Effective Indoor Navigation in a Metro System and Dependency on the Positioning Precision

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Abstract

The paper presents a practical and cost-effective approach to indoor navigation that reduces reliance on high-precision positioning systems. Developed within the LIFT project at the Warsaw University of Technology, the proposed system is tailored for metro environments and supports users, in navigating through stations with greater confidence and autonomy. By combining Bluetooth Low Energy (BLE) -based positioning with landmark-based instructions, contextual images, and Augumented Reality (AR) elements, the system delivers intuitive guidance without requiring sub-meter accuracy. A three-layer spatial data model underpins the route generation and instruction framework, emphasizing user interpretability over constant real-time tracking. The mobile application, deployed and tested in the Warsaw Metro received positive feedback for its usability and accessibility. The findings demonstrate that effective indoor navigation can be achieved through intelligent instruction design and user-centric interface development, rather than solely through technical enhancements in positioning accuracy.

Keywords

Metro system, wayfinding, BLE beacons, landmark-based instructions, indoor navigation

1. Introduction

Indoor navigation and positioning are research areas that have seen significant development over the past two decades. Technologies such as Infrared (IR) were initially explored, followed by the adoption of Wireless Fidelity (WIFI), Bluetooth Low Energy (BLE), and Ultra Wide Band (UWB), achieving sub-meter positioning accuracy. Despite these technological advancements, widespread adoption remains limited. Indoor navigation systems are often treated as supplementary features rather than essential tools that add clear value to end users.

Several factors contribute to this situation, with the most prominent being high deployment and maintenance costs, as well as inconsistent accuracy and reliability. Although some technologies meet performance expectations, they tend to be prohibitively expensive. This has led to ongoing research efforts aimed at finding a balanced solution—an indoor positioning technology that is both accurate and reliable, yet cost-effective to deploy and maintain.

A quantitative review of BLE-based indoor positioning research in [1] highlights a significant focus on the positioning component, often overlooking the broader complexity of indoor navigation systems. This narrow approach tends to result in systems that are technically advanced in one area but fail to deliver a comprehensive and user-friendly experience. An effective indoor navigation system requires the integration of several key components, including instruction generation and visualization, route rendering, detailed indoor maps, and overall app usability. Focusing exclusively on the positioning aspect complicates the development of a truly functional and helpful navigation tool.

This research is conducted within the framework of the project titled "Development of a prototype of a system supporting the movement of people with special needs inside architectural structures related to rail transport – LIFT", launched at the Warsaw University of Technology in 2022. The project is funded by the National Center for Research and Development and involves a multidisciplinary team from the

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Faculties of Geodesy and Cartography, Electronics and Information Technology, Civil Engineering, and Architecture. Beyond the development of technical solutions, the research has included study visits to cities such as Barcelona and Los Angeles to examine effective indoor navigation practices. The project also benefits from close collaboration with organizations representing people with disabilities, ensuring that the solutions developed are grounded in real-world needs. Preliminary results were presented at the CSUN Assistive Technology Conference [2], receiving positive feedback. The final outcome of the project was the launch of a mobile application for Warsaw Metro users in September 2024.

This paper presents the conceptual foundation of a system designed to navigate users through metro stations efficiently, without requiring sub-meter positioning accuracy. The proposed solution is based on a customized spatial data model and an adaptive instruction generation algorithm.

The paper is structured as follows: Section 2 reviews the current landscape of indoor positioning systems and their limitations in enabling high-quality navigation. Section 3 introduces the developed system, and Section 4 evaluates its applicability in real-world environments.

2. Related Work

Indoor navigation systems are widely used in transportation hubs such as airports, metro stations, and train terminals. These systems are implemented either via customized venue-specific apps or through general-purpose apps developed by third-party providers. Custom apps typically offer deeper integration, incorporating maps, points of interest, and contextual features such as notifications. This makes navigation smoother and more intuitive. On the other hand, general apps provide only basic venue maps, requiring users to manually select their destination, often with limited context. The analysis of both types of apps shows that most existing solutions use traditional step-by-step navigation, which relies heavily on the precision of the underlying positioning system. When positioning fails or is not accurate enough, the instructions become unreliable.

2.1. Airport navigation systems

Research on indoor navigation in airport environments shows a strong focus on improving positioning systems, particularly in enhancing accuracy and reliability. For example, the solution presented in [3] emphasizes the security aspects of indoor positioning. In [4] and [5], researchers explore new approaches for designing positioning modules. Despite the high interest in deploying indoor positioning systems in airports, little attention has been paid to addressing the limitations of these systems through strategies such as refining instruction generation or incorporating dense networks of points of interest (POIs) to provide richer contextual guidance. An example of the most common navigation methodology in airport navigation apps can be observed in Figure 1. It typically involves the use of instructions based on distances in meters, which are often not intuitive for average users.

2.2. Metro navigation systems

The metro stations and buildings are usually complex and architecturally distinct from other typical indoor venues. They consist of numerous corridors, which are often narrow and prone to high pedestrian density. Compared to airports, there are significantly fewer applications specifically designed for metro navigation. In [6], the authors introduce a multimodal positioning method aimed at improving location accuracy. Meanwhile, [7] demonstrates a marker-based navigation system combined with Inertial Measurement Unit (IMU) data from smartphones. Although this is not the authors' primary focus, they also propose an Augmented Reality (AR) guidance mechanism that enhances contextual understanding and mitigates the effects of positioning inaccuracies. These examples highlight that, while advances in positioning technologies are being explored, there remains a lack of comprehensive systems offering end-to-end navigation tailored to the metro environment—indicating a stronger emphasis on improving positioning accuracy rather than on holistic user guidance.

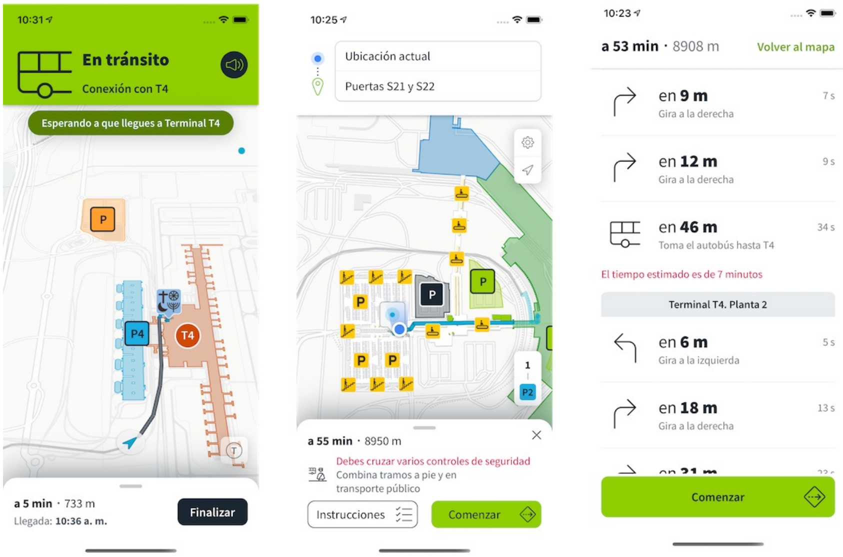

Figure 1: Example of navigation around an airport presented in the Aena Maps application

2.3. Special solutions enhancing indoor navigation

Extensive research has been conducted on how individuals navigate through indoor environments and how architectural and signage design can facilitate intuitive wayfinding. In [8], researchers identify key features of route descriptions that enhance their effectiveness in unfamiliar settings. Building on this insight, the authors of [9] developed a framework for generating landmark-based instructions using data about spatial object categories—data that is commonly available in existing spatial databases. At the Indoor Positioning and Indoor Navigation Conference, researchers from Aachen University presented a novel indoor navigation system that guides users using images of their surroundings and descriptive text, without relying on hardware-based positioning. This approach leverages contextual interpretation by users, promoting resilience against positioning inaccuracies. While these publications provided a valuable foundation for the development of the system described below, they fell short of demonstrating a fully implemented and practically deployed solution capable of delivering intuitive, real-world indoor navigation for users.

3. Main components of the system

The previous chapter focused on reviewing literature relevant to the topic. While the solutions presented in these studies are not without limitations, they provide a solid foundation upon which the proposed system is built. The system developed in this work aims to address the issues identified above by designing an indoor navigation solution that does not rely on sub-meter positioning accuracy. Instead, it leverages the user's ability to interpret contextual information by providing landmark-based instructions and images of the surroundings, enhanced with AR elements.

3.1. Implemented indoor positioning module

While the methodology for implementing the positioning module is not the primary focus of this paper, it is important to briefly describe the technology used and the achieved accuracy in order to provide context regarding the extent to which positioning inaccuracies can be mitigated by the applied methods.

The indoor positioning module is based on BLE beacons installed throughout the metro stations. The positioning technique used is fingerprinting [10][11], chosen primarily because the creation of the station's signal map could be synchronized with the process of capturing images for the image-based instructions, thereby reducing the overall workload.

After collecting the signal data necessary for positioning, a machine learning model was trained. Three different algorithms were evaluated:

- K-Nearest Neighbours (KNN)
- Support Vector Machine (SVM)
- Random Forest (RF)

Among these, the RF algorithm yielded the highest classification accuracy of 77% resulting in the average distance between the user's true position and the predicted node of the navigational graph of 6.15 meters This level of precision is sufficient for the system's needs, as the accuracy of user positioning is inherently constrained by the data model. Specifically, the user's position is always snapped to the nearest node in the routing graph, where the average spacing between nodes is approximately 8.5 meters.

3.2. Station architecture

The system has been specifically designed for the Warsaw Metro, and the architectural analysis is therefore tailored to the characteristics of this transit network. Metro stations typically feature entrances with staircases that lead into narrow corridors, eventually connecting to the main station area with turnstiles [12]. The layout is generally linear, guiding passengers from the entrance to the platform and vice versa, which naturally reduces the need for high-precision indoor positioning.

Unlike office buildings or malls, metro stations lack complex branching paths or numerous individual rooms. In such buildings, users often need to be directed to specific rooms or areas, increasing the demand for precise localization. Metro stations, by contrast, are designed to accommodate large volumes of pedestrian traffic, resulting in wider corridors and open spaces. Additionally, the boundaries between functional areas in metro stations are less distinct—these are primarily transit spaces, and heavy spatial separation (e.g. via doors or partitions) would hinder passenger flow and reduce system efficiency.

Table 1
Comparison of architectural aspects of metro stations and buildings

Aspect	**Metro stations**	**Buildings**
Purpose	High-throughput transit	Functional
Areas	Stairs, concourse, platform	Lobby, corridors, rooms
Connectivity characteristics	Deep vertical transition with emphasis on safety and evacuation	Multi-level circulation with public/private distinction

3.3. User Interface

Another important consideration in the system's development was designing the user interface and application flow to function independently of the indoor positioning module [13]. By default, the user manually selects the starting point and destination of the journey, as they may not currently be located within the metro station. The application also provides an option to determine the user's location via GPS, which is particularly useful when outdoors; in such cases, the nearest station entrance is automatically selected as the starting point.

While the indoor positioning module runs in the background, if it successfully detects the user's location, a pop-up notification prompts the user to confirm whether they would like to see their location (Figure 2). Later on they can select it as a starting point of their journey. Importantly, the application does not continuously track the user's movement during navigation. This decision is based on the rationale that displaying live location updates or highlighting real-time instructions may introduce confusion if the positioning data is inaccurate. Instead, the system relies on the user's ability to interpret contextual cues and navigate based on provided instructions.

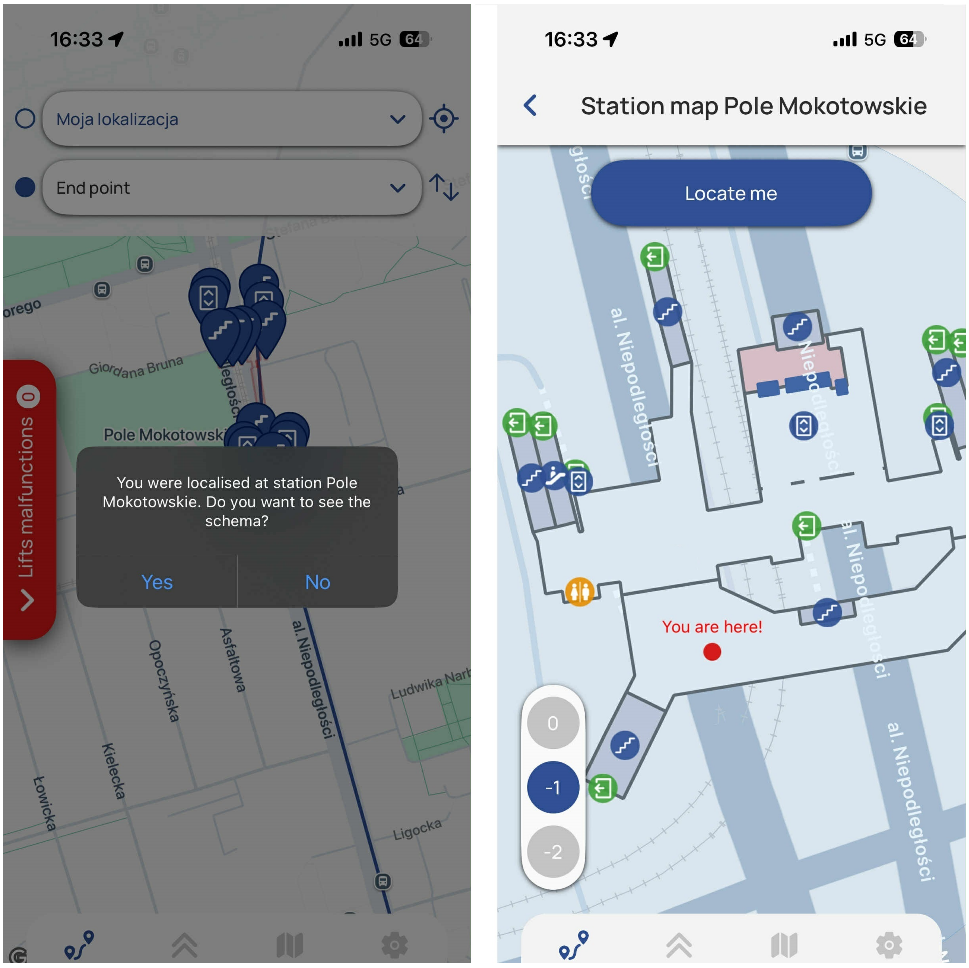

Figure 2: Pop-up notification displayed after successful localization of the user

3.4. Landmark-based instructions

The generation of landmark-based instructions is closely linked to both the system's data model and the algorithm used for generating the instructions. The overall process has been described in detail in a previous publication by the research team [14].

The data model consists of three distinct layers:

- Transport Network
- Room Topology
- Topography

The Transport Network layer is primarily used for route calculation, as it contains the geometries of path segments. However, the layers most relevant to landmark-based instruction generation are the Room Topology and Topography layers.

The Room Topology layer identifies when a change in spatial context occurs—such as moving from one room to another, ascending a staircase, or similar transitions. At this stage, instructions may lack full contextual detail, but identifying such transitions is essential for meaningful navigation.

The Topography layer enriches instructions with contextual information. It includes details about interior features, named zones within stations, and descriptions of prominent landmarks. This layer plays a key role in generating intuitive and user-friendly guidance.

3.5. Usage of images

To ensure that users can navigate the metro system freely without relying on sub-meter positional accuracy, an additional solution has been implemented: the inclusion of visual cues. The data model has been extended to incorporate a link between the geometries of path segments and images representing the surrounding environment within the Transport Network layer. This allows the application to display relevant images to the user once a path has been determined, helping them visually confirm the correct route.

Additionally, the application utilizes AR to further assist passengers by overlaying navigational guidance directly onto the real-world environment (Figure 3).

Navigation instructions generated by the algorithm fall into five possible maneuver types:

- right turn
- mild right turn
- left turn
- mild left turn
- straight

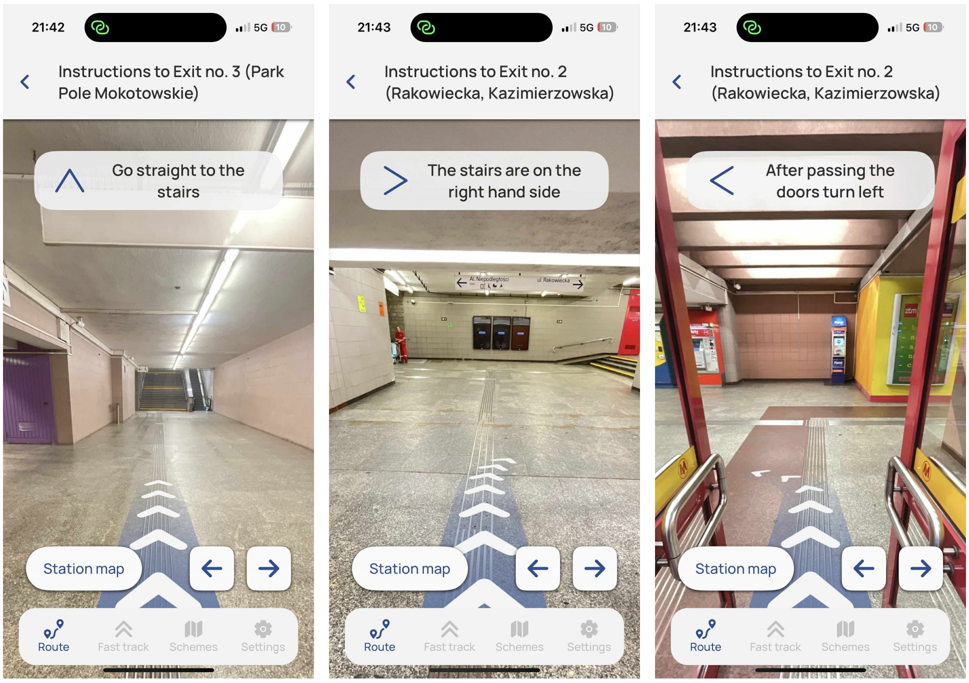

Figure 3: AR arrows representing instructions respectively: go straight, mild right turn, left turn

The type of maneuver selected depends on the distance over which the user must make the turn. If the turn is executed over a longer distance, a mild turn (implying a smaller angle) is selected. For shorter distances, a sharper turn is expected, so a standard left or right turn is chosen.

4. Method and Experimental setup

Usability tests were conducted with over 30 participants representing diverse backgrounds, age groups, and familiarity levels with the metro system, with additional feedback collected from real-life users via the publicly available application on the Apple App Store and Google Play Store. To ensure objectivity, none of the core test participants had prior experience with the mobile application. Each participant completed a designated nine-stop metro journey, including one line transfer, both with and without the app. The route, shown in Figure 4, was intentionally designed to involve elevator navigation and a transfer to reflect realistic, moderately complex travel scenarios. After a brief introduction, participants used the in-app map to locate the nearest elevator and initiate the "to platform" navigation, which provided on-screen guidance from the surface to the metro platform. Following a 15-minute journey and a line change, they arrived at the destination station, where they used the "to surface" function to set route parameters and receive step-by-step instructions to the target tram stop. Upon completing the journey, participants filled out a short questionnaire, which asked whether using the mobile app affected their comfort with the metro system, whether a more precise indoor positioning module would improve or worsen the experience, and whether they relied on text-based landmark instructions, image-based instructions, or both while navigating.

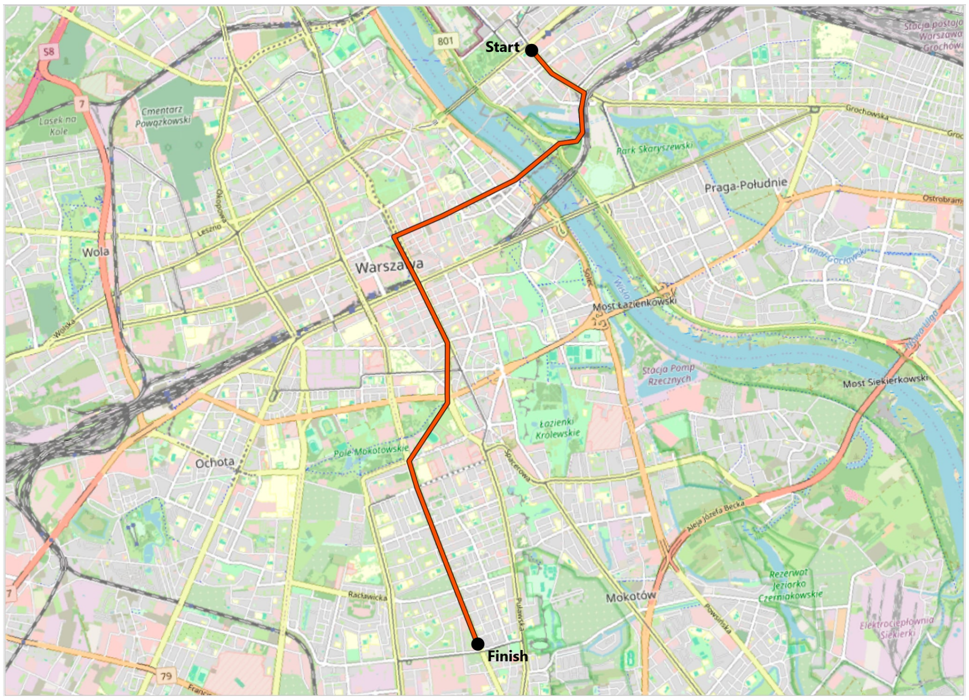

Figure 4: Map of a route followed during tests

5. Conclusion

An exact explanation of the process of analysis of the results has been omitted due to the page limitation of the paper. Collected feedback allowed us to draw the following conclusions:

- Overall, user feedback was positive. Most users reported that the application increased their comfort and confidence when using the metro. None of the participants indicated issues related to their positioning within metro stations or expressed a need for a highly precise indoor positioning system. This confirms the main thesis of this paper: sub-meter accuracy is not required for effective metro navigation. Among the implemented features, landmark-based instructions received the most praise. Users appreciated being informed about their surroundings and what to expect along their journey, which helped them avoid major navigational errors.
- Positive feedback was also received from users with visual impairments. Although they could not benefit from image-based instructions, the landmark-based guidance significantly enhanced their ability to visualize the route and increased their travel confidence. Unlike standard indoor navigation apps that rely on rigid, step-by-step instructions, this system offers a more intuitive and flexible approach. Users are not forced to follow a predefined path precisely, reducing dependency on the system and decreasing the risk of accidents caused by incorrect positioning—particularly important for visually impaired users who rely more heavily on the navigation system.

Another benefit for this group is the ability to pre-plan routes at home without needing an active indoor positioning module, allowing them to mentally prepare by visualizing the environment beforehand.

Despite the generally positive feedback, several limitations of the application were identified. One notable issue was a decrease in user attention to their physical surroundings during navigation. The use of the mobile device led some users to focus more on the screen than on their environment, increasing the likelihood of minor mistakes that may not have occurred otherwise. Additionally, in certain instances, users made significant navigational errors without being immediately aware of them. When this happened, the visual or textual instructions provided by the application no longer matched the user's surroundings, resulting in confusion and a loss of time as users attempted to determine whether the instructions were incorrect. In some cases, this led to users arriving at unintended locations.

To address these limitations, future development could incorporate a detour detection mechanism. This feature would monitor a user's position relative to the planned route and detect significant deviations. Upon detecting a detour, the system could issue timely alerts to guide the user back to the correct path or, at the very least, inform them that they are off-course. Such a capability would reduce confusion and minimize time lost in returning to the intended route. Another improvement involves mitigating ambiguity in complex environments, such as areas with similar-looking doors or adjacent elevators. By incorporating a spatial analysis algorithm capable of detecting such situations, the system could either alert users to potential confusion or offer more detailed instructions, thereby enhancing clarity and user confidence during navigation.

Declaration on Generative AI

The author(s) have not employed any Generative AI tools.

References

[1] A. A. Morgan, On the accuracy of ble indoor localization systems: An assessment survey, Computers and Electrical Engineering 118 (2024) 109455. URL: https://www.sciencedirect.com/science/article/pii/S0045790624003823. doi:https://doi.org/10.1016/j.compeleceng.2024.109455.

[2] California State University, Northridge, Csun assistive technology conference, https://www.csun.edu/, 2024. URL: https://www.csun.edu/, accessed: 2025-06-08.

[3] I. Santos-González, A. Rivero-García, P. Caballero-Gil, Secure indoor location for airport environments, in: 2018 4th International Conference on Big Data Innovations and Applications (Innovate-Data), IEEE, 2018, pp. 60–64.

[4] B. Molina, E. Olivares, C. E. Palau, M. Esteve, A multimodal fingerprint-based indoor positioning system for airports, Ieee Access 6 (2018) 10092–10106.

[5] M. Vieira, M. A. Vieira, G. Galvão, P. Louro, P. Vieira, A. Fantoni, Optimizing indoor airport navigation with advanced visible light communication systems, Sensors (Basel, Switzerland) 24 (2024) 5445.

[6] C. Sun, X. Yang, Y. Zhen, Y. Bai, L. Peng, Research on multimodal fusion indoor positioning under high-throughput passenger flow: A case study of metro station, in: 2024 IEEE 27th International Conference on Intelligent Transportation Systems (ITSC), 2024, pp. 2214–2220. doi:10.1109/ITSC58415.2024.10920202.

[7] G. Lee, H. Kim, A hybrid marker-based indoor positioning system for pedestrian tracking in subway stations, Applied Sciences 10 (2020). URL: https://www.mdpi.com/2076-3417/10/21/7421. doi:10.3390/app10217421.

[8] M.-P. Daniel, M. Denis, Spatial descriptions as navigational aids: A cognitive analysis of route directions, Kognitionswissenschaft 7 (1998) 45–52.

[9] I. Fellner, H. Huang, G. Gartner, "turn left after the wc, and use the lift to go to the 2nd floor"—generation of landmark-based route instructions for indoor navigation, ISPRS International Journal of Geo-Information 6 (2017). URL: https://www.mdpi.com/2220-9964/6/6/183. doi:10.3390/ijgi6060183.
[10] P. I. Philippopoulos, K. N. Koutrakis, E. D. Tsafaras, E. G. Papadopoulou, D. Sigalas, N. D. Tselikas, S. Ougiaroglou, C. Vassilakis, Cost-efficient rssi-based indoor proximity positioning, for large/-complex museum exhibition spaces, Sensors 25 (2025). URL: https://www.mdpi.com/1424-8220/25/9/2713. doi:10.3390/s25092713.
[11] E. Skýpalová, M. Boroš, T. Loveček, A. Veľas, Innovative indoor positioning: Ble beacons for healthcare tracking, Electronics 14 (2025). URL: https://www.mdpi.com/2079-9292/14/10/2018. doi:10.3390/electronics14102018.
[12] A. Tofiluk, M. Domagalski, B. Wiktorzak, Analiza wybranych aspektów przestrzeni warszawskiego metra w kontekście dostosowania do potrzeb osób z niepełnosprawnością ruchu, Builder 27 (2023) 20–26.
[13] G. Szewczuk, R. Olszewski, Development of methodology for designing indoor cartographic visualizations for use in navigation for persons with special needs, Polish Cartographical Review 56 (2025) 115–133.
[14] J. B. Marciniak, B. Wiktorzak, Automatic generation of guidance for indoor navigation at metro stations, Applied Sciences 14 (2024). URL: https://www.mdpi.com/2076-3417/14/22/10252. doi:10.3390/app142210252.