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Optimizing assembly processes with augmented reality: a case study on TurtleBots

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ABSTRACT

Augmented reality (AR) technology is revolutionizing traditional assembly processes, offering intuitive and interactive guidance that significantly enhances operational efficiency and accuracy. This study investigates the impact of AR on the assembly of Turtlebots, a complex task representative of industrial applications. Through a comparative analysis involving traditional paper manuals, modified paper manuals, and AR-based manuals, the benefits of AR integration are quantitatively assessed. Participants utilizing AR-based manuals completed the Turtlebot assembly 21.72% faster than those using traditional paper manuals, with a notable reduction in assembly time from an average of 03:00:40 to 02:21:26. Furthermore, the incidence of assembly errors significantly decreased, with AR manual users making an average of 2.25 errors compared to 5 by paper manual users. These findings underscore the potential of AR to expedite complex assembly tasks and enhance the accuracy of these processes. The study highlights the novel application of AR in improving both the speed and quality of assembly in an industrial context, demonstrating AR's role as a pivotal technology for the future of manufacturing.

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1. INTRODUCTION

Augmented reality (AR), an innovative technology blending digital information with the physical world, has significantly impacted various sectors, including medical [1], [2], manufacturing [3]–[6], education [7]–[10], tourism [11], and aviation [12], [13]. This technology enhances human perception and interaction by overlaying digital content onto the real world, a capability that is pivotal across diverse applications [14]–[16].

In the realm of industrial operations, AR's application extends to maintenance assistance, notably in assembly and disassembly tasks, offering unprecedented precision and efficiency [17]. While previous research has affirmed AR's utility in assembly operations, these studies predominantly focus on short-term tasks or employ simplified models, limiting the exploration of AR's full potential in complex industrial settings [18]–[26]. This research gap underscores the necessity for in-depth investigations into AR's application in prolonged, intricate assembly processes that more accurately mirror industrial complexities.

This study employs the TurtleBot as a testbench, given its relevance to industrial applications in mapping, service, and environmental sensing [27]–[29]. The choice of Turtlebot facilitates a comprehensive examination of AR's effectiveness in enhancing assembly efficiency and accuracy, aligning with the broader objective of optimizing manufacturing processes. Through detailed analysis, this research evaluates AR's impact on assembly operations using established performance metrics, including task completion times, error rates, and subjective workload assessments [18], [26], [30], [31]. These metrics provide a robust framework for assessing the advantages of integrating AR into industrial assembly tasks, contributing valuable insights into operational efficiency and the potential for energy optimization in autonomous mobile robots (AMRs) [32]. Table 1 lists the performance metrics used by other research to determine the efficiency of AR.

Table 1. List of performance metrics by other research to determine efficiency of AR

Author	Test subjects	Performance metrics
Erkoyuncu *et al.* [33]	– 8 (4 person in 2 groups) – No age range specified – Participant background - unspecified	– Total task completion duration
Funk *et al.* [34]	– 6 (3 person per group) – Age range specified as 43.34 ± 4.49 and 45.67 ± 12.65 – Participant background - unspecified	– Total task completion duration
Gattullo *et al.* [30]	– 22 (Groups unspecified) – Age range specified as 36.5 ± 13.7 years old – Participant background - workers and undergraduates	– Questionnaire with Likert scale – Questionnaire about perceived missing information – Questionnaire regarding improvements, criticalities, and remarks
Aschenbrenner *et al.* [31]	– 50 (Groups unspecified) – Age range between 19 to 26 years old – Participant background - higher education entrance qualification, vocational school, and secondary school	– Total task completion duration – Number of task errors – QUESI – NASA-TLX – SART – ISONORM
Mourtzis *et al.* [18]	– Unspecified – Age range between 19 to 29 years old – Participant background - operators from automotive industry	– Total task completion duration – Number of task errors – NASA-TLX – Questionnaire with Likert scale
Wang *et al.* [19]	– 25 (groups unspecified) – Age range specified as mean of 24.5 – Participant background - engineering	– Total task completion duration – Questionnaire with Likert scale
Hietanen *et al.* [35]	– 20 (groups unspecified) – No age range specified – Participant background - university students	– Total task completion duration – Questionnaire with Likert scale
Alves *et al.* [26]	– 30 (10 person in three groups) – Age range specified between 19 to 51 years old – Participant background - faculty members, researchers, from different fields but do not have prior experience with case study	– Total task completion duration – Questionnaire with Likert scale – NASA-TLX – Number of task errors

2. METHOD

This study evaluates the effectiveness of different instructional methods on the assembly performance of Turtlebots, focusing on traditional paper manuals, modified paper manuals, and AR-based manuals. The primary objectives include assessing assembly time efficiency and error rate reduction. To achieve these objectives, the study employs a structured approach to compare and analyze the impact of each instructional method on the participants' performance.

2.1. Participants

Twelve volunteers, aged between 12 to 45 years and without prior TurtleBot assembly experience, were recruited. The participants were equally divided among the three instructional methods. All participants received a standardized briefing on the assembly tasks and tools to ensure a consistent knowledge base and minimize pre-existing knowledge effects.

2.2. Experimental setup

The assembly workbench was arranged to ensure all necessary components, tools, and instructional materials were within easy reach. This setup aimed to mimic an optimized industrial workstation to facilitate an efficient assembly process. Figure 1 illustrates the organized workbench layout, providing a conducive environment for participants to focus on assembly without unnecessary disruptions. As shown in Figure 2, each assembly component and tool was labeled and grouped accordingly to facilitate easy identification and access, further optimizing the assembly process.

Figure 1. Top view of assembly workbench layout (left) and setup of assembly workbench (right)

Figure 2. Assembly components on workbench

2.3. Assembly task and data collection

Participants assembled a TurtleBot using the assigned manual type. The assembly was untimed, prioritizing accuracy and participant interaction with the instructional method over speed. Data collected included:

– Total assembly time: duration from the start to the completion of the assembly.
– Number of errors: identified post-assembly, including any missing or incorrectly assembled parts.
– Participant feedback: assessed using a Likert scale and NASA-TLX questionnaire, focusing on mental demand, effort, and frustration levels.

2.4. AR-based manual setup

Participants using the AR-based manual interacted with an augmented reality application that overlaid step-by-step assembly instructions directly onto their field of view. This setup was intended to make the assembly process more intuitive and engaging, helping participants follow the instructions with greater ease and accuracy. Figure 3 illustrates the AR-based manual interface, demonstrating how the augmented reality application provided real-time, interactive guidance. This integration aimed to improve the efficiency and precision of the assembly tasks.

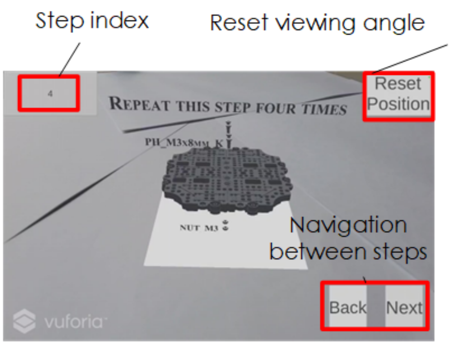

Figure 3. AR view for participants to perform assembly tasks

2.5. Experimental workflow

The methodology followed a structured process, starting with the setup of the assembly workbench. This was followed by a briefing session to prepare participants, the actual assembly task, and finally, data collection and analysis. Figure 4 outlines the complete methodology flow, ensuring a systematic approach from the initial setup to the final analysis. This structured workflow ensured consistency and reliability in the study's execution and results.

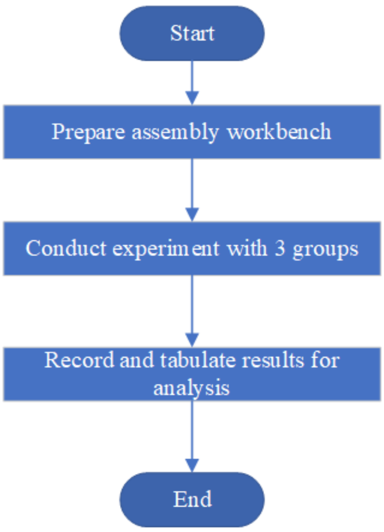

Figure 4. Flowchart of methodology

2.6. Statistical analysis

Performance metrics, including assembly time and error rates, were analyzed to compare the effectiveness of traditional, modified paper, and AR-based manuals. Statistical tests, such as Mann-Whitney tests, were employed to evaluate differences in performance metrics across the instructional methods. This methodology was designed for a detailed comparison of instructional methods on TurtleBot assembly performance. The comprehensive setup and structured experimental design ensure reproducibility and the applicability of findings to similar industrial assembly tasks.

3. RESULTS AND DISCUSSION

The evaluation of AR's impact on TurtleBot assembly provided detailed insights into its effectiveness. It compared the performance outcomes across three different instructional methods: traditional paper manuals, modified paper manuals, and AR-based manuals. This comparison highlighted the varying degrees of efficiency and accuracy achieved with each method.

3.1. Assembly time efficiency

The statistical analysis revealed a significant reduction in assembly time when participants used AR-based manuals. The average completion time was 02:21:26, representing a 21.72% improvement over traditional paper manuals and a 7.5% improvement over modified paper manuals, as shown in Table 2. This improvement highlights AR's potential to streamline complex assembly operations through interactive and intuitive guidance.

Table 2. Mean total assembly time by manual type

Manual type	Average total assembly duration (hh:mm:ss)
Paper manual	03:00:40
Modified paper manual	02:47:07
AR-based manual	02:21:26

3.2. Error rate reduction

The reduction in the number of assembly errors further validates AR's efficacy. Participants using AR-based manuals made an average of 2.25 errors, compared to 5 by those using paper manuals as shown in Figure 5. This finding highlights AR's role in enhancing precision and reducing oversight in assembly tasks, likely due to the more engaging and detailed instructions AR provides.

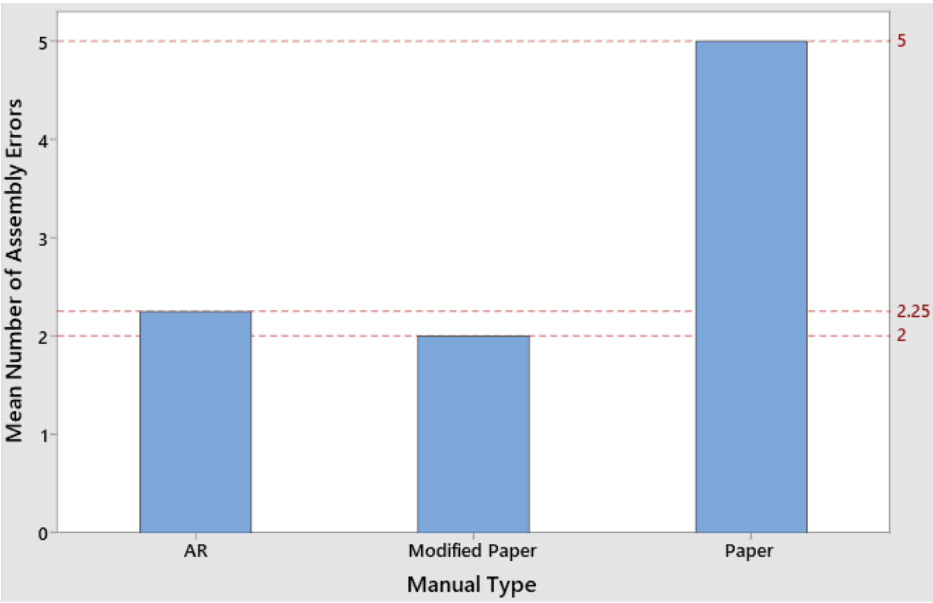

Figure 5. Bar chart of mean number of errors by manual type

3.3. Participant satisfaction and workload

User satisfaction and NASA-TLX scores offer insights into the subjective experience of using AR for assembly tasks. While AR-based manuals scored higher in satisfaction as shown in Figure 6, they also resulted in higher perceived mental workload as shown in Figure 7. This dichotomy suggests that while AR improves task efficiency and satisfaction, it may also increase cognitive demands on users.

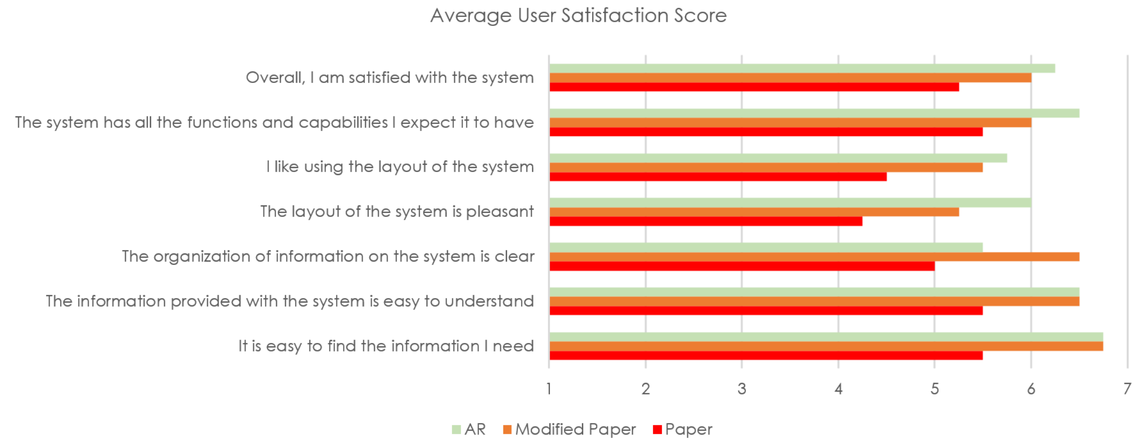

Figure 6. User satisfaction score using Likert scale with score range between 1-7

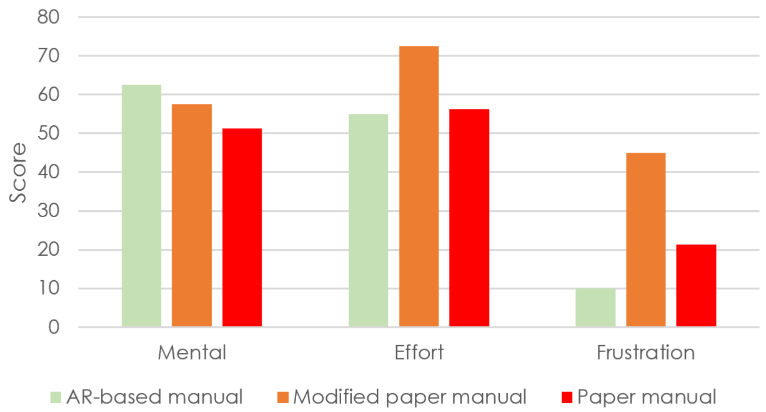

Figure 7. NASA-TLX scoring from user survey (lower score is better)

3.4. Critical analysis and future directions

The superiority of AR in enhancing assembly performance and reducing errors aligns with the technology's promise to revolutionize manufacturing processes. However, the increased mental workload reported highlights a crucial area for future research: optimizing AR interfaces to minimize cognitive strain without compromising efficiency. The study's limitations, including the small sample size and the specific context of TurtleBot assembly, suggest caution in generalizing the findings. Future research should explore the scalability of AR applications in manufacturing, potentially incorporating machine learning algorithms to personalize and streamline the AR experience based on user feedback and performance metrics. Moreover, investigating the long-term impacts of AR on learning curves and skill retention in assembly tasks can offer deeper insights into its educational and training potentials, alongside its immediate benefits in operational efficiency.

4. CONCLUSION

The study demonstrated significant benefits of utilizing AR-based manuals for the assembly of TurtleBots, showing a 21.72% improvement in assembly time compared to traditional paper manuals, and a 7.5% improvement over modified paper manuals. Moreover, the error rates for users of AR-based and modified paper manuals were considerably lower, averaging 2.25 and 2 errors respectively, versus an average of 5 errors with traditional paper manual users. These findings underscore the effectiveness of AR-based and modified paper manuals in enhancing assembly efficiency and accuracy. Additionally, the incorporation of animated 3D graphics in AR-based manuals was found to notably improve assembly times for a wide range of tasks. However, for simpler tasks such as snap-fit operations, the advantages over modified paper manuals were not significant. This indicates that the efficacy of AR instruction may vary depending on the complexity of the task at hand. It is important to note that AR-based manuals, while associated with improved performance, also led to a higher perceived mental workload among users, as reflected by NASA-TLX scores. This suggests a potential trade-off between the immersive, intuitive experience provided by AR and the cognitive load it introduces. The study presents compelling evidence of the effectiveness of AR-based manuals in assembly tasks within the scope of its investigation. Future research could focus on extending the application of these findings to broader contexts and exploring the impact of AR manuals on individuals with specific technical expertise in fields such as robotics engineering. Examining the long-term effects of AR on learning and skill retention through repeated assembly tasks could also provide further insights into its educational benefits.

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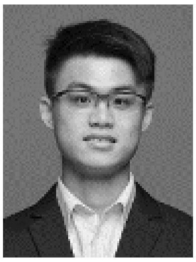

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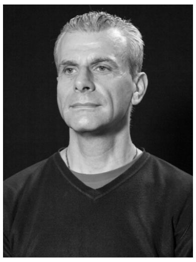

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