

Research Article

Adaptive Human Robot Collaboration Model Using Computer Vision and Intelligent Control for Flexible Manufacturing Workstations

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Abstract: The rapid development of modern manufacturing technology has driven the emergence of human-robot collaboration (HRC) as part of the transformation toward a human-centric intelligent production system. In collaborative work environments, robots are not only required to work efficiently but also to interact safely and responsively with operators. However, most conventional industrial robot systems still use rigid motion controls and are unable to dynamically adapt to human activity around them. This research aims to develop a human-robot collaboration system by integrating computer vision technology to detect operator movement and applying adaptive control algorithms to the robot manipulator. The research methodology includes designing a collaborative workstation, implementing a computer vision-based motion detection system, developing an adaptive control algorithm, and evaluating system performance through various experimental scenarios. Evaluation parameters include task completion time, safe distance, and system response time. The results show that the developed system significantly improves the efficiency and safety of human-robot interaction compared to conventional systems, with shorter task times, optimal safe distances, and faster system response to operator movements.

Keywords: Adaptive Control; Collaborative Robotics; Computer Vision; Human Robot Collaboration; Smart Manufacturing

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1. Introduction

The rapid development of modern manufacturing technologies has encouraged the emergence of new paradigms in production systems that emphasize flexibility, adaptability, and human-centered design. One of the most prominent approaches is the implementation of human robot collaborative workspaces, where humans and robots operate together within the same working environment. This concept has become an essential component of the transformation toward smart manufacturing and Industry 5.0, which promotes synergy between human intelligence and machine automation [1], [2]. In such systems, humans contribute cognitive capabilities such as creativity, decision-making, and problem-solving, while robots provide precision, strength, and consistent performance in repetitive tasks [3]. The integration of these complementary capabilities enables manufacturing processes to become more efficient while preserving the central role of human workers in industrial environments.

The implementation of human robot collaboration is closely associated with the development of collaborative robots, commonly known as cobots. Unlike traditional industrial robots that operate in isolated workspaces, cobots are designed to interact directly with human operators within shared environments while maintaining safety and efficiency. This capability allows manufacturers to increase productivity while enabling humans and



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robots to complement each other in performing manufacturing tasks [4]. Furthermore, collaborative systems can improve workplace ergonomics by reducing the physical workload of human operators, particularly in tasks involving heavy lifting or repetitive movements that may cause occupational injuries [5]. Consequently, the development of human robot collaborative systems has become a major focus in modern manufacturing research.

Despite the numerous advantages offered by collaborative robotics, the implementation of human robot collaboration also presents several technical and operational challenges. One of the most critical concerns is ensuring the safety of human operators working alongside robots. In collaborative environments, robots must be capable of detecting human presence and avoiding potential collisions in real time to prevent workplace accidents [6]. This requires the integration of advanced sensing technologies and intelligent control algorithms capable of responding quickly to dynamic environmental conditions. Without robust safety mechanisms, direct interaction between humans and robots may introduce significant risks in manufacturing processes [7].

Beyond physical safety, effective coordination between humans and robots also requires a high level of cognitive compatibility and interaction efficiency. Robots must be able to interpret human actions and intentions in order to collaborate effectively within shared workspaces. This requirement has encouraged the development of multimodal communication systems that allow robots to recognize human gestures, process voice commands, and respond to various sensor-based interactions [8]. Such communication capabilities enable robots to adapt their operational behavior according to human activities, thereby creating a more natural and intuitive collaborative environment [9].

Another challenge lies in the flexibility of robotic systems when operating in dynamic production environments. Many conventional industrial robots still rely on rigid programming structures that limit their ability to adapt to changing work conditions or task variations. In modern manufacturing systems that require high flexibility, robots must be capable of adjusting their operational strategies in real time based on environmental conditions and human activities [10]. Therefore, the development of intelligent and adaptive control systems is essential to ensure that robots can operate effectively in continuously evolving manufacturing environments [11].

In addition to technical challenges, the success of human robot collaboration is also influenced by psychological and social factors among human workers. Some studies indicate that workers may experience discomfort or anxiety when working in close proximity to robots, particularly due to concerns about safety and trust in automated systems [12]. Therefore, it is important to design collaborative systems that not only ensure technical safety but also provide a sense of control and comfort for human operators during the interaction process. Ergonomic workspace design and intuitive human machine interfaces can play a significant role in improving worker acceptance of collaborative robotic technologies [13].

To address these challenges, visual perception technologies play a crucial role in enabling effective human robot collaboration. Computer vision-based perception systems allow robots to understand the surrounding environment more comprehensively. Through the use of cameras, depth sensors, and advanced image processing algorithms, robots can detect human presence, recognize objects, and monitor movements within the workspace in real time [7]. This capability enables robots to adapt their movements and behaviors according to environmental conditions and human activities [14].

Furthermore, the integration of artificial intelligence with computer vision technologies has significantly enhanced the capabilities of robotic perception systems. By combining visual sensing with AI-based algorithms, robots can analyze visual data more efficiently and accurately. Techniques such as object detection, human pose estimation, and behavioral analysis enable robots to better understand the context of human robot interactions [8]. As a result, robots can anticipate human actions and optimize task coordination in complex manufacturing environments.

In addition to visual perception systems, adaptive control mechanisms represent another key component in enabling safe and efficient human robot collaboration. Adaptive control allows robots to adjust their force, speed, and motion direction in response to interactions with human operators. Approaches such as impedance control and admittance control allow robots to respond safely and flexibly to physical contact with humans [10]. With such control mechanisms, interactions between humans and robots can occur more naturally and safely within collaborative workspaces [11].

Overall, the development of intelligent human robot collaboration models has significant potential to improve manufacturing productivity, workplace safety, and the quality

of human machine interaction. The integration of computer vision technologies, artificial intelligence, and adaptive control systems enables the creation of safer and more efficient collaborative environments. Therefore, research focusing on human robot collaboration models based on visual perception and intelligent control systems is essential for supporting the development of human-centered smart manufacturing systems in the future [2], [5].

2. Literature Review

Human Robot Collaboration in Smart Manufacturing

Human Robot Collaboration (HRC) has become a key component in the development of smart manufacturing systems, where humans and robots work together to improve productivity, flexibility, and operational efficiency. In modern industrial environments, HRC enables the integration of human cognitive abilities with robotic precision and automation capabilities. This integration allows manufacturing systems to handle complex and dynamic production processes more effectively while maintaining high levels of safety and efficiency [3]. Furthermore, collaborative robotics has contributed significantly to improving production adaptability and enabling human-centered manufacturing environments, which are essential in the context of Industry 5.0 [1].

The advancement of HRC technologies has also been driven by the integration of human cognitive abilities into robotic systems. Through sensor fusion and advanced perception technologies, robots can interpret environmental conditions and human actions in real time. This capability allows collaborative robots to adapt their behavior dynamically during task execution. Sensor fusion frameworks play a critical role in enabling robots to interpret human intentions and respond appropriately to human actions in collaborative environments [15]. As a result, the integration of cognitive capabilities enhances the effectiveness of human robot teamwork in complex industrial scenarios.

Recent research trends emphasize proactive collaboration between humans and robots. Unlike traditional robotic systems that follow predefined instructions, proactive HRC systems are designed to anticipate human actions and adjust their behavior accordingly. These systems rely on mutual cognitive understanding, predictive capabilities, and self-organizing collaboration strategies to improve efficiency and coordination in manufacturing tasks [16]. Proactive HRC aims to establish a symbiotic relationship between humans and robots, where both entities actively contribute to decision-making processes and task execution in real time.

Another important aspect of human robot collaboration is the development of multimodal communication methods that facilitate intuitive interaction between humans and machines. Programming-free approaches such as gesture recognition, voice commands, and tactile interaction allow operators to communicate with robots naturally without requiring complex programming skills. These interaction techniques enhance usability and accessibility in collaborative work environments, making it easier for workers to interact with robotic systems during manufacturing operations [17]. Consequently, multimodal communication plays a crucial role in improving the efficiency and acceptance of collaborative robotic technologies.

Technological advancements in artificial intelligence have also significantly influenced the development of HRC systems. In particular, the integration of Large Language Models (LLMs) and Vision Language Models (VLMs) has opened new opportunities for intelligent human robot interaction. These technologies enable robots to interpret human instructions, perform task planning, and adapt to complex production scenarios through natural language and visual understanding. The application of LLM-based frameworks has demonstrated promising results in facilitating seamless collaboration between humans and robots in assembly and manufacturing environments [18]. Such technologies also support knowledge transfer between human operators and robotic systems.

Despite these technological advancements, several challenges remain in implementing effective HRC systems. One of the primary challenges is interoperability between different robotic platforms, sensors, and industrial systems. Additionally, worker acceptance and trust toward collaborative robots remain important issues that must be addressed to ensure successful implementation. Ethical considerations, including safety standards and responsible AI usage, also play a significant role in shaping the future of collaborative robotics [5]. Addressing these challenges is essential to enable the widespread adoption of HRC technologies in industrial environments.

Overall, the evolution of human robot collaboration technologies is moving toward the creation of resilient, adaptive, and human-centered manufacturing systems. By leveraging

advanced sensing technologies, artificial intelligence, and intuitive interfaces, HRC systems can significantly enhance production efficiency while ensuring worker safety and comfort. These advancements highlight the growing importance of collaborative robotics in supporting the next generation of intelligent manufacturing systems [1].

Computer Vision for Object Detection and Motion Tracking

Computer vision technologies have become fundamental tools in various intelligent systems, particularly for object detection and motion tracking applications. Object detection refers to the process of identifying and localizing objects within images or video frames, while motion tracking focuses on monitoring object movement across multiple frames in a sequence. These capabilities are essential in numerous applications, including surveillance systems, autonomous vehicles, robotics, and human machine interaction systems [19]. As computer vision technology continues to evolve, deep learning techniques have significantly improved the accuracy and efficiency of object detection and tracking algorithms.

Object detection methods can generally be categorized into two main approaches: two-stage detectors and one-stage detectors. Two-stage detectors, such as Region-based Convolutional Neural Networks (R-CNN), operate by first generating candidate object regions and then classifying them into predefined categories. These approaches typically achieve high detection accuracy but require relatively high computational resources [20]. In contrast, one-stage detectors such as the You Only Look Once (YOLO) algorithm perform object localization and classification simultaneously, allowing faster detection speeds suitable for real-time applications [21].

The rapid development of deep learning techniques has also expanded the capabilities of object detection systems, particularly in complex and dynamic environments. Modern deep learning-based detection models are capable of identifying multiple objects within a scene while maintaining high levels of accuracy and speed. Additionally, three-dimensional object detection methods have been developed to provide spatial information about objects, enabling improved scene understanding in robotics and autonomous systems [22]. These advancements are particularly beneficial for applications requiring precise environmental perception.

Motion tracking represents another essential component of computer vision systems. Motion tracking algorithms enable systems to follow objects across consecutive video frames, allowing continuous monitoring of object movement. Techniques such as multi-object tracking and optical flow analysis are commonly used to analyze object trajectories and interactions within dynamic environments [23]. These tracking techniques are widely used in applications such as traffic monitoring, surveillance, and emergency response systems.

However, motion tracking systems face several challenges when applied in real-world environments. Factors such as occlusion, lighting variations, and complex backgrounds can significantly affect tracking accuracy. To address these challenges, researchers have developed advanced tracking algorithms that combine appearance-based features with motion-based information to improve robustness and reliability [19]. These hybrid approaches allow computer vision systems to maintain accurate object tracking even in challenging environmental conditions.

Emerging trends in computer vision research have also introduced innovative approaches for improving detection and tracking performance. For example, thermal imaging technologies have been utilized to detect and track objects in low-light or night-time conditions where traditional cameras may struggle. Thermal imaging-based object detection has shown promising results in enhancing detection accuracy under challenging environmental conditions [24]. Such technologies are particularly useful in security monitoring and search-and-rescue operations.

Another emerging approach involves the use of panoramic vision systems that combine multiple camera inputs to create wider fields of view for motion tracking. By integrating video streams from multiple cameras, panoramic vision systems can monitor large areas more effectively and improve the accuracy of object tracking in critical situations. This approach has been applied in scenarios such as disaster response and flood rescue operations, where monitoring large environments is essential [23].

In conclusion, computer vision technologies continue to evolve rapidly, enabling more accurate and efficient object detection and motion tracking capabilities. Advances in deep learning, sensor technologies, and data processing algorithms have significantly enhanced the ability of intelligent systems to perceive and understand dynamic environments. These

developments play a crucial role in supporting advanced applications such as autonomous systems, smart surveillance, and collaborative robotics [19], [20].

Intelligent Control Systems for Robot Manipulators

Robot manipulators play a crucial role in modern automation and smart manufacturing systems. Their capability to perform complex tasks such as assembly, material handling, and precision operations has made them indispensable in industrial environments. However, the dynamic behavior of robot manipulators is inherently nonlinear and involves multiple inputs and outputs, making control design challenging. To address these complexities, researchers have developed intelligent control systems that improve the adaptability, robustness, and performance of robotic manipulators [25].

One of the key approaches in intelligent control systems is the integration of adaptive and robust control strategies. These methods are designed to handle parameter uncertainties, nonlinear dynamics, and external disturbances that frequently occur during robotic operations. Sliding Mode Control (SMC) has been widely used due to its robustness against uncertainties. For instance, combining SMC with fuzzy logic controllers allows the system to adjust control parameters dynamically while maintaining stability. Research by [26] demonstrated that an adaptive robust control scheme based on SMC and fuzzy logic significantly improves trajectory tracking accuracy in robotic manipulators. Such hybrid controllers reduce steady-state errors and enhance system stability even under varying operating conditions.

Another important development in intelligent control systems involves the integration of artificial intelligence techniques. AI-based control strategies such as Artificial Neural Networks (ANN), Fuzzy Logic Control (FLC), and metaheuristic optimization algorithms are increasingly employed to emulate human-like decision-making capabilities in robotic systems. These techniques enable controllers to learn from data and adjust their parameters accordingly to improve performance. [27] reported that intelligent algorithms can optimize trajectory control and minimize positioning errors in robotic manipulators. Similarly, metaheuristic algorithms have been successfully applied to optimize control parameters for trajectory tracking and path planning tasks, thereby improving efficiency and accuracy in robotic motion control [25].

In addition to traditional AI methods, hybrid and self-configuring control systems have recently gained attention in robotic research. Hybrid control architectures combine centralized and decentralized control strategies to improve flexibility and adaptability in complex robotic systems. One notable approach involves integrating Deep Reinforcement Learning (DRL) with sliding mode control to create self-configuring controllers that automatically adjust control parameters based on environmental feedback. [28] proposed a DRL-based self-configuring sliding mode control scheme that significantly improves the robustness and adaptability of robot manipulators in uncertain environments. This approach allows robotic systems to dynamically adjust their control strategies according to task requirements and environmental changes.

Recent advancements have also explored innovative human-machine interaction technologies such as Brain Computer Interfaces (BCI) for robotic manipulator control. BCIs enable users to control robotic systems directly through neural signals, providing an intuitive interface between humans and machines. [29] demonstrated that electroencephalography (EEG)-based BCI systems combined with visual fusion technologies can effectively control robotic arms. This approach allows users to perform complex tasks through cognitive commands, significantly enhancing human robot interaction and control efficiency.

Furthermore, intelligent control systems are increasingly being applied in smart manufacturing environments. In such environments, robotic manipulators must perform complex tasks while adapting to dynamic production requirements. [30] highlighted the importance of intelligent control techniques for multi-joint robotic manipulators used in smart factories. Their research emphasized the need for advanced control algorithms capable of managing complex kinematic structures and ensuring stable operation in automated production systems.

In addition to control performance, modern robotic systems operating within Industrial Internet of Things (IIoT) environments must also address cybersecurity challenges. As robotic manipulators become interconnected through distributed networks and edge computing platforms, protecting communication channels and system infrastructure becomes increasingly important. Advanced machine learning approaches such as hybrid federated ensemble learning have been proposed to detect and mitigate cyber threats, including

Distributed Denial-of-Service (DDoS) attacks, in IIoT environments [31]. Such intelligent detection mechanisms can enhance the reliability and security of networked robotic systems by enabling real-time monitoring and adaptive threat mitigation.

Moreover, secure data management and communication infrastructures are essential for ensuring the safe operation of interconnected robotic systems. Blockchain technology has been explored as a decentralized security mechanism capable of improving data integrity, authentication, and access control in distributed computing environments. A systematic literature review conducted by [32] highlighted the potential of blockchain-based solutions in enhancing server security and preventing unauthorized access in networked systems. The integration of such security frameworks may support the development of secure cyber-physical systems in smart manufacturing environments where robotic manipulators operate within connected industrial networks.

Overall, intelligent control systems provide essential solutions for improving the performance and reliability of robotic manipulators. By combining adaptive control, artificial intelligence techniques, hybrid control architectures, advanced human-machine interfaces, and secure network infrastructures, modern robotic systems can effectively address challenges related to nonlinear dynamics, parameter uncertainties, real-time adaptability, and cybersecurity in interconnected industrial environments.

Safety Standards in Collaborative Robotics

Collaborative robotics has emerged as a key component of modern industrial automation, enabling humans and robots to work together within shared workspaces. Unlike traditional industrial robots that operate in isolated environments, collaborative robots (cobots) are designed to interact directly with human workers. This interaction requires strict safety measures to prevent injuries and ensure safe operation. Consequently, safety standards and regulatory frameworks play a critical role in the development and deployment of collaborative robotic systems [33].

One of the most important safety standards for collaborative robotics is ISO/TS 15066. This technical specification provides detailed guidelines for the safe operation of collaborative robots, including requirements for contact force limits, speed restrictions, and separation monitoring between humans and robots. According to [34], ISO/TS 15066 defines several safety modes for collaborative operation, such as safety-rated monitored stop, hand-guiding, power and force limiting, and speed and separation monitoring. These guidelines help manufacturers design robotic systems that comply with international safety requirements while maintaining operational efficiency.

Speed and Separation Monitoring (SSM) is one of the key mechanisms introduced by ISO/TS 15066 to ensure safe human robot interaction. This method involves continuously monitoring the distance between the robot and human operators and adjusting the robot's speed accordingly to avoid potential collisions. [35] proposed a probabilistic model for estimating human hand intrusion during robotic operations, which improves the accuracy of separation monitoring. Their approach enhances safety by predicting potential collisions before they occur, allowing the robotic system to respond proactively.

In addition to monitoring approaches, risk assessment plays a fundamental role in ensuring safety in collaborative robotics. Risk assessment procedures typically involve identifying potential hazards, evaluating possible collision scenarios, and determining appropriate safety measures. Simulation-based tools such as Computer-Aided Safety Assessment (CASA) allow engineers to analyze robot motion trajectories and estimate potential contact forces during collisions. [33] emphasized that comprehensive risk assessment procedures are essential for minimizing hazards in collaborative work environments.

Another promising approach to improving safety in collaborative robotics is the implementation of dynamic safety zones. Unlike fixed safety boundaries, dynamic safety zones adjust in real time based on the positions and movements of both humans and robots. This adaptive mechanism allows robotic systems to maintain safe distances while minimizing unnecessary production interruptions. [36] proposed dynamically scaled safety zones based on ISO/TS 15066 that optimize stopping trajectories and separation distances. Similarly, [37] demonstrated that dynamic safety zones significantly improve operational efficiency while maintaining compliance with safety regulations.

Recent advancements in artificial intelligence and computer vision have also contributed to improving safety mechanisms in collaborative robotics. Edge AI systems combined with multi-camera vision technologies can detect human presence in real time and adjust robotic movements accordingly. [38] developed an Edge AI-driven multi-camera system capable of

dynamically controlling robot speed in safety-critical environments. Their system enables robots to adapt their operational behavior based on human proximity, thereby reducing the risk of accidents while maintaining productivity.

Another important aspect of collaborative robot safety involves understanding the nature of physical collisions between humans and robots. Research by [39] analyzed different types of collisions in collaborative robotic systems using pneumatic artificial muscles. Their study provides insights into the mechanical behavior of robotic actuators during impact events, which is essential for designing safer collaborative robotic mechanisms.

Moreover, real-time estimation of robot speed limits can further enhance safety in collaborative environments. [40] introduced a human-in-the-loop system for estimating safe robot speed limits during collaborative operations. This method allows the robotic system to dynamically adjust its speed based on human presence and environmental conditions, ensuring safe interaction without unnecessarily restricting robot performance.

In summary, safety standards and advanced safety mechanisms are essential components of collaborative robotics. International standards such as ISO/TS 15066 provide a regulatory framework for safe human robot interaction, while technological advancements such as dynamic safety zones, AI-based monitoring systems, and predictive collision models further enhance safety performance. These developments play a crucial role in enabling safe and efficient human robot collaboration in modern industrial environments.

3. Research Methods

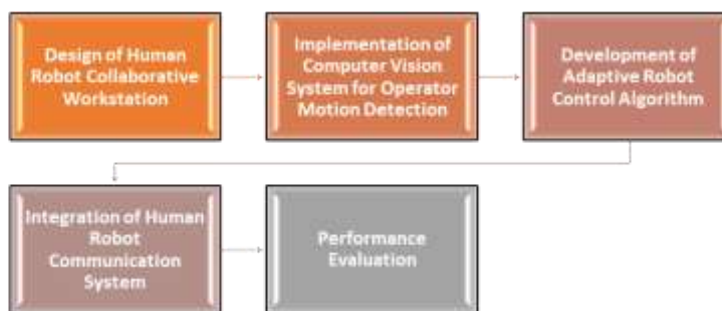


Figure 1. Research Methodology Flowchart.

Design of Human Robot Collaborative Workstation

The first stage of the research involves designing a collaborative workstation that enables safe and efficient interaction between a human operator and an industrial robot manipulator. The workstation is structured to allow both entities to share the same workspace while performing complementary tasks such as object handling, assembly assistance, or cooperative manipulation. The robot manipulator is positioned within a predefined collaborative zone equipped with safety boundaries and task-specific fixtures. The layout design considers ergonomic factors, human accessibility, and robot reachability to ensure efficient task execution. In addition, safety standards for human–robot collaboration, such as speed and separation monitoring and workspace segmentation, are incorporated into the workstation design. The physical setup also includes sensors, cameras, and communication interfaces that support real-time monitoring of human movements and robot states during collaborative operations.

Implementation of Computer Vision System for Operator Motion Detection

A computer vision system is implemented to detect and analyze the movements of the human operator within the collaborative workspace. The system utilizes RGB or depth cameras installed at strategic positions to capture real-time visual data of the workstation. Image processing and object detection algorithms are applied to identify the operator's body posture, hand movements, and position relative to the robot. Feature extraction techniques are used to convert visual data into meaningful motion information that can be interpreted by the control system. The detection process enables the system to recognize operator actions, estimate proximity between the human and the robot, and determine potential safety risks. By continuously monitoring the operator's movements, the computer vision system provides essential input data for adaptive robot control and safety decision-making during collaborative tasks.

Development of Adaptive Robot Control Algorithm

An adaptive control algorithm is developed to regulate the behavior of the robot manipulator based on real-time environmental conditions and human operator activities. The control algorithm dynamically adjusts robot parameters such as speed, trajectory, and acceleration according to the information received from the computer vision system. When the operator approaches the collaborative zone, the robot automatically modifies its motion parameters to maintain safe interaction while continuing the assigned task. The algorithm integrates intelligent decision-making mechanisms that allow the robot to respond to dynamic changes in the workspace. Control strategies such as rule-based adaptation, feedback control, or learning based optimization may be applied to ensure stable and responsive robot behavior. This adaptive control mechanism enables the robot to operate efficiently while maintaining high levels of safety and interaction awareness.

Integration of Human Robot Communication System

To facilitate effective collaboration, a communication system is integrated between the human operator and the robotic system. This communication interface enables bidirectional information exchange, allowing the robot to receive commands from the operator and provide feedback regarding its operational status. The communication system may include visual indicators, graphical user interfaces, or gesture-based interaction mechanisms. Through this interface, operators can initiate tasks, adjust robot actions, or monitor system performance in real time. Additionally, communication protocols are implemented to ensure reliable data transmission between the computer vision module, control algorithm, and robot controller. The integration of this communication system enhances coordination between human and robot agents, supporting smoother task execution in collaborative manufacturing environments.

Performance Evaluation

The final stage of the research focuses on evaluating the performance of the proposed human robot collaborative system. The evaluation is conducted through a series of experimental scenarios in which the robot and human operator perform predefined collaborative tasks. System performance is measured using several evaluation metrics, including task completion time, safety metrics, and system responsiveness. Task completion time is used to assess the efficiency of collaborative task execution, while safety metrics evaluate the effectiveness of the system in maintaining safe distances and preventing collisions between the human and the robot. System responsiveness measures the ability of the robot to react to operator movements and environmental changes in real time. The experimental results are analyzed to determine the effectiveness of the proposed system and to identify potential improvements for future development.

4. Results and Discussion

Results

The proposed human robot collaborative system was evaluated through a series of controlled experiments conducted within the designed collaborative workstation. The objective of the experiment was to assess the effectiveness of integrating a computer vision-based perception system with an adaptive robot control algorithm in supporting safe and efficient human robot collaboration. During the experiments, a human operator and a robotic manipulator performed cooperative tasks involving object transfer and simple assembly assistance. The collaborative workstation allowed both agents to operate within the same workspace while maintaining real-time monitoring and adaptive motion control.

The computer vision module continuously captured visual data of the workspace using cameras positioned above the collaborative area. The captured images were processed using object detection and motion analysis algorithms to determine the operator's position and movement patterns. Based on the detected human movement, the adaptive control system dynamically adjusted the robot's speed, trajectory, and operational parameters to maintain safe and efficient interaction. To ensure reliability, each experimental scenario was repeated multiple times, and the average performance results were recorded. The system performance

was evaluated using three primary metrics: task completion time, safety distance, and system response time.

Table 1. System Performance Evaluation Results.

System Configuration	Task Completion Time (s)	Safety Distance (cm)	System Response Time (ms)
Baseline Robot Operation	52.4	35	180
Vision-Based Detection System	48.7	42	120
Proposed Adaptive Collaborative System	44.1	50	85

Table 1 presents the comparative performance results for three different system configurations evaluated during the experiment. The baseline robot operation represents a conventional robotic system operating without advanced perception capabilities or adaptive control mechanisms. In this configuration, the robot executes predefined motion trajectories without adjusting its behavior based on the presence of the human operator. The second configuration introduces a computer vision-based detection system that allows the robot to detect human presence but does not yet fully integrate adaptive motion control.

The results indicate that the proposed adaptive collaborative system achieves the best performance across all evaluation metrics. The task completion time decreases from 52.4 seconds in the baseline system to 44.1 seconds, demonstrating a significant improvement in operational efficiency. The average safety distance also increases from 35 cm to 50 cm, indicating that the perception system and adaptive control algorithm effectively maintain safe interaction between the human operator and the robotic manipulator. Additionally, the system response time decreases significantly from 180 milliseconds to 85 milliseconds, showing that the proposed system can react more quickly to changes in the collaborative environment.

To further analyze the efficiency improvement achieved by the proposed system, the task completion time results were visualized using a graphical comparison between the evaluated system configurations.

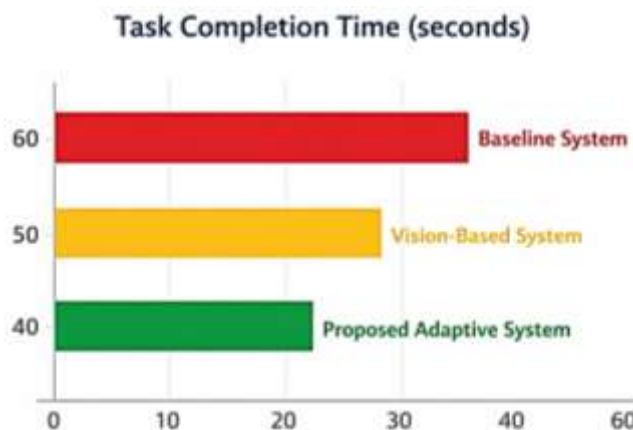


Figure 2. Task Completion Time Comparison.

Figure 2 illustrates the difference in task completion time among the three evaluated system configurations. The baseline system exhibits the longest task completion time because the robot operates using fixed motion trajectories without considering the movement of the human operator. As a result, the robot may experience delays or pauses during collaborative tasks, which reduces overall operational efficiency.

The vision-based system demonstrates moderate improvement because the perception module allows the robot to detect the operator's presence in the workspace. However, without a fully integrated adaptive control mechanism, the robot cannot dynamically adjust its motion parameters to optimize task coordination. In contrast, the proposed adaptive collaborative system achieves the shortest task completion time because it integrates real-time human motion detection with adaptive robot control. This integration enables the robot to anticipate human movements and adjust its trajectory and speed accordingly, thereby reducing unnecessary idle time during collaborative operations.

Maintaining an appropriate safety distance between humans and robots is essential in collaborative robotic environments. The safety distance results obtained from the experimental evaluation are presented in Figure 3.

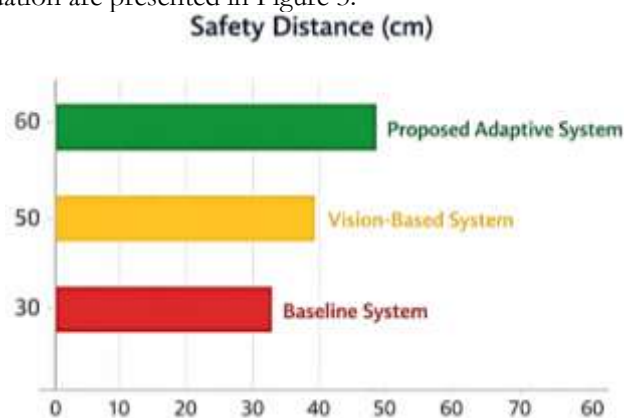


Figure 3. Safety Distance Comparison.

The results presented in Figure 3 indicate that the proposed adaptive collaborative system maintains the highest average safety distance during operation. In the baseline system, the robot operates without awareness of the operator's presence, which leads to relatively smaller safety margins. Although basic safety mechanisms are implemented in the robotic system, the lack of real-time perception limits the robot's ability to adjust its motion dynamically.

The introduction of the computer vision system in the second configuration improves safety performance by enabling the robot to detect human presence within the workspace. However, the safety distance remains limited because the robot's motion control is still largely predefined. The proposed system significantly improves safety performance by integrating perception and adaptive control mechanisms. When the operator approaches the collaborative workspace, the system automatically adjusts the robot's motion parameters to maintain an appropriate separation distance, thereby reducing the risk of accidental contact or collision.

The responsiveness of the collaborative robotic system is another critical factor influencing the quality of human robot interaction. System response time refers to the duration required for the robot to detect human movement and adjust its operational parameters accordingly.

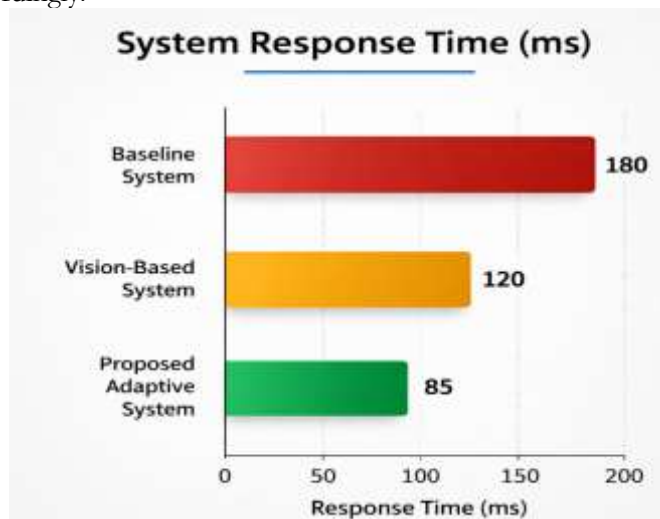


Figure 4. System Response Time Comparison.

The graphical results in Figure 4 show that the proposed adaptive collaborative system achieves the fastest response time among the evaluated configurations. In the baseline system, the robot operates using predefined control parameters and does not continuously monitor environmental changes. Consequently, the system response time is relatively high, as the robot requires more time to adjust its behavior when unexpected events occur.

The vision-based detection system improves responsiveness by enabling real-time monitoring of the operator's movement. However, the response speed is still limited because the robot control algorithm does not fully adapt its motion parameters dynamically. The proposed adaptive system significantly reduces the response time by combining perception-

based monitoring with adaptive motion control. This integration enables the robot to react more quickly to human movement and environmental changes, ensuring smoother interaction during collaborative tasks.

Discussion

The experimental results demonstrate that the integration of computer vision-based perception with adaptive robot control mechanisms significantly improves the performance of human robot collaborative systems. The improvements observed in task completion time, safety distance, and system response time indicate that the proposed framework provides a more effective approach for managing interaction between human operators and robotic manipulators within shared workspaces. In collaborative manufacturing environments, robots must not only perform tasks efficiently but also maintain safe and responsive interaction with human workers. The results obtained in this study show that combining real-time perception with adaptive control strategies can address these requirements simultaneously.

One of the most significant findings of this study is the reduction in task completion time achieved by the proposed system. Compared with the baseline robotic system, the adaptive collaborative system demonstrates improved operational efficiency due to its ability to dynamically adjust robot behavior based on human movement. In traditional industrial robotic systems, robots typically operate using fixed trajectories and predefined motion parameters. Such rigid operational structures limit the ability of robots to adapt to dynamic working environments where human operators are actively involved in the production process. By integrating a computer vision system that continuously monitors human movement, the proposed system allows the robot to anticipate operator actions and modify its trajectory and speed accordingly. This capability reduces unnecessary idle time and improves coordination between human and robotic agents during collaborative tasks.

The improvement in task efficiency observed in this study is consistent with recent research on human robot collaboration in smart manufacturing environments. Previous studies have highlighted that adaptive robotic systems capable of perceiving human activities can significantly enhance workflow efficiency by enabling robots to respond to changes in the workspace in real time. The findings of this study support the argument that perception-driven robotic systems play an essential role in improving the effectiveness of collaborative manufacturing processes. In addition, the integration of intelligent perception and adaptive control mechanisms aligns with the broader objectives of Industry 5.0, which emphasizes human-centered automation and the synergy between human cognitive capabilities and machine precision.

Another important outcome of this study is the improvement in safety performance achieved by the proposed system. Maintaining an appropriate safety distance between human operators and robotic manipulators is a critical requirement in collaborative robotics. The experimental results show that the proposed system maintains a larger safety distance compared with the baseline system and the vision-only configuration. This improvement can be attributed to the real-time perception capability of the computer vision module, which continuously monitors the operator's position and estimates the spatial relationship between the human and the robot.

The integration of perception-based monitoring with adaptive motion control enables the robotic system to dynamically adjust its movement when the operator approaches the collaborative workspace. Instead of abruptly stopping the robot or maintaining fixed safety boundaries, the system can gradually modify the robot's speed and trajectory to maintain safe interaction. Such adaptive safety mechanisms are particularly important in collaborative work environments where humans and robots operate within close proximity. The results obtained in this study demonstrate that perception-driven safety monitoring can significantly reduce the risk of accidental collisions while maintaining operational efficiency.

The reduction in system response time further highlights the advantages of integrating perception and adaptive control in collaborative robotic systems. In dynamic manufacturing environments, human movements are often unpredictable, and robotic systems must be capable of reacting quickly to ensure safe interaction. The experimental results show that the proposed system significantly reduces response time compared with the baseline configuration. Faster response times enable the robotic manipulator to adjust its motion parameters more rapidly when human movement is detected, thereby improving both safety and interaction smoothness.

From a system design perspective, the improved responsiveness observed in this study demonstrates the importance of real-time data processing and efficient control algorithms in collaborative robotics. The integration of computer vision technologies allows the robotic

system to continuously analyze environmental information, while the adaptive control algorithm translates this information into appropriate robot actions. This combination creates a responsive interaction loop in which perception and control processes operate simultaneously to maintain safe and efficient collaboration.

Beyond performance improvements, the findings of this study also provide important insights for the development of human-centered manufacturing systems. Industry 5.0 promotes the concept of collaborative automation, where robots are designed to assist human workers rather than replace them. In such environments, robots must be capable of understanding human behavior, adapting to human actions, and maintaining safe interaction during collaborative tasks. The proposed system contributes to this vision by enabling robots to perceive human movement and adjust their behavior accordingly.

In addition, the results highlight the importance of designing collaborative systems that balance efficiency and safety. Many traditional robotic systems prioritize productivity while relying on strict physical barriers to protect human workers. However, collaborative robotics requires a different approach, where safety is achieved through intelligent monitoring and adaptive control rather than physical separation. The perception-driven framework proposed in this study demonstrates that it is possible to maintain high productivity levels while ensuring safe interaction between humans and robots.

Despite the promising results obtained in this study, several limitations should be acknowledged. The experimental evaluation was conducted within a controlled collaborative workstation environment, which may not fully represent the complexity of real industrial production systems. In large-scale manufacturing environments, additional factors such as multiple operators, varying lighting conditions, and complex object interactions may influence system performance. Therefore, further research is needed to evaluate the proposed framework in more complex industrial scenarios.

Future research may also explore the integration of advanced artificial intelligence techniques to further enhance human robot collaboration. For example, deep learning-based human intention prediction models could enable robots to anticipate operator actions more accurately. Reinforcement learning algorithms could also be used to optimize robot motion strategies in dynamic environments. Additionally, integrating multimodal sensing technologies such as depth sensors, wearable sensors, and tactile sensors could improve the robustness of human detection and interaction monitoring.

Overall, the results of this study demonstrate that integrating computer vision-based perception with adaptive control mechanisms provides a promising approach for improving the efficiency, safety, and responsiveness of human robot collaborative systems. By enabling robots to perceive human movement and dynamically adapt their behavior, the proposed framework supports the development of intelligent collaborative environments that align with the principles of Industry 5.0 and the future of human-centered smart manufacturing.

5. Comparison

The performance of the proposed adaptive collaborative system was compared with two baseline configurations: a conventional robotic system without perception capabilities and a vision-based detection system without adaptive motion control. The baseline robotic system operates using predefined trajectories and fixed control parameters, which limits its ability to respond to dynamic changes within the collaborative workspace. As a result, the baseline configuration exhibits the highest task completion time and the slowest system response. These limitations highlight the challenges faced by traditional industrial robotic systems when operating in environments where human operators are actively involved in the production process.

The vision-based detection system demonstrates improved performance compared with the baseline system because it introduces environmental awareness through computer vision technologies. By enabling the robot to detect the presence and position of the human operator, the system improves safety monitoring within the collaborative workspace. However, the absence of adaptive motion control mechanisms prevents the robot from fully utilizing the perception data to optimize its operational behavior. Consequently, although the vision-based system improves safety distance and response time compared with the baseline configuration, its task efficiency remains limited due to the lack of dynamic motion adaptation.

In contrast, the proposed adaptive collaborative system integrates computer vision-based perception with an adaptive robot control algorithm, allowing the robotic manipulator to dynamically adjust its motion based on real-time environmental information. This integration enables the system to simultaneously improve efficiency, safety, and responsiveness during collaborative tasks. The experimental results indicate that the proposed system achieves the lowest task completion time, the highest safety distance, and the fastest system response time among the evaluated configurations. These improvements demonstrate that combining perception technologies with adaptive control mechanisms provides a more effective framework for supporting human robot collaboration in smart manufacturing environments.

6. Conclusion

This study presented an intelligent human–robot collaborative framework that integrates computer vision-based human motion detection with adaptive robot control mechanisms to improve collaboration performance within shared workspaces. The experimental evaluation demonstrated that the proposed system significantly improves operational efficiency, safety performance, and system responsiveness compared with conventional robotic configurations. By enabling the robot to perceive human movement and dynamically adjust its motion parameters, the system successfully reduces task completion time, increases safety distance, and improves response speed during collaborative operations.

Overall, the findings of this research highlight the importance of integrating perception technologies and adaptive control strategies in the development of human-centered manufacturing systems. The proposed approach contributes to the advancement of collaborative robotics aligned with the principles of Industry 5.0, where robots function as intelligent partners that assist human workers rather than replace them. Future research may extend this work by incorporating advanced artificial intelligence techniques such as human intention prediction and reinforcement learning-based motion planning to further enhance the adaptability and intelligence of human robot collaborative systems.

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