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

Mingyu Wu1,2, Ye Sheng Koh2, Che Fai Yeong2, Kai Woon Goh2, Marvin Dares2, Eileen Su Lee Ming2, William Holderbaum3, Mohd Shahrizal Sunar4

1Jiaxing Key Laboratory of Industrial Internet Security, Jiaxing Vocational and Technical College, Jiaxing, China
2Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Johor, Malaysia
3School of Engineering, Metropolitan Manchester University, Manchester, United Kingdom
4Media and Game Innovation Centre of Excellence, Institute of Human Centered Engineering, Universiti Teknologi Malaysia, Johor, Malaysia

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.

This is an open access article under the CC BY-SA license.

Corresponding Author:
Che Fai Yeong
Faculty of Electrical Engineering, Universiti Teknologi Malaysia
Skudai, 81300 Johor, Malaysia
Email: cfyeong@utm.my

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]–[25]. 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>
<thead>
<tr>
<th>Author</th>
<th>Test subjects</th>
<th>Performance metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Erkoyuncu et al. [33]</td>
<td>8 (4 person in 2 groups)</td>
<td>Total task completion duration</td>
</tr>
<tr>
<td>Funk et al. [34]</td>
<td>6 (3 person per group)</td>
<td>Total task completion duration</td>
</tr>
<tr>
<td>Gattullo et al. [30]</td>
<td>22 (Groups unspecified)</td>
<td>Questionnaire with Likert scale</td>
</tr>
<tr>
<td>Aschenbrenner et al. [31]</td>
<td>50 (Groups unspecified)</td>
<td>Total task completion duration</td>
</tr>
<tr>
<td>Mourtzis et al. [18]</td>
<td>Unspecified</td>
<td>Total task completion duration</td>
</tr>
<tr>
<td>Wang et al. [19]</td>
<td>25 (groups unspecified)</td>
<td>Total task completion duration</td>
</tr>
<tr>
<td>Hietanen et al. [35]</td>
<td>20 (groups unspecified)</td>
<td>Total task completion duration</td>
</tr>
<tr>
<td>Alves et al. [26]</td>
<td>30 (10 person in three groups)</td>
<td>Total task completion duration</td>
</tr>
</tbody>
</table>

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)](image)

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

---

*Optimizing assembly processes with augmented reality: a case study on TurtleBots (Mingyu Wu)*
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.

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.

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>
<thead>
<tr>
<th>Manual type</th>
<th>Average total assembly duration (hh:mm:ss)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper manual</td>
<td>03:00:40</td>
</tr>
<tr>
<td>Modified paper manual</td>
<td>02:47:07</td>
</tr>
<tr>
<td>AR-based manual</td>
<td>02:21:26</td>
</tr>
</tbody>
</table>

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.

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

Figure 6. Mean number of Assembly Errors by Manual Type

Figure 7. NASA-TLX scores for different manual types
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

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)
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.

ACKNOWLEDGEMENTS
This research work is supported by Universiti Teknologi Malaysia Research Grant [01M85, 4B402] and the Collaborative Research in Engineering, Science, and Technology (CREST) R&D grant [T20C2-18]. Mingyu Wu and Ye Sheng Koh are designated as co-first author, having equally contributed to this work.

REFERENCES
BIOGRAPHIES OF AUTHORS

Mingyu Wu
Mingyu Wu received the BS degree in Software Engineering from Zhejiang Normal University, China in 2020, and the MS degree in Electrical Engineering from Temple University, USA in 2021. He is currently an instructor in the Department of Industrial Internet at Jiaxing Vocational and Technical College, China. His research interests include system and software integration using commercial-off-the-shelf products, computer vision, data analysis, and machine learning. Since November 2022, he has been pursuing a Ph.D. in Electrical Engineering at University of Technology Malaysia, focusing on the energy optimisation of industrial robots. He currently also serves as an editorial board member for the special issue of Academia Engineering Journal and as the guest chair for the special session at the 25th IEEE International Conference on Industrial Technology. He can be contacted at email: wmy@jxvtc.edu.cn.

Ye Sheng Koh
Ye Sheng Koh received a B.Eng. in mechatronics in 2018 from Universiti Sains Malaysia and is now pursuing a M.Eng. in Electrical Engineering at Universiti Teknologi Malaysia (UTM). His research interests are in machine learning and augmented reality. He can be contacted at email: yskoh@graduate.utm.my.

Che Fai Yeong is an Associate Professor at Universiti Teknologi Malaysia and also serves as the CEO and Co-founder of DF Automation and Robotics. He earned his Ph.D. from Imperial College London and specializes in AI, robotics, and entrepreneurship. With over 100 publications to his name, he has co-founded several companies. One of his most notable ventures is DF, which produces Industry 4.0-enabled robots that have been successfully exported to various countries. Additionally, he is a frequent keynote speaker and has spoken at TEDx events three times. He can be contacted at email: cfyeong@utm.my.

Kai Woon Goh received a B.Eng. in mechatronics in 2018 and is now pursuing a M.Eng. in electrical engineering at Universiti Teknologi Malaysia (UTM). His research interests are data analytics and machine learning. He can be contacted at email: kwgoh4@graduate.utm.my.

Marvin Dares received a B.Eng. in mechatronics in 2018 and is now pursuing a M.Eng. in electrical engineering at Universiti Teknologi Malaysia (UTM). His research interests are automated guided vehicles and machine learning. He can be contacted at email: marvdares95@gmail.com.

Eileen Su Lee Ming received the B.Eng. degree in Mechatronics and the M.Eng. degree in Electrical Engineering from Universiti Teknologi Malaysia, and the Ph.D. degree in Bioengineering from Imperial College London. She is currently an Associate Professor in the Faculty of Electrical Engineering at Universiti Teknologi Malaysia. Her research interests include medical monitoring devices, surgical simulators, virtual reality systems, rehabilitation robots, haptic devices, machine vision, robotics, automation, and artificial intelligence. She holds the titles of Chartered Engineer (Engineering Council UK), Professional Engineer (Board of Engineers Malaysia), and Professional Technologist (Malaysia Board of Technologists). She can be contacted at email: eileensu@utm.my.

William Holderbaum received his Ph.D. in Automatic Control from the University of Lille, focusing on developing new methodologies for control laws in hybrid systems. He began his academic career at the University of Glasgow, later becoming a Lecturer, Senior Lecturer, and Professor at the University of Reading. Recently appointed as a Professor in Control Engineering at Manchester Metropolitan University, his research spans mathematical modeling, control theory, rehabilitation engineering, smart grids, power generation, and autonomous vehicles. He has published over 100 papers and serves as an expert reviewer for the EPSRC and MRC, holding memberships in IEEE, the Higher Education Academy, and IEE. He can be contacted at email: w.holderbaum@mmu.ac.uk.

Mohd Shahrizal Sunar is the Director of Institute of Human Centered Engineering (iHumEn) and Founding Director of Media and Game Innovation Centre of Excellence (MaGICX), Universiti Teknologi Malaysia. He obtained his Ph.D. from the National University of Malaysia. His major field of study is real-time and interactive computer graphics and virtual environment. He received his M.Sc. in Computer Graphics and Virtual Environment from The University of Hull, United Kingdom and B.Sc. degree in Computer Science majoring in Computer Graphics from Universiti Teknologi Malaysia. He received scholarships awards from Sultan Iskandar Johor Foundation for both his postgraduate study. He can be contacted at email: shahrizal@utm.my.