Designing Effective AR Interfaces for Human-Robot Interaction: A Scoping Review and Practical Guidelines for Robot Pick-and-Place Tasks

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Augmented Reality (AR) interfaces for industrial robotics could transform human-robot interaction (HRI), particularly in teaching robots to perform pick-and-place (P&P) tasks. This scoping review critiques recent developments in AR interfaces for robot communication and programming actions. Through thematic analysis, we identify the main drivers and applications of AR interface design in HRI, with a focus on industrial P&P activities. The study examines recent work on AR interfaces to determine how they assist users in programming industrial robots, highlighting both benefits and limitations. These include improvements in operational efficiency, task accuracy, and overall user experience (UX). The findings offer firm guidelines for future research and practice, aiding the development of industry-specific AR tools for workers with varying technical expertise. AR technologies have the potential to bridge the gap between modern robotic systems and user-friendly interfaces, increasing operational efficiency and innovation in industries.

CCS Concepts: • **Human-centered computing → Mixed / augmented reality**; **User interface design**; • **Computer systems organization → External interfaces for robotics**.

Additional Key Words and Phrases: Human-robot interaction, User-centered design, Human-robot collaboration, User experience

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1 INTRODUCTION

The manufacturing sector has frequently used automation to enhance efficiency and reduce costs. In recent years, a shift in manufacturing processes has driven advances in artificial intelligence, machine learning, and robotics. The latest technologies provide advanced systems that not only boost productivity but also ensure the quality of work output and the safety of workers. Included as part of these new technologies are extended reality (XR) technologies, which include augmented reality (AR). AR technology, such as AR headsets or tablet devices, can integrate virtual media content (i.e. images, animations, and sound) with the physical environment to deliver context-aware information [21]. AR can potentially take human-robot interaction (HRI) to another level of capability in industries such as manufacturing, healthcare, or construction. AR has quickly become a technology that demonstrates potential for improving how humans and robots can work together, especially for dull, dirty and dangerous tasks [57]. One of the more significant advantages of AR is that it can give human users visual feedback and help them understand the space around them, which is advantageous in industrial environments such as busy factories. For this reason, AR provides a practical technology that can interface with robotics and help reduce the mental effort needed for humans to do the job. AR can

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also allow more straightforward communication between a robot and the human user for more accurate and accessible robot commands [38], visualizing robot intended movements and task planning [20].

Although AR is now established as a versatile technology that can be leveraged for advanced systems in industrial applications [6], much exploration is still needed in how we can design interfaces for use, especially when working with robots. Interfaces that allow humans to communicate with robots need to be easy to use and specific to the context they are used in, such as demanding industrial settings. Currently, many robot interfaces struggle with the problem of achieving a balance between user-friendly designs, useful visualizations of data, and giving feedback when it is needed. Our research looks at the challenges associated with designing and making AR interfaces work better with robots and aims to form guidelines that can be used for future HRI applications. This study focuses on using AR for human-robot communication, and how principles of designing AR interfaces can make robot-related tasks and future implementations of HRI easier and more efficient.

The question guiding this research study is: *"How can augmented reality interfaces be effectively designed to enhance human-robot interaction for pick-and-place (P&P) tasks in industrial contexts?"*

Beyond understanding the current advantages of using AR interfaces in HRI, the study's main objective identifies design principles for AR user interfaces (UI). These design principles facilitate better collaboration for human-robot interactions in the context of industrial environments that use robots for P&P tasks. The outcome of this exploration aimed at developing actionable guidelines that designers and developers can use to create AR applications. These applications can significantly improve both the operational efficiency of industrial robots and promote the well-being of human users. By progressing towards identifying design principles for AR-UI, this research contributes to the advancement of augmented reality technologies and HRI for industry sectors, particularly to enhance robotic system usability and effectiveness.

The study contributes to the academic community and industry practitioners through empirically grounded insights into AR-UI design for industrial robotics. By addressing the gaps in the current understanding of AR interface design, this work specifically enhances the usability of applications for robot control and the visualization of robot intentions [21][68]. The proposed guidelines could help promote improvements in the efficiency of AR systems in industrial environments and practical deployment for efficiency and safe user experience (UX). This research study is highly relevant to the current direction in which reality technologies are being implemented and offers new perspectives on HRI integrated with emerging technologies through user-centered design (UCD) principles.

This paper's novel contribution lies in its practical AR guidelines tailored to industrial P&P tasks, specifically addressing HRI challenges such as cognitive load management, ergonomic efficiency, and intuitive interface design.

2 RELATED WORKS

To provide context for this research within an existing body of knowledge, we reviewed relevant literature on AR when applied to HRI – mainly focusing on interface design, the functionality of AR currently available, and AR application within industrial P&P tasks.

2.1 Existing Literature Reviews in AR-HRI

Several recent literature reviews provide valuable overviews of AR applications in industrial HRI. For instance, Méndez and Velázquez [40] systematically review 60 studies on AR in Industry 4.0 for assistance and training, highlighting AR's potential to enhance task efficiency and operator safety. However, they do not delve into specific interface design guidelines for collaborative tasks. Wozniak et al. [70] survey virtual, augmented, and mixed reality for HRI, focusing on taxonomies and interaction modalities but offering limited practical design recommendations for AR interfaces in industrial settings. Chandramowleeswaran et al. [12] discuss HRI implementations with surveillance robots in industrial environments but lack emphasis on AR interface design or user-centred guidelines. Ho et al. [26] explore AR applications in industrial manufacturing processes, addressing quality control and assembly challenges but without providing detailed UI guidelines for collaborative HRI tasks. Lastly, Siewert and Gerhard [59] presents advancements in realizing HRI in industrial environments but does not focus on AR interface design for P&P operations.

Building upon these foundations, our study specifically targets the gaps left by these reviews by providing actionable design guidelines for AR interfaces in collaborative, task-focused industrial settings. We address aspects that directly impact the effectiveness of AR-HRI deployment in P&P tasks.

2.2 AR in HRI

Previous studies demonstrate the potential of AR for facilitating HRI, which is evident when enhancing spatial awareness [38] and task planning [20]. Overall, AR enhances HRI by improving the UX and facilitating collaboration while optimizing task performance. AR interfaces allow for intuitive communication between humans and robots, although challenges such as increased cognitive loading and confusion with situational awareness persist. Pei et al. [46] found that AR can predict and improve user comfort in HRI, especially when physiological data is used to refine interaction strategies. Applications such as those developed for AR devices enable bi-directional interaction, allowing users to receive data from robots and send commands. Carriero et al. [9] identified that visualizing robot state and manipulating end-effector (e.g. an attached robot tool) trajectories enhance usability when compared to traditional robot interfaces. In studies by Lunding et al. [38], workspace awareness and task coordination are also shown to be supported through AR when providing real-time data to users, such as dynamic task lists and other path visualizations. However, Kalatzis et al. [29] have shown that AR interfaces can increase cognitive load and extend task completion times, especially when they are not optimized for specific tasks. Tong et al. [66] also identified that AR could be used to convey safety-critical messages. However, the effectiveness of AR in improving trust in HRI systems is not conclusive, as the individual user's perception of the technology plays a significant role.

2.3 Interface Design for Industrial Applications

The effectiveness of AR systems in industrial settings is heavily reliant on interface design. Designing UI for industrial settings is an essential contributor to ensuring user-friendliness, intuitive functions, and information delivery. A study by Koreng and Krömker [33] has shown that AR interfaces in industrial settings must cater to specific user needs and tasks. These designs are usually based on observational or ethnographic studies and empirical data gathering to understand the requirements for designing HRI systems [33]. A case study by Jeffri and Rambli [28] found that AR-assisted manual assembly tasks, including AR visual cues and clear contextual instructions, helped reduce mental workload and enhance task performance. In a case study looking at maintenance systems, Kim et al. [31] found that AR provides augmented guidance and remote assistance, allowing inexperienced staff to perform complex tasks. Another study into usability by Sidiropoulus et al. [58] shows that an application that tailors UI functionalities to different users helps promote UI engagement and maintain user awareness. However, a study by Kiourexidou et al. [32] shows the importance of interface design for engagement and learning outcomes – which requires careful integration of AR elements with 'the reality' of the real world. Overall, standardizing interface design approaches across diverse industrial applications remains a challenge because of the versatility of robot task applications. These approaches necessitate the need for 'readily adaptable' and flexible design solutions in UI interfaces for most industry applications.

2.4 Unexplored Opportunities in AR-HRI Design for Industrial Applications

While the established benefits of AR in industrial settings have been shown to have strong support, several key areas remain under exploration, and there are opportunities for advancing AR-HRI through design and implementation. Research by Siewert and Gerhard [59] emphasizes that AR Integration in an industrial context can maximize adoption through both usability and demonstrating effectiveness. Arguably, the design of AR-UIs has to consider physical and psychological comfort to build user trust and confidence in the technology [41]. In industrial training, a study by Beveridge et al. [5] demonstrates that gamification in AR training leads to better user engagement and more effective learning. Liu et al. [37] suggests that AR-based interfaces integrate human factors and human-centered design (HCD), which can enhance human decision making during HRI tasks and significantly enhance the interaction between human and robot. However, research by Talami et al. [65] reveals that despite AR offering the potential for real-time assistance and improving task efficiency for users, the familiarity of the interface must be considered, particularly for new AR users. Braun [7] suggests that AR can play a pivotal role in the digital transformation of many industries, particularly coordination of complex manufacturing. Despite this potential, AR is challenged by factors such as systems integration, cost, and user acceptance, which need to be considered or addressed to realize AR-HRI benefits in industry. However, as suggested in literature presented here, design approaches, such as specialized UCD provide a pathway to overcome such challenges and support further implementation of AR for interaction with robots in industrial contexts.

3 METHOD

This study utilized a scoping literature review to explore recent applications of AR in robotics research, with a specific focus on P&P tasks. A scoping review was considered an appropriate method given the rapidly evolving nature of AR technologies particularly in industrial settings where the boundaries of knowledge are still emerging and being defined. The primary objective of the scoping review was to identify key trends in robot types used, functionality of interfaces, and practical implications to help form a set of guidelines that could be used in designing AR-HRI systems for P&P activities.

3.1 PRISMA Framework

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was employed to ensure a rigorous and systematic approach to the review process [43]. The PRISMA framework involves a series of steps that include identification of studies, screening for relevance, assessing eligibility, and final inclusion of studies. Using the PRISMA framework ensures that the review process is transparent, comprehensive, and replicable – which are important factors in emerging fields of research.

3.2 Data Collection Methods

The Scopus and Web of Science databases were used for initial sources of publications to review. These databases were selected due to their extensive coverage of peer-reviewed literature in the fields of AR, HRI and industry-linked research. The database search strategy used the following keywords: 'augmented reality' or 'AR', 'pick and place' tasks, and 'robot*'. This search resulted in a total of 58 documents. To refine the search, we selected inclusion criteria that only included journal articles, conference papers, or reviews. Additionally, the literature published from 2017 to 2025 was filtered for inclusion, to capture recent advancements in research. The search query used was as follows: *(augmented AND reality) AND (pick AND place) AND robot* AND PUBYEAR > 2017 AND PUBYEAR < 2025 AND LANGUAGE =*

English AND (DOCTYPE = "cp" OR DOCTYPE = "ar" OR DOCTYPE = "re"). This search query refined the pool of relevant literature to 44 documents.

Following the database search, a 'snowball' technique was used to identify additional relevant studies. The snowball technique involved examining the reference lists of the selected papers to find earlier, frequently cited (i.e. seminal papers) or highly relevant AR-HRI works that were also cited by recent studies [39]. We identified 4 seminal papers from the years 2000 [55], 2007[60], 2014[22], and 2017[8] – and an additional 20 relevant papers. Duplicate papers (N=11) were identified in the search results, and these were removed, yielding 57 publications suitable for review and analysis.

3.3 Analysis Approach

Three researchers performed a thematic analysis of the selected literature – using an inductive approach, where themes emerged from the data without preconceived codes. The process of analysis involved systematically organizing the findings into categories and subcategories. The categories represent key themes that emerged from the literature including broad areas of importance for AR-HRI design. These categories demonstrate the most significant and recurring concepts uncovered in the literature reviewed. A second round of coding allowed more specific subcategories to be identified, and these represent more selective themes in targeted areas of focus, and more nuanced topics of AR-HRI systems uncovered from the reviewed literature. After the categorization of the findings, the research team conducted an iterative process of interpreting subcategory topics to develop actionable guidelines. This approach included considering how each theme could be practically implemented to improve the usability and functionality of an AR interface used for a robot P&P task. The objective of this process was to create guidelines that are grounded in literature, but also practical for implementation by designers and developers.

4 FINDINGS

The findings from this study are organized into six key categories, each highlighting important aspects of AR interface design in industrial P&P tasks. Table 1 provides a summary of these categories (with detailed guidelines in the Appendix A), while the sections below expand on key insights derived from each area.

4.1 Enhanced Depth Perception

Depth perception is necessary for precision in P&P tasks, where accurate spatial judgments help reduce errors and increase efficiency. AR interfaces improve depth perception through techniques including *visual overlays*, *shadow casting*, and interactive cues such as *virtual cage bars* (i.e. simulated visual boundaries), which support operators in gauging distances and spatial relationships precisely [14][47][48][2][15]. These features are particularly helpful in high-risk industrial environments, where misjudgments in spatial awareness could impact both safety and productivity. By delivering depth cues, AR interfaces ease cognitive strain on operators, enabling quicker, more assured decision-making [11][3][64].

4.2 User-Centered Design (UCD)

UCD is important for AR interface usability, promoting adaptability and reducing user strain in industrial environments. *Ergonomic interface designs* lessen physical fatigue and cognitive load, supporting sustained productivity [3][53]. *Customizable elements*, such as adjustable overlays and *heads-up displays (HUDs)*, allow users to modify the interface to personal preferences, boosting both comfort and operational effectiveness [8][30][49]. *Scalable designs* accommodate

Table 1. Summary of (1) key categories and (2) subcategories identified in the thematic analysis of AR-HRI Literature. Detailed table in Appendix A.

Key Category	Subcategory
Enhanced Depth Perception	AR Interfaces for Depth Perception
	Interactive Visual Cues
User-Centered Design (UCD)	Ergonomics and Comfort
	Customizable UI Elements
	Ergonomic Positioning of Information
	Scalability of the Interface
Hands-Free Interactions	Eye Gaze and Head Movements
	Voice Commands Integration
Real-Time Feedback and Task Guidance	Real-Time Feedback
	Context-Sensitive Help
	Real-Time Error Correction
	Training and Simulation
Cognitive Load Reduction	Clear, Contextual Information
	Simplifying the UI
Collaborative Interaction	Human-Robot Collaboration
	Multi-User Collaboration
	Dynamic Task Allocation
	Accuracy and Control

varied skill levels, making the system practical across diverse workforce capabilities and simplifying onboarding for new operators [11][64]. *Hands-free interaction*, using eye gaze and voice commands, further eases manual strain, encouraging intuitive control that can elevate performance in repetitive, high-intensity tasks [4][24][31].

4.3 Real-Time Feedback and Task Guidance

Providing *real-time feedback* in AR interfaces boosts task accuracy and efficiency by offering current, usable information during operations [24][63]. *Context-sensitive assistance*, such as pop-ups and prompts, reduces cognitive load by guiding users through complex tasks with time-specific help [16][72]. These features allow operators to manage dynamic tasks without needing to pause for further instructions, which is necessary in fast-moving industrial workflows. *Real-time error correction* further advances outcomes by allowing users to identify and fix mistakes without delay, reducing downtime and preventing costly errors [2][68]. For skill development, *training and simulation tools* within AR interfaces enable users to practice tasks in a controlled environment, building proficiency and confidence before real-world application [27][62].

4.4 Cognitive Load Reduction

Reducing cognitive load is key for maintaining user performance and task efficiency, particularly in settings where operators must process substantial amounts of information under pressure. AR interfaces achieve this by providing *clear, contextual information* that minimizes mental calculations and supports situational awareness [3][64][13]. A streamlined *user interface design* prevents information overload, allowing users to focus on the most pertinent data. This focus improves task outcomes by removing unnecessary complexity and supporting faster, more precise responses [11][22][50].

4.5 Collaborative Interaction

AR interfaces play a major role in facilitating *collaborative interaction* between humans and robots, which is vital for coordinated task performance in Industry 4.0 settings [9][53]. *Multi-user capabilities* support effective teamwork within AR environments, enabling operators to coordinate, share information, and oversee tasks in real time [3][23][30]. *Dynamic task allocation*, managed through real-time AR data, improves workflow by assigning tasks based on current conditions and individual operator strengths, thus improving both team productivity and adaptability in response to shifting demands [4][44].

5 GUIDELINES FOR AR INTERFACE DESIGN IN HRI

The guidelines for AR interface design in HRI were developed through a thematic analysis of the literature, and a summary is presented in Table 2 (with detailed guidelines in the Appendix B). Grounded in empirical research and practical insights, these guidelines offer actionable recommendations to improve usability, safety, and operational efficiency in industrial HRI settings. Each guideline addresses key challenges such as enhancing spatial awareness, promoting ergonomic design, and supporting collaborative interaction, ensuring relevance across various industrial applications.

5.1 Spatial Awareness, Depth Perception, and Real-Time Feedback

Effective spatial awareness and depth perception are foundational for precision in tasks requiring high accuracy. AR interfaces should integrate *visual overlays* including pale grids and HUD markers to help users gauge distances and stay aware of spatial relationships [14][47]. Advanced depth cues such as *stereoscopic rendering* and *spatial audio* further refine depth perception, providing critical support for handling complex 3D environments [64][3].

Real-time feedback also plays a crucial role by keeping users informed of robot status and task progression through features such as *progress indicators* and *error visualization* [16][61]. This immediacy not only improves efficiency but allows users to address issues promptly, supporting high-stakes operations where any delay can lead to costly disruptions. Together, these elements form a comprehensive approach to situational awareness, essential for maintaining precision and minimizing error rates in dynamic industrial contexts.

5.2 User-Centered, Ergonomic, and Adaptable Design

User-centered design principles ensure that AR interfaces remain adaptable and comfortable for prolonged use, especially in demanding industrial environments. *Adjustable UI positioning* and *customizable interface elements* allow operators to personalize their setup according to ergonomic needs, reducing fatigue and enhancing focus during repetitive or high-intensity tasks [11][8]. Personalization options such as these not only improve individual comfort but also broaden

Table 2. This table shows (1) guidelines with (2) features to include for AR interface design in HRI. Detailed table in Appendix B.

Guideline	Feature to Include
1. Utilize AR visual overlays to support and enhance depth perception.	Pale grid to indicate distance
	HUD marker, base point of robot
	3D depth map overlay
	Stereoscopic rendering
	Spatial audio cues for depth
2. Implement interactive visual cues to aid spatial understanding and accuracy.	Color-coded distance indicators
	Dynamic object highlighting
3. Prioritise ergonomic design to reduce user fatigue and increase comfort.	Adjustable UI positioning
	Eye strain reduction features
4. Integrate customizable UI elements to enhance usability.	User-defined widget layouts
	Adaptive UI based on user expertise
5. Implement ergonomic positioning of information to improve user comfort and efficiency.	Gaze-contingent information display
	Task-specific information clustering
6. Ensure scalability of the interface to remain effective across various scenarios.	Multi-resolution UI elements
	Progressive disclosure of complex information
	Scalable typography and iconography
7. Develop hands-free interaction methods using eye gaze and head movements.	Gaze-based selection and activation
	Head gesture recognition for commands
8. Integrate voice commands to enhance interaction flexibility.	Natural language processing for robot control
	Voice-activated UI navigation
9. Provide real-time feedback and task guidance through AR UIs.	Visual confirmation of robot actions
	Progress indicators for ongoing tasks
	Status updates through AR overlays
	Error visualization in 3D space
	Real-time performance metrics display
10. Implement context-sensitive help features to support complex task completion.	AR tooltips for UI elements
	Interactive AR tutorials
	Context-aware assistance prompts
11. Implement real-time error correction mechanisms to improve task performance.	Predictive collision warnings
	Real-time path adjustment visualization
12. Use AR interfaces for training and simulation to improve proficiency and confidence.	AR-enhanced training scenarios
	Virtual practice environments
	Guided AR walkthroughs of procedures
	Skill assessment through AR challenges
13. Employ indirect manipulation techniques to enhance precision and reduce strain.	Head-tracked 3D menu navigation

the interface's usability across diverse user profiles, accommodating various skill levels from novices to seasoned operators.

Scalability is equally critical. Interfaces should allow for *adaptive UI complexity* based on UX, enabling straightforward or advanced modes as needed [8][16]. This scalability ensures the system remains intuitive for new users while offering robust functionality for more experienced operators, supporting effective training, on-boarding, and ongoing use. Emphasizing comfort, adaptability, and accessibility, this guideline encourages inclusive AR designs that remain viable across diverse operational demands and workforce capabilities.

5.3 Collaborative Interaction, Hands-Free Operation, and Task Allocation

In collaborative industrial environments, AR interfaces should facilitate smooth interaction between human operators and robots. *Hands-free features* such as *gaze-based selection* and *voice command integration* allow operators to control the interface without manual input, streamlining task flow and reducing physical strain [45][49]. Such hands-free options are invaluable in high-mobility tasks, where users need their hands free to manage tools or other equipment, allowing for a seamless, multitasking-friendly workflow.

Collaborative efficiency is further supported by *dynamic task allocation* features that adjust responsibilities based on real-time conditions, improving adaptability in response to shifting workloads or environmental changes [4][44]. By integrating task allocation and multi-user collaboration capabilities, these interfaces can enhance team productivity and foster a coordinated working environment, critical for synchronized human-robot operations within Industry 4.0 settings.

5.4 Training, Simulation, and Context-Sensitive Support

AR-enabled training and simulation tools are essential for developing user skills, offering operators the chance to engage in realistic, controlled scenarios before entering high-stakes tasks. *AR-enhanced training modules* and *interactive simulations* help users gain confidence by practicing tasks within risk-free environments, preparing them for the complexities of real-world applications [50][23]. These training scenarios also serve as valuable on-boarding resources, reducing the learning curve for new operators and minimizing initial errors during early adoption stages.

In addition to training, *context-sensitive assistance* features such as *predictive collision warnings* and *contextual tool-tips* guide users through complex tasks, offering on-demand support when and where it's needed [22][67]. This real-time guidance helps reduce cognitive load, enabling users to make informed decisions quickly and effectively. Such support is invaluable in fast-paced industrial settings where task accuracy is critical and operator attention must be maintained.

5.5 Guideline Application in Industrial Practice

These guidelines are intended to be adaptable, allowing developers and industry practitioners to selectively apply the most relevant recommendations based on operational needs rather than adopting all elements simultaneously. For instance, high-precision environments may prioritize spatial awareness and real-time feedback features, while collaborative settings may emphasize task allocation and hands-free options.

In practice, these guidelines should be applied iteratively, with developers testing and refining features to meet evolving requirements. This flexible approach enables a tailored AR interface that enhances usability, safety, and productivity in industrial HRI, providing measurable value across diverse applications. By focusing on context-specific needs, these guidelines help practitioners optimize HRI, supporting seamless AR-HRI integration that aligns with the demands of modern industrial environments.

6 DISCUSSION AND FUTURE WORK

This research highlights the potential of AR UIs to provide features that can assist with HRI systems, such as augmentation of depth perception, ergonomic user comfort for communication, and enabling collaborative virtual environments. These findings are an important contributor for the design and development of AR-HRI systems, where optimizing UX and operational efficiency of robot tasks can assist with the implementation of future robotic systems, and better methods for operators to interact and communicate with robots used in industries such as manufacturing.

The guidelines derived from our research provide a foundation for creating AR interfaces that are both technically robust and centered around user needs. Our research contribution to the domain of AR-HRI lies in the translation of theoretical concepts and case studies, into practical guidelines that are specifically tailored for task such as industrial robot P&P applications. These guidelines serve as an important starting point to link academic research with industry practice, while also offering a guide for the effective development of AR interfaces. As AR-HRI systems become increasingly prevalent in industrial environments, these guidelines and future research will play an important role in ensuring that HRI technology is user-friendly and efficient when implemented in real industry settings [47, 48].

It is important to acknowledge that this study's approach using a review of contemporary and key publications could result in the exclusion of certain elements AR-HRI technology, highlighting a necessity for empirical research to validate the guidelines and confirming their practical application. Future research should expand the focus of AR-HRI systems to include diverse industrial settings to confirm the usefulness of these guidelines. Moreover, the integration of AR with other emerging technologies warrants investigation to further enhance human-robot collaboration (HRC) and system capabilities. Longitudinal studies would also benefit to evaluate the long-term impacts of AR interfaces on user performance and system efficiency and providing further insights into the sustainability of these systems within industry.

Exploring the customization of AR interfaces based on user feedback could lead to more personalized and effective solutions for HRI. This is in line with previous works advocating for more personalized approaches in the design of spaces where humans and robots collaborate on a task [8, 11, 16, 64]. Furthermore, the guidelines presented in this study also consider the integration of robots (or collaborative robots) into organizational workflows and human-robot teams. Future studies can optimize the deployment of HRI systems, leading to improvements in productivity, safety, and overall efficiency. As research in AR-HRI progresses, these findings can continue to inform industry-related projects, which can promote further technological innovation.

7 CONCLUSION

This paper presents a set of AR interface design guidelines for HRI in industrial P&P tasks, developed through a detailed thematic analysis of existing studies. These guidelines directly address key HRI needs—cognitive load management, ergonomic interaction, real-time feedback, and collaborative engagement—forming a practical foundation for creating more intuitive, effective, and adaptable AR interfaces across industrial settings. As AR integration advances, these guidelines provide developers and practitioners with clear steps for enhancing human-robot collaboration.

The recommendations here reflect a deep alignment with industry demands, supporting UCD, cognitive ease, and hands-free interaction. Enhanced spatial perception and interactive guidance empower operators to handle complex tasks with greater precision and comfort, which is an important consideration in demanding environments such as manufacturing. By improving UX and supporting safety, these guidelines offer adaptable solutions to meet diverse industrial requirements.

Future work should consider empirical studies to test these principles in-situ with industrial contexts, further refining them to meet specific sector needs and varying user expertise. Longitudinal research could shed light on the broader impacts of AR on task flow, UX, and overall productivity.

This study highlights new areas for AR-HRI development, such as the integration of adaptive, AI-driven interfaces and multimodal feedback mechanisms that can strengthen interaction quality. Subsequent research in these areas may drive the development of AR interfaces that are not only practical but responsive to the dynamic nature of human-robot teams. As industries explore AR’s potential to connect human skills with robotic precision, these guidelines act as a blueprint for advancing HRI toward safer, smarter, and more agile workspaces.

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A ADDITIONAL CATEGORIES DETAILS

Table 3. This table shows detailed results from the thematic analysis of (1) key categories, (2) subcategories, (3) subcategory descriptions identified in the thematic analysis of AR-HRI Literature, and with (4) associated references.

KEY CATEGORY	SUBCATEGORY	DESCRIPTION	REFERENCE
Enhanced Depth Perception	AR Interfaces for Depth Perception	AR interfaces improve depth perception, crucial for PnP tasks.	[3], [2], [3], [14], [15], [19], [47, 48], [63], [64], [72]
	Interactive Visual Cues	Interactive visual cues aid spatial understanding and accuracy.	[10, 11], [14], [16, 17], [22], [48], [49], [56], [69]
User-Centered Design (UCD)	Ergonomics and Comfort	Ergonomic AR interfaces reduce fatigue and increase comfort.	[3], [3], [10], [22], [45], [48], [49], [53], [63]
	Customizable UI Elements	Customizable UI elements enhance usability and comfort.	[8], [16], [18], [22], [29], [34], [49], [60], [61]
	Ergonomic Positioning of Information	Ergonomically positioned information improves comfort and efficiency.	[22], [45]
	Scalability of the Interface	Scalable AR interfaces remain effective across various scenarios.	[8], [13], [29, 30], [34], [64]
Hands-Free Interactions	Eye Gaze and Head Movements	Using eye gaze and head movements for hands-free interaction.	[4], [8], [9], [10, 11], [16, 17], [19], [23], [30], [36], [44], [47, 48], [53], [56], [67]
	Voice Commands Integration	Integrating voice commands for enhanced hands-free interaction.	[1], [3], [3], [2], [25], [31], [34], [47, 48], [49]
Real-Time Feedback and Task Guidance	Real-Time Feedback	Real-time guidance and feedback improve task performance.	[24], [35], [42], [51], [54], [63], [71]
	Context-Sensitive Help	Context-sensitive help guides users through complex tasks.	[16], [72]
	Real-Time Error Correction	Real-time error correction and feedback reduce error rates.	[2], [10, 11], [22], [31], [64]
	Training and Simulation	AR for training and simulation improves proficiency and confidence.	[27], [31], [51], [56], [69]
Cognitive Load Reduction	Clear, Contextual Information	Clear information reduces cognitive load and mental calculations.	[3], [9], [10, 11], [13], [29, 30], [47, 48]
	Simplifying the UI	Simplifying the UI avoids information overload.	[10, 11], [13], [22], [24], [49], [50]
Collaborative Interaction	Human-Robot Collaboration	Seamless human-robot collaboration improves task outcomes.	[4], [9], [10, 11], [23], [29, 30], [44], [51], [52], [53]
	Multi-User Collaboration	Enabling multiple users to interact and coordinate effectively.	[3], [9], [10], [17], [22], [23], [29], [50], [62]
	Dynamic Task Allocation	Optimize task allocation based on real-time conditions.	[4], [9], [10, 11], [13], [17], [22], [44], [50], [64]
	Accuracy and Control	Uses AR-MR for intuitive programming and debugging.	[3], [4], [16], [29, 30], [44], [52]

B ADDITIONAL GUIDELINES DETAILS

Table 4. This table shows guidelines developed for AR interface design in HRI including (1) category, (2) feature to include, (3) feature description, and (4) key references.

Category	Features to Include	Feature Description	Key References
Guideline 1: Utilize AR visual overlays to support and enhance depth perception.			
AR Interfaces for Depth Perception	Pale grid to indicate distance	A grid overlay that helps users gauge distances by showing a pale grid in the AR environment.	[14]; [47, 48]
	HUD marker, base point of robot	A heads-up display (HUD) marker that indicates the base point of the robot, helping maintain spatial awareness.	[15]; [19]
	3D depth map overlay	A 3D map overlay that provides depth understanding crucial for accurate manipulation in 3D space.	[64]; [72]
	Stereoscopic rendering	A rendering technique that enhances depth perception by displaying slightly different images to each eye.	[63]
	Spatial audio cues for depth	Audio cues that change based on object distance, enhancing depth perception through sound.	[3]; [19]
Guideline 2: Implement interactive visual cues to aid spatial understanding and accuracy.			
Interactive Visual Cues	Color-coded distance indicators	Colors that change based on distance, providing visual feedback on object proximity.	[3]; [48]
	Dynamic object highlighting	Highlights objects of interest dynamically to make them stand out in the AR environment.	[2]; [49]
Guideline 3: Use ergonomic design to reduce user fatigue and increase comfort.			
Ergonomics and Comfort	Adjustable UI positioning	Allows users to move and reposition UI elements, improving ergonomics and comfort.	[10]; [22]
	Eye strain reduction features	Features designed to minimize eye strain, ensuring comfort during prolonged use.	[49]; [53]
Guideline 4: Integrate customizable UI elements to enhance usability.			
Customizable UI Elements	User-defined widget layouts	Users can create and arrange their own widget layouts, tailoring the interface to their needs.	[10, 11]; [64]
	Adaptive UI based on user expertise	UI changes complexity based on the user's experience level, offering both beginner and advanced modes.	[8]; [17]
Guideline 5: Implement ergonomic positioning of information to improve user comfort and efficiency.			
Ergonomic Positioning of Information	Gaze-contingent information display	Information appears or changes based on where the user is looking, reducing unnecessary eye or head movements.	[45]; [51]
	Task-specific information clustering	Groups related information together based on the current task, helping users stay focused and reduce cognitive load.	[22]; [30]
Guideline 6: Implement ergonomic positioning of information to improve user comfort and efficiency.			
Scalability of the Interface	Multi-resolution UI elements	UI elements change resolution based on their importance and distance from the user.	[64]; [13]
	Progressive disclosure of complex information	Only necessary information is shown initially, with more details available as needed.	[34]; [30]
	Scalable typography and iconography	Text and icons adjust in size depending on user preferences and context, ensuring readability.	[17]; [8]
Guideline 7: Develop hands-free interaction methods using eye gaze and head movements.			
Eye Gaze and Head Movements	Gaze-based selection and activation	Users can select and activate UI elements just by looking at them, enabling hands-free interaction.	[45]; [63]
	Head gesture recognition for commands	The system recognizes head gestures as commands, allowing control without using hands.	[2, 3]; [53]
Guideline 8: Integrate voice commands to enhance interaction flexibility			
Voice Commands Integration	Natural language processing for robot control	The system understands and processes spoken commands, enabling robot control through natural speech.	[49]; [31]
	Voice-activated UI navigation	Users can navigate the UI through voice commands, reducing the need for manual input.	[19]; [24]
Guideline 9: Provide real-time feedback and task guidance through AR UIs.			
Real-Time Feedback	Visual confirmation of robot actions	The interface visually confirms the robot's actions, providing feedback on its status.	[16]; [34]
	Progress indicators for ongoing tasks	Visual indicators that show the progress of tasks, helping users keep track of ongoing processes.	[61]; [8]
	Status updates through AR overlays	Status information overlaid directly in the AR view, keeping users informed about the robot's condition.	[29]; [9]
	Error visualization in 3D space	Errors are displayed visually in 3D space, helping users identify and address issues quickly.	[67]; [9]
	Real-time performance metrics display	Key performance metrics shown in real-time, enabling users to monitor task performance.	[63]; [35]
Guideline 10: Implement context-sensitive help features to support complex task completion.			
Context-Sensitive Help	AR tooltips for UI elements	Tooltips that appear when a user hovers or looks at a UI element, providing contextual help.	[22]; [16]
	Interactive AR tutorials	Tutorials that guide users step-by-step within the AR environment, facilitating learning.	[60]; [18]
	Context-aware assistance prompts	Prompts that appear based on user actions and context, offering helpful suggestions or guidance.	[29, 30]; [48]
Guideline 11: Implement real-time error correction mechanisms to improve task performance.			
Real-Time Error Correction	Predictive collision warnings	The system predicts potential collisions and warns the user in advance, helping prevent errors.	[67]; [36]
	Real-time path adjustment visualization	Changes to the robot's path are visualized in real-time, helping users understand and manage adjustments.	[67]; [8]
Guideline 12: Use AR interfaces for training and simulation to improve proficiency and confidence.			
Training and Simulation	AR-enhanced training scenarios	Training scenarios enhanced with AR, allowing users to practice tasks in a simulated environment.	[50]; [23]
	Virtual practice environments	Simulated environments where users can practice tasks and procedures in AR without real-world consequences.	[11]; [3]
	Guided AR walkthroughs of procedures	Step-by-step AR guides for complex procedures, ensuring accuracy and confidence.	[62]; [17]
	Skill assessment through AR challenges	AR-based challenges that assess the user's skills and provide feedback.	[29]; [9]
Guideline 13: Employ indirect manipulation techniques to enhance precision and reduce strain.			
Indirect Manipulation Techniques	Head-tracked 3D menu navigation	Menus track the user's head movements, enabling seamless navigation through 3D menus.	[9]

C PRISMA REVIEW AND THEMATIC ANALYSIS DATA

PRISMA review data and guideline themes submitted as spreadsheets as a Supplementary Material Description ZIP file.