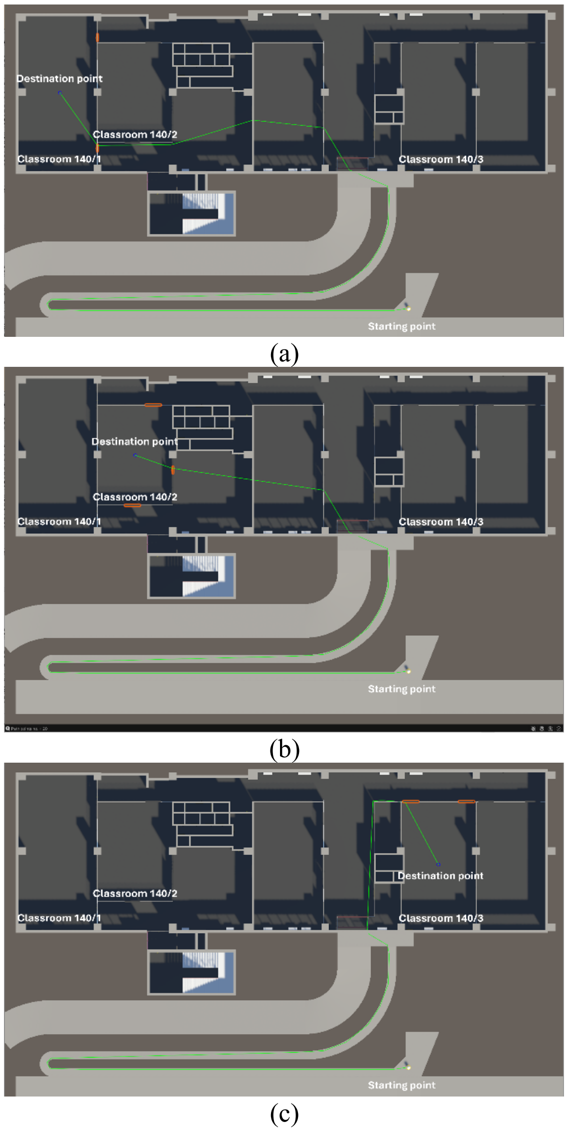

Figure 3. Graphical representation of the computed paths depicted in green connecting the starting and the destination points related to (a) classroom 140/1, (b) classroom 140/2, and (c) classroom 140/3.

obtained by running for experimental purposes, the path planning engine on a laptop equipped with a 13th Gen Intel® Core™ i9-13900H 2.60 GHz processor, 32 GB of RAM, and an NVIDIA GeForce GTX 4070. Unity3D LTS 2022.3.40f1 is the release adopted for developing the proposed tool. The performance will be even higher on field applications, since the graphic rendering, required for the experimental and debug purposes of the study, will be disabled (Table 1). This proves the efficiency of such a technical solution, hence enabling near real-time applications.

Conclusions

The progression of navigation tools for BVIPs underscores a shift from basic mechanical aids (e.g., white canes) to advanced electronic devices that harness several sensing and feedback technologies to enhance mobility and promote independence. As emerged from the literature review, none of the existing navigation systems for BVIPs exploit spatial information condensed in BIM models for path planning. To cover this gap, this study has proposed the integration of a BIM-based path planning engine with the AAR navigation assistant presented in (Messi, Vaccarini, et al., 2024), deployed as a smartphone-based application. This enables the computation of the reference path while obviating the need for prior environmental surveys, preparatory interventions, or the deployment of cumbersome devices for spatial data acquisition and processing.

Limitations of the proposed solution deserve consideration. Firstly, the functionality of the system is inherently reliant on the availability of BIM models. While this dependency currently constrains its deployment to environments where such models are already available, the ongoing digital transformation in the construction industry is progressively mitigating this limitation. The increasing adoption of BIM for both new developments and retrofitting of existing buildings - driven by smart city strategies and digital twin frameworks – indicates that the applicability of the proposed system will expand significantly in the near future. A further limitation concerns the potential generation of navigation paths that traverse areas not accessible to the public, such as classrooms or restricted zones. This issue arises due to the absence of semantic constraints within the pathfinding algorithm. Future research should incorporate semantic information from BIM models to guide path planning along designated circulation areas both indoors (e.g., hallways) and outdoors (e.g., sidewalk), ensuring realistic routes that respect physical and functional constraints.

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References

Abidi, M. H., Noor Siddiquee, A., Alkhalefah, H., & Srivastava, V. (2024). A comprehensive review of navigation systems for visually impaired individuals. *Heliyon*, *10*(11). https://doi.org/10.1016/j.heliyon.2024.e31825

Ahmetovic, D., Gleason, C., Ruan, C., Kitani, K., Takagi, H., & Asakawa, C. (2016). NavCog: A navigational cognitive assistant for the blind. *18th International Conference on Human-Computer Interaction with Mobile Devices and Services*, 90–99. https://doi.org/10.1145/2935334.2935361

Azuma, R., Lee, J. W., Jiang, B., Park, J., You, S., & Neumann, U. (1999). Augmented Reality Tracking in unprepared environments for augmented reality systems. *Computers & Graphics*, *23*, 787–793. https://doi.org/10.1016/S0097-8493(99)00104-1

Bai, J., Lian, S., Liu, Z., Wang, K., & Liu, D. (2018). Virtual-Blind-Road Following-Based Wearable Navigation Device for Blind People. *IEEE Transactions on Consumer Electronics*, *64*(1), 136–143. https://doi.org/10.1109/TCE.2018.2812498

Bai, J., Su, G., Liu, D., & Fu, Z. (2017). A cloud and vision-based navigation system used for blind people. *ACM International Conference Proceeding Series*, *Part F128531*. https://doi.org/10.1145/3080845.3080867

Chaccour, K., & Badr, G. (2015). Novel indoor navigation system for Visually Impaired and blind people. *2015 International Conference on Applied Research in Computer Science and Engineering (ICAR)*. https://doi.org/10.1109/ARCSE.2015.7338143

Croce, D., Giarré, L., Pascucci, F., Tinnirello, I., Galioto, G. E., Garlisi, D., & Lo Valvo, A. (2019). An Indoor and Outdoor Navigation System for Visually Impaired People. *IEEE Access*, *7*, 170406–170418. https://doi.org/10.1109/ACCESS.2019.2955046

Fernando, N., McMeekin, D. A., & Murray, I. (2023). Route planning methods in indoor navigation tools for vision impaired persons: a systematic review. In *Disability and Rehabilitation: Assistive Technology* (Vol. 18, Issue 6, pp. 763–782). Taylor and Francis Ltd. https://doi.org/10.1080/17483107.2021.1922522

Google for Developers. (2024). *Build global-scale, immersive, location-based AR experiences with the ARCore Geospatial API*. https://developers.google.com/ar/develop/geospatial

Granberg, A. (2020). *A* Pathfinding Project Pro*. Documentation. https://arongranberg.com/astar/docs/

Hung, N., Rego, F., Quintas, J., Cruz, J., Jacinto, M., Souto, D., Potes, A., Sebastiao, L., & Pascoal, A. (2023). A review of path following control strategies for autonomous robotic vehicles: Theory, simulations, and experiments. *Journal of Field Robotics*, *40*(3), 747–779. https://doi.org/10.1002/rob.22142

ISO 16739-1:2024. (2024). *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries*.

Jonas, S. M., Sirazitdinova, E., Lensen, J., Kochanov, D., Mayzek, H., De Heus, T., Houben, R., Slijp, H., & Deserno, T. M. (2015). IMAGO: Image-guided navigation for visually impaired people. *Journal of Ambient Intelligence and Smart Environments*, *7*(5), 679–692. https://doi.org/10.3233/AIS-150334

Kim, I. J. (2024). Recent advancements in indoor electronic travel aids for the blind or visually impaired: a comprehensive review of technologies and implementations. *Universal Access in the Information Society*. https://doi.org/10.1007/s10209-023-01086-8

Kuriakose, B., Shrestha, R., & Sandnes, F. E. (2022). Tools and Technologies for Blind and Visually Impaired Navigation Support: A review. *IETE Technical Review (Institution of Electronics and Telecommunication Engineers, India)*, *39*(1), 3–18. https://doi.org/10.1080/02564602.2020.1819893

Lee, Y. H., & Medioni, G. (2016). RGB-D camera based wearable navigation system for the visually impaired. *Computer Vision and Image Understanding*, *149*, 3–20. https://doi.org/10.1016/j.cviu.2016.03.019

Martinez-Sala, A. S., Losilla, F., Sánchez-Aarnoutse, J. C., & García-Haro, J. (2015). Design, implementation and evaluation of an indoor navigation system for visually impaired people. *Sensors*, *15*(12), 32168–32187. https://doi.org/10.3390/s151229912

Messaoudi, M. D., Menelas, B. A. J., & Mcheick, H. (2022). Review of Navigation Assistive Tools and Technologies for the Visually Impaired. *Sensors*, *22*(20). https://doi.org/10.3390/s22207888

Messi, L., Corneli, A., Spegni, F., Binni, L., & Vaccarini, M. (2024). Infrastructure-Free Localization System for Augmented Reality Registration in Indoor Environments: A First Accuracy Assessment. *2024 IEEE International Workshop on Metrology for Living Environment*.

Messi, L., Vaccarini, M., Corneli, A., Carbonari, A., & Binni, L. (2024). *Audio Augmented Reality Seamless Navigation Assistant Based on GNSS and Computer Vision for Blind and Visually Impaired People*.

Naticchia, B., Messi, L., & Carbonari, A. (2019). BIM-based Holonic System for Real-Time Pathfinding in Building Emergency Scenario. *2019 European Conference for Computing in Construction*, *1*, 117–124. https://doi.org/10.35490/ec3.2019.174

OpenCV. (2023). *Perspective-n-Point (PnP) pose computation*. https://docs.opencv.org/4.x/d5/d1f/calib3d_solvePnP.html

Reinhardt, T. (2019). *Using Global Localization to Improve Navigation*. https://research.google/blog/using-global-localization-to-improve-navigation/

Sarlin, P.-E., Cadena, C., Siegwart, R., & Dymczyk, M. (2018, December 9). From Coarse to Fine: Robust Hierarchical Localization at Large Scale. *2019 IEEE CVF Conference on Computer Vision and Pattern Recognition (CVPR)*. https://doi.org/10.48550/arXiv.1812.03506

Schönberger, J. L., & Frahm, J.-M. (2016). Structure-from-Motion Revisited. *2016 IEEE Conference on Computer Vision and Pattern Recognition (CVPR)*. https://doi.org/10.1109/CVPR.2016.445

Unity Technologies. (2025). *Unity glTFast Documentation*. https://docs.unity3d.com/Packages/com.unity.cloud.gltfast@6.10/manual/index.html

Yamashita, A., Sato, K., & Matsubayashi, K. (2017). Pedestrian Navigation System for Visually Impaired People Using HoloLens and RFID. *2017 Conference on Technologies and Applications of Artificial Intelligence (TAAI)*. https://doi.org/10.1109/TAAI.2017.9

Yang, J., Barde, A., & Billinghurst, M. (2022). Audio Augmented Reality: A Systematic Review of Technologies, Applications, and Future Research Directions. *AES: Journal of the Audio Engineering Society*, *70*(10), 788–809. https://doi.org/10.17743/jaes.2022.0048

Zafar, S., Asif, M., Ahmad, M. Bin, Ghazal, T. M., Faiz, T., Ahmad, M., & Khan, M. A. (2022). Assistive Devices Analysis for Visually Impaired Persons: A Review on Taxonomy. In *IEEE Access* (Vol. 10, pp. 13354–13366). Institute of Electrical and Electronics Engineers Inc. https://doi.org/10.1109/ACCESS.2022.3146728

Zhang, X., Yao, X., Zhu, Y., & Hu, F. (2019). An ARCore based user centric assistive navigation system for visually impaired people. *Applied Sciences*, *9*(5). https://doi.org/10.3390/app9050989