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A Comparative Evaluation of Augmented Reality Indoor Navigation versus Conventional Approaches

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Abstract: In the context of Industry 4.0, augmented reality (AR) is becoming a key element for innovations in the field of lifetime usability of products and optimisation of production processes. Its integrated use outdoors via GPS and Simultaneous Location and Mapping (SLAM) indoors with a focus on inertial technologies enables precise positioning and efficient navigation in industrial environments. The aim of this study is to test the user-friendliness of the proposed indoor navigation system using inertial sensors. The AR application provides indoor navigation between defined points of interest representing key locations. ARCore and ARFoundation were used for development. Participants are tested using three different approaches to orientation in the environment. Their task is to evaluate the user-friendliness and compare the use of a smartphone with an ARNAV app, 2DMAP with visual elements, and variants without wayfinding support "BLIND". User acceptance is validated using a standardized SUS questionnaire. The evaluation results show similar perceptions of the system among most respondents, except for the need for technical support and the presence of inconsistencies, where the ARNAV group showed different opinions, indicating the need for optimisation in these specific areas to improve the user experience. In line with other studies the results suggest that despite advances in augmented reality, there is still a lack of added value, especially for inexperienced users. Despite the number of studies available, user testing of the proposed systems remains poorly carried out, with the emphasis more on functional verification. The results of the study suggest that the low variety and simplicity of tasks in the studied environment limits significant differences in the perception of AR navigation. Future research should focus on the use of augmented reality in complex environments and in solving more complex tasks.

Keywords: Augmented Reality; Indoor Navigation; Industry 4.0; Logistics; User Acceptance

1 INTRODUCTION

Industry 4.0 uses cyber-physical system (CPS) technology to create a platform of cyber-physical production systems (CPPS). This platform is also used to connect the virtual space with the real world in order to increase the intelligence of the equipment in a smart factory [1]. To achieve the fundamental design principles of digital transformation in Industry 4.0, the implementation and integration of diverse information, digital and operational technologies (IDOT) is essential. This integration ranges from simple to advanced technological elements such as industrial sensors, controllers and automated guided vehicles [2]. Within the Industry 4.0 concept, there is an opportunity to interact with technology paradigms that include the Internet of Things (IoT), artificial intelligence (AI), robotics, big data processing, and cloud storage. In addition to these aspects, other innovative technologies, namely virtual and augmented reality, are also being used [3]. Fraga-Lamas et al. [4] describe areas of industry that are suitable for the application of augmented reality systems - manufacturing, service or training.

Augmented Reality (AR) is a technology that provides the user with a means to present a polysynthetic world. Azuma [5] also presents specific application perspectives of augmented reality in the context of situations where it can be effectively used, for example, through navigation maps or visualisation of the current and planned environment. Augmented reality technology relies on different methodological approaches. One of them is markerless AR, which is a form of augmented reality that allows the placement of virtual objects without the need for a reference node. Specifically, this is accomplished by simultaneously displaying a virtual object associated with a precise location obtained through technologies such as GPS and a digital compass. Marker-based AR relies on real-time recognition of images, eyes and other real-world objects to provide digital content to the user [6, 7].

Research oriented towards navigation in the physical environment can be broadly classified into three main groups: external navigation, internal navigation and their integration [8, 9].

Navigation solutions, such as the Google Maps application, rely on information from GPS, aerial imagery and satellite imagery, but with a primary focus on the external environment [10]. Alternatively, an integrated solution can be implemented that combines technologies such as GNSS and LiDAR or SLAM [11, 12]. In outdoor navigation, we exclusively encounter the application of GPS technology [13-15].

For today's large-scale structures such as organisations, universities, business centres and logistics warehouses, navigation is an increasingly complex challenge. An effective solution to this challenge lies in an integrated approach that harmonises external and internal navigation. This integration brings significant benefits in optimising time and facilitating navigation in complex environments [16, 17].

1. 1 Related Work in Augmented Reality Indoor Navigation

De Souza Cardoso et al. [18] identified the prevalent augmented reality applications in industrial environments that are primarily focused on manual assembly processes. These applications provide users with work instructions to perform specific tasks. At the other end of the spectrum is the logistics domain. Rejeb et al. [19] identified limitations to the benefits of augmented reality technology in the area of logistics and supply chain management. They emphasise the need to support human-centred designs for effective and successful user experiences with AR. Trebuňa et al. [20] describe the issue of truck logistics analysis using GPS location technology.

For indoor navigation solutions, there is a wide range of technologies that are used to pinpoint the user's location in confined spaces. These technologies include Bluetooth, radio frequency identification (RFID), Wi-Fi, magnetic navigation and even LED light technology [21-24]. One frequently used approach is the use of Inertial Measurement Unit (IMU) sensors. These use a magnetometer, gyroscope, and accelerometer, which together enable tracking of the user's movement and orientation in space [13, 17].

Bajpai and Amir-Mohammadian [26] introduced an indoor navigation system that operates without the need for physical signs and uses ARKit technology for the iOS platform. This system works with a server that stores and retrieves 3D map data. An open-source visual SLAM framework called OpenVSLAM is used to implement the 3D map reconstruction.

Romli et al. [27] focused on the development of an AR application with an emphasis on the urbanisation domain. A library was chosen as the demonstration environment for the AR prototype. The Vuforia SDK technology was used for specific scene identification and navigation in the space, which allows setting image markers. The marker system was also introduced by Sato [28], but his solution was extended to include BLE transmitters in order to minimise the energy burden of the mobile device.

The idea of creating augmented reality-enabled 2D and 3D indoor maps has been addressed by Cankiri et al. [29]. They presented a system design that incorporates 3D humanoid agents for realistic navigation scenarios created in an AR environment and integrates IMU and SLAM sensors. Other research is focused on the implementation of a 3D point cloud through Google Glass devices. This study concludes that computer vision technologies are an effective alternative to other methods of simultaneous localisation and mapping [30].

Yao et al. [31] developed a system that relies on the A* algorithm for optimised route planning based on a 2D map. The optimal route is then passed to the navigation module in the form of a sequence of nodes. This navigation module uses AR based on location-based services (LBS). For comparison, they also conducted experiments with a Wi-Fi system, where this approach was found to be significantly less accurate with respect to the real location, in the range of 3 to 8 metres.

Wang [32] presents the concept of an iBeacon positioning mechanism that features the ability to flexibly adapt appropriate detection values for different iBeacon devices at variable distances. The goal of this approach is to provide stable indoor localisation. At the same time, it is intertwined with the AR display functionality without the use of markers.

Extended support in robotics is addressed by Kapinus et al. [33], who present a framework called ARCOR2. This framework focuses on the efficient management of robotic workstations using AR. The authors approach this problem with a methodological foundation, which is paralleled in our paper where we investigate user-friendliness.

1. 2 Hypothesis Setting and Research Questions

We formulated the questions based on the standardised System Usability Scale (SUS) questionnaire [34], which is used later in the paper. For each question we established a null hypothesis (H0) and an alternative hypothesis (H1). H0 assumes that there are no significant differences between respondents in their perception of a particular aspect of the system, and H1 assumes that there is a significant difference between at least two groups of respondents.

Q1: There are significant differences between groups in perceptions of increased use of the system.
Q2: There are significant differences between groups in perceptions of unnecessary complexity of the system.
Q3: There are significant differences between groups in perceptions of the ease of use of the system.
Q4: There are significant differences between groups in the perception of the help needed from a technical support person to use the system.
Q5: There are significant differences between the groups in the perception of good integration of the different functions of the system.
Q6: There are significant differences between groups in perceptions of inconsistencies in the system.
Q7: There are significant differences between groups in perceptions of very quick learning to use by most people.
Q8: There are significant differences between groups in perceptions of the great difficulty of using the system.
Q9: There are significant differences between groups in perceptions of great confidence in using the system.
Q10: There are significant differences between groups in perceptions of the need to learn new knowledge before using the system.

Here we set the research question RQ1: Which of the proposed options is the most favourable in terms of SUS score?

In the introduction of the article, we delve into the elements of Industry 4.0 and their integration with augmented reality, specifically focusing on navigation in logistical processes. Stemming from the main AR panel, we formulate hypotheses and research questions. Subsequently, we describe the methodology, proposing three navigation variants, including an AR application with a graphical user interface and system functionality. We present the results through processed SUS questionnaires, focusing on key aspects of these questionnaires. In the discussion, we compare our findings with similar experimental results from other authors.

2 METHODOLOGY

The aim of this study is to conduct an experimental investigation aimed at comparing the user-friendliness of different forms of indoor navigation support. Specifically, this is in a laboratory environment where a fully illuminated corridor serves as a representation of the space. This area contains individual offices that represent points of interest involved in a simulated logistics process. A secondary output of this study is also the evaluation of the proposed algorithm operating at the augmented reality level, whereby the algorithm simultaneously operates in a markerless environment. The experiment uses standardised AR packages (described later), which were selected based on a search in the internal environment. We deliberately dropped the use of GPS, which is not relevant in indoor environments. Among the frequently discussed applications are technologies working with inertial measurement units. One of the advantages of this technology is the possibility to operate without the need for additional external tools, moreover, the required technologies are present in common smartphones.

A smartphone serves as the primary device using AR technology in this study. This decision is based on the fact that despite the widespread use of head-mounted display AR glasses, the deployment of AR glasses is still limited, especially due to the high cost of the device (for example, Microsoft HoloLens 2 costs $3,500 - March 2024) [35]. In parallel, we still observe a lack of progress in software capabilities for these devices. We experimentally compare variants using 2D maps, where we are inspired by the concept of visual management [36]. Another source of inspiration for our experiment is the 5S system, which works with colour variants to facilitate spatial understanding and visual management [37]. The purpose of this comparison is to evaluate how technologically advanced orientation support will contribute to user-friendliness. To achieve this idea, it is necessary to explore technological differences, with the most logical approach being to analyse the 2D map aspect of the traditional view.

The application testing was conducted on a Xiaomi Redmi Note 11 Pro mobile device, which has ARCore Depth API support. The characteristics of this test device can be classified as representative of lower-end mobile phones. The operating system of the mobile phone used for testing is Android 11, with a display refresh rate of 120 Hz. The main camera has a resolution of 108 megapixels, and the battery capacity reaches 5000 mAh.

Three variants are analysed in the framework of the indoor navigation analysis:

1) Absence of navigation support to assess the natural orientation in space - BLIND.
2) Navigation using a two-dimensional (2D) map as part of a visual management concept - 2DMAP.
3) Navigation through an augmented reality (AR) application on a smartphone - ARNAV.

The user experience was retrospectively evaluated using the System Usability Scale (SUS) questionnaire [34], which is the most widely used standardised instrument for evaluating the perceived usability of the system being tested. In the context of its psychometric properties, it can be concluded that the SUS questionnaire proved to be effective in terms of reliability, validity, and sensitivity of the outputs. In this questionnaire, it should be considered that users who experience a higher level of satisfaction in the initial use of the system are likely to show a tendency to use the product more often, which will enable them to achieve a high level of skill with the product. The current trend favours the use of short scales because of their efficiency and ease of administration. The standard version of the questionnaire contains a mix of positive and negative items, with odd items worded positively and even items negatively. Respondents rate their level of agreement with each item using a five-point scale from 1 (strongly disagree) to 5 (strongly agree). The SUS total score is calculated by converting each item to a 0-4 scale, where higher values correspond to higher perceived usability. We then sum the converted scores. Finally, we multiply the sum by $*2.5$. This procedure generates scores that can range from 0 to 100, with higher scores indicating a higher level of perceived usability of the system [38]. The analysis was performed in Excel with RealStatistic using Excel add-in version 2210 installed [39].

2. 1 Description of the AR Application for the ARNAV Variant

There are specific requirements that must be met by the application. The primary purpose of the application is for the user to easily navigate using AR, which in our case involves displaying virtual navigation lines leading to points of interest. The system includes a simulation of the processes of loading and unloading objects, and these processes are displayed in the form of a task list that visualises the sequential steps. The application is optimised to work on specified frameworks. A limitation of the application is the specific environment for which it was designed. The application uses the standardised ARCore and ARFoundation libraries, which are designed for Android devices.

Figure 1 User interface: A – application input interface, B - drop-down list of positions.

The experimental application, the interface seen in Fig. 1, features a miniature floorplan of the defined environment. The control of the application is implemented through buttons in the graphical interface. The "LINE VISIBILITY" button displays a virtual line that navigates in space according to the generated NavMesh. To generate a line to the exact point of interest, a dropdown list is implemented, in which the individual locations are listed. From this list we can select our preferred location. To minimise the need for additional cues during the experiment, a "LIST" button was created. Pressing it displays a list of tasks that the proband must complete during the experiment. During the implementation of the user interface, we emphasised the criteria of simplicity, clarity, and maximum user-friendliness.

2.2 Methodology for Testing Variants

Participants are thoroughly briefed on the testing procedure at the beginning of the experimental process. For the purposes of the first phase of the experiment, we chose the environment of the University of West Bohemia, considering the possible influence of the complexity of the environment and unstable lighting conditions on the results of the experiment. The experiment itself is initiated in a fairly sterile environment consisting of a flat and symmetrically lit corridor, which allows better control of any environmental effects. In this primary part of the experiment, special emphasis is placed on evaluating the results from the questionnaire that the probands complete.

This experiment represents a logistical process where the proband assumes the role of a new worker in a warehouse. The aim of the experiment is to use one of the available spatial orientation aids to facilitate and optimise the navigation process.

The proband's task is to determine the direction of the location of objects in the warehouse and then, according to a predetermined procedure, to distribute these objects around the production area. Each specific location in this context represents the location of a production machine and one central warehouse.

2.2.1 Variant 1 (Without support tools - BLIND)

This experimental variant represents a basic and direct approach to interacting with the surrounding space, but at the same time presents a more challenging spatial orientation task. The proband is provided with a list of tasks to complete. Coloured labels representing different objects are placed on a door symbolising a warehouse. The proband follows the task list, collecting the required number of labels of different colours from the door. They then place these labels on the doors that represent the production machines. The colours of the labels must match the task list. When all the labels have been distributed, the experiment is terminated. Immediately after completion, the proband conducts an evaluation using the SUS questionnaire. To simplify and speed up the response process, a QR code is placed on the wall that links to a Google Form questionnaire specifically designed for this experiment.

2.2.2 Variant 2 (Using 2D Maps - 2DMAP)

The second variant of the experiment operates with a background in the form of a 2D map (Fig. 2), which is given to the proband simultaneously with the task list. Emphasis is placed on the fact that the use of the attached map is an integrated part of the experiment and the proband is actively encouraged to use it to improve their orientation in space. Subsequently, the proband completes the same procedure as in the first variant. After completing all tasks from the list, the proband again completes the SUS questionnaire.

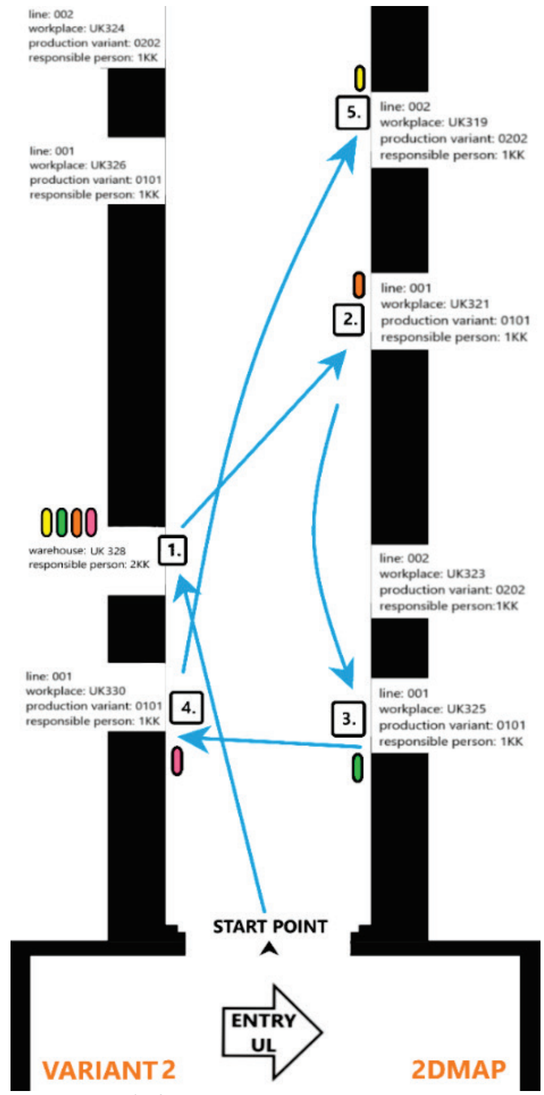

Figure 2 Diagram of a 2D map with visualisation elements given to probands during the 2DMAP experiment.

2.2.3 Variant 3 (Use of AR - ARNAV)

The experiment starts with the proband receiving a mobile phone with an app installed which is capable of visualising the surrounding space through augmented reality. The aim of the app is to display a virtual route leading to points of interest, represented by each door in the corridor. These doors represent locations in a warehouse or production area and are followed in the same way as in the previous versions of the experiment. Before running the experiment, the functions of the app are explained to the proband, and a brief description is provided of what to expect in the app and how to interact with it. As mentioned earlier, we tried to configure the augmented reality system in such a way that the proband does not need any additional information. The information about the tasks to be performed by the proband is available directly in the augmented reality application.

Before starting the application, the proband stands in the zero position and starts the application. After quick familiarisation with the list of tasks found under the "LIST" button, they select the desired position from the drop-down list. They then click on the "LINE VISIBILITY" button and a virtual line in space appears on the mobile device's display to navigate to the selected location. Following the on-screen instructions, the proband performs an action, such as picking up or sticking a piece of paper on a door. They then check the list of tasks again and repeat the process until all the tasks are completed. An example of the process can be seen in Fig. 3. The experiment ends with the proband completing a questionnaire evaluating the system and its features.

Figure 3 Visualisation of the experimental procedure in the ARNAV variant; A - Sheet with the list of tasks, B - Representation of the navigation line, C - Placement of a coloured label at a specific position.

3 RESULTS

The evaluation works with three different variants of support systems for orientation in an unfamiliar environment, namely:

1) Variant 1: Navigation without support "BLIND" with the participation of 18 respondents.
2) Variant 2: Navigation with 2D map "2DMAP" with 25 respondents.
3) Variant 3: Navigation with augmented reality application "ARNAV" with 22 respondents.

The Kruskal-Wallis test was used for a targeted comparison of the means of the three different variants. This is a non-parametric statistical method, applicable when comparing the means of several independent groups, especially in cases where the assumptions for parametric tests are not met. These assumptions include, for example, the independence of the data (meaning different numbers of respondents coming from different groups), failure to meet the assumption of a normal distribution of the data, or the use of unmeasured metrics where only rankings and comparisons are available. Its undeniable advantage is its relative ease of interpretation and implementation, which is significant for statistical analysis without extensive assumptions [40, 41]. As part of the evaluation process, ten questions (Q1 ... Q10) were formulated that directly correspond to the standardised questions in the SUS questionnaire. The alpha level of significance was set at 0.05 when the Kruskal-Wallis test was performed. This level determines whether we can reject the null hypothesis. The result of this statistic is obtained through the p-value, which is the result of the test performed, and can be seen in Tab. 1. Furthermore, the comparison of the median values for each variant is shown in Fig. 4.

Table 1 Summary of the values of the Kruskal-Wallis test for the stated hypotheses supplemented by the evaluation of the hypotheses.

Question	H-ties	p-value	Result
1	2.519	0.284	There are no significant differences between the variants
2	0.528	0.768	There are no significant differences between the variants
3	2.119	0.347	There are no significant differences between the variants
4	8.225	0.016	Significant differences in perception were shown by the DUNN method between the 2DMAP and ARNAV groups
5	1.417	0.493	There are no significant differences between the variants
6	5.273	0.037	Significant differences in perception were shown by the DUNN method between the 2DMAP and ARNAV groups
7	2.628	0.269	There are no significant differences between the variants
8	1.869	0.393	There are no significant differences between the variants
9	0.199	0.886	There are no significant differences between the variants
10	3.577	0.031	There are significant differences between the variants

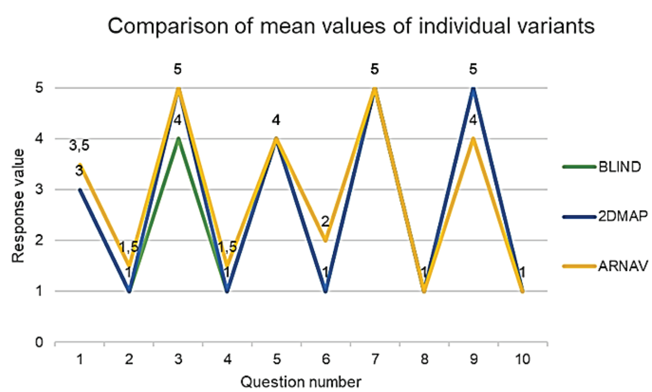

Figure 4 Comparison of mean results for each question of the SUS questionnaire.

For Q1, Q2, Q3, Q5, Q7, Q8 and Q9, no significant differences were found for any respondent groups and the **null hypotheses are not rejected**. Therefore, only Q4, Q6 and Q10, where **significant differences were found between at least two groups of respondents**, need to be examined in further detail.

Q4:
H0: *There are no significant differences between the groups in perceptions of assistance from a technical support person.*
H1: *There are significant differences between groups in perceptions of the help of a technical support person.*

The *p*-value of the test was found to be $p = 0.016$, leading to the rejection of the null hypothesis. However, the median values of the BLIND and 2DMAP groups are the same and equal to 1, while the ARNAV group is equal to 1.5. Half of the respondents from the BLIND and 2DMAP groups responded with a value of 1. That is, they strongly disagree that they would need the support of a technical person to use the system. Respondents in the ARNAV group reported responses ranging from 1 to 2, or that they did not need the support of a technical person. Significant differences in perceptions were found between the 2DMAP and ARNAV groups, with ARNAV respondents showing higher levels of agreement with the need for technical resource support than 2DMAP group respondents.

After rejecting the null hypothesis in the test of mean equality, a post hoc analysis was conducted to identify groups with statistically significant differences. The Dunnett's test was used for this analysis, which is suitable when compared groups have different sample sizes. The analysis revealed a statistically significant difference between the 2DMAP and ARNAV groups ($p = 0.004 < p = 0.016$), see Fig. 5.

Q4	DUNNETT´s TEST	alpha = 0.05
group 1	*group 2*	*p-value*
BLIND	2DMAP	0.095
BLIND	ARNAV	0.324
2DMAP	ARNAV	**0.004**

Figure 5 Comparison of Dunnett test variants for question 4

Q6:
H0: *There are no significant differences between the groups in their perception of good integration of different system functions.*
H1: *There are significant differences between groups in perceptions of good integration of different system functions.*

The *p*-value of the test was found to be $p = 0.037$, again leading to the rejection of the null hypothesis. The medians of the BLIND and 2DMAP groups are equal to 1. The median of the ARNAV group is equal to 2. Half of the respondents in the BLIND and 2DMAP groups answered 1. So they do not perceive any irregularities in the system. The third group ARNAV answered 2 or less. Significant differences in perception were found between the 2DMAP and ARNAV groups, with ARNAV respondents showing a higher level of agreement with too many irregularities in the system than 2DMAP group respondents.

Q6	DUNNETT´s TEST	alpha = 0.05
group 1	*group 2*	*p-value*
BLIND	2DMAP	0.719
BLIND	ARNAV	0.058
2DMAP	ARNAV	**0.014**

Figure 6 Comparison of Dunnett test variants for question 6

We conducted the same analysis, the Dunnett's test, after rejecting the null hypothesis for question 6 as well. We found a statistically significant difference between the 2DMAP and ARNAV groups ($p = 0.014 < p = 0.037$), as shown in Fig. 6.

Q10:
H0: *There are no significant differences between the groups in their perceptions of gaining new knowledge before using the system.*
H1: *There are significant differences between groups in perceptions of new knowledge gain before using the system.*

Despite the rejection of the null hypothesis, the same median values were found in all groups, namely the value of 1. Thus, it can be concluded that respondents do not perceive the necessity of gaining new knowledge before using the system. In each group, one half of the respondents clearly chose the answer 1. For this reason, a post-hoc analysis was performed, but no pair with a significant difference was identified.

Table 2 Summary of SUS questionnaire scores for individual variants.

SUS score			
Respondent	BLIND	2DMAP	ARNAV
1	52.5	97.5	42.5
2	90	100	82.5
3	85	77.5	82.5
4	97.5	82.5	80
5	80	87.5	82.5
6	97.5	95	62.5
7	45	65	87.5
8	72.5	92.5	80
9	92.5	82.5	77.5
10	100	97.5	80
11	77.5	92.5	95
12	55	70	100
13	90	97.5	90
14	77.5	97.5	92.5
15	92.5	90	87.5
16	100	87.5	97.5
17	37.5	90	77.5
18	80	100	72.5
19		27.5	82.5
20		62.5	65
21		95	85
22		95	80
23		52.5	
24		82.5	
25		85	
MEAN VALUE	**79.03**	**84.10**	**81.02**
MEDIAN	**82.5**	**90**	**82.5**

Parallel to this, an evaluation of the SUS questionnaire was carried out in a standardised form, which is described in the introduction of the methodology. These outputs are summarised in Tab. 2. The higher the SUS score, the higher the level of user acceptance of a given system. This score answers our question: which of the proposed options is the most favourable in terms of SUS score? The output shows 2DMAP as the most preferred option with a value of exactly 90 for the median score. The secondary output of the evaluation of the AR navigation algorithm demonstrated the successful completion of the functionality of the whole system.

A final Kruskal-Wallis test was performed for the SUS score. Here the hypothesis was posed: There are significant differences in median SUS scores between groups. After performing the Kruskal-Wallis test, the *p*-value was calculated as $p = 0.301$ with an alpha value of 0.05. The hypothesis was rejected.

4 DISCUSSION

The analysis and evaluation of mobile navigation compared to traditional maps has been studied in the past. With our experimental variants, we achieved identical designs - mobile app, a paper 2D map and direct experience. The research confirmed that the directional errors of the participants in the different groups did not show significant differences from each other [42]. A similar study is designed to assess the AR experience in comparison to the map-based experience. However, it is conducted within a VR context. This analysis mainly focuses on the effect of AR on driving performance and route learning ability in the context of a virtual environment [43]. In a similar vein, they conducted an analysis of the forklift navigation process in VR within a logistics process [44]. In many aspects, we can observe the substitution of augmented reality for virtual reality environments. As VR currently has more advanced technology, it provides more significant support for the application of AR elements and their research [45].

In an outdoor environment, Mulloni et al. [46] performed an experimental comparison of an AR application with a traditional map. A significant finding of the research is that users predominantly use augmented reality near road intersections. This location appears to be crucial to effectively support accurate tracking. This result shows that despite the progress made in AR, there is still a lack of sufficient added value, especially for inexperienced users.

Conversely, Dünser et al. [47] identified that while using map backgrounds integrated into an AR application, users focused their gaze on the screen for the longest time, especially when walking. The authors state that this can be explained by the different design of the study conducted. The results of this analysis also show that users generally look at the screen less frequently with the AR interface. The authors interpret this fact to mean that this interface is primarily used for quick verification at decision points and for confirming directions. Sekhavat and Parsons [48] discuss the design and comparison of two tracking methods in outdoor augmented reality applications: location-based augmented reality (LAR) and marker-based augmented reality (MAR). The results show that the characteristics of the location-based tracking method bring the need for less time to locate points of interest; reducing the number of errors in locating specific POIs; inducing a higher perception of the quality of the user experience and promoting a higher acceptance rate to using AR technology.

QR codes are an important integration into AR navigation systems, serving not only as markers for location definition, but increasingly as key elements for identifying points of interest (PoI). In parallel with this functionality, applications are being developed to optimise cloud connectivity. The main impetus for this implementation is to minimise the energy consumption of hardware devices - smartphones or AR glasses [49-52].

Tadepalli et al. [53] presented a solution with some similarities using the A* algorithm. However, it should be noted that this is a rather simplistic approach that has not been developed, for example, in the form of experimental testing.

5 CONCLUSION

Industry 4.0 opens up the possibility of interacting with technological paradigms such as the Internet of Things, artificial intelligence, robotics, big data processing and augmented reality. Augmented reality is a technology with various applications, including navigation and environmental visualisation. In the area of navigation in physical environments, the integration of external and internal navigation is key to effectively addressing the challenges of navigating complex environments, bringing significant benefits in optimising time and facilitating navigation.

In industrial environments, augmented reality is widely applied in manual assembly processes, while in logistics it faces constraints requiring human-centric designs for optimal user experiences. In indoor navigation a variety of technologies from Bluetooth to IMU sensors enable accurate user location in confined spaces. Research in AR navigation includes innovative approaches such as the use of standardised frameworks for iOS and Android platforms or the combination of 3D map data with visual SLAM. The broad spectrum of research also includes optimised route planning using the A* algorithm and the development of positioning mechanisms such as iBeacon and RFID for stable indoor localisation and efficient integration with AR displays.

Our experiment conducted on indoor AR navigation is structured to systematically evaluate the factors affecting the effectiveness of AR technologies and the user experience. The creation of an augmented reality-enabled application based on IMU sensors for a smartphone will enable the assessment of the potential of AR navigation and the optimisation of the research results. The proposed algorithm uses standardised packages to support Android devices, namely ARCore and ARFoundation.

The experiment systematically presents the process of testing AR navigation in indoor environments, starting in a test environment for the first phase and gradually moving to an industrial setting. Participants are introduced to the experimental process and detailed tasks, with each variant of the experiment involving specific means of navigation. The experimental conditions are carefully designed to maintain symmetrical results and obtain quality feedback from participants. Each variant of the experiment simulates a logistics process with the proband in the role of a warehouse worker. The experimental variants include different approaches to interacting with the environment, including the use of a 2D map and a mobile app with AR navigation, as well as a variant without any orientation support.

During the evaluation of the system, no statistically significant differences were found between the three groups of respondents on most of the questions investigated. Questions related to frequent use of the system, its complexity, ease of use, correct integration, presence of inconsistencies, speed of learning and confidence in use did not show statistically significant differences between the different variants. It can be concluded that the respondents from the total sample had similar views on different aspects of the system.

However, significant differences in the perception of different aspects of the system emerged on the issue of the need for technical support. The 2DMAP group, which required a lower level of technical support, was statistically different from the ARNAV group, which required a higher level of technical support. Respondents in the ARNAV group showed greater agreement that they would need the support of a technical person. Similarly, there were significant differences for the question regarding the presence of inconsistencies in the system, where respondents in the ARNAV group were more likely to agree that there were too many inconsistencies in the system than respondents in the 2DMAP group.

Overall, while most respondents' perceptions of the system were similar, it is important to focus on specific areas where significant differences emerged between the groups. These findings may be key to further optimising the system and improving the user experience. It is significant to note that the initially expected negative evaluation of the system by the BLIND and 2DMAP groups was not confirmed. Nevertheless, the ARNAV group was not statistically different in its perception of the system.

The cause of these results is attributed to the low level of task variety and complexity, as well as the specifics of the environment. This fact can be considered a limitation of this study. Within a low-diversity and non-complex environment, the chosen technology is not a decisive factor, and the user experience is very similar. A key question for further research is to what extent the use of augmented reality support is significant in complex environments and when dealing with complex tasks. This step is the subject of future research.

Some studies suggest that experiments with mobile apps, paper maps and direct experience have confirmed that directional errors between these methods do not show significant differences. Other studies have compared the use of an AR app with a traditional map in outdoor environments, with proximity to road intersections being a key area for effective support. The results also suggest that despite the successes in AR, users still prefer quick verification at decision points and confirmation of directions.

Integrating QR codes into AR navigation systems and optimising cloud connectivity are also identified as key elements for the effective use of these technologies. Although advanced algorithms such as A* exist, the need for further experimental testing to fully evaluate their effectiveness in real navigation conditions should be emphasised. Overall, there is a dynamic and diverse approach to the development of navigation technologies, especially in conjunction with augmented reality.

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Institutional Review Board Statement

The study was approved by the internal university ethics committee (ZCU 002459/2024).

6 REFERENCES

[1] Zhou, K., Liu, T. & Zhou, L. (2015). Industry 4.0: Towards future industrial opportunities and challenges. In *The 12th IEEE International Conference on Fuzzy Systems and Knowledge Discovery (FSKD)*, Zhangjiajie, China, 2147-2152. https://doi.org/10.1109/FSKD.2015.7382284

[2] Ghobakhloo, M. (2020). Industry 4.0, digitization, and opportunities for sustainability. *Journal of Cleaner Production, 252*, p. 119869, https://doi.org/10.1016/j.jclepro.2019.119869

[3] Hofmann, E. & Rüsch, M. (2017). Industry 4.0 and the current status as well as future prospects on logistics. *Computers in Industry, 89*, 23-34. https://doi.org/10.1016/j.compind.2017.04.002

[4] Fraga-Lamas, P., Fernandez-Carames, T. M., Blanco-Novoa, O. & Vilar-Montesinos, M. A. (2018). A Review on Industrial Augmented Reality Systems for the Industry 4.0 Shipyard. *IEEE Access, 6*, 13358-13375. https://doi.org/10.1109/ACCESS.2018.2808326

[5] Azuma, R. T. (1997). A Survey of Augmented Reality. *Presence: Teleoperators & Virtual Environments*, 6(4), 355-385. https://doi.org/10.1162/pres.1997.6.4.355

[6] Jomsri, P. (2018). Implementing Virtual 3D Model and Augmented Reality Navigation for Library in University. *International Journal of Modeling and Optimization (IJMO), 8*(6), 315-317. https://doi.org/10.7763/IJMO.2018.V8.671

[7] Fleck, S., Hachet, M. & Bastien, J. M. C. (2015). Marker-based augmented reality: instructional-design to improve children interactions with astronomical concepts. In *Proceedings of the 14th International Conference on Interaction Design and Children*, Boston Massachusetts: ACM, 21-28. https://doi.org/10.1145/2771839.2771842

[8] Iftikhar, H., Asghar, S. & Luximon, Y. (2020). The efficacy of campus wayfinding signage: a comparative study from Hong Kong and Pakistan. *Facilities, 38*(11/12), 871-892. https://doi.org/10.1108/F-04-2020-0035

[9] Munion, A. K., Stefanucci, J. K., Rovira, E., Squire, P. & Hendricks, M. (2019). Gender differences in spatial navigation: Characterizing wayfinding behaviors. *Psychon Bull Rev, 26*(6), 1933-1940. https://doi.org/10.3758/s13423-019-01659-w

[10] Martinez-Cruz, S., Morales-Hernandez, L. A., Perez-Soto, G. I., Benitez-Rangel, J. P. & Camarillo-Gomez, K. A. (2021). An Outdoor Navigation Assistance System for Visually Impaired People in Public Transportation. *IEEE Access, 9*, 130767-130777. https://doi.org/10.1109/ACCESS.2021.3111544

[11] Ren, G., Ai, C., Xu, Q., Wang, Z., Wang, Z. & Geng, D. (2020). Research on Indoor and Outdoor Navigation Technology Based on the Combination of Differential GNSS and Lidar SLAM. In *The IEEE International Conference on Real-time Computing and Robotics (RCAR)*, Asahikawa, Japan, 134-139. https://doi.org/10.1109/RCAR49640.2020.9303252

[12] Aoki, R., Tanaka, H., Izumi, K. & Tsujimura, T. (2018). Self-Position Estimation based on Road Sign using Augmented

Reality Technology. *The 12th IEEE France-Japan and the 10th Europe-Asia Congress on Mechatronics*, 39-42. https://doi.org/10.1109/MECATRONICS.2018.8495815
[13] Chung, C. O., He, Y. & Jung, H. K. (2016). Augmented Reality Navigation System on Android. *International Journal of Electrical and Computer Engineering (IJECE), 6*(1), p. 406. https://doi.org/10.11591/ijece.v6i1.pp406-412
[14] Rao, J., Qiao, Y., Ren, F., Wang, J. & Du, Q. (2017). A Mobile Outdoor Augmented Reality Method Combining Deep Learning Object Detection and Spatial Relationships for Geovisualization. *Sensors*, 17(9), p. 1951. https://doi.org/10.3390/s17091951
[15] Lin, C.-H., Chung, Y., Chou, B.-Y., Chen, H.-Y. & Tsai, C.-Y. (2018). A novel campus navigation APP with augmented reality and deep learning. *The IEEE International Conference on Applied System Invention (ICASI)*, Chiba, 1075-1077. https://doi.org/10.1109/ICASI.2018.8394464
[16] Vanclooster, A. & De Maeyer, P. (2012). Combining Indoor and Outdoor Navigation: The Current Approach of Route Planners. In *Advances in Location-Based Services*, Gartner, G. & Ortag, F. Eds., in Lecture Notes in Geoinformation and Cartography. Berlin, Heidelberg: Springer Berlin Heidelberg, 283-303. https://doi.org/10.1007/978-3-642-24198-7_19
[17] Yang, J., Kang, Z., Zeng, L., Hope Akwensi, P. & Sester, M. (2021). Semantics-guided reconstruction of indoor navigation elements from 3D colorized points. *ISPRS Journal of Photogrammetry and Remote Sensing, 173*, 238-261. https://doi.org/10.1016/j.isprsjprs.2021.01.013
[18] De Souza Cardoso, L. F., Mariano, F. C. M. Q. & Zorzal, E. R. (2020). A survey of industrial augmented reality. *Computers & Industrial Engineering, 139*, p. 106159. https://doi.org/10.1016/j.cie.2019.106159
[19] Rejeb, A., Keogh, J. G., Leong, G. K. & Treiblmaier, H. (2021). Potentials and challenges of augmented reality smart glasses in logistics and supply chain management: a systematic literature review. *International Journal of Production Research, 59*(12), 3747-3776. https://doi.org/10.1080/00207543.2021.1876942
[20] Trebuňa, P., Mizerák, M., Pekarčíková, M., Kliment, M. & Matiscsák, M. (2023). Tracking of Trucks Using the GPS System for the Purpose of Logistics Analysis. *Advances in Design, Simulation and Manufacturing VI*, Ivanov, V., Trojanowska, J., Pavlenko, I., Rauch, E. & Piteľ, J., Eds., in *Lecture Notes in Mechanical Engineering*. Cham: Springer Nature Switzerland, 162-171. https://doi.org/10.1007/978-3-031-32767-4_16
[21] Torres-Sospedra, J. et al. (2015). Enhancing integrated indoor/outdoor mobility in a smart campus. *International Journal of Geographical Information Science, 29*(11), 1955-1968. https://doi.org/10.1080/13658816.2015.1049541
[22] Kunhoth, J., Karkar, A., Al-Maadeed, S. & Al-Attiyah, A. (2019). Comparative analysis of computer-vision and BLE technology based indoor navigation systems for people with visual impairments. *Int J Health Geogr, 18*(1), p. 29. https://doi.org/10.1186/s12942-019-0193-9
[23] Zhang, H. et al. (2022). Visual Indoor Navigation Using Mobile Augmented Reality. *Advances in Computer Graphics, vol. 13443*, Magnenat-Thalmann, N., Zhang, J., Kim, J., Papagiannakis, G., Sheng, B., Thalmann, D. & Gavrilova, M., Eds., in *Lecture Notes in Computer Science, vol. 13443*. Cham: Springer Nature Switzerland, 145-156. https://doi.org/10.1007/978-3-031-23473-6_12
[24] Gualda, D. et al. (2021). LOCATE-US: Indoor Positioning for Mobile Devices Using Encoded Ultrasonic Signals, Inertial Sensors and Graph-Matching. *Sensors*, 21(6), p. 1950. https://doi.org/10.3390/s21061950
[25] Mulloni, A., Seichter, H. & Schmalstieg, D. (2011). Handheld augmented reality indoor navigation with activity-based instructions. *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services*, Stockholm Sweden: ACM, 211-220. https://doi.org/10.1145/2037373.2037406
[26] Bajpai, A. & Amir-Mohammadian, S. (2021). Towards an Indoor Navigation System Using Monocular Visual SLAM. In *The 45th IEEE Annual Computers, Software, and Applications Conference (COMPSAC)*, Madrid, Spain, 520-525. https://doi.org/10.1109/COMPSAC51774.2021.00077
[27] Romli, R., Razali, A. F., Ghazali, N. H., Hanin, N. A. & Ibrahim, S. Z. (2020). Mobile Augmented Reality (AR) Marker-based for Indoor Library Navigation. *IOP Conf. Ser.: Mater. Sci. Eng.*, 767(1), p. 012062. https://doi.org/10.1088/1757-899X/767/1/012062
[28] Sato, F. (2018). Indoor Navigation System Based on Augmented Reality Markers. *Innovative Mobile and Internet Services in Ubiquitous Computing, vol. 612*, Barolli, L. & Enokido, T., Eds., in *Advances in Intelligent Systems and Computing, vol. 612*. Cham: Springer International Publishing, 266-274. https://doi.org/10.1007/978-3-319-61542-4_25
[29] Cankiri, Z. T., Marasli, E. E., Akturk, S., Sonlu, S. & Gudukbay, U. (2020). Guido: Augmented Reality for Indoor Navigation Using Commodity Hardware. *The 24th IEEE International Conference Information Visualisation (IV)*, Melbourne, Australia, 708-713. https://doi.org/10.1109/IV51561.2020.00123
[30] Rehman. U. & Cao, S. (2015). Augmented Reality-Based Indoor Navigation Using Google Glass as a Wearable Head-Mounted Display. *The IEEE International Conference on Systems, Man, and Cybernetics*, Kowloon, 1452-1457. https://doi.org/10.1109/SMC.2015.257
[31] Yao, D., Park, D.-W., An, S.-O. & Kim, S. K. (2019). Development of Augmented Reality Indoor Navigation System based on Enhanced A* Algorithm. *KSII TIIS, 13*(9). https://doi.org/10.3837/tiis.2019.09.016
[32] Wang, C.-S. (2019). An AR mobile navigation system integrating indoor positioning and content recommendation services. *World Wide Web*, 22(3), 1241-1262. https://doi.org/10.1007/s11280-018-0580-3
[33] Kapinus, M., Materna, Z., Bambušek, D., Beran, V. & Smrž, P. (2023). ARCOR2: Framework for Collaborative End-User Management of Industrial Robotic Workplaces using Augmented Reality. https://doi.org/10.48550/arXiv.2306.08464
[34] Lewis, J. R. & Sauro, J. (2009). The Factor Structure of the System Usability Scale. *Human Centered Design*, Kurosu, M., Ed., in *Lecture Notes in Computer Science*. Berlin, Heidelberg: Springer, 94-103. https://doi.org/10.1007/978-3-642-02806-9_12
[35] HoloLens 2—Pricing and Options | Microsoft HoloLens. Accessed: Feb. 22, 2024. Available: https://www.microsoft.com/en-us/hololens/buy
[36] El Manti, S. and El Abbadi, L. (2022). Integration of Visual Management in the Industry 4.0: Case Study. *The 2nd IEEE International Conference on Innovative Research in Applied Science, Engineering and Technology (IRASET)*, Meknes, Morocco, 1-4. https://doi.org/10.1109/IRASET52964.2022.9738102
[37] Senthil Kumar, K. M., Akila, K., Arun, K. K., Prabhu, S. & Selvakumar, C. (2022). Implementation of 5S practices in a small scale manufacturing industries. *Materials Today: Proceedings, 62*, 1913-1916. https://doi.org/10.1016/j.matpr.2022.01.402
[38] Borsci, S., Federici, S., Bacci, S., Gnaldi, M. & Bartolucci, F. (2015). Assessing User Satisfaction in the Era of User

Experience: Comparison of the SUS, UMUX, and UMUX-LITE as a Function of Product Experience. *International Journal of Human-Computer Interaction, 31*(8), 484-495. https://doi.org/10.1080/10447318.2015.1064648

[39] Home Page (Welcome) | Real Statistics Using Excel. Accessed: Mar. 05, 2024. Available: https://real-statistics.com/

[40] Svoboda, M., Gangur, M. & Mičudová, K. (2019). *Statistické zpracování dat*, 1. vydání. Plzeň: Západočeská univerzita v Plzni. (in Poland)

[41] Rosenstein, L. D. (2019). *Research design and analysis: a primer for the non-statistician*. Hoboken, NJ: John Wiley & Sons, Inc. https://doi.org/10.1002/9781119563600

[42] Ishikawa, T., Fujiwara, H., Imai, O. & Okabe, A. (2008). Wayfinding with a GPS-based mobile navigation system: A comparison with maps and direct experience. *Journal of Environmental Psychology, 28*(1), 74-82. https://doi.org/10.1016/j.jenvp.2007.09.002

[43] Yount, Z. F., Kass, S. J. & Arruda, J. E. (2022). Route learning with augmented reality navigation aids. *Transportation Research Part F: Traffic Psychology and Behaviour, 88*, 132-140. https://doi.org/10.1016/j.trf.2022.05.019

[44] Pereira, A., Lee, G. A., Almeida, E. & Billinghurst, M. (2016). A Study in Virtual Navigation Cues for Forklift Operators. *The XVIII IEEE Symposium on Virtual and Augmented Reality (SVR)*, Gramado, Brazil, 95-99. https://doi.org/10.1109/SVR.2016.25

[45] Medeiros, D., Wilson, G., Mcgill, M. & Brewster, S. A. (2023). The Benefits of Passive Haptics and Perceptual Manipulation for Extended Reality Interactions in Constrained Passenger Spaces. *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, Hamburg Germany: ACM, 1-19. https://doi.org/10.1145/3544548.3581079

[46] Mulloni, A., Seichter, H. & Schmalstieg, D. (2011). User experiences with augmented reality aided navigation on phones. *The 10th IEEE International Symposium on Mixed and Augmented Reality*, Basel, 229-230. https://doi.org/10.1109/ISMAR.2011.6092390

[47] Dünser, A., Billinghurst, M., Wen, J., Lehtinen, V. & Nurminen, A. (2012). Exploring the use of handheld AR for outdoor navigation. *Computers & Graphics, 36*(8), 1084-1095. https://doi.org/10.1016/j.cag.2012.10.001

[48] Sekhavat, Y. A. & Parsons, J. (2018). The effect of tracking technique on the quality of user experience for augmented reality mobile navigation. *Multimed Tools Appl, 77*(10), 11635-11668. https://doi.org/10.1007/s11042-017-4810-y

[49] Yeh, H.-T., Chen, B.-C., Yang, C.-T. & Weng, P.-L. (2018). New Navigation System Combining QR-Code and Augmented Reality. *J. Internet Technol., 19*(2), 565-571. https://doi.org/10.3966/160792642018031902024

[50] Fajrianti, E. D. et al. (2023). INSUS: Indoor Navigation System Using Unity and Smartphone for User Ambulation Assistance', *Information, 14*(7), p. 359. https://doi.org/10.3390/info14070359

[51] Szymczyk, T., Montusiewicz, J. & Gutek, D. (2016). Navigation in Large-Format Buildings Based on RFID Sensors and QR and AR Markers. *Adv. Sci. Technol. Res. J.*, 10(31), 263-273. https://doi.org/10.12913/22998624/64059

[52] Verma, P., Agrawal, K. & Sarasvathi, V. (2020). Indoor Navigation Using Augmented Reality. *Proceedings of the 4th International Conference on Virtual and Augmented Reality Simulations*, Sydney NSW Australia: ACM, 58-63. https://doi.org/10.1145/3385378.3385387

[53] Tadepalli, S. K., Ega, P. A. & Inugurthi, P. K. (2021). Indoor Navigation Using Augmented Reality. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology (IJSRCSEIT), 7*(4), 588-592. https://doi.org/10.32628/CSEIT2174134

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