Acta Mechanica Slovaca **30 (1): 26 - 32,** March **2026**
https://doi.org/10.21496/ams.2026.008

Acta Mechanica Slovaca
ISSN 1335-2393
www.actamechanica.sk

Visual-Inertial Tracking in Augmented Reality: Impacts on Wayfinding Behaviour and User Experience

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Abstract: Accurate pose estimation is a prerequisite for usable handheld augmented reality (AR) wayfinding indoors, yet users experience navigation less as a positioning number and more as a sequence of micro-corrections shaped by visual-inertial tracking. This paper examines how inertial measurement unit (IMU)-driven drift, heading instability and re-anchoring events influence spatial orientation, trust and comfort during smartphone-based AR guidance. We introduce a human-computer interaction (HCI)-oriented evaluation approach that couple's sensor diagnostics (e.g., inertial bias indicators, heading stability, and relocalisation frequency) with human measures of wayfinding behaviour (reorientation episodes, stop-and-check patterns, route confidence) and subjective experience (perceived control, workload and discomfort). Using an AR wayfinding prototype as a testbed, we report findings from a controlled navigation study and an in-situ deployment in a large indoor environment. We show that tracking instability systematically increases users' reliance on non-AR cues, disrupts orientation continuity and reduces trust in the guidance. We also demonstrate that simple interaction techniques, such as communicating tracking confidence and providing lightweight re-anchoring prompts, can mitigate these effects. We conclude with design recommendations for IMU-aware AR wayfinding systems and discuss implications for future hands-free and multi-sensor AR navigation.

Keywords: augmented reality; indoor navigation; ARCore; sensor fusion; A* path planning; usability evaluation; system usability scale

1. Introduction

Augmented reality (AR) has become a prominent enabling technology within the Industry 4.0 paradigm, where cyber-physical systems connect digital models with the physical shop floor to support faster and less error-prone decisions [1,2]. In logistics and warehousing, AR is increasingly investigated for operator support tasks such as picking, maintenance, training and real-time data access [3,4]. Beyond productivity-oriented Industry 4.0 goals, the Industry 5.0 perspective emphasizes human-centricity, resilience and sustainability; accordingly, digital assistance systems should augment workers' capabilities rather than merely automate isolated tasks [5,6].

From this perspective, AR is valuable not only because it overlays information in situ, but also because it can reduce context switching, support novice operators and improve situational awareness when it is aligned with operator workflows and ergonomic constraints [4-6]. However, these benefits are contingent on learnability, stability and user acceptance. Reviews of industrial AR adoption show that usability, perceived usefulness, hardware ergonomics and user-centred design are recurring determinants of successful deployment [6-8].

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Indoor navigation is a particularly relevant AR use case in warehouses and large industrial facilities, where workers must locate racks, machines or workstations under time pressure and where global navigation satellite systems are unavailable. Azuma already identified navigation as a core AR application [9], and recent systems combine simultaneous localisation and mapping (SLAM), inertial sensing and marker-based relocalisation to provide route guidance in indoor environments [10-12]. Compared with conventional 2D maps, AR guidance can embed instructions directly into the first-person view and may therefore reduce the need to translate abstract symbols into action [13-15].

Against this background, consolidated validation of both user-facing benefits and technical performance on the same prototype remains limited. This paper evaluates ARNAV, a smartphone-based indoor AR navigation prototype [12,16]. Study A is a controlled user study with three navigation conditions (BLIND, 2DMAP and ARNAV), assessed using the System Usability Scale (SUS) and non-parametric statistics [17,18]. Study B verifies technical performance in a real warehouse over 100 routes by quantifying positional error and navigation reliability. Together, the two studies address (RQ1) the usability benefit of AR in simple indoor routes and (RQ2) the software and calibration changes that most influence accuracy and reliability.

2. Experimental Materials and Methods

2.1. System and environments

The ARNAV prototype runs on an Android smartphone (6.1″ display) and was implemented in Unity 2022 using AR Foundation and ARCore. The system combines camera tracking with an inertial measurement unit (IMU; accelerometer, gyroscope and magnetometer). Raw IMU streams are processed through a sensor-fusion filter to estimate device orientation, which is refined by ARCore's visual-inertial SLAM service (motion tracking, environment understanding and light estimation).

Route guidance is computed on a navigation mesh generated from a 3D model of the warehouse. When a target location is selected, an A* planner computes the shortest path, which is rendered as a floor-aligned guidance line with arrows and a highlighted goal. As the user approaches the destination, the interface supplements the floor guidance line with a local target indicator, namely a virtual arrow aligned with the specific storage position and a textual target label. This final cue is intended to support last-metre identification of the correct rack location. Absolute alignment between the virtual scene and the warehouse is established by scanning a QR code at the entrance; recalibration can be repeated if tracking drifts. Figure 1 summarises the overall system architecture, and Figure 2 illustrates the ARNAV interface in a warehouse aisle (left) and in a laboratory corridor (right).

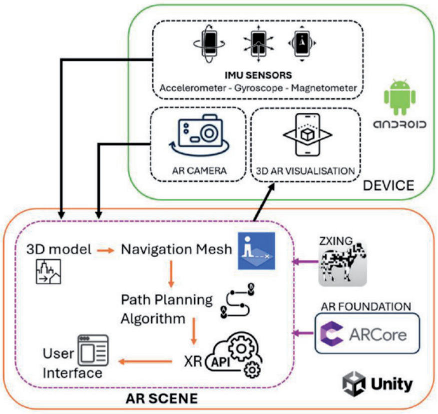

Figure 1: ARNAV architecture and key hardware/software components used for indoor AR navigation.

Figure 2: ARNAV user interface: examples of AR guidance in a warehouse (left) and a laboratory corridor (right).

Study A was conducted in a controlled laboratory corridor representing a simplified warehouse layout. Study B took place in a real warehouse with two long racks arranged into three aisles (footprint 36 × 40 m). Each rack contained four shelf levels labelled with alphanumeric codes, and target locations were defined on the front face of the racks for unambiguous identification. Before testing, the AR scene was manually calibrated: a marked floor point was mapped to the application origin (0, 0 m), ensuring that the virtual map and guidance cues were aligned with the physical environment.

2.2. Study A – usability evaluation

Study A evaluated perceived usability and user experience across three navigation conditions: BLIND (no visual aid), 2DMAP (a schematic 2D map showing current position and target) and ARNAV (AR guidance overlaid onto the camera view). The BLIND condition provided only a textual target identifier (e.g., "A3"), and participants relied on aisle signage to locate the rack. The ARNAV condition corresponds to a pick-by-vision approach in which direction cues are embedded directly into the first-person view, reducing the need to interpret abstract symbols [14].

Sixty-five volunteers participated. All had at least basic smartphone experience, while most had not previously used AR applications. A between-subject design was used: each participant completed tasks in one condition only. After a short familiarisation, participants were asked to locate and "pick" a target item from a specified rack position as quickly as possible. Each participant completed three tasks with different targets to avoid route repetition.

Perceived usability was measured using the System Usability Scale (SUS), which consists of 10 items (Q1 ÷ Q10) rated on a 1 ÷ 5 Likert scale [17]. Responses were converted to an overall SUS score (0 ÷ 100) using the standard scoring procedure [18]. Because item responses are ordinal and did not meet normality assumptions, group differences were tested using the Kruskal-Wallis test ($\alpha = 0.05$), followed by Dunn's post-hoc pairwise comparisons.

2.3. Study B – technical validation

Study B quantified navigation accuracy and reliability of the ARNAV system in the real warehouse. The application continuously logged estimated user pose from ARCore and IMU sensing, transformed to a 2D floor coordinate system (x, y) in metres. For each route, the true target coordinates were defined in the same reference frame based on warehouse dimensions and layout. Route completion was defined through two complementary criteria. At the interaction level, the participant had to visually identify the indicated storage position and confirm it by scanning the QR code attached to that location; proximity alone was not counted as successful arrival. At the metric level, a run was classified as successful when this confirmation was achieved without major failure and the final logged position was within 1 m of the target coordinate. If the scanned QR code did not correspond to the active destination, the application returned an error message and the route remained unfinished [12].

Accuracy was evaluated as the absolute positional error at task completion, i.e., the distance between the logged user position when the participant confirmed reaching the goal and the target coordinate. Across all routes, mean absolute error (MAE) and its standard deviation were computed.

Reliability was assessed from logged failure events, in particular tracking loss requiring recalibration and cases of incorrect goal indication. A critical failure was recorded when tracking drift or route loss prevented successful completion of the route, i.e., the user could not recover the correct guidance, the intended target was not successfully confirmed, and the run had to be terminated or restarted. Temporary losses of the guidance line that could be resolved without losing the destination were classified as non-critical events [12]. Summary metrics included the proportion of successful runs (participant reached within 1 m of the target without major failure) and a reliability index based on per-route scores (0 ÷ 3). Tests were performed under typical indoor conditions with stable artificial lighting and without moving obstacles that could confound visual tracking.

3. Results and Discussion

3.1. Usability results

Sixty-five participants completed the laboratory corridor task and were distributed across the three conditions as follows: BLIND ($n = 18$), 2DMAP ($n = 25$) and ARNAV ($n = 22$). Figure 3 reports mean and median SUS scores. The mean scores were 79.03 (BLIND), 84.10 (2DMAP) and 81.02 (ARNAV), while the corresponding medians were 82.5, 90.0 and 82.5, respectively. All medians were above 80, which corresponds to at least a "Good" usability rating on the Bangor adjective scale [19].

Kruskal-Wallis tests ($\alpha = 0.05$) indicated statistically significant differences for SUS item Q4 (need for technical support; p = 0.016) and Q6 (perceived inconsistencies; p = 0.037). The corresponding p-values across all items are shown in Figure 4. Dunn's post-hoc comparisons found that ARNAV participants reported a higher need for assistance (Q4) and more inconsistencies (Q6) than the 2DMAP group ($p < 0.05$), as summarised in Table 1. Figure 4 also shows a significant overall Kruskal-Wallis result for Q10 (p = 0.031). However, all three groups shared the same median response (1), and Dunn's post-hoc analysis did not identify any pairwise comparison that remained significant. For this reason, Q10 was not interpreted as a practically meaningful driver of between-condition differences [16].

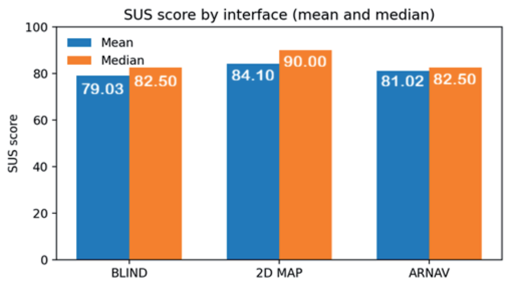

Figure 3: Mean and median System Usability Scale (SUS) scores for the three navigation conditions

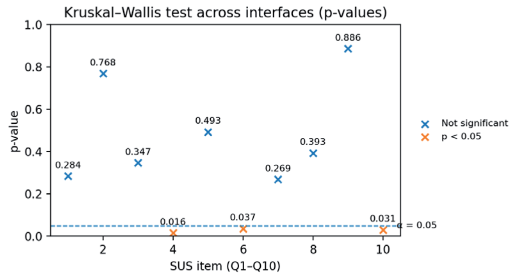

Figure 4: Kruskal-Wallis p-values for SUS items Q1 ÷ Q10 across navigation conditions (α = 0.05).

Table 1: Dunn's post-hoc pairwise comparisons for significant SUS items (α = 0.05).

Item	Group 1	Group 2	p-value
Q4	BLIND	2DMAP	0.095
Q4	BLIND	ARNAV	0.324
Q4	2DMAP	ARNAV	0.004
Q6	BLIND	2DMAP	0.719
Q6	BLIND	ARNAV	0.058
Q6	2DMAP	ARNAV	0.014

Note: Q10 reached overall significance in the Kruskal-Wallis test, but no pairwise comparison was significant in Dunn's post-hoc analysis; therefore, it is not listed in the table.

3.2. Technical validation results

Technical evaluation was performed in a 36 × 40 m warehouse over 100 navigation routes (mean length 29 m). Following an initial beta version, two development iterations were systematically compared. Between the iterations, four implementation changes were introduced: (i) disabling automatic recalibration after each QR-code scan, (ii) using conditional recalibration only after repeated scans or on user request, (iii) refining user-interface cues (lowering the guidance line closer to the floor and adding a turning-direction arrow on the minimap), and (iv) optimising navigation-mesh corner nodes to smooth sharp turns.

Table 2 summarises the resulting performance. The final iteration achieved a mean absolute target error of 0.48 m with an 83% success rate (reaching within 1 m of the target without tracking loss). The reliability index increased from 2.20 to 2.41, and the number of critical failures (user did not reach the goal) was reduced from eight to four.

Table 2: Comparison of ARNAV development iterations using key navigation metrics.

Metric	Definition	Iteration #1[1]	Iteration #2[2]	Δ
Successful guidance	User reached ≤ 1 m from target without tracking loss	22/30 (73%)	59/70 (83%)	+10 pp
MAE [m]	Mean absolute linear error to the target	0.45	0.48	≈
SD [m]	Standard deviation of target error	1.12	0.91	-0.21
Reliability index	Mean per-route score on a 0–3 scale[4]	2.20	2.41	+0.21
Critical failures	Route lost; target not confirmed; run terminated/restarted	8	4	-50%

Notes: [1] "2nd development iteration" (30 runs). [2] "Innovated application", i.e., final version (70 runs). [4] Scale: Low = 0 ÷ 1; Medium = 1 ÷ 2; High = 2 ÷ 3.

3.3. Discussion and implications

The SUS profile suggests a more nuanced interpretation than the overall score alone. Although ARNAV reached a median SUS of 82.5, indicating generally good perceived usability, the item-level pattern reveals specific adoption frictions. Compared with 2DMAP, ARNAV users reported a higher need for technical support (Q4) and more inconsistencies (Q6). In an Industry 4.0/5.0 context, these findings matter because human-centred industrial assistance systems should reduce interpretation effort and fit heterogeneous operator capabilities rather than transfer additional troubleshooting or calibration effort to the user [5,6].

Practically, the results do not suggest that AR guidance is unusable; rather, they indicate that the benefit of spatially embedded cues may be offset in simple routes when interface behaviour is not fully predictable. A system can be easy to start using yet still create friction in routine operation. This distinction is visible in the present data: Q10 does not indicate a strong learning barrier, whereas Q4 and Q6 point to support and consistency as the more relevant design bottlenecks. For industrial deployment, this implies that onboarding, recovery from drift, and clear feedback during relocalisation are at least as important as absolute positional accuracy.

In terms of positioning, reported indoor navigation accuracy varies widely across technologies and test conditions. For example, Zhang et al. compared satellite positioning and visual-inertial SLAM and reported errors ranging from sub-centimetre values under laboratory conditions to ~0.5 m for GPS [20]. Beacon-based indoor localisation typically yields larger errors: Sato et al. reported an average of 1.65 m for Bluetooth Low Energy (BLE) markers, and hybrid BLE + QR-marker solutions have been reported around 1.6 m [21,22]. The present warehouse results (MAE ≈ 0.48 m) are therefore comparable to, or better than, common BLE scenarios, but remain sensitive to lighting and texture conditions.

Backlighting and low-texture aisles remained key limitations, consistent with benchmark studies that report tracking degradation for ARCore under abrupt illumination changes in industrial environments [23]. While location-based AR can produce substantial efficiency gains in more complex scenarios [24], robust deployment in warehouses is likely to require hybrid relocalisation strategies (e.g., SLAM supported by additional anchors) as well as careful lighting design.

More broadly, adoption depends on user acceptance and ergonomic fit. Evidence from industrial AR suggests that user-centred design, iterative usability testing and alignment with operator workflows are prerequisites for sustainable benefits [6-8]. Handheld devices can increase mental and physical load compared with head-mounted displays [25,26], which motivates further evaluation on hands-free mixed-reality headsets and passthrough systems [27,28]. Beyond navigation, MR has also been applied to factory layout planning and process visualisation, enabling rapid verification of spatial arrangements before physical implementation [29-31]. Complementary simulation tools have been proposed to quantify and reduce the carbon footprint of engineering production, supporting sustainability-oriented decision making [32].

This work has methodological limitations that should be considered when interpreting the findings. Participants in Study A were predominantly technically skilled students rather than warehouse employees, which limits external validity for industrial deployment. In real warehouses, first-time users may differ substantially in digital literacy, familiarity with smartphones, and tolerance for calibration or relocalisation procedures. These factors are likely to affect perceived learnability, need for support, and trust in AR guidance [6,8]. Consequently, the present usability results should be interpreted as an early-stage evaluation of interface behaviour rather than as a direct estimate of operator acceptance in production. Future studies should therefore recruit warehouse workers with heterogeneous digital skills, compare novice and experienced users, and examine whether targeted onboarding reduces the higher Q4 and Q6 scores observed for ARNAV.

Completion time was not analysed in the present paper because Study B was designed primarily as a software-validation protocol focused on endpoint accuracy and failure behaviour across randomly generated routes of different lengths. Under these conditions, raw time would be strongly confounded by route distance, QR-scanning duration and recalibration events. We therefore prioritised positional error and route completion reliability in this iteration of testing. Nevertheless, because time-to-completion is operationally relevant in warehouse environments, future studies should include normalised efficiency metrics such as seconds per metre or seconds per confirmed pick [13].

4. Conclusions

This paper evaluated a smartphone-based indoor AR navigation prototype (ARNAV) using a combined usability and technical validation protocol. In a simple corridor task, perceived usability was already high without AR, and AR guidance did not outperform a conventional 2D map. The main usability drawbacks of ARNAV were a higher perceived need for technical support and inconsistencies, indicating that interface stability and learnability are critical in low-complexity layouts.

In a real warehouse, ARNAV achieved a mean absolute target error of 0.48 m and guided users successfully in 83% of 100 routes. Iterative changes to calibration logic, user-interface redundancy and navigation-mesh corner handling improved the reliability index (from 2.20 to 2.41) and reduced critical failures by 50%. These results suggest that smartphone-based AR can reach accuracy comparable to beacon-based systems, but robust tracking under challenging lighting remains a prerequisite for operational deployment.

Implementation recommendations derived from the development iterations are: (1) minimise forced recalibration and trigger it only when drift is likely or on explicit user request; (2) design redundant guidance cues (floor line + minimap + target highlighting) to maintain orientation after short tracking losses; (3) tune the navigation mesh for human motion, especially around corners and narrow passages; and (4) plan for a graceful fallback (e.g., 2D map) when tracking quality degrades.

Acknowledgments

This contribution was prepared with the support of the SGS-2025-026 project entitled "Artificial intelligence algorithms in sustainable manufacturing", financed by the Ministry of Education, Youth and Sports of the Czech Republic.

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