International Journal of Leading Research Publication (IJLRP)

E-ISSN: 2582-8010● Website: www.ijlrp.com● Email: editor@ijlrp.com

Robots and Safety in Industrial Environments: Challenges and Progress in Human-Robot Collaboration

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Abstract

The advent of Industry 4.0 has revolutionized industrial manufacturing, with human-robot collaboration (HRC) playing a pivotal role in enhancing productivity and flexibility within smart factories. This shift toward intelligent manufacturing requires rethinking traditional safety procedures, as the strict separation of human and robot workspaces is removed. In response, industrial robotics has seen significant changes in safety standards over the past decade, leading to extensive research aimed at preventing human-robot collisions and mitigating the risks associated with them. This review paper examines the key safety systems implemented in industrial robotic environments, highlighting developments in safety regulations and emerging technologies designed to ensure safe collaboration. The paper discusses multidisciplinary approaches such as collision prevention systems, impact detection technologies, and methods for evaluating injuries resulting from human-robot interactions. Additionally, the paper reviews the ISO 15066 standard, outlining the challenges of aligning design safeguards with hazard analysis and risk assessment in collaborative robotic workspaces. The review emphasizes the importance of creating safer human-robot collaborations to facilitate the broader adoption of flexible and intelligent automation in industry.

Keywords: Human-robot collaboration (HRC), Industry 4.0, Safety systems, Industrial robotics, Collaborative robots, Hazard analysis, Risk assessment, Safety assurance

Introduction:

Over the past five decades, industrial robots have played a transformative role in manufacturing, replacing humans in repetitive, dangerous, or unhealthy tasks. While this has improved efficiency and safety in many industries, it has also introduced new risks to human workers. Traditional safety measures, such as physically separating human and robot workspaces, were codified in standards like ISO 10218, ISO/TS 15066:2016, ANSI/RIA R15.06, and UNE-EN 755:1996, among others. These regulations mandated the use of sensors and other safety systems to prevent accidents in hazardous areas where robotic systems operated. However, as the industrial landscape evolved, so did the need for more sophisticated safety systems that could enable human-robot collaboration (HRC). Recent updates to standards, particularly those introduced in ISO 10218 from 2006 onward, reflect the growing shift toward collaborative work environments, where robots and humans share workspaces without rigid barriers, relying instead on advanced detection, avoidance strategies, and mitigation techniques to ensure safety.

This paradigm shift toward human-robot collaboration is driven by the rise of Industry 4.0, which integrates cutting-edge information and communication technologies, data analysis, and smart devices into industrial processes. Collaborative robots, or "cobots," represent a key technology within this framework, enabling humans and machines to work together in dynamic environments. While these systems offer the potential to boost efficiency and innovation, they also introduce significant challenges in terms of safety, ergonomics, and human factors. Ensuring safe physical interaction between humans and robots requires not only hardware-related safeguards, such as collision-avoidance sensors and force-limiting technologies, but also sophisticated control strategies that minimize risks in real-time. Furthermore, cognitive ergonomics, psychological stress, and operator well-being must be carefully considered in the design of collaborative workspaces. Thus, this paper explores the current state of safety measures in human-robot collaboration, highlights emerging research challenges, and proposes frameworks for addressing these complex issues in industrial settings.

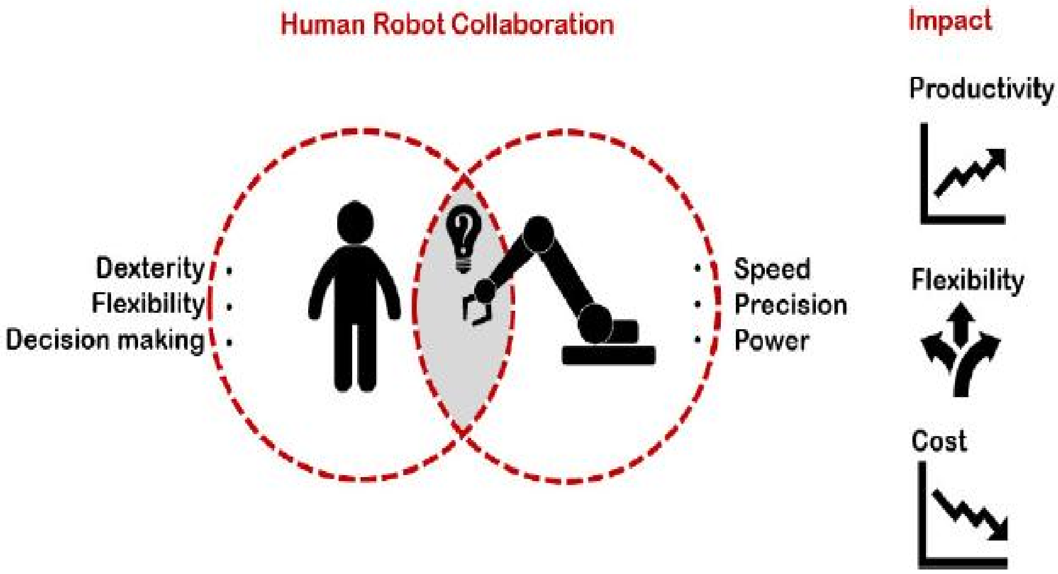

Fig. 1 Importance of Human-Robot Collaboration (HRC) and its impact in industry. Source [1]

Framework and Key Concepts

Human-Robot Collaboration Taxonomy

Human-Robot Collaboration (HRC) can be classified based on various criteria, including the multiplicity of interactions and the autonomy of the agents involved. HRC scenarios can involve single or multiple humans and robots, leading to various collaborative configurations such as teams of humans and robots working together. This classification helps in understanding the dynamics of HRC and informs the design of collaborative systems. Additionally, the roles of the human and robot during the collaborative task can be categorized based on their autonomy and initiative, defining them as active, supportive, or inactive agents. An active agent has the autonomy to initiate and perform tasks independently, while a supportive agent assists the active participant in executing the task.

Moreover, HRC can be characterized by the spatial and temporal overlap of human and robot workspaces. This dimension of classification is crucial for understanding how collaboration can occur effectively while ensuring safety and efficiency in shared environments. The levels of HRC operations can vary, with the most common collaborative modes being coexistence and sequential collaboration. Coexistence refers to scenarios where humans and robots work in a shared workspace without physical barriers, while sequential collaboration involves tasks performed alternately by humans and robots, highlighting the complexity and intelligence required in their interactions.

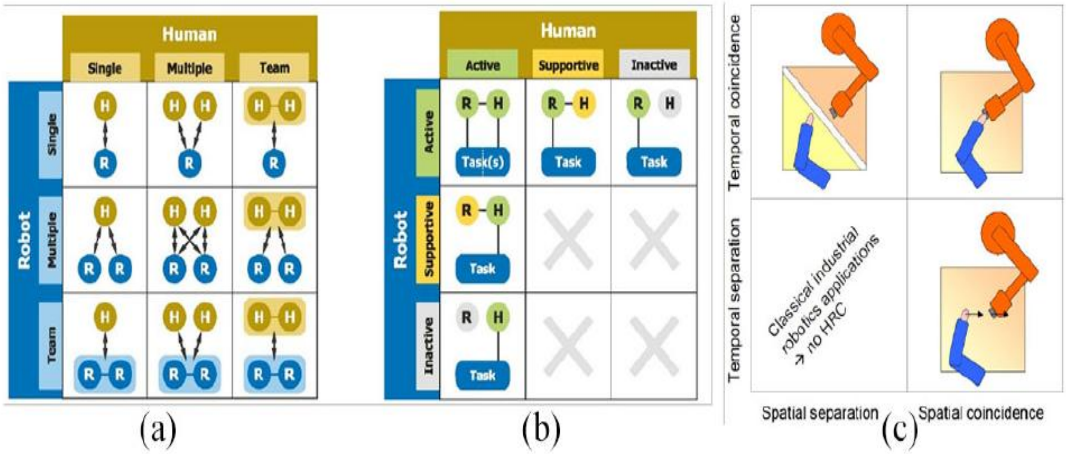

Fig. 2(a) Classification of Human-Robot Collaboration (HRC) based on interaction (b) levels of autonomy and initiative (c) spatial and temporal overlap. Source [1]

Separation of Human and Robot Workspaces

To ensure safety in environments where humans and robots coexist, it is vital to establish clear separations between their workspaces. Industrial robots, typically large and heavy, pose significant risks due to their high-speed movements. Previous standards emphasized the need for compulsory separation to prevent collisions and protect human operators. This approach involves detecting human intrusions into robot workspaces and adapting robot behavior accordingly. Implementing these separation protocols is essential in minimizing the risk of injury while maintaining operational efficiency.

Different protection levels have been developed to safeguard human workers in shared workspaces. Levels 1, 2, and 3 represent the most commonly implemented safety measures, while Level 5 is application-specific, such as in metal welding tasks. The advent of collaborative robots (cobots), like Rethink Robotics' Baxter and Kuka LWR iiWA, demonstrates the industry's response to the need for improved safety measures that allow for closer human-robot interactions without compromising safety.

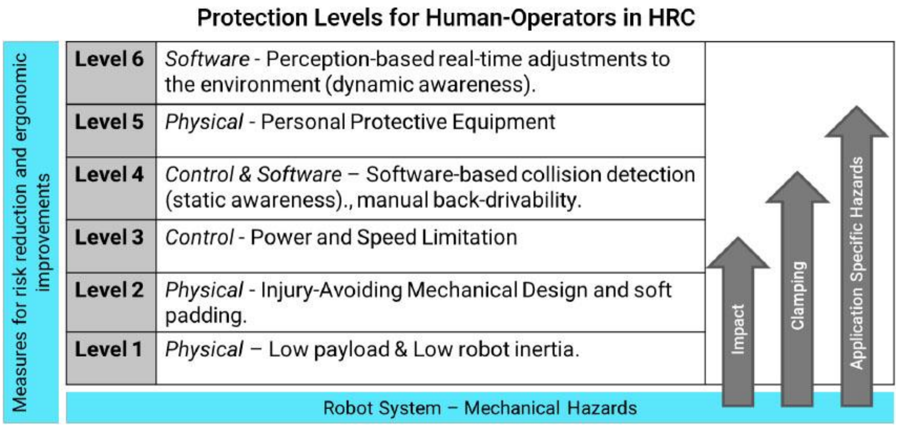

Fig. 3 Various protection levels for human operators in shared human-robot workspaces. Source [1]

Shared Human and Robot Workspaces

While shared human-robot workspaces offer numerous benefits in terms of productivity and efficiency, they also introduce new risks that must be addressed. The elimination of physical barriers between humans and robots necessitates robust safety measures to mitigate the dangers associated with potential collisions. Understanding the consequences of such collisions is critical for developing effective safety systems. Research in this area typically explores two main approaches: estimating pain tolerance in humans during collisions and quantifying the level of injury resulting from these interactions.

To minimize injuries in the event of a collision, various mechanical compliance systems have been proposed, such as viscoelastic coverings, absorption elastic systems, and lightweight structures. These solutions aim to reduce the energy transferred during a collision, thus lowering the potential for harm. Additionally, incorporating safety strategies that involve collision detection and avoidance can significantly enhance the safety of human-robot collaboration. Techniques such as motion capture systems, artificial vision, and range imaging are being increasingly utilized to create safer collaborative environments by providing real-time information about the workspace and preventing accidents before they occur.

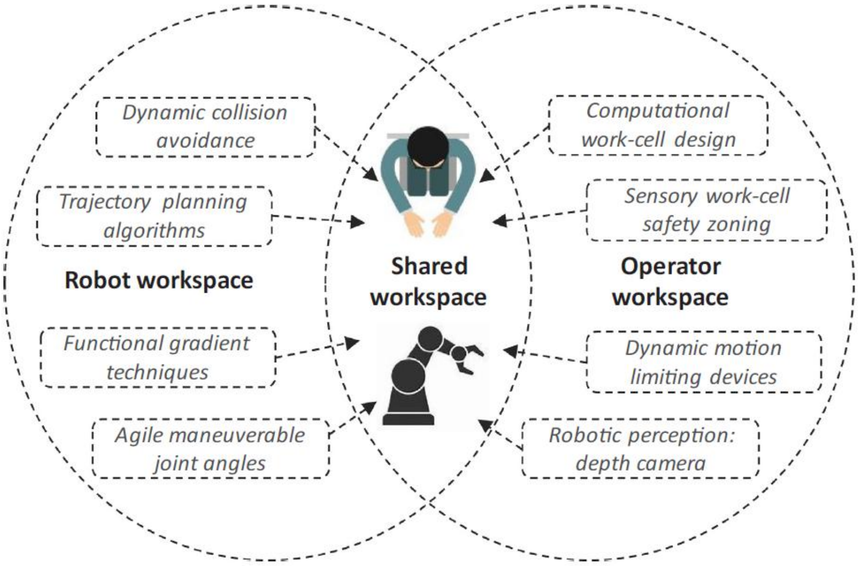

Fig. 4 Example of Shared workspace. Source [2]

Challenges in Human-Robot Collaboration

In the industrial landscape, arm robots are extensively utilized for automation, offering precise, rapid, and robust solutions for tasks that are often hazardous, repetitive, or beyond human capability. Their deployment spans various sectors, including manufacturing, transportation, and packaging, significantly enhancing productivity due to their programmable flexibility. However, the integration of robots also raises safety and ergonomic concerns, as their lack of inherent intelligence increases the risk of human injury, necessitating stringent safety measures. Traditional approaches to ensuring safety include safeguarding robots within dedicated cells or zones, as per guidelines from the International Standards Organization (ISO). These measures, while effective, can restrict collaborative operations, particularly in Human-Robot Collaboration (HRC) setups. Two primary strategies have emerged to address these challenges: the development of collaborative robots (cobots) designed to work alongside humans by incorporating compliance features to minimize injury risk, and the implementation of electronic safeguarding measures that use various sensors to monitor human presence and prevent collisions. Speed and separation monitoring (SSM) is a prominent technique that adjusts the robot's speed based on the proximity and movement of human operators, enhancing safety without sacrificing productivity. Evaluating the effectiveness of HRC systems involves a combination of objective measures—such as safety performance and productivity—and subjective assessments based on human feedback regarding their comfort and trust in working with robots. This multifaceted evaluation approach is critical for optimizing HRC configurations, ensuring that both safety and productivity are maintained in collaborative environments.

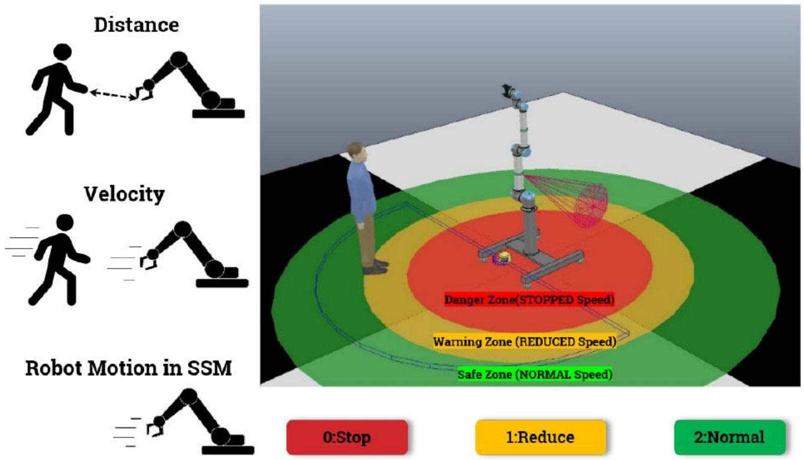

Fig. 5Basic SSM setup in a simulation showing static 2D safety zones around the robot. Source [6,9,10]

Safety Measures and Standards in HRC

The integration of arm robots in industrial settings has revolutionized automation, enhancing productivity and efficiency across diverse applications such as manufacturing, transportation, and packaging. However, this increased reliance on robotic systems has also introduced significant safety concerns, primarily due to the lack of inherent intelligence in these machines. To mitigate risks of human injury, particularly in Human-Robot Collaboration (HRC) environments, industry standards, particularly from the International Organization for Standardization (ISO), have outlined comprehensive safety measures. Key among these is ISO 15066, which sets normative standards for the design and operation of collaborative robots, emphasizing the necessity of hardware and software safeguards. Collaborative robots, or cobots, are engineered to work alongside humans safely, incorporating features such as force sensing and protective stops to prevent injuries during interaction. Various electronic safety devices, including safeguarded perimeter door switches and light curtains, help define safe zones around robotic work cells, further reducing collision risks. Moreover, the ISO 10218 standard delineates safety requirements for industrial robots, focusing on risk assessment processes and the implementation of safety-rated monitored functions that ensure safe collaborative operations. By aligning design safeguards with these established standards, industries can create safer working environments, promoting effective human-robot collaboration while minimizing hazards associated with automation.

Conclusion:

In conclusion, the advancement of robotics and the integration of Human-Robot Collaboration (HRC) in industrial settings present both opportunities and challenges. While arm robots enhance productivity and efficiency across various applications, ensuring the safety of human operators is paramount. The establishment of comprehensive safety measures and standards, particularly those outlined by ISO 15066 and ISO 10218, provides a robust framework for mitigating risks associated with robotic operations. These standards advocate for the development of collaborative robots designed to operate alongside humans safely, employing innovative technologies such as force sensing and electronic safeguarding measures. By implementing these guidelines, industries can foster environments that prioritize human safety while reaping the benefits of robotic automation. As the landscape of robotics continues to evolve, ongoing collaboration between engineers, safety experts, and industry stakeholders will be essential in advancing safety practices and ensuring that the integration of robotics in the workforce is both effective and secure.

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