Design considerations of ergonomic human-robot collaboration (EHRC) for modular construction manufacturing

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Abstract –

Manufacturing is a critical stage in modular construction, as it directly affects cost, schedule, and quality. Human-robot collaboration (HRC) has the potential to enhance modular construction manufacturing (MCM) productivity while preserving essential flexibility. Despite these benefits, previous studies on designing HRC workplaces for MCM have primarily focused on efficiency, often overlooking ergonomics and human factors. This oversight can negatively affect workers' occupational safety and health (OSH) and overall well-being. Therefore, this research aims to promote the concept of ergonomic HRC (EHRC) and inform the EHRC design for MCM. Three cases are further presented to demonstrate the design of EHRC under different variables and considerations. This study encourages researchers and practitioners to place human well-being at the center of the production system.

Keywords –

Human-robot collaboration (HRC); modular construction; ergonomics; human-centric HRC; workplace design

1 Introduction

Modular construction is a process where building modules are manufactured offsite and then transported to the construction sites for the final assembly [1]. Various terms are used in the literature to describe this manufacturing-oriented construction approach, including offsite construction [2], prefabricated construction [3], or industrialized construction [4]. To clarify, this study uses the term "modules" to encompass all prefabricated components, including 1D elements, 2D panelized systems, and 3D volumetric units [5]. Modular construction has been considered a viable alternative to traditional construction methods due to its improved productivity, quality, safety, and sustainability [6]. With its controlled manufacturing environment, robots can play a significant role in modular construction manufacturing (MCM) processes by alleviating workers' fatigue, improving quality, and boosting productivity [7, 8].

Despite the increasing use of automation in producing standardized building modules, significant challenges persist in MCM. First, MCM must accommodate diverse design styles to meet varying demands and adapt to economic fluctuations, resulting in considerable variability in manufacturing workflows [9]. This customization presents a challenge for standard automation, as conventional robotic systems lack the flexibility needed to handle frequent production changes. Second, fully automating MCM processes requires substantial upfront investments, such as the cost of equipment and factory reconfiguration [10]. This can be a barrier for small and medium-sized manufacturers with limited tolerance for financial risks [11]. Third, many MCM tasks require human involvement for the dexterous use of construction tools and the improvisational skills to adapt to material variations [12], while robots struggle to cope with these complexities.

To address these challenges, combining human expertise with robotic systems in MCM processes presents a promising solution through efficient human-robot collaboration (HRC) [13]. HRC capitalizes on the complementary strengths of humans and robots: humans excel at flexibility and adaptability for creative and ill-defined tasks, while robots offer unparalleled precision and consistency. Consequently, HRC offers significant potential for achieving the trade-off between MCM productivity and flexibility.

HRC workplace designs require careful consideration of various factors. Existing studies on HRC for MCM often prioritize productivity, efficiency, and flexibility by developing innovative workflows. For example, Tavares, Costa [14] presented a collaborative welding system where both a robot and a human share part of the physical welding task. Lee and Han [15] designed a novel robot system for welding, with an interactive interface for human fine-tuning. However, these studies paid limited attention to ergonomics and human factors, which may adversely affect workers' occupational safety and health

(OSH) and well-being [16]. With the advance of Industry 5.0, there is an increasing focus on human-centric HRC, where human well-being is prioritized in production processes [17]. Safety and ergonomics are central to this human-centric paradigm, yet current studies often fail to integrate ergonomic factors into HRC designs for MCM [18]. Besides, little research has been conducted in exploring HRC design considerations for MCM.

To bridge the gap, this paper aims to explore different HRC schemes in MCM and discuss critical considerations in designing ergonomic HRC (EHRC) workplaces. This study adopts an exploratory research approach, combining a literature review with case study analysis. First, we synthesize existing research to define EHRC and identify its design considerations in MCM. Second, we illustrate these considerations through three case studies derived from prior work, representing diverse MCM tasks, human roles, and robot types. By shifting the focus from productivity to human well-being, this study contributes to the development of human-centric and ergonomically optimized HRC applications in MCM.

2 Preliminary concepts for EHRC

HRC is gaining prominence to achieve the trade-off between flexibility and efficiency in production [19]. Its main goal is to reduce the physical and repetitive workload on human workers by enabling robots to assist in labor-intensive tasks. In the manufacturing industry, HRC typically involves humans and robots collaborating in a shared workplace towards a common goal. While similarities between MCM and traditional product manufacturing have been indicated [20], the make-to-order and elaborate nature of MCM presents unique challenges for implementing industrial HRC solutions effectively. Therefore, this paper adopts a broad definition of "collaboration" emphasizing joint efforts between individuals, especially in intellectual or creative pursuits [21].

To address worker well-being in such systems, ergonomics offers a critical foundation. The International Ergonomics Association (IEA) defines ergonomics as, "*the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance.*" [22]. Although the terms "ergonomics" and "human factors" are sometimes distinguished - ergonomics being linked to physical aspects and human factors to psychological and cognitive aspects - they are often used interchangeably [22-24]. For clarity, this study adopts the IEA definition of ergonomics, encompassing both the physical and cognitive/psychological dimensions of human interaction. Furthermore, this study narrows its focus to the individual worker level, aligning with the scope of micro-ergonomics, which addresses both physical and cognitive factors [25] that directly impact worker well-being. Building on this, the study defines ergonomic human-robot collaboration (EHRC) as "using ergonomics principles to design a workplace where humans and robots collaborate safely, efficiently, and in support of worker well-being".

The EHRC further draws on the industrial human needs pyramid [17], which consists of five levels: (1) safety, the foundational level, which ensures physical protection and legal rights; (2) health, the next level, which focuses on creating a healthy work environment to support physical, cognitive, and psychological well-being; (3) belonging, which meets social needs of workers and to promote connections and trust between human-machine team; (4) esteem, which enhances workers' confidence, self-belief, and respect from peers; and (5) self-actualization, the highest level, which enables personal growth, fulfillment, and sense of purpose through meaningful work. This pyramid highlights that human health is founded on physical safety while facilitating higher levels of well-being. Mapping to the HRC domain, safe HRC primarily fulfills the safety level by mitigating physical hazards, while EHRC extends this to the health level by addressing physical, cognitive, and psychological factors to promote long-term well-being. Figure 1 illustrates this relationship, highlighting how EHRC builds upon safe HRC within the industrial human needs pyramid to enhance workplace design.

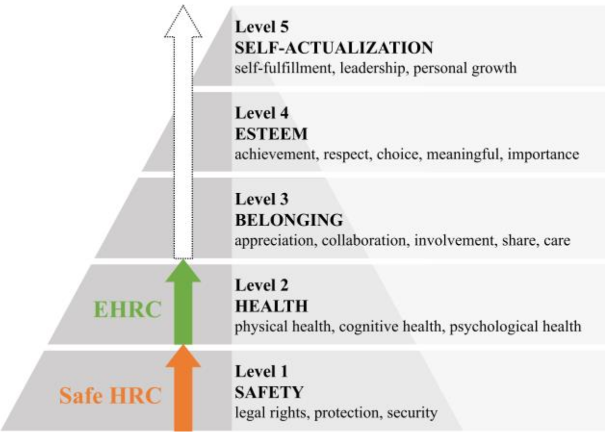

Figure 1. Role of EHRC in the industrial human needs pyramid (adapted from [17])

3 Design considerations of EHRC for MCM

3.1 HRC variables in MCM

Different HRC variables involve different requirements. Workers collaborating with robots on MCM tasks face specific ergonomic challenges that differ from the standardized and lightweight tasks in conventional manufacturing. This paper summarizes three critical HRC variables in MCM, i.e., MCM tasks, human roles, and robot types.

MCM tasks can be generally summarized into three types, i.e., small-size component production, 1D and 2D prefabricated component production, and 3D volumetric module production:

- Small-size component production: This involves manufacturing smaller components (e.g., windows and plumbing elements) that are later assembled on larger modules or buildings. In MCM, tasks to produce small components are less repetitive since size and specification needs vary in different projects. Intermittent and varied tasks require workers to make frequent postural or tool adjustments, increasing physical strain and cognitive burden.
- 1D and 2D prefabricated component production: This involves manufacturing structural elements such as steel beams (1D) and timber panels (2D) that bear the loads and stresses of the building. These components can be produced in assembly lines or fixed-position setups. Assembly-line workers face shoulder and back strain from repetitive lifting (e.g., aligning beams for robotic welding), while fixed-position tasks require prolonged leaning or twisting, increasing musculoskeletal risks.
- 3D volumetric module production: This refers to the manufacture of 3D volumetric housing prefabricated units. These volumetric modules can be prefabricated, pre-finished, and even pre-furnished, representing different levels of completion in modular construction. The large size and weight of these modules often confine workers and robots to fixed-position workstations. When working on the interior of a module, workers must collaborate with robots in tight spaces, which increases safety hazards while potentially further restricting workers' movement and forcing them to maintain awkward postures. As for exterior work such as cladding or window sealing, workers have more room to maneuver but face the challenges of working from heights or extending their arms.

Human roles can be categorized into four types: supervisor, teammate, operator, and bystander [13]:

- Supervisor: Supervisors are responsible for monitoring the robot and instructing the robot to perform the task. This role requires sustained attention to one or more robots performing diverse tasks in a cluttered MCM environment. As a result, this role requires constant vigilance, with increased cognitive load and mental fatigue.
- Teammate: Teammates are responsible for completing physical activities beyond the capabilities of the robot to achieve a common goal. As teammates are required to share physical tasks, they cannot avoid the postural risks associated with lifting, pushing, or adjusting materials. Collaborating in close proximity to the robot also increases the mental workload of the worker.
- Operator: Operators take direct control of the actions of the robot during the execution of the task. The control can be either in close proximity (e.g., guiding a gantry robot installing a window) or remotely (e.g., guiding a robot with VR controllers). Proximity control requires repetitive body postures, while telecontrol increases eyestrain and cognitive load.
- Bystander: Bystanders work in the same space as robots without direct interaction, but should be concerned with issues related to safety and situation awareness. Bystanders must be distracted from the robot's movements while focusing on the MCM task at hand, which causes additional mental stress and cognitive burden.

Robots commonly adopted in MCM can be classified into three categories, i.e., stationary, mobile, and wearable robots [26]:

- Stationary robot: Stationary robots are fixed in the workplace, have a limited working range, and cannot move freely. The most common stationary robot is robot arms that are bolted in the workstation. Due to their large payloads and high power, safety protocols prioritize isolation over proximity HRC. This physical isolation shifts the ergonomic challenge to remote monitoring.
- Mobile robot: Mobile robots provide enough flexibility to create an adaptive workplace. Automated guided vehicles (AGVs) are commonly used to transport materials around the factories. Robot arms (e.g., collaborative robots) mounted on AGVs or gantries are also considered mobile as they can reconfigure their location freely in the factory. Since these robots offer flexibility to work around workers, they are either with lower payload and power, or are less automated and require workers' direct control to ensure safety. Collaboration with these robots can be physically

demanding and cognitively taxing.

- Wearable robot: Wearable robots, commonly known as exoskeletons, are designed to boost human physical strength and endurance. These robots not only enable individuals to handle heavier loads but also help improve body posture during tasks, reducing the risk of strain and injury. Due to the complexity of controls and fewer applications, they can be an added cognitive burden for workers.

3.2 Design considerations for EHRC

Designing EHRC workplaces in MCM requires careful attention to safety strategies, physical ergonomic design, and cognitive ergonomic design.

3.2.1 Safety strategies

Safety strategies in HRC include a blender of separation protection, passive protection, and proactive protection. These strategies should be carefully selected in the EHRC design.

- Separation protection: Separation protection ensures safety by keeping humans and robots physically separated. This protection method is typically achieved through safeguards such as guards (e.g., fences, barriers, and light curtains). When collaborating with heavy industrial robots, maintaining a strict separation between humans and robots is essential.
- Passive protection: Passive protection ensures safety with robots' built-in design features without requiring active monitoring and prediction of human state. Collaborative robots typically have passive protection mechanisms such as limited payload and end-effector state detection, since they are designed to allow closed collaboration in a shared workplace.
- Proactive protection: Proactive protection perceives and predicts the human state and adapts robot behavior in real time to avoid safety risks. This method integrates advanced sensors such as depth cameras and wearable devices to monitor humans and adopt actions before an unsafe event occurs.

3.2.2 Ergonomic design considerations

In addition to keeping workers away from safety hazards, EHRC prioritizes worker health and well-being through ergonomic design, consisting of both physical and cognitive aspects [17]. Physical ergonomics examines human postures and behaviors that could cause musculoskeletal injuries [27], assessed through tools such as rapid upper limb assessment (RULA) [28] and rapid entire body assessment (REBA) [29], which evaluate posture risks, and biomechanics analysis (e.g., OpenSim), which measures muscle tension and joint loads. Cognitive ergonomics focuses on reducing the mental stress and psychological challenges faced by workers sharing the workplace with robots [30], evaluated using self-report scales such as NASA task load index (NASA-TLX) [31], supplemented by physiological data (e.g., electrodermal activity, heart activity, electroencephalography, electromyogram, eye activity) from wearable sensors. These physical and cognitive ergonomic principles are integrated into three design considerations tailored to MCM:

- Ergonomic task design: This balances task demands to reduce physical and cognitive strain. By optimizing task sequences, repetitive actions are delegated to robots, while workers engage in varied movements to lower musculoskeletal injury risks in assembly-line or fixed-position setups. Dynamic task adaptation allows robots to sense human states (e.g., physical fatigue and cognitive overload) in order to react by taking over demanding tasks or adjusting the speed of work, ensuring the well-being of workers in a custom-driven workflow. Real-time task feedback can help workers make informed decisions with a high level of trust and low cognitive workload.
- Ergonomic workstation design: This optimizes the physical workspace to minimize strain and environmental stress. Adjustable workstations allow workers to maintain natural postures minimizing the need for excessive bending or overextension during tasks. Additionally, mitigating adverse environmental factors such as noise and vibration generated by robots can preserve worker well-being and minimize ergonomic stress.
- Ergonomic interaction design: This enhances the usability and cognitive comfort of human-robot interaction. Intuitive interfaces allow workers to interact seamlessly with the robot, improving usability while reducing frustration and cognitive effort. Predictable robot motion can enhance worker trust and situational awareness and reduce stress when interacting with robots. Personalized interface settings cater to a diverse workforce in MCM, avoiding information overload for experienced operators while ensuring sufficient guidance for novices.

Although EHRC is a human-centric paradigm prioritizing human well-being, the system's efficiency cannot be ignored. However, the efficiency is not deeply examined in the paper, but its impact is presented in the discussion.

4 Case study

Three case studies under MCM scenarios are presented based on different EHRC requirements.

4.1 Case 1: Window installation on 3D modules

The first case is from our previous work [18], where a material-handling robot is applied to install a window component in an opening of a building module, as shown in Figure 2(a). Since 3D volumetric module production typically involves fixed-position workplace layouts that require workers and robots to work around the module, robot mobility is critical, which can be achieved with gantry cranes specialized for factory environments. The case has developed a 5-degree-of-freedom (DOF) gantry robot with 3 translational and 2 rotational servo-controlled axes. It is used to handle heavy window glasses; thus, the end-effector consists of a gripper with four vacuum cups. The worker is required to physically operate the robot to secure the window and haul the robot to its final location. Specifically, the worker first operates the two-handed handle with sensors, by moving it downward until it makes contact with the window glass. Once in position, the worker activates the gripping mechanism to secure the glass, enabling easy manipulation. Subsequently, the forward rotation button is engaged to orient the window to an upright position. The worker then guides the robot, along with the secured glass, to align it with the designated opening in the building module. After carefully adjusting the window to fit the opening, the worker releases the glass by pressing the release button. Finally, the robot is guided back to its initial position, and the gripper's rotation is reset, thereby completing one task cycle.

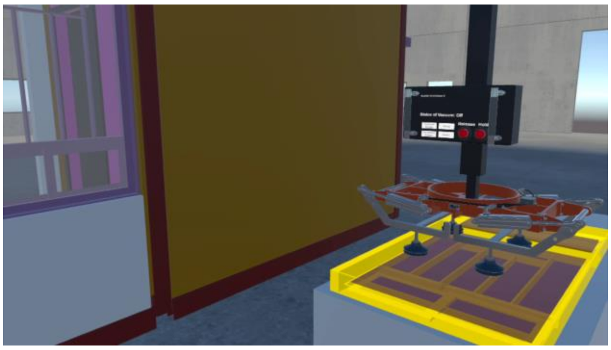

Figure 2. VR-based iterative EHRC design in case 1 [18]

The design of this collaborative robot allows humans to operate in close proximity, and the method of ensuring safety relies on its built-in mechanism design. The end-effector releases the part only after all the weight has been removed. If any problem occurs, the emergency stop button can be pressed.

The design of the HRC workstation meets ergonomics requirements from both physical and cognitive aspects. To improve physical ergonomics, the height of the worktable and the width between the two handles on the collaborative robot have been carefully designed, and both RULA and REBA tools show low risk. In terms of cognitive ergonomics, the cognitive workload and trust in the robot can be kept at an acceptable level due to the simplicity of the operation process and the intuitive human-robot interface. It is worth noting that the ergonomic assessment of this case was conducted in a virtual reality (VR) environment [Figure 2(b)], which offers a cost-efficient and iterative platform for designers to evaluate and refine ergonomic parameters with minimal resource expenditure.

4.2 Case 2: 2D timber panel production

The case 2 [11] adopts the TIM platform [32], which incorporates two KUKA KR-500 industrial robots and a swiveling table. Figure 3(a) shows the configuration of case 2. The industrial robots utilized have a scope of 2830 mm, including the end effector, a payload capacity of 500 kg, excluding the end effector, and maintain a pose repeatability accuracy of +- 0.08 mm. The robots are equipped with different end effectors each, namely a mechanical gripper, pneumatic gripper, and 3D-Camera for the PINP robot, and a nail gun, spindle and glue gun for the GNM robot, thus defining their respective skills. In this case study, the PINP robot uses the mechanical gripper for picking up the slat, placing and securing it, whereas the GNM robot employs the nail gun to fasten it. The swiveling table facilitates an extended reach for the robots by repositioning the workpieces.

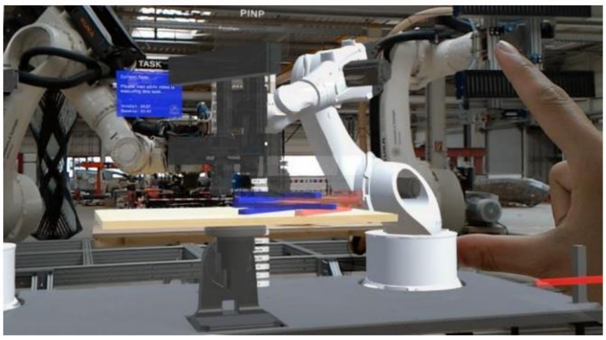

Figure 3. AR-based EHRC in case 2 [11]

This case adopts industrial robots to handle large-scale materials, which are too dangerous for physical collaboration. Therefore, separation protection is used to ensure human safety. By getting away from robots, human supervisors can avoid hazards from potential crashes. When humans need to enter the range of the high-payload industrial robots to conduct tasks such as material supply, confirming that the robots are inactive is crucial to prevent accidents.

As supervisors, humans are required high-level cognitive capacities. This case provides an intuitive and smooth augmented reality (AR) interface for humans to improve their cognitive ergonomics, as shown in Figure 3(b). Although improper use of HRC systems could affect physical ergonomics, the motion introduced by AR (e.g., shoulder uplift motion associated with gesture recognition used in human-robot interaction) is neglectable from a biomechanical loading perspective.

4.3 Case 3: Window frame processing

The last case is from [33], which adopts a collaborative robot, UR5e robot arm, for holding the workpiece (i.e., a window frame), and a human conducts processing tasks on the workpiece. Specifically, the human is required to hold a power drill to punch four holes in each corner of the window frame, while the robot is responsible for adapting the workpiece's position and orientation to provide an ergonomic work condition. The configuration of case 3 is shown in Figure 4.

Figure 4. Proactive EHRC in case 3 [33]

This EHRC workstation ensures safety through proactive protection. On the one hand, the built-in safety mechanisms of the UR5e are designed in compliance with EN ISO 13849-1 and EN ISO 10218-1. On the other hand, the RealSense camera is used to perceive the safety condition of humans so as to prevent hazards proactively.

The robot can improve physical ergonomics by monitoring the 3D skeleton of the human, evaluating posture-related risks based on RULA tools, and adapting its motion accordingly to reduce the risks. In addition, the human wears AR glasses, which provide task-related information and hands-on instruction. The worker awareness and trust in robots can also improve through robot digital twins.

4.4 Discussion

Table 1 summarizes the three EHRC cases under study. These MCM cases illustrate differences in MCM tasks, human roles and robot types. Additionally, they involve different design considerations, offering insights for EHRC design in MCM:

- For 3D volumetric module production (Case 1), the fixed-position workplace layout confines workers and robots to work around the module, exposing workers to both physical and cognitive ergonomic risks. The case assigns heavy lifting to the robot, while the worker is only responsible for precise positioning, thus greatly reducing the burden on muscles. To design an ergonomic workstation, this case carefully designs a mobile gantry robot with adjustable gripper height, reducing awkward postures during window installation. The intuitive interface supports ergonomic interaction by simplifying operation, minimizing cognitive effort in this task. By adopting an ergonomic design, this case remains ergonomic risks to an acceptable level both physically (i.e., RULA and REBA) and cognitively (i.e., cognitive workload and trust).
- In 2D timber panel production (Case 2), heavy-duty industrial robots require separation protection, shifting human roles to supervisors focused on monitoring. The case assigns almost all of the physical work to the robot, with the worker needing only supervision and guidance. Ergonomic workstation design plays a minimal role here due to physical isolation. The AR interface enhances ergonomic interaction by providing seamless and intuitive task oversight, improving comprehension and reducing mental fatigue. This case does not directly demonstrate ergonomic design improvements for workers from physical and cognitive perspectives, but the intuitiveness, task support, and skill enhancement provided by AR technology are highly aligned with cognitive ergonomics principles.
- For small-size component tasks like window frame processing (Case 3), this case leaves the dexterity task to the worker, while the robot is responsible for helping to adjust the position of the workpiece, thus allowing the worker to reduce postural risks. The workstation senses human states (e.g., improper posture) in real time through sensors and adjusts the robot's pose to provide ergonomic working conditions that ensure worker health. An AR-driven interface enhances ergonomic interactions by providing ergonomic warnings, task guidance, and robot trajectory prediction, thereby improving situational awareness and cognitive capacity. The ergonomic design of this case keeps the RULA risk scores of the workers' arms and wrists at a low-risk level and improves their cognitive understanding of the HRC task and their trust in the robot.

Table 1. Summary of EHRC cases under study

Variables	Case 1	Case 2	Case 3
Task	Window installation on 3D modules	2D timber panel production	Window frame processing
Robot type	Mobile robot (Gantry robot)	Stationary robot (Industrial robots)	Mobile robot (collaborative robots)
Human role	Operator	Supervisor	Teammate
Safety strategy	Passive	Separation	Proactive
Ergonomic task design	Aligning robots for heavy lifting	Aligning robots for primary work	Aligning robots for workpiece adjustment
Ergonomic workstation design	Adjustable design	-	Adjustable design
Ergonomic interaction design	Intuitive controls	Intuitive AR, predictable robot motion	Intuitive AR, predictable robot motion

5 Conclusion

This paper establishes a rigorous definition of EHRC, emphasizing the design of workplaces where humans and robots work together safely, comfortably, and efficiently. It further delineates design considerations under MCM scenarios, considering HRC variables and specific challenges in MCM. Through the analysis of three case studies, this paper elucidates practical insights into the development of EHRC systems tailored to MCM. Theoretically, this study advances this field by identifying current HRC ergonomic challenges in MCM and proposing tailored design solutions that prioritize human-centric systems. It also provides a roadmap for practitioners to enhance worker safety and comfort, while mitigating expenditures on workers' compensation claims.

This paper serves as an initial blueprint for EHRC. Three future directions are proposed:

- *Multidisciplinary integration in EHRC design*. The complexity of EHRC requires a multidisciplinary approach, bridging ergonomics with robotics, medicine, psychology, human resources, and end-user perspectives. To achieve this, interoperability between these diverse fields is crucial [34]. A collaborative team of experts from these disciplines must work together to ensure that their insights and solutions are not only comprehensive but also seamlessly integrated.
- *Customized interaction interfaces.* Customized human-robot interaction interfaces are essential for achieving effective EHRC. Future efforts should focus on developing diverse interfaces for users to choose from, complemented by empirical user studies. Such studies are critical to assessing the impact of varying interface designs on different workers, optimizing information load, presentation modalities, and input mechanisms for enhanced usability and performance.
- *Dynamic adaptation in real-time systems*. Static and offline methodologies fail to account for the variability in human actions and states during real-time operations. Future systems must incorporate dynamic task allocation within human-robot teams [35] and adaptive robotic responses contingent on real-time human states. This requires perceiving and responding to human conditions, such as improper postures or elevated cognitive loads, ensuring safe and ergonomic collaboration.

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