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Human-Robot Interaction in Museum Exhibition Assembly: A Framework for Adaptive Collaboration

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Abstract

Exhibition assembly in museums represents a critical phase in translating abstract curatorial concepts into tangible physical forms. Unlike structured industrial settings, museum environments are often unstructured and unpredictable, posing considerable challenges for human-robot interaction (HRI). This study proposes an adaptive collaboration framework for HRI, specifically tailored to meet the unique demands of museum exhibition assembly. The framework is structured around three core interaction mechanisms: behavioral coordination, intention sharing, and role collaboration. It addresses key challenges such as the sensitivity of cultural artifacts, environmental complexity, and the necessity of establishing trust between humans and robots. To improve collaborative accuracy, the framework incorporates hierarchical task modeling, adaptive behavior adjustment, and multimodal information exchange. For intention sharing, it introduces multidimensional situational modeling, context-aware intention inference algorithms, and perceivable feedback systems. To optimize role allocation, it employs a flexible role assignment strategy, adaptive interaction patterns, and clear role status indicators. By extending HRI research beyond industrial applications, the framework offers novel insights into collaborative systems within complex cultural contexts. Nevertheless, further empirical validation and context-specific analysis are required to fully bridge the gap between theoretical development and practical implementation.

Keywords

museum, human-robot interaction, exhibition assembly, adaptive design

1. Introduction

Human-robot interaction (HRI) is an increasingly prominent interdisciplinary research field, with broad applications in intelligent manufacturing, medical rehabilitation, and service industries (Sheridan, 2016). In tasks that require high precision, repetitive labor, or operation in hazardous environments, human-robot interaction systems offer superior flexibility, environmental adaptability, and efficiency compared to traditional automation or manual methods (Villani et al., 2018). In recent years, robotic technologies have also expanded into non-industrial domains such as cultural heritage preservation and museum exhibitions, demonstrating significant potential in artifact restoration, exhibition assembly, and visitor engagement (Bazunu et al., 2025). Among these, collaborative assembly tasks in museums-where humans and robots jointly assemble, maintain, or update exhibition components-have emerged as a promising approach to enhance preparation efficiency, reduce labor-related risks, and improve overall working conditions.

Unlike the standardized and structured tasks typical of industrial manufacturing, museum exhibition assembly presents more complex challenges for human-robot interaction. First, museum artifacts often possess significant historical, cultural, and artistic value. Their fragility and irreplaceability demand exceptionally high levels of precision and safety during handling and assembly, as even minor errors may cause irreversible damage. Second, museum environments are inherently dynamic. Evolving curatorial concepts, diverse exhibit types, varied spatial layouts, and the unpredictable movement of visitors require robotic systems to demonstrate advanced environmental adaptability. Robots must perceive changes in real time and execute precise path planning and task coordination accordingly. Furthermore, as public cultural spaces, museums necessitate frequent interactions among robots, staff, and visitors during exhibition assembly. The reliability and transparency of these interactions are critical for building public trust in robotic systems, which directly impacts the efficiency and effectiveness of human-robot collaboration (Hellou et al., 2022).

Currently, museum exhibition assembly remains heavily reliant on manual labor, which not only limits operational efficiency but also heightens the risk of irreversible damage to fragile cultural artifacts due to human error. Integrating robotic systems into these processes offers substantial practical advantages, including enhanced efficiency and improved operational safety. This integration addresses urgent real-world needs while simultaneously presenting significant research opportunities. However, in the structurally complex and dynamically evolving environments of museums, establishing effective and reliable human-robot interaction mechanisms remains a major challenge. In particular, enabling robots to accurately interpret human intentions, adapt to diverse task scenarios, and collaborate seamlessly and intuitively with human partners is a pressing issue that current human-robot interaction research must urgently address.

Recent research has begun to explore the use of robots in museum environments; however, the focus has largely remained on functional tasks such as visitor guidance, security, and information display (Velentza et al., 2020). For instance, some museums have deployed robotic guides capable of delivering verbal explanations to visitors. While a few studies have preliminarily investigated the supportive role of robots in artifact restoration and exhibition setup, most existing work emphasizes hardware development, control algorithm optimization, or the application of specific technologies such as augmented reality and 3D modeling. A significant gap remains in the systematic exploration of human-robot interaction mechanisms, collaborative models, and the theoretical foundations of trust within these contexts. Given this background, it is critical to assess the suitability of current interaction mechanisms in relation to the specific task requirements and cultural contexts inherent to museum exhibition assembly. This study aims to systematically investigate human-robot interaction models tailored to exhibition assembly tasks, thereby advancing theoretical discourse on human-robot collaboration in non-industrial domains and offering practical strategies to enhance exhibition efficiency and operational safety.

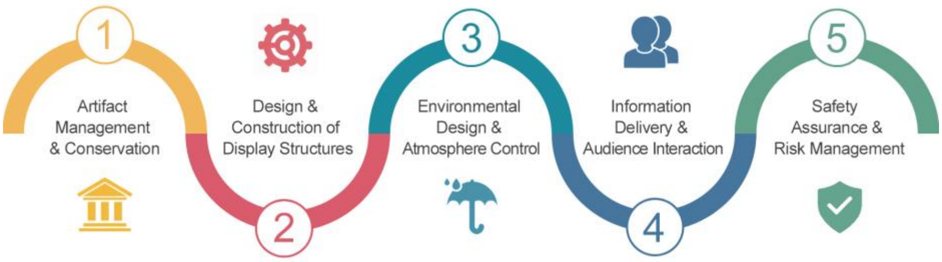
2. Literature Review

2.1 Concept and Key Components of Exhibition Assembly

Exhibition assembly is a pivotal stage in transforming abstract curatorial concepts into tangible physical environments through spatial design and display strategies (Stuedahl & Smordal, 2011). This process is inherently complex, involving the integration of diverse elements such as exhibits, display structures, environmental features, and supporting facilities. Its primary objective is to achieve a cohesive synthesis of information delivery and visitor experience. Effective implementation requires the systematic consideration and coordinated management of five core components (see Figure 1).

First, artifact management and conservation form the foundation of exhibition assembly. This involves the receipt, inspection, installation, and ongoing maintenance of artifacts to ensure their safety, stability, and visibility throughout the exhibition period (Kamal, 2022). Second, the design and construction of display structures not only fulfill functional requirements for support and protection but also must visually align with the exhibition's thematic narrative. These structures must comply with structural safety standards while ensuring accessibility for all visitors (Tzortzi, 2007). Third, environmental design and atmosphere control-achieved through spatial layout, color schemes, and lighting-play a critical role in shaping visitors' emotional responses and cognitive engagement, thereby enhancing both narrative coherence and immersive experience (Shen, 2023). Fourth, information delivery and audience interaction rely on interpretive tools such as labels, guide texts, and multimedia installations to encourage active participation and deeper exploration. These elements reinforce the exhibition's educational function and its capacity for cultural communication (Wang & Xia, 2019). Finally, safety assurance and risk management serve as essential safeguards in exhibition implementation. This includes protecting both personnel and artifacts, as well as developing emergency response protocols, which require the establishment of comprehensive safety and risk control systems.

Figure 1: Key components of exhibition assembly



2.2 Interaction Logic in Museum Exhibitions

As culturally significant public spaces, museums require human-robot interaction designs that go beyond basic functional requirements to incorporate cultural context, educational objectives, and visitor experience considerations (Germak et al., 2015). In contrast to industrial environments, museums differ markedly in both spatial characteristics and interaction logic. These distinctions are manifested across four key dimensions (see Figure 2).

Figure 2: Interaction logic in museum exhibitions

First, cultural significance is the defining attribute of museum environments. As repositories of historical memory and social meaning, all activities within museums must uphold and reflect cultural values. Consequently, the visual appearance and behavioral patterns of robotic systems should conform to the principle of cultural compatibility (Earle, 2013). Second, educational value is central to the museum's mission. Exhibitions and interactions serve not only as channels for information transmission but also as platforms for knowledge construction and public enlightenment. Accordingly, human-robot interaction systems in museums should incorporate instructional functions and support strategies for effective knowledge presentation (Hein, 2006). Third, immersive experience plays a crucial role in enhancing visitor engagement and emotional resonance. Through thoughtful exhibition layout, movement guidance, and atmospheric elements such as lighting, immersive environments can be created to evoke deeper cognitive and perceptual involvement (Yi et al., 2024). Finally, safety is the foundational condition for effective human-robot collaboration. This encompasses both the physical well-being of visitors and the protection of cultural artifacts during robotic operations (Runhovde, 2021). In summary, human-robot interaction design in museum contexts is not merely a technical challenge but a comprehensive design endeavor that must balance system functionality with cultural, educational, and experiential values. Achieving this dynamic equilibrium is essential for the development of human-centered robotic systems in public cultural spaces.

2.3 Human-Robot Interaction Mechanisms in Collaborative Assembly

Human-robot interaction is a highly interdisciplinary research field that draws upon theoretical and methodological contributions from design, robotics, artificial intelligence, psychology, cognitive science, and human factors engineering (Sheridan, 2016). Its primary objective is to develop interaction systems that are intuitive, efficient, and safe (Mourtzis et al., 2023). In the context of collaborative assembly tasks, the design of human-robot interaction mechanisms focuses on three critical dimensions: behavioral coordination, intention sharing, and role collaboration. These dimensions are essential for establishing a stable and effective partnership between humans and robots, ultimately enhancing system performance and task execution quality.

Within human-robot interaction systems, behavioral coordination serves as the foundational mechanism for enabling basic collaborative functionality. Its primary function is to ensure temporal synchronization and motion alignment between humans and robots during task execution, thereby facilitating stable and efficient cooperation (Oshio et al., 2021). Coordination strategies are generally categorized into three types. The first is explicit coordination, which involves direct communication through verbal commands, graphical interfaces, or gesture inputs. The second is implicit coordination, which relies on the robot's ability to perceive and interpret human behaviors-such as motion trajectories, facial expressions, or task context-to infer intentions and respond appropriately (Che et al., 2020). The third is hybrid coordination, which integrates both explicit and implicit methods. This approach enhances interaction efficiency while preserving naturalness and is currently regarded as one of the most effective coordination strategies (Correll & Rus, 2013).

The intention sharing mechanism is another critical factor for improving collaborative quality. It enables robots to accurately interpret human goals, operational strategies, and focal areas throughout the task. Establishing a shared understanding of task status and environmental context between humans and robots is vital for effective cooperation (Kim et al., 2024). Existing approaches to intention understanding are primarily divided into two types. The first is rule-based, which employs semantic rules or expert knowledge to translate human commands into executable robot actions (Awais et al., 2020). The second is machine learning-based, which utilizes large-scale datasets to train models capable of identifying deeper associations between user behaviors and commands, thereby enabling predictive and adaptive responses to human intent (Zou et al., 2023). A robust intention sharing mechanism reduces miscommunication and coordination delays, ultimately enhancing interaction continuity and system stability.

The role collaboration mechanism addresses the allocation of responsibilities between humans and robots to leverage their complementary strengths and optimize task performance (Song et al., 2022). Role allocation strategies are typically classified into two types. Static allocation involves predefined responsibilities and workflows set before task execution, making it suitable for structured tasks in stable environments (Messeri et al., 2022). By contrast, dynamic allocation allows for real-time adjustment of roles based on task progression and environmental changes, making it more appropriate for complex, unstructured scenarios (Giele et al., 2015). In collaborative assembly contexts, common role configurations include human-led with robotic execution, robot-assisted with human guidance, and task-sharing models. Well-structured role allocation not only improves task efficiency but also mitigates the risk of human-robot conflict, thereby enhancing overall system performance.

3. Adaptive Collaboration Framework in Museum Exhibition Assembly

3.1 Behavioral Coordination Mechanism

In museum exhibition assembly tasks, establishing an effective behavioral coordination mechanism is crucial for enabling smooth human-robot collaboration. The primary objective is to synchronize movements and align strategies between humans and robots in order to manage task complexity and adapt to environmental uncertainties. Designing such a mechanism requires the systematic consideration of three core attributes: hierarchy, adaptability, and interactivity. From a hierarchical standpoint, assembly tasks can generally be divided into three levels: the task level (goal setting), the strategy level (path planning and coordination logic), and the action level (execution of specific operations). Developing coordination strategies at each level enhances both organizational efficiency and alignment precision. Given the dynamic nature of the task environment, robots must continuously adapt their behavior in real time based on task progression, environmental changes, and human feedback. This adaptability is particularly critical when responding to unexpected events, such as path obstructions or changes in artifact conditions. Interactivity emphasizes the importance of information symmetry and timely feedback between human and robot agents. Achieving this requires robust capabilities in state perception, intention communication, and responsive behavior to ensure coherent and safe collaboration. As Mohammad and Nishida (2007) noted, the clear expression of internal states and perceivable intentions is fundamental to natural interaction. Li et al. (2021) further argued that effective behavioral coordination depends on cognitive alignment and shared task awareness. In practice, human operators often rely on multimodal sensory inputs-including visual, tactile, and auditory cues-to monitor robot status and adjust their actions accordingly. Based on these insights, three strategies are proposed to establish an effective behavioral coordination mechanism:

(1) Develop a hierarchical task model that decomposes complex assembly activities into structured subtasks, optimizing capability allocation between human and robot agents;

(2) Design context-aware, adaptive behavioral strategies that enable robots to dynamically refine their responses based on situational changes;

(3) Enhance multimodal interaction channels-such as voice commands, graphical interfaces, and haptic feedback-to improve the perceivability of robot states and intentions, thereby strengthening real-time coordination.

3.2 Intention Sharing Mechanism

In museum exhibition assembly tasks, accurately understanding and sharing intentions is essential for achieving high-quality human-robot collaboration. The primary objective of an intention sharing mechanism is to establish mutual awareness between humans and robots regarding their respective goals, behavioral plans, and environmental perceptions. This shared understanding enhances coordination efficiency and ensures system safety. To support intention sharing, context modeling must be implemented. This involves the structured representation and analysis of key variables that influence interaction, providing a semantic foundation for intention inference. Critical factors affecting intention sharing include the physical environment (e.g., spatial layout, lighting), task-specific requirements (e.g., artifact fragility, assembly complexity), and the sociocultural context (e.g., technology acceptance, interaction norms). By constructing a multidimensional context model, robots can better interpret human behavior, thereby enabling more natural and adaptive collaboration. For example, a physical environment model helps predict human movement paths and avoid collisions; a task model enables robots to understand operational goals and provide appropriate support; and a sociocultural model allows systems to tailor information presentation according to user expectations. As Riley et al. (2016) argued, context awareness is a fundamental prerequisite for effective human-robot interaction. Goodrich and Shan et al. (2020) further emphasized that intention sharing not only improves collaboration efficiency but also significantly enhances system robustness and safety. To establish an effective intention sharing mechanism, this study proposes three key strategies:

(1) Develop a multidimensional context model that systematically integrates physical, task-related, and sociocultural information;

(2) Design context-aware intention inference algorithms that combine rule-based reasoning with machine learning to improve predictive accuracy;

(3) Establish multimodal, perceivable feedback mechanisms using visual, auditory, and behavioral cues to enhance operator understanding of robot intentions and support timely, informed responses.

3.3 Role Collaboration Mechanism

In museum exhibition assembly tasks, clearly defined human-robot role allocation and interaction models are fundamental for achieving efficient collaboration and maintaining task quality. The core of the role collaboration mechanism lies in assigning responsibilities based on task complexity, participants' skill sets, and situational conditions. These roles must be aligned with appropriate interaction strategies to leverage complementary strengths and enhance coordination. Unlike the fixed role configurations commonly used in industrial environments, museum contexts demand greater flexibility and contextual adaptability due to the dynamic nature of exhibition tasks and the distinctive characteristics of cultural spaces. Typical role configurations include the following: Leader-Executor Model: humans lead while robots execute operations;

Collaborator-Assistant Model: both agents jointly participate in task execution; Supervisor-Autonomous Agent Model: robots operate with a degree of autonomous decision-making. In most scenarios, humans are responsible for high-level functions such as goal setting, strategic planning, and quality control, while robots handle repetitive, precision-based, or high-risk operations. The role model proposed by Han et al. (2005) provides a theoretical foundation for structuring human-robot interaction, and Sasabuchi et al. (2020) further refined role allocation and task matching through empirical studies. Based on these role structures, common interaction patterns include: Directive Interaction: humans issue explicit commands; Guided Interaction: emphasizes demonstration and procedural cues; Negotiated Interaction: allows for dynamic, feedback-driven task adjustment between agents. In practice, role configurations and interaction modes must be dynamically adapted based on task complexity, operator expertise, and robotic capabilities. To enhance the effectiveness of role collaboration mechanisms, this study proposes three design strategies:

(1) Develop a context-aware dynamic role allocation model to support the flexible reassignment of responsibilities;

(2) Design an adaptive interaction system capable of transitioning between multiple interaction modes across different task phases;

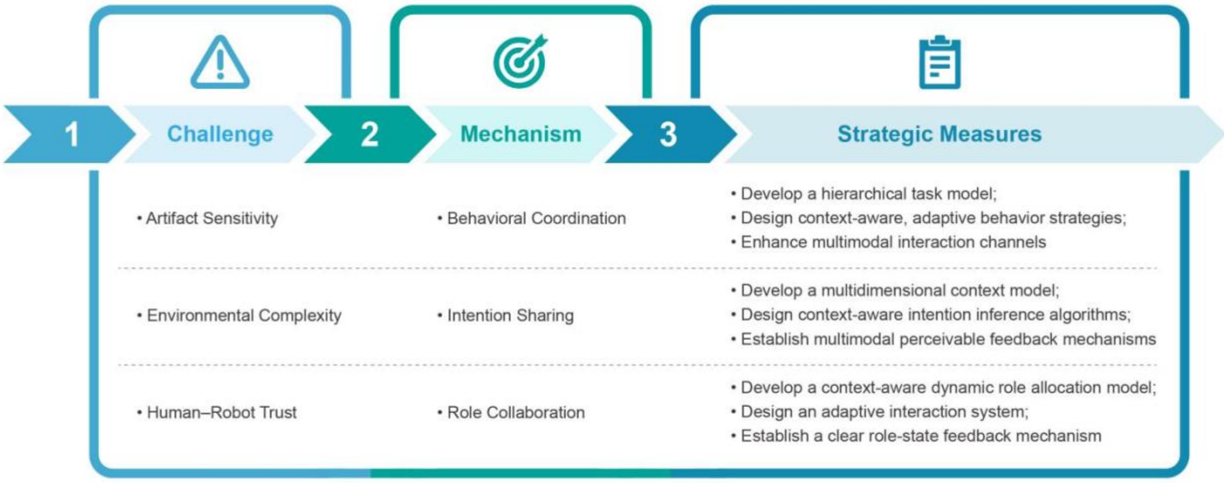
(3) Establish a clear role-state feedback mechanism to enable real-time monitoring of the robot's role, allowing timely human intervention or task reassignment when necessary.

4. Discussion

Based on a review of existing research, human-robot interaction mechanisms in museum exhibition assembly face three primary challenges. First is the issue of artifact sensitivity. Museum artifacts are irreplaceable and extremely fragile, necessitating assembly operations conducted with the utmost precision and care. Even minor mishandling can result in irreversible cultural loss. Therefore, robotic actions must be rigorously controlled, incorporating multilayered safety mechanisms and adopting non-invasive operational strategies. Second, environmental complexity presents significant challenges. Museum spaces are often architecturally intricate and subject to frequent human traffic, placing high demands on robots' spatial awareness, path planning, and real-time responsiveness. These challenges are further amplified in scenarios involving densely arranged exhibits or high visitor presence, making dynamic environmental adaptation essential for effective interaction. Third, the level of human-robot trust plays a critical role in determining both system acceptance and collaborative efficiency. The degree to which museum staff and visitors trust robotic systems directly influences their willingness to engage with and rely on them. To foster trust, it is essential to enhance operational transparency, improve interface usability, and increase system explainability.

To address the aforementioned challenges, this study systematically examines three key human-robot interaction mechanisms in relation to the contextual characteristics of museum exhibition assembly tasks (see Figure 3). Regarding the behavioral coordination mechanism, the integration of hierarchical task modeling, adaptive behavior strategies, and multimodal information exchange is intended to improve coordination precision and response flexibility. These strategies address the hierarchical structure, dynamic variability, and interactional complexity inherent to exhibition tasks. However, their effectiveness is highly dependent on the accurate construction of task models and real-time environmental perception-both of which remain challenging in the complex and ever-changing settings of museums. For the intention sharing mechanism, the development of multidimensional context models-combined with rule-based reasoning and machine learning algorithms-aims to improve robots' ability to recognize human goals and behavioral intentions. In practice, however, constructing such comprehensive models requires the integration of diverse data types, including physical, task-related, and sociocultural information. In resource-constrained and heterogeneous museum environments, difficulties in data acquisition and semantic knowledge modeling may impede effective implementation. With respect to the role collaboration mechanism, the application of flexible role assignment models and adaptive interaction strategies supports dynamic coordination and efficient task division between humans and robots. Nevertheless, real-world deployment hinges on the accurate assessment of operator skills and preferences, as well as the design of user interfaces that enable seamless transitions across role structures and task phases. These requirements place considerable demands on the system's interaction intelligence and human-centered adaptability. In summary, while the proposed human-robot interaction mechanisms demonstrate strong theoretical adaptability and collaborative potential for museum exhibition assembly, their practical implementation necessitates further refinement. Future work should prioritize enhancing system modeling capabilities, deepening contextual understanding, and advancing interaction design to fully meet the demands of precision, safety, and human-centric collaboration in cultural heritage settings.

Figure 3: Adaptive collaboration framework in museum exhibition assembly



5. Conclusion

This study presents a systematic investigation into the adaptability and design strategies of human-robot interaction within the context of museum exhibition assembly. Grounded in an in-depth analysis of task characteristics and cultural settings, the research explores three core mechanisms-behavioral coordination, intention sharing, and role collaboration-to address current limitations in human-robot interaction systems related to artifact preservation, environmental adaptability, and trust building. The proposed human-robot interaction framework is specifically tailored to exhibition assembly scenarios and contributes to the theoretical advancement of human-robot collaboration in non-industrial domains. Additionally, it offers valuable insights and methodological support for enhancing exhibition efficiency, operational safety, and human-centered collaboration.

Despite these contributions, the study has several limitations. First, the research is primarily theoretical in nature, focusing on framework construction and the formulation of design strategies. Experimental validation in real museum environments has not yet been conducted, leaving the practical effectiveness and feasibility of the proposed solutions untested. Second, the analysis of exhibition assembly tasks is largely derived from a literature review, which may not fully capture the diversity of spatial configurations, curatorial themes, and visitor behaviors across different types of museums. This reliance introduces a degree of generalization bias.

To address these limitations, future research can proceed in two key directions. First, through field case studies and system prototyping, researchers can deploy human-robot interaction systems in actual museum settings to evaluate the adaptability of interaction mechanisms, user acceptance, and operational safety. Insights gained from real-world implementations can inform iterative design refinements. Second, future studies should place greater emphasis on the differentiated needs of various museum types. By considering factors such as institutional scale, exhibition formats, and operational workflows, researchers can develop more targeted and context-sensitive human-robot interaction models-thereby strengthening the alignment between theoretical innovation and practical application.

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Conflicts of Interest

The authors declare no conflict of interest.

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