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Development of a Control System for Safe Collaborative Human-Robot Work in Welding Applications

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Declaration:

I, Nada El Yasmine Aichaoui, declare that the dissertation entitled Development of a Control System for Safe Collaborative Human-Robot Work in Welding Applications I wrote myself, using only the sources given in the list of references. All passages that I have taken verbatim or with identical content but paraphrased from other sources are clearly indicated by citing the source.

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GENERAL INTRODUCTION

The history of robotics stretches back to ancient times, with early innovations seen in Greek and Egyptian civilizations. These cultures built impressive mechanical devices, some of which were designed for automated functions or to serve as deterrents against enemies. One notable example is the giant Greek automaton Talos, which was intended to protect the island of Crete. Moreover, these civilizations crafted various mechanical devices for entertainment and practical purposes, such as Heron's theatre, which featured automated stage effects, and Ktesibius' and Philon's water organ - an early form of automated musical instrument. The earliest documented theories on automation come from the writings of Heron of Alexandria and Ktesibius Philon around 270 BC. Heron's works included detailed descriptions of steam-powered devices and other early automation concepts (Altin and Pedaste, 2013). The Renaissance period saw a revival of mechanical innovation, highlighted by Leonardo da Vinci's designs for various machines, including his famous mechanical lion, capable of moving its body and roaring. By the 18th century, the field of robotics began to take shape with notable inventions. Blaise Pascal developed one of the first mechanical calculators, which laid the groundwork for future computing devices. Pierre Jaquet-Droz created humanoid robots that could perform simple tasks like writing or playing music, showcasing the potential for robotics in personal and entertainment applications. Jacques de Vaucanson was famous for his mechanical ducks, which could mimic the movements of real ducks, illustrating the era's fascination with creating lifelike automata. These early robots and mechanical devices reflected the technological advancements of their times, moreover, they set the way for the modern robotics field. In recent decades, one of the significant milestones in industrial science and technology has been the rapid advancement in robotics, which began to gain momentum in the 1960s. Robotics involves a technological system that enhances productivity by connecting various components, greatly increasing production rates while reducing the reliance on human labour at the same time [2], [3].

The term "robot" originally comes from the Czech word "robota", which means "work". It was first used in Karel Čapek's play "Rossum's Universal Robots" to describe biological human-like machines used for work. The concept continues to a large extent in modern robotics, where many robots are designed either to replace humans or to assist them in specific tasks [4]. Today, robots come in various forms, from humanoid robots designed for technological and human interaction to mobile robots that operate in hazardous or inaccessible environments, such as nuclear power plants or space. Nonetheless, most robots in use today are industrial machines programmed to perform repetitive or dangerous tasks more quickly and efficiently than humans.

Collaborative robotics, also known as cobots, is a rapidly growing field of robotics that has gained significant attention and is becoming increasingly important in society. Unlike traditional industrial robots, which are confined to specific isolated areas known as “cells” or “fenced robots” to ensure operator safety _ typically perform high-safety tasks such as material handling with minimal human interaction with safety barriers limiting any direct contact between humans and robots, collaborative robots are designed to work alongside humans in the same space [5].

The concept of the "cobot" was introduced in 1996 by researchers Colgate, Wan Nasuphoprasit, and Peshkin from the Department of Mechanical Engineering at Northwestern University in the United States. The prototype of an industrial collaborative robot was developed in 1998 in collaboration with General Motors to assist workers with tasks such as unpacking vehicle doors. Initially, human-robot interaction was primarily explored in specific fields like search and rescue, human services, military applications, and space exploration. Cobots were designed to assist humans, enhance their capabilities, and operate in environments that are dangerous or difficult for people to access [6]. Robots are gradually taking over jobs that require significant physical effort or are dangerous in the industrial sector. This trend is evident in the automotive industry, where much of the assembly line work is automated. These robots typically operate autonomously, with human intervention restricted for safety reasons. However, not all industrial tasks can be fully automated, as some require the agility, flexibility, and problem-solving abilities of human workers. For instance, in automotive assembly, operators often need to install small parts in hard-to-reach areas while maintaining fast cycle times and adapting to unexpected challenges. In such cases, robots help by handling heavy components, such as dashboards, but they still rely on human guidance. Therefore, combining the strengths of human operators with robotic assistance at the same workstation is valuable. While robots may not yet match human efficiency or reliability in certain tasks, cobots enable humans to focus on higher-value activities by taking over more routine tasks like handling, positioning, or pre-assembly operations. Overall, unlike traditional robotics, cobotics are capable of involving humans in the process, allowing for shared workspaces and direct interaction between humans and robots [7].

Human-robot collaboration (HRC) is advancing quickly, driven by the need for safety, flexibility, and integration into different industries. Today, the use of cobots in industry is guided by strict safety standards that cover robot speed, power levels, and proximity to human workers. While these safety measures work well when humans and robots are just sharing the same space, their effectiveness in more hands-on, interactive situations is still being studied. Cobots are especially useful for Small and Medium-Sized Enterprises (SMEs), where flexibility and the ability to quickly adapt to customer needs are crucial. Researchers are also working on making these robots more aware of their surroundings, including understanding human emotions and social signals and adjusting their actions based on individual needs. Additionally, there is growing interest in how multiple robots and humans can work together better, with a focus on improving teamwork and decision-making. Alongside these technological developments, there is also a growing awareness of the ethical and social challenges of HRC, such as the impact on jobs, privacy, and human independence, which are becoming more important as robots become a bigger part of our workplaces [7].

Formulation of the scientific problem

The rapid advancement of automation and robotics within industrial settings, particularly in manufacturing and welding operations, has significantly reshaped production processes. Welding, a critical yet inherently hazardous activity, has traditionally relied on human operators working in challenging environments where they face numerous risks, such as exposure to ultraviolet (UV) radiation, excessive heat, toxic fumes, and the potential for physical injuries. The integration of robotic systems into welding processes has enabled industries to achieve notable improvements in productivity, precision, and workplace safety. Nevertheless, despite these technological strides, fully automating welding processes remains impractical in many scenarios due to the indispensable role of human expertise, which provides the flexibility and adaptability needed for handling complex or customized welding tasks.

To address this issue, collaborative robots (cobots) have been introduced to operate alongside human workers, combining the precision and efficiency of robotics with human decision-making capabilities. While this collaboration presents significant benefits, it also raises critical safety concerns, particularly in hazardous environments like welding. Protecting human operators, especially in cases where they might unintentionally enter high-risk areas such as those exposed to intense UV radiation, is a major challenge. Although existing control systems provide basic safety measures, they often lack the real-time adaptability needed to respond effectively to unpredictable situations, such as the sudden presence of a worker in a hazardous zone. This shortcoming not only heightens the risk of accidents but also disrupts the fragile balance between ensuring worker safety and maintaining operational efficiency, ultimately affecting the reliability of collaborative welding systems.

Despite extensive research efforts, no previous study has successfully developed a comprehensive control system that simultaneously ensures both safety and efficiency in collaborative welding environments. The existing literature predominantly focuses on either improving safety mechanisms or optimizing efficiency, but not both in an integrated manner. Furthermore, while various safety strategies have been proposed, none have introduced an adaptive, real-time virtual barrier that dynamically adjusts to human presence without disrupting workflow. This gap in the research has left an unresolved challenge in the field of collaborative welding robotics.

The core problem addressed in this research is the development of a novel control system that overcomes these limitations by ensuring safe and efficient collaboration between humans and robots in welding applications. This system incorporates real-time monitoring, dynamic decision-making, and a newly designed virtual barrier—an unprecedented approach in the field. Unlike previous safety solutions, this virtual barrier does not rely on static protective enclosures but rather adapts dynamically to the movement of human operators, ensuring maximum safety while maintaining high production efficiency.

The following research questions are formulated to address this problem:

- How can a control system be designed to ensure real-time adaptability in collaborative human-robot welding environments?
- What safety protocols and Artificial Intelligence (AI)-driven solutions can be integrated to prevent accidents in high-risk zones like UV radiation areas?
- How can the system optimize the welding process while ensuring that human safety is the top priority?

- How can a virtual barrier be designed and implemented to enhance safety without compromising production efficiency?

This research focuses on analyzing and developing a control system for collaborative human-robot welding environments that prioritizes human safety through real-time monitoring, AI-driven decision-making, and the implementation of the first-ever virtual barrier in this field. The study explores how adaptive control mechanisms can be employed to simultaneously optimize both safety and production efficiency, addressing a gap that no previous study has successfully resolved. By integrating advanced sensors, safety protocols, and machine learning models, this research provides an innovative and effective solution to the dual challenges of safety and efficiency in collaborative welding environments.

Objectives

The scientific and practical objectives of this research aim to address the problem of human safety in collaborative human-robot welding environments and to propose a system that maintains high productivity and welding quality without compromising safety.

The scientific objectives of this research are:

- To design a control system architecture for collaborative human-robot work environments, focusing on welding applications, that integrates real-time monitoring and AI-driven decision-making for enhanced safety.
- To analyze the role of adaptive control strategies in ensuring system responsiveness to human presence and unpredictable changes within the welding environment.
- To investigate the integration of advanced sensors and safety protocols in the proposed system to guarantee human safety without compromising the welding process.

The practical objectives of this research are:

- To develop and implement a control system that can dynamically monitor human and robot interactions in a welding environment and make decisions in real time to prevent accidents.

- To propose safety protocols and adaptive control strategies that enable the system to adjust to varying conditions in the welding process, such as changes in workpiece geometry or material properties, while maintaining high-quality welds.

- To demonstrate the effectiveness of the proposed system through simulations and real-world testing, showcasing its ability to ensure safety and optimize performance under different risk scenarios.

- To recommend future improvements by incorporating more advanced AI models and sensor technologies to further enhance the system's adaptability, risk prediction accuracy, and overall reliability.

Hypotheses of the topic research

In line with the research objectives, the following hypotheses have been formulated for this study in the case of GMAW (Gas Metal Arc Welding) robot weldig process:

- Hypothesis 1: A real-time adaptive control system integrating AI and advanced sensors, along with a virtual barrier system, can significantly enhance human safety in collaborative human-robot welding environments while maintaining high productivity and welding quality. The virtual barrier, designed as a digital alternative to physical barriers, ensures worker safety by dynamically adjusting to human presence and hazardous conditions in real-time.
- Hypothesis 2: The AI-driven virtual barrier system enables the control system to respond dynamically to human proximity and unpredictable environmental changes, ensuring safety without compromising operational efficiency. By continuously monitoring worker movements and process variables, the system prioritizes human well-being while optimizing workflow.
- Hypothesis 3: An adaptive control strategy incorporating AI-based decision-making optimizes welding parameters (e.g., current, arc voltage, torch orientation) in real time. The UV intensity mostly depends on the welding current, welding speed and the shielding gas kind. The UV intensity calculation based on the practise and the determined equation of other researcher made by AI as a function ont he used parameters. This strategy compensates for disturbances such as human intrusion or workpiece changes while maintaining process stability, weld quality, and safety through the virtual barrier system.

- Hypothesis 4: The virtual barrier system, supported by real-time monitoring and machine learning models, effectively predicts and mitigates risks in hazardous welding zones, including exposure to UV radiation and thermal hazards. AI-based safety protocols ensure compliance with industrial safety standards, making it a viable alternative to conventional physical barriers.
- Hypothesis 5: The implementation of the virtual barrier system not only enhances safety but also establishes a foundation for quality assurance in welded samples. Experimental validation in simulated and real-world environments will demonstrate the feasibility and effectiveness of this AI-integrated control system in ensuring high performance across diverse welding scenarios.

Justification and Determinants of Research

The justification for this research is rooted in both the scientific and social importance of ensuring safe human-robot collaboration in welding applications, which is a vital aspect of modern manufacturing. As industries continue to integrate more automation and robotics into production processes, the demand for solutions that ensure worker safety while maintaining productivity has become a pressing need. Welding, as a hazardous task, presents a unique challenge in terms of balancing safety with efficiency, particularly in collaborative human-robot environments where human workers are exposed to potential risks such as UV radiation, heat, and physical harm.

This research contributes to the growing body of knowledge on control systems for collaborative human-robot work by proposing a novel solution that prioritizes human safety while optimizing the welding process. The study's relevance extends beyond the welding industry as it addresses broader concerns regarding human-robot interaction in hazardous environments, offering insights that could be applied to other high-risk sectors of manufacturing. From a practical standpoint, this research aims to offer a control system solution that can be implemented in real-world welding environments, providing industries with a tool to enhance safety, productivity, and quality. By demonstrating the system's effectiveness through simulations and experimental testing, the research aims to establish a framework for future innovations in adaptive control systems for human-robot collaboration. The disciplinary determination of this research spans multiple fields, including robotics, control systems engineering, safety engineering, and artificial intelligence. It draws upon principles from these disciplines to design a system that can ensure the safety of human workers in hazardous environments while maintaining the operational efficiency of robots. The multidisciplinary nature of this research highlights its relevance to both engineering and industrial safety disciplines.

Research methods

To address the research problem and validate the hypotheses, this study adopts a multi-method approach that integrates theoretical and empirical research methods. The methodology ensures a comprehensive understanding of the control mechanisms, safety requirements, and efficiency challenges in collaborative human-robot welding environments. By systematically analyzing existing knowledge, designing an intelligent control system, and testing its effectiveness, this research provides a robust framework for improving worker safety and welding performance.

The first phase of the research involved an extensive content analysis to collect and study relevant information on control systems, human-robot collaboration, and welding safety. This included reviewing academic research papers, industrial reports, and international safety standards such as ISO/TS 15066, ISO 10218, and ANSI/RIA R15.06. Examining these regulations ensured that the proposed control system aligns with established safety requirements for collaborative robots [8]. Additionally, case studies from industrial welding applications were analyzed to identify real-world constraints, best practices, and potential improvements in safety mechanisms. By investigating risk assessment strategies and hazard mitigation techniques, this research established a strong theoretical foundation for developing a reliable control system. Following the content analysis, a theoretical study was conducted to design the conceptual framework of the AI-driven control system. This phase explores adaptive control strategies that optimize welding parameters in real time while ensuring worker protection. The integration of machine learning models was examined to enable predictive safety measures and intelligent decision-making in human-robot collaboration. Various sensor technologies, including infrared, LiDAR, and vision-based systems, were analyzed for their effectiveness in detecting human presence and monitoring environmental hazards. Special attention was given to developing a virtual barrier system, an innovative approach that replaces traditional physical barriers with an AI-driven dynamic safety mechanism.

The next stage of the research involved system design and the development process. The control system was programmed using Python, integrating AI algorithms to process sensor data and adjust welding parameters based on real-time risk assessments. The virtual barrier system was implemented as part of the intelligent safety framework, dynamically adjusting to human movement and environmental changes. A key aspect of the system's design was the seamless interaction between the robot, safety sensors, and AI-driven decision-making modules. Camera-based tracking, proximity sensors, and thermal imaging were integrated into the system to provide continuous real-time monitoring of the collaborative workspace. These technological advancements ensured that the control system was capable of delivering both safety and operational efficiency.

To validate the effectiveness of the developed control system, a rigorous experimental evaluation was conducted. The system was tested in a simulated environment, where its ability to detect human presence, activate the virtual barrier, and prevent hazardous incidents was assessed under different risk scenarios. Several key performance indicators were evaluated, including safety response time, detection accuracy, welding precision, and defect minimization. The system's ability to maintain high-quality welds while preventing workplace accidents was compared against conventional physical safety barriers.

These results confirmed that the AI-integrated adaptive control system, combined with the virtual barrier, significantly enhances worker safety without compromising productivity. The system effectively detected and responded to human movements, dynamically adjusting welding parameters and enforcing safety measures in real-time. By mitigating risks such as UV radiation exposure, the virtual barrier proved to be a viable alternative to traditional physical barriers. Additionally, the system's integration with AI-based monitoring contributed to quality assurance in welded samples, ensuring precision and consistency in industrial applications.

In conclusion, this research employed a comprehensive methodology that combined content analysis, theoretical exploration, system design, and experimental validation. By developing and testing an intelligent control system for safe human-robot collaboration in welding, this study provides valuable contributions to industrial automation and workplace safety. The findings serve as a foundation for future research in adaptive control systems, AI-driven risk mitigation, and intelligent robotic safety mechanisms. This approach not only enhances the efficiency of collaborative welding applications but also sets a new standard for human-robot interaction in high-risk industrial environments.

1 LITERATURE REVIEW AND ANALYSIS OF HUMAN-ROBOT INTERACTION SAFETY IN WELDING APPLICATIONS

1.1 INTRODUCTION

In the evolving landscape of industrial automation, Human-Robot Interaction (HRI) is becoming increasingly critical. Collaborative robots, or cobots, are designed to work alongside humans, unlike traditional robots that typically operate in isolated environments. This shift has opened up a myriad of possibilities across various sectors, including manufacturing, electronics, pharmaceuticals, food and beverage, and logistics. However, as cobots and humans begin to share workspaces more closely, ensuring safety becomes paramount, especially in high-risk applications like welding [8].

Welding robots are a great example of how cobots can boost productivity, accuracy, and efficiency. More and more, these robots are being used in manufacturing to take on jobs that are dangerous, repetitive, or need high precision, which helps keep workers safe from harmful fumes, extreme heat, and burns. While the advantages of using welding robots are well-known, there is a need for a closer look at the risks of having humans and robots work together in such hazardous settings. Even though there are safety guidelines and protocols in place, there is still a lack of thorough analysis and understanding of safety in HRI, especially when it comes to using collaborative robots in welding tasks [9].

This chapter aims to address this gap by exploring various interaction scenarios between humans and welding robots, from coexistence in shared spaces with clear boundaries to fully integrated, cooperative tasks. Each scenario presents unique safety challenges and opportunities for improving both worker protection and production efficiency. Through a critical review of existing literature, this paper will assess the state of the art in collaborative robotics, focusing on the necessity of implementing rigorous safety measures to safeguard human operators. By examining different HRI scenarios, safety standards, and the specific case of welding applications, this paper seeks to provide a holistic understanding of how to balance safety and productivity in human-robot collaborative environments, with a particular focus on the unique risks and opportunities associated with welding robots.

1.2 Existence of Human-Robot Interaction Scenarios and Applications

Under the terms of human-machine interaction, published sources and pieces of literature discuss the need to conduct a critical analysis of safety [10]. However, the content that conducts critical analysis is still missing when it comes to the state of the art of collaboration robotics. Which still lacks the focus of proper critical review analysis despite its numerous contributions to the field [11] and [12]. To properly evaluate the contributions of these robots to the field of collaboration, it is extremely necessary to conduct a thorough and complete evaluation of the interaction of the robot with humans [11]: Figure 1 below shows the existence of the most known forms of interaction with Human-Robot.

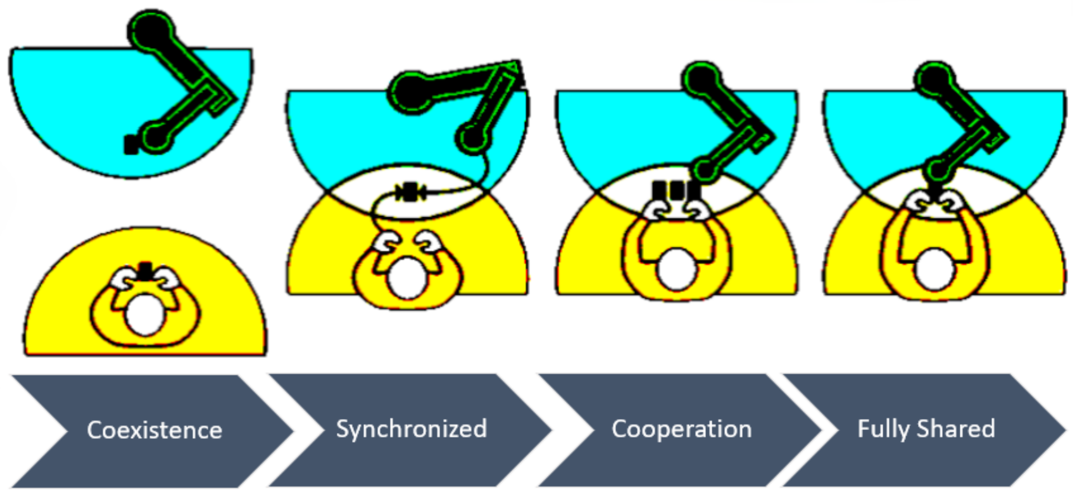


Figure 1: The most known forms of interaction with human-Robot.

1.2.1 Coexistence: Shared Spaces with Clear Boundaries

The "Coexistence" approach involves humans and cobots working in the same space but with clear divisions to separate their areas. This method is widely used in many industries. For example, in car manufacturing, cobots handle repetitive tasks like screwing and moving parts, letting human workers focus on making adjustments and checking quality. In electronics, cobots precisely place components on circuit boards while humans do the soldering and quality checks.

Also, cobots can be found in coexistence interaction with humans in other crucial fields. For instance, in the pharmaceutical and medical device industries, cobots help with packaging, labelling, and handling samples, while humans oversee and carry out more complex tasks. The food and beverage sector uses cobots for packaging, sorting, and quality control, which helps reduce repetitive strain on human workers. In consumer goods manufacturing, cobots assist with assembly, painting, and coating, leaving final assembly and customization to humans, or in logistics and warehousing, cobots help with picking orders, sorting, and distribution, freeing human workers to handle exceptions and ensure everything is accurate [13].

Despite these benefits, the "Coexistence" approach has its challenges. This setup can prevent both the robots and humans from fully using their skills and capabilities, potentially lowering the overall effectiveness of their collaboration. Balancing human and robotic roles is essential to make the most of both.

1.2.2 Synchronized Scenarios: Sequential Operations

In the Synchronized scenario, a human operator and a cobot work in the same space but at different times, either simultaneously in parallel or consecutively. In a parallel setup, the operator moves through the shared area, waiting for the cobot to finish its task before starting its own work. In consecutive order, the operator waits while the cobot work is done and then moves back to the workspace to continue on their own. For example, in welding applications, the operator waits for the cobot to complete welding so the workpieces can stabilize before the operator continues. This method allows for greater freedom of movement within the workspace, such as setting up equipment without needing safety barriers. However, it means that the human operator and cobot do not interact directly at the same time, requiring a sequential operation [13].

While this approach simplifies the system by avoiding the need for complex control mechanisms, it can lead to problems if tasks are not done in the correct order. Cobots follow specific patterns and might not handle tasks effectively if they are performed randomly, which can be an issue in jobs that require precision. Although this setup reduces the risk of direct collisions between humans and robots, it can still pose indirect hazards. For instance, in welding, workers might be exposed to harmful effects like UV radiation, fumes, and heat, which can cause skin burns, eye damage, or respiratory issues if exposure is prolonged [14].

To address these risks, it’s important to carry out a detailed risk analysis to ensure the safety of the sequential method. Understanding the risks associated with the working environment and equipment helps implement safety measures and avoid conflicts with the cobot. According to Shahar et al. [15], controlling the environment where humans and cobots operate together can limit potential dangers, ensuring the safety of workers. They also suggest using predictive maintenance to prevent accidents and reduce risks related to equipment. While this approach has its benefits, it may require more time and resources due to the added safety measures, potentially increasing overall costs compared to other interaction scenarios.

1.2.3 Cooperation Interaction

In the "Cooperation" scenario, a human operator and a robot work close to each other, performing different tasks simultaneously without needing to interact directly. For example, in a woodworking setup, the human might place a piece of wood while the robot cuts it. Once the cutting is done, the human moves the next piece into place while the robot continues its task. This arrangement allows the human to control the robot, adjust its settings, and manage multiple tasks simultaneously. However, this setup often requires a large workspace and a significant financial investment. While the cost for clients may be relatively low, the need for careful time management and the potential for delays due to manual data entry can be challenging. Additionally, there is a risk of collisions or damage in the shared workspace, but with proper precautions, these risks can be managed effectively [14], [15].

1.2.4 Fully Shared Interaction

In contrast, the "Fully Shared" scenario involves both the human and the robot working together in the same workspace, interacting closely to complete a joint task. Here, the human operator uses controls within the workspace to guide and adjust the robot's actions directly. This setup enables both the human and the robot to collaborate on a single goal rather than working separately. It offers flexibility by allowing the use of robots for various tasks without needing specific robots for each application, making it possible to automate a wide range of repetitive and time-consuming jobs [13].

Successful implementation of the Fully Shared scenario requires careful planning and extensive training. The operator’s skill level, the robot's capabilities, and the complexity of the tasks are crucial in reducing risks in a shared workspace. More training for the operator and a more advanced robotic system can lower the chance of accidents. However, it’s important to recognize that accidents can still happen, so ongoing safety measures and continuous improvements in both human and robotic performance are essential [15].

1.3 Safety in Human-Robot Interaction

1.3.1 The Importance of Safety

In the fast-changing world of industrial automation, integrating cobots into workplaces that are centered around human workers offers great potential for improving efficiency and productivity. As cobots become more common in various industries, it's crucial to focus on the safety of human workers who interact with these machines. It is obvious that cobots are totally different from traditional robots in terms of their design to work close to humans and sometimes even in the same workspace. Thus, this proximity brings its own set of risks, making it essential to implement strict safety measures to prevent accidents and injuries.

Ensuring safety in HRIs is vital not only to protect workers from physical harm but also to encompass psychological aspects as well. Workers must feel secure in their environments to maximize productivity and collaboration. Without proper safety protocols, the risk of accidents—such as collisions, exposure to dangerous materials, or operational mistakes—can negate the advantages of automation. Thus, safety is more than just a regulatory necessity; it's a key factor in the successful integration of cobots into the workplace. By ensuring that cobots operate safely alongside humans, we build trust in these systems, which encourages wider adoption and further innovation in the field [10].

1.3.2 Safety Standards and Regulations of Cobots

Clear standards and rules have been established to address the safety issues of collaborative robots. These guidelines make sure that cobots can work safely alongside human workers. A key standard is ISO/TS 15066:2016, which provides detailed rules for the safe use of collaborative industrial robots. It sets limits on things like force and speed to keep interactions safe and offers ways to check and reduce risks [8].

Another important standard is EN ISO 10218, which covers safety for all industrial robots but also includes parts specific to collaborative robots. It highlights the need for risk assessments to identify possible dangers and implement safety measures. This standard also mentions using safety devices like sensors and emergency stop buttons to prevent accidents [8].

In addition to these international standards, regional regulations are also important. For instance, the European Machinery Directive (2006/42/EC) and OSHA, also known as the Occupational Safety and Health Administration guidelines in the U.S., require cobots to undergo thorough testing and certification before being used in workplaces. Following these regulations is essential to ensure that cobots remain safe to use, even when reprogrammed or assigned new tasks [16].

1.3.3 The Sequential Scenario of the Welding Robot

Specific safety challenges arise in a sequential work setup where humans and robots share the same workspace but operate at different times. In this scenario, a human might first prepare or set up the workpiece, and then a welding robot takes over to complete the welding.

This approach may lower the chance of direct collisions because the robot and human do not work at the same time. However, it brings other risks. For example, welding creates UV radiation, high heat, infrared light, and fumes, which can be harmful if not properly controlled. Even if the operator isn't working directly with the robot while it welds, they can still be exposed to these dangers if the workspace isn't well protected. For instance, UV radiation is measured primarily in watts per square meter (W/m^2) or joules per square meter (J/m^2) and can be categorized into three types: UVA (320-400 nm), UVB (280-320 nm), and UVC (100-280 nm). According to the American Conference of Governmental and Industrial Hygienists (ACGIH), an average human can safely handle about 30 J/m^2 of UVB exposure per day, with varying exposure limits based on skin type and conditions [17]. Various sensors and devices are available to monitor UV levels in real-time, including handheld UV meters that provide direct readings, wearable dosimeters that track individual exposure, and environmental monitoring stations that measure UV radiation across broader areas. Ensuring safety is crucial in these contexts, as UV exposure poses significant health risks, including skin damage and increased cancer risk [18].

To ensure safety in this setup, both preventive and protective measures are essential. Preventive steps include scheduling tasks so that hazardous materials can dissipate and surfaces can cool before the operator returns to work. Protective measures involve using personal protective equipment (PPE) like UV-resistant clothing, gloves, and masks to guard against radiation and fumes. Proper ventilation is also crucial for removing harmful fumes, and barriers or shields should be used to protect workers from lingering heat and radiation [8], [19].

Continuous monitoring of the workspace is also important to detect and address any remaining risks. For example, sensors can measure hazardous fume levels and ensure surfaces are cool before human workers enter the area. By implementing these safety measures, the risks associated with using welding robots can be minimized, ensuring human operators stay safe while still benefiting from the efficiency of robotic automation [16].

In summary, while collaborative robots provide significant efficiency and flexibility, prioritizing human safety is crucial. Adhering to strict safety standards and implementing comprehensive safety measures—particularly in scenarios like sequential welding—helps create safer and more productive work environments where humans and robots can effectively collaborate.

1.4 Analyze Articles about the safety mechanisms used in HRI in welding applications

In the fast-changing world of industrial automation, making sure workers are safe while keeping things running smoothly is a top priority, especially in dangerous processes like welding. Welding robots have transformed production by boosting accuracy, reliability, and speed. However, bringing these robots into workspaces where humans are present creates significant safety issues that need to be managed to keep workers safe. This literature review looks at various research papers that discuss how welding robots are controlled and how this affects human safety. By exploring different methods of robot control, safety precautions, and their impact on production efficiency, this review offers a detailed look at current strategies used to protect human workers in robotic welding settings. It also examines whether control steps are taken into account when humans enter hazardous areas, emphasizing the crucial balance between advancing technology and maintaining workplace safety.

Based on the article "Safety Issues Concerning Installation of Welding Robots" [20], implementing safety measures is crucial for protecting humans working with welding robots. The article highlights the need for mechanical safety features and proper fencing around the robot's work area. This fencing helps prevent accidental human access and protects against physical injuries and harmful arc light. The article also mentions using testable software security applications to ensure that the robot operates safely. However, it does not provide specific details about how the robot should respond mechanically if a human enters the danger zone, focusing instead on preventive measures to avoid such situations.

On the other hand, in terms of efficiency, since there is fencing that forbids humans from getting hurt by the welding robot, which means there is somehow negligible interaction between the robot and human, the rate and the quality of the production can be affected in this case, Moreover, this paper does not address strategies or methods to optimize or maintain production efficiency. The primary focus is on preventing accidents and ensuring a safe working environment rather than on enhancing or sustaining production efficiency in the welding process.

Overall, the research in this paper leaves several important gaps related to production efficiency. By not addressing how to maintain or enhance efficiency in the welding process, it overlooks the crucial need to balance safety and productivity. Strict safety measures, such as extensive fencing and software restrictions, might lead to slower operation speeds and conservative robot capabilities, potentially decreasing production efficiency. This focus on safety can also result in increased cycle times and reduced productivity rates, which might lead to challenges in meeting production targets.

The article also points out that while comprehensive safety measures for welding robots are important, they can be expensive and might reduce production efficiency, leading to higher costs per unit and affecting profitability. It does not address the cost-benefit trade-offs between investing in safety and potential losses in efficiency and output. Additionally, strict safety protocols can limit flexibility, making it harder to adjust to new production needs or processes. Strategies are needed that balance both safety and flexibility for welding robots. The article also overlooks the importance of human-robot interaction and training, which are essential for optimizing both safety and efficiency. Effective training and clear interaction guidelines help operators make the best use of robots while maintaining safety standards. Furthermore, the article does not explore how advanced technologies like AI, machine learning, and IoT could improve safety and efficiency through real-time monitoring and adaptive control [21]. Addressing these aspects could lead to a more rounded approach to welding robot operations, ensuring worker safety while enhancing production efficiency and competitiveness.

The paper titled "Situational Awareness Oriented Interfaces on Human-Robot Interaction for Industrial Welding Processes" [22] analyzes the critical role of situational awareness

(SA) in human-robot interaction, particularly in industrial welding settings. It highlights the importance of designing interfaces that enhance operators' awareness of the robot's actions and the environment, thereby allowing for timely and informed decision-making to prevent accidents. The paper discusses various safety standards, such as ISO 12100 and IEC 61508, which provide guidelines for reducing risks through effective control strategies and clear safety procedures. It categorizes different levels of human-robot interaction, emphasizing that safety is crucial at all levels to ensure safe coexistence. Although the article does not detail specific automatic shutdown mechanisms when a human enters the danger zone, it stresses the need for proper situational awareness and interface design to enable operators to intervene quickly and prevent accidents. In essence, the focus is on preventing hazardous scenarios through enhanced awareness and control rather than detailing mechanical responses to human entry into dangerous areas.

Overall, by enhancing the interfaces that operators use to monitor and control the welding robots, the paper suggests that operators can more effectively manage the welding process, thus, it could hypothetically reduce downtime and errors. This improved oversight allows for more consistent and reliable operations, which contributes to maintaining a high rate of production efficiency. Additionally, the focus on adhering to safety standards ensures that the welding robots can operate continuously with minimal interruptions due to safety incidents, further supporting efficient production. However, the article does not provide specific metrics or detailed methodologies on how exactly these improvements translate into measurable efficiency gains in the welding process. The emphasis is more on the potential benefits of better situational awareness and safety for maintaining overall efficiency rather than providing concrete data or examples.

Furthermore, the method used in the research focuses on preventing accidents through better human supervision, but it might not cover how to respond when unexpected problems happen. Depending too much on human operators could cause problems like fatigue or mental overload, making SA less effective. Also, the article might miss out on using advanced safety technologies like real-time monitoring systems and AI for predictive maintenance, which could offer more proactive safety solutions. Concentrating mainly on avoiding risks could lead to overly careful operations, which might slow down production. Therefore, combining SA with automated safety features, advanced monitoring tools, and methods to improve production efficiency would likely offer a more balanced and effective approach.

The article "Survey on human-robot collaboration in industrial settings: Safety, intuitive interfaces and applications" [23] discusses safety aspects related to the control of welding robots in human-robot collaborative environments, with a focus on protecting humans from harm. It emphasizes the importance of integrating safety features into welding robots, such as sensors and real-time monitoring systems, which are crucial for detecting the presence of humans in the robot's working area and taking appropriate actions to prevent accidents. Moreover, the paper highlights the need for collision detection systems that can slow down or stop the robot's movements if a human is detected nearby, which implies that welding robots would likely react by slowing down, stopping, or altering their operations to avoid harm, but it does not offer explicit details on these actions. Furthermore, it underscores the importance of adhering to industry safety standards and implementing robust safety protocols, ensuring that robots are capable of responding appropriately to human presence to minimize risks.

In terms of efficiency, although the paper does touch upon the production process when using welding robots, it does not provide detailed guidance on how to maintain the rate of efficiency, specifically in the welding process. It generally discusses the benefits of using cobots in industrial settings, including welding, by highlighting their potential to enhance productivity. The article suggests that cobots can take over repetitive and hazardous tasks, allowing human workers to focus on more complex activities, which could lead to overall improvements in efficiency. However, the discussion lacks specifics on strategies or methods to optimize the welding process efficiency, such as detailed workflow integration, cycle time optimization, or the use of advanced welding techniques and technologies. The focus remains primarily on safety and the collaborative aspects of human-robot interaction rather than on detailed productivity optimization measures for the welding process.

Thus, by focusing mainly on safety without equally considering production efficiency, the article misses an important aspect of optimizing welding robots in industrial settings. This oversight can create several problems. First, it becomes challenging to balance safety and productivity. Overly strict safety measures, like frequently slowing or stopping robots, can slow down production, affecting output and profitability. Moreover, frequent safety-related interruptions can lead to downtime, disrupting the production line and causing inefficiencies. The article's lack of emphasis on efficiency also means missing opportunities to streamline workflows, reduce downtime, and make the most of collaborative robots. Neglecting efficiency can result in higher operational costs, as lower output might require more time and resources to meet production goals, increasing expenses for labor, energy, and maintenance. Finally, focusing too much on safety at the expense of productivity could put companies at a competitive disadvantage, as those who successfully integrate both safety and efficiency might produce higher-quality products more quickly and at lower costs. To tackle these issues, a balanced approach that considers both safety and efficiency is needed to optimize the overall performance of welding robots in collaborative environments.

The article titled "Toward Welding Robot With Human Knowledge: A Remotely-Controlled Approach" [24] mainly covers the development of a teleoperation system that lets a welding robot be controlled from a distance using human expertise. It focuses on how human welders can share their skills with the robot through a virtual interface and predictive control system, which improves the welding process's accuracy and efficiency. While this setup does provide some safety by keeping the operator away from hazardous conditions, the article doesn't specifically address safety measures for situations where a person might enter the robot's work area. It lacks a detailed discussion on safety protocols or how the robot should respond if a human enters its operational zone. Instead, the article concentrates on the technical improvements of robot performance through remote control without exploring the safety aspects of human-robot interaction in dangerous environments.

Therefore, by using a virtual interface and predictive control, the system ensures that the welding robot can perform tasks with precision and accuracy similar to that of a skilled human welder. This remote control setup not only reduces the chances of errors but also allows for continuous operation, as the robot can work without the need for breaks that a human would typically require. Additionally, the integration of human knowledge into the robot's operations helps to optimize welding techniques, reducing waste and improving the quality of the welds. Thus, the article suggests that this approach can lead to significant improvements in production efficiency as it combines the precision and endurance of robots with the expertise and decision-making abilities of human operators.

Unlike the previous papers, this research significantly enhances the precision and efficiency of welding processes by integrating human expertise with robotic capabilities. However, there are notable gaps and challenges that it does not fully address, particularly concerning maintaining safety and optimizing production rates. In terms of safety, the article lacks detailed safety protocols to handle situations where humans might inadvertently enter the robot's operational danger zone. In industry, depending only on human-shared knowledge is not enough; hands-on work is crucial for achieving smooth, flexible operations. Regarding production efficiency, the article focuses on improving the precision of the welding process but does not address scalability and adaptability. The teleoperation system's reliance on continuous input and oversight by skilled human operators may limit scalability in high-demand production environments. It also overlooks strategies for minimizing downtime or addressing reliability issues, which are critical in industrial settings where any malfunction or recalibration needs could lead to significant production delays. Challenges include integrating advanced safety features such as real-time monitoring and collision detection, balancing human and robotic contributions to avoid over-reliance on human intervention, and managing the training and skill requirements needed for effective teleoperation. Addressing these gaps by implementing comprehensive safety protocols, optimizing the balance between human and robotic tasks, and ensuring system reliability will be crucial for the broader adoption of such systems.

Continuously on the same pattern, the article titled "Virtual reality human-robot collaborative welding: A case study of weaving gas tungsten arc welding" [25] explores the use of a virtual reality (VR) system that enables human operators to remotely control welding robots. This system leverages VR to combine the cognitive abilities of human operators with the precision of robots, creating a collaborative and safe working environment. By using VR, the human operator can guide the welding robot's movements along the weld seam through a motion-tracked handle without needing to be physically present in the hazardous welding area. This remote operation effectively acts as a safety measure, minimizing the risk of exposure to dangerous fumes, gases, and arc radiation. Overall, it implemented the primary safety strategy emphasizing the prevention of such risks by ensuring that the human operator remains in a safe, remote location while controlling the robot.

Based on the latter, the system merges human decision-making with robotic accuracy to improve welding tasks. It helps cut down on downtime caused by safety issues since operators can control and monitor the welding process safely from a distance, reducing the need for frequent stops. Moreover, the use of VR enables real-time adjustments and fine-tuning of the welding operations, leading to high-quality welds and steady production rates. Thus, the article indicates that this approach not only boosts safety but also supports a smooth and efficient workflow in welding, enhancing overall production efficiency.

While this research effectively highlights the advantages of using a virtual reality system for remote control of welding robots, ensuring both safety and efficiency, there are still potential gaps and challenges that it may not fully address, particularly concerning safety and efficiency. One significant issue is the real-time response and potential latency of the VR system. In high-precision tasks like welding, any delay can lead to errors, affecting the quality of the welds and posing safety risks if corrective actions are not timely. Additionally, some researchers declared that the reliance on this technology introduces concerns about system reliability, including software glitches, hardware malfunctions, or connectivity problems, which could disrupt workflow and impact efficiency. Another challenge lies in the human factors and operator training. The paper does not address the need for comprehensive training to ensure operators can effectively use the VR controls, nor does it discuss the potential for discomfort or fatigue from extended VR use, which could reduce both safety and productivity. Moreover, while the focus is on remote operation, the article does not discuss physical safety measures for scenarios where a human might inadvertently enter the danger zone, such as emergency stop mechanisms or automatic shutdown features to ensure maximum safety. Ergonomic concerns also arise with the prolonged use of VR headsets and controls, which could lead to strain or discomfort, further affecting efficiency over time. Lastly, the article does not delve into the challenges of integrating the VR-based control system with existing welding equipment and processes, such as compatibility with different types of welding robots, interoperability with other automation systems, or necessary infrastructure modifications. Addressing these gaps by focusing on real-time reliability, operator training, safety protocols, ergonomic design, and seamless system integration is essential to fully realize the benefits of VR-controlled welding robots in ensuring both safety and efficiency.

1.5 Conclusion

The reviewed literature offers important information about the use of welding robots, with an emphasis on improving safety and efficiency in industrial environments. Nonetheless, despite the credibility of these studies, they fall short in considering the development of a collaborative environment where control systems can enhance both safety and efficiency at the same time. This limitation leads to gaps in the literature, as individual studies often focus on one aspect at the expense of the other, resulting in an unbalanced perspective.

In the realm of welding manufacturing, it is crucial to maintain high production quality while ensuring the health and safety of workers. Collaborative robots play a vital role in this balance, as they are designed to work alongside humans without the need for restrictive barriers. Their ability to move freely and adapt to different tasks enhances both operational flexibility and safety. Despite these advantages, existing studies do not fully explore how to implement these cobots in a way that maximizes both safety and production efficiency.

My research aims to address this gap by focusing on a novel approach that has not been extensively covered in the existing literature. In particular, I developed a virtual barrier—an innovative safety mechanism that dynamically adjusts to human presence, ensuring protection without compromising efficiency. Unlike physical barriers or conventional safety measures, this virtual barrier provides real-time adaptability, responding instantly to potential risks while maintaining seamless workflow continuity. None of the reviewed studies or previous research has implemented such an approach, making this a pioneering contribution to the field. By integrating this virtual barrier within new control mechanisms, my research ensures both human safety and high levels of production efficiency, contributing to a more integrated understanding of how welding robots can be effectively used in collaborative environments. This groundbreaking approach has the potential to significantly advance the field, providing a comprehensive solution to the dual challenges of safety and efficiency in robotic welding applications.

2 RISK ASSESSMENT OF INDUSTRIAL COLLABORATIVE WELDING ROBOTS

2.1 INTRODUCTION

Prejudging potential risks has become essential, focusing research on guidelines from the current international standards for risk assessment and management to avoid negative outcomes that could lead to serious consequences. The principle of industrial safety management involves studying, analyzing, and organizing enough data to boost each enterprise's productivity. This approach allows the formation of one or more hypotheses to make quick, effective decisions to maintain ongoing control of current risk factors while ensuring continuous production. This strategy helps manage and control the organization's various production lines and risk levels, as well as monitor and manage real-time safety checks. Regularly checking the effectiveness of this strategy is critical to reducing emergencies and preventing human-caused crises [16], [26].

Moving to the field of robotics, especially collaborative robotics, human beings work with robots in a common environment in order to accomplish tasks immediately and optimally. It is most likely obvious that it is necessary to add safety measures above imitation [27]. The tests carried out on this workstation over the years have shown that this complete combined format yields gains in terms of productivity and quality, however, the possibility of risks such as collisions cannot be denied due to the removal of barriers that can lead to human and material disasters, so the robots must be subject to strict safety standards and controls in which Asimov's three laws are preserved, which is that the robot should not harm humans or remain silent about what may cause harm to them, it must obey human orders unless it contradicts the first law, and finally, it must maintain its survival and ensure the safety of other robots in case of an interaction between them, as long as it does not conflict with the first and second laws [28].

The international standard ISO 10218 outlines safety requirements for robot-human interaction and cooperation, while the use of collaborative robots in industry must comply with ISO 15066 safety standards and certification. These standards are widely used in contexts where humans and robots coexist, but their use in more collaborative settings is still being explored and developed by manufacturers for sensor-equipped robots or intelligent virtual control systems. Furthermore, these standards prioritize safety measures related to risk assessment strategies, such as robot speed, energy, effort, and distance to operators [29].

The principle of "power and force limitation" is a type of safety control mode defined by the ISO/TS 15066 standard [30], which is suitable for robotic solutions requiring direct cooperation between humans and robots. In these cases, the human operator works near the robot and may need to be in contact with it. Based on experience with pick-and-place tasks, it is crucial to set maximum strength limits according to different body parts, as specified by the ISO standard. Results have shown that adding more analysis and evaluation processes is necessary to reduce risks and ensure safety, as merely following ISO standards is not enough to prevent accidents. Therefore, risk analysis is vital to successfully implementing cooperative solutions [29].

One major application of human-robot interaction in industries is the welding robot, which has become increasingly important for its ability to quickly and easily weld metal objects [31]. However, several risks related to these robots need to be assessed. These risks may not be purely physical but could involve hazards caused by human attitudes and perceptions towards the robots. Factors like operation speed, safety mechanisms, and the presence of people near the workstation make using robots more dangerous than experienced welders [32]. Additionally, robots can endanger welders due to sudden movements that the welder is unaware of, leading to a higher likelihood of physical harm. A significant concern is when robots continue to operate, which causes accidents due to the welder's lack of awareness. This situation can result in the welder getting hurt if the robot suddenly stops or stops within striking distance [33]. This chapter will discuss risk and hazard assessments for welding robots, focusing on examining the hazards they pose by identifying and evaluating relevant risks, determining their likelihood, and suggesting measures to limit these risks.

2.2 Assessing the State-of-the-Art Welding Robotics: Potential Risks and Safety Challenges

2.2.1 Safety Standards and Risk Management

The use of welding robots, especially in collaborative settings, has become more common in industrial environments because of their ability to increase production, lower labour costs, and improve worker safety. These robots are designed to work alongside humans in shared workspaces, handling tasks that used to require manual labour. However, this interaction can introduce unique safety challenges that need to be carefully managed to prevent accidents and injuries.

Welding itself is inherently dangerous, exposing workers to hazards such as flying sparks, burns, falls, noise, dust, fumes, and toxic chemical exposure Figure 2. When welding robots are introduced into the workplace, these risks can be compounded by the mechanical actions of the robots, which can pose additional dangers if not properly controlled. Collaborative robots, under ISO 10218, are defined as robots designed for safe interaction with humans, but ensuring this safety requires stringent measures.

Figure 2: Common Welding Hazards and Safety Risks [34]

The safety of collaborative welding robots is governed by several key standards. ISO 10218-1 and ISO 10218-2 provide comprehensive guidelines for the design and integration of collaborative robots in industrial environments. These standards emphasize the need for safety control systems that enable controlled stopping and restarting of robot movements, ensuring that any malfunction or unintended movement does not result in harm [35], [36]. The American standard ANSI/RIA R15.06 aligns closely with ISO 10218 but includes additional specifications tailored to North American practices, offering guidelines for robot use and deployment in compliance with local safety norms [37]. ISO-TS 15066 further specifies the safety requirements for collaborative operations, detailing four distinct protective modes—safety-rated monitored stop, hand guiding, speed and separation monitoring, and power and force limiting. These modes are critical for ensuring that robots can interact safely with human workers without causing injury [38].

In addition to the physical safety features, collaborative welding robots must also comply with standards such as IEC 61508 [39], ISO 2859, and ISO 14701, which outline the safety requirements for designing, maintaining, and operating welding robots. These standards ensure that the robots are not only efficient but also reliable and safe for use in complex industrial environments [40], [41]. The risks associated with welding robots include mechanical hazards, heat radiation, sparks, chemicals, and electricity, all of which require rigorous safety protocols to mitigate.

Further safety standards like ISO 13849 and ISO 14048 specify requirements for the systems and environments in which welding robots operate, ensuring that both the robots and their surroundings are safe [40], [41]. EN ISO 12100 outlines general principles for risk assessment and reduction, which are essential for evaluating the safety of AI-controlled robots and the specific risks they may pose. These principles include assessing the robot's operational envelope, payload, and speed, as well as the potential forces that could be applied in case of a collision [8].

Compliance with established international and regional standards is essential to ensure the safety and efficiency of collaborative human-robot work, especially in high-risk environments like welding applications. A major automotive manufacturer successfully integrated ISO safety standards, such as ISO 10218-1/2 and ISO/TS 15066, to enhance workplace safety in its welding operations. By implementing automated safety protocols, the company equipped collaborative robots with power and force-limiting mechanisms, real-time hazard detection sensors, and emergency stop systems to prevent accidents. Additionally, the company redefined safety zones, using advanced laser scanners and vision systems to monitor human-robot interactions, ensuring that robots slowed down or stopped when workers were nearby. To further minimize risks, comprehensive worker training programs were introduced, educating employees on safety best practices, emergency response, and proper robot interaction. As a result, the manufacturer reported a 50% reduction in workplace accidents, leading to lower injury rates, reduced downtime, and increased productivity. This case highlights how integrating ISO-compliant automation, enhanced training, and strategic safety zoning can significantly improve workplace safety in collaborative welding environments.

Therefore, these standards provide comprehensive guidelines for designing, integrating, and operating robotic systems, focusing on risk assessment, functional safety, and human-robot interaction.

Therefore, by analyzing and comparing some crucial standards, the following Table 1 serves as a foundation for identifying the most relevant frameworks applicable to collaborative welding applications.

Table 1: Comparison between the most relevant collaborative welding application standards

Standard	Scope	Key Requirements	Applications in Collaborative Welding	Reference
ISO 10218-1	Safety requirements for industrial robots (design and construction)	Outlines mechanical and electrical safety requirements for industrial robots.	Ensures base-level safety of welding robots in an industrial setting.	International Organization for Standardization. (2011). ISO 10218-1:2011 Robots and robotic devices – Safety requirements for industrial robots – Part 1 [35].
ISO 10218-2	Safety requirements for robot systems and integration	Defines safety measures for the integration of robotic systems into the workplace.	Ensures safe installation and operation of collaborative welding robots.	International Organization for Standardization. (2011). ISO 10218-2:2011 Robots and robotic devices – Safety requirements for industrial robots – Part 2 [36].
ISO/TS 15066	Collaborative robots (cobots)	Specifies safety limits for human-robot collaboration, including speed, force, and separation distances.	Ensures human safety during welding tasks in shared workspaces.	International Organization for Standardization. (2016). ISO/TS 15066:2016 Robots and robotic devices – Collaborative robots [38].
ANSI/RIA R15.06	Industrial robot safety standard (U.S.-based equivalent to ISO 10218)	Provides detailed risk assessment guidelines and safety protocols	Supports compliance in North America, particularly for integrating	Robotic Industries Association (RIA). (2012). ANSI/RIA R15.06:2012 Industrial Robot Safety Standard [37].

		for industrial robots.	robots in welding.	
IEC 61508	Functional safety of electrical/electronic systems	Framework for designing safety-critical systems, including robotics.	Relevant for developing fail-safe electronic control systems in welding robots.	International Electrotechnical Commission. (2010). IEC 61508: Functional safety of electrical/electronic/programmable electronic systems [39].

While welding robots deliver high-quality joints with minimal human involvement, their potential dangers should not be underestimated. Risks such as electrical sparks, UV radiation, and the possibility of fire underscore the need to follow safety standards closely. Although some UV radiation is beneficial for vitamin D production, prolonged exposure to high-intensity UV light from welding can be very harmful. This type of UV radiation can lead to temporary vision loss. Long-term exposure to UV radiation can also increase the risk of cataracts, other serious eye conditions, skin burns, and, in severe cases, skin cancer.

These hazards underscore the critical need for protective measures, such as appropriate eye and skin protection, to safeguard workers. Even with proper safety protocols, human operators may face health issues from prolonged exposure to welding-related hazards such as UV light, noise, or fumes, which can lead to hearing loss, respiratory problems, and other health concerns. The cumulative effect of these risks reinforces the necessity of rigorous safety standards and continuous monitoring to protect the health and safety of workers in environments where collaborative welding robots are used.

As the use of collaborative robots in welding applications grows, manufacturers and operators need to follow comprehensive safety standards. Regularly updating risk assessments and adhering to established regulations are critical for managing the risks associated with these robots and ensuring a safe and productive working environment for all employees [21].

2.2.2 Identification of the safety zone of the welding robot

Identifying the safety zone of welding robots is a common need in manufacturing industries. The risk of a robot injuring a worker is unacceptably high, mainly because there are currently no reliable tools for pinpointing potential danger areas. Developing safe robots requires a complete understanding of the robot's abilities and limits. There's also a need for standardized, safe working practices and a shared understanding of the design features that make robots safer.

A safety zone is a part of the robot's workspace where it can operate without risking injury to the user. Understanding this is crucial for designing and developing a safe workspace. Identifying safety zones is a key step towards creating safe robots and effective working practices. Currently, this process relies on manual methods that are not always accurate. These methods include measuring physical dimensions, observing the robot, and analyzing its motion. As shown in Figure 3, OSHA suggests an approach to identifying safety zones based on geometric modelling and the physical characteristics of welding robots [21]:

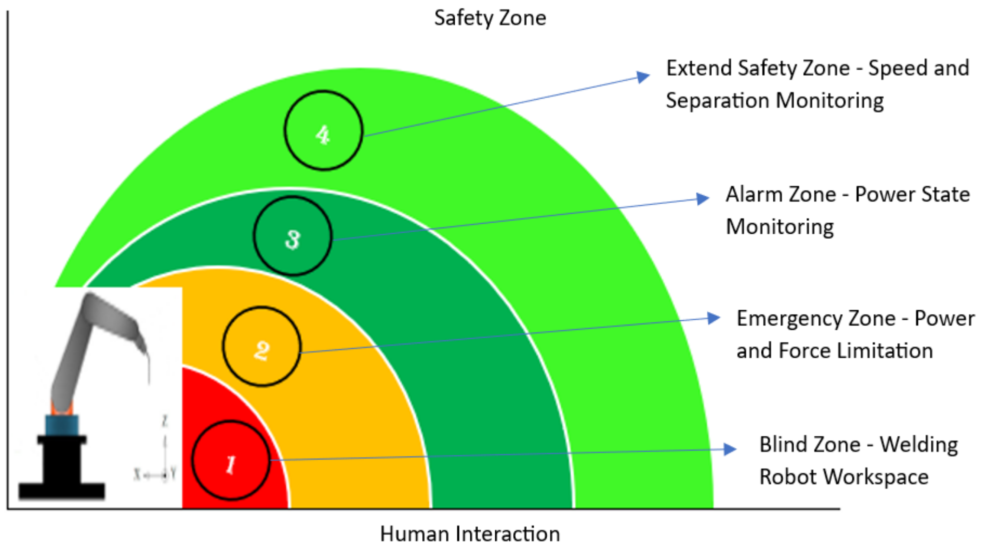


Figure 3: Safety zone identification of the welding robot [21]

A reliable tool is needed to properly assess the safety zone of welding robots and identify potential hazards within the workspace. According to research, several methods can be used to define the safety zone of welding robots:

1. Analysis of Welding Processes: Many studies have analyzed robot welding processes to establish safe working practices.

2. Measurements of Physical Dimensions: Tools such as laser distance meters and tape measures can measure the physical dimensions of the workspace and identify safe zones.

3. Observations of the Robot: By observing the robot in action, one can identify the points of contact between the robot and the parts being welded.

4. Analysis of the Robot's Motion: Different robotic welding machines have different movements, which can be analyzed to identify hazardous areas within the workspace.

In summary, the safest working practices can be identified by following the steps mentioned in Figure 3, where safety zones are drawn in three dimensions (2, 3, and 4) by a combination of these methods.

The dimensions 2, 3, and 4 identify the area of the safety where it can still be safe for human if they enter in one of them. Nevertheless, the dimmension 1 is the working space of the robot which is not safe at all if human enters it.

These procedures are useful in identifying hazardous areas that can be avoided, but they can also be improved and made more reliable by using advanced machine learning techniques such as artificial intelligence and machine learning to allow the robot to learn and adapt to its environment as it performs its tasks. However, these approaches are based on statistical analysis and do not take into account the uncertainties and variabilities in the welding processes and robot movements, which can lead to a large margin of error and unreliable results [21].

Welding robots are designed to increase welding efficiency and reduce human error. With the rise of automation, these robots have become increasingly popular in industrial settings. To maximize their benefits, better control systems and safer operating methods need to be developed. By using multiple control strategies, the safety zone of the robot can be modelled by specifying the robot’s workspace, defining the limits of permissible motion, and ensuring that the tool and workpiece trajectories stay within these limits.

One effective strategy for identifying and modelling the safety zone is based on the robot's force-velocity characteristics. This approach includes using virtual sensors to identify force and acceleration singularities and defining valid paths for tool motion.

Robotics is a specialized field within mechanical engineering. Traditionally, robotic systems have been controlled using electromecha nical or electronic systems that rely on sensor feedback. Modern advanced robotic systems use a combination of sensors and actuators to provide feedback and control. Commonly used sensors in industrial robots for end-effector position include proximity sensors like Linear Variable Differential Transformers (LVDTs) and rotary encoders. These sensors offer high accuracy but have a limited field of view and require significant power. Advanced systems use motion capture for absolute position measurement and real-time feedback, offering a full field of view with high accuracy and low cost. These systems also enable the use of computer vision techniques to track objects and adjust the end effector's position, which is valuable in environments like warehouses where precise object location is necessary.

In two experiments described in [42], a hybrid force/velocity control method was used at the contact point. This method functions even without a force sensor by quickly estimating the contact force. The results showed that this control method works consistently as long as the estimated force exceeds a specific limit. However, in some cases, such as intentional disconnection from the robot, the estimated force may drop below the required level. This finding highlights the importance of how humans and robots interact, creating a framework where tasks can be controlled based on force in one direction and speed in another direction.

2.3 Strategies for Mitigating Risks Associated with Welding Robots

Most welding robot hazards can be reduced through proper design and the implementation of effective safety protocols. One of the key strategies to consider is the implementation of a lockout/tagout (LOTO) procedure. This ensures that the operator cannot use the robot while it is being installed or serviced. The LOTO should include a separate set of controls and instruments specifically for the welding robot to prevent accidental operation. It should also come with a written procedure for implementation, with a designated person responsible for ensuring it is always followed correctly [43].

Another important strategy is to test the machine thoroughly before it is installed on the production line. However, testing alone may not guarantee safe and reliable operation, as human errors can still lead to accidents during interaction with the robot. To address this, internet-based training through 3D software can be used to provide a virtual environment where workers can learn how to safely and effectively operate the welding robot. This training helps workers understand their tasks better and avoid mistakes. Human involvement remains crucial for flexible and controlled welding operations, even when robots are synchronized. Operators must be well-versed in safety considerations, including proper equipment setup and the use of safety devices like pressure limits and emergency stop switches. All operators should receive thorough training before using the robots in a production environment to prevent unintended movements or startups during dangerous situations [43], [44].

All workers in the manufacturing process need to wear protective gear, such as hard hats and gloves, to protect against hazards like flying sparks, molten metal splashes, or intense heat. However, protective equipment alone is not enough, especially if workers are not adequately trained in its use. Therefore, clear guidelines must be provided to ensure adherence to safety procedures and minimize injuries. Workers should always wear metal fume goggles and suitable respirators to protect against weld fumes and dust. Adjusting factors such as operating temperatures and material compatibility according to the manufacturer's recommendations is also important. When multiple operators are present, teamwork is essential to ensure that all necessary safety steps are taken. Adopting safety standards such as ISO 11511 and OHSAS 18001 can help ensure that the plant meets industry safety requirements and best practices [45]. Figure 4 shows the most essential safety rules for a hazard-free workspace.

Figure 4: Essential Welding Safety Rules for a Hazard-Free Workplace

In addition to reducing risks to humans, it is also crucial to consider the quality of the work produced by the welding robot. For example, if a human accidentally interrupts the welding process and causes a defect in the product, this could indicate a need for design or mechanical changes to the welding robot, or it might point to errors in the welding procedure itself. Using computer programs to optimize the welding process and set the required welding parameters can help prevent such issues. However, welding robots have limitations in terms of the designs they can produce and the maximum size of the products they can handle, unlike human workers who can adjust to specific requirements and desired shapes [44], [45].

2.4 Conclusion

Critically analyzing potential workplace risks is crucial for any company. Evaluating hazards must follow established safety and security standards, prioritizing both equipment and human safety. In terms of collaboration, using collaborative robots often means removing barriers or safety partitions between humans and robots, which raises significant safety concerns.

The aim of this project was to assess the potential risks that welding robots pose to both people and the environment. After reviewing existing research on this topic, it was clear that there is a lack of information, prompting the study to fill this gap by conducting an initial analysis of the hazards and risks associated with welding robots using a qualitative approach. This approach highlighted certain gaps in the literature, such as the limited number of studies specifically addressing the use of robots in welding, the weaknesses in methodology and data in existing studies, and the lack of consensus on the acceptability of these devices.

Based on the available information and analysis in this study, welding robots can pose a significant risk to human health and safety, especially if they are not installed, maintained, or operated correctly. Therefore, it is essential to implement appropriate safety measures and procedures to reduce the risks associated with welding robots. Additionally, future research should aim to develop more comprehensive risk assessment methods that consider not only the physical hazards of welding robots but also their environmental impact and potential long-term health effects on workers.

3 DESIGN AND ANALYSIS OF A CONTROL SYSTEM FOR SAFE AND EFFICIENT HUMAN-ROBOT COLLABORATION IN WELDING APPLICATIONS

3.1 INTRODUCTION

Cobotics is a relatively nascent discipline compared to its counterparts in the scientific realm. At its core, a robot encompasses an amalgamation of technologies such as motors, sensors, and computing systems. A distinguishing aspect of cobotics lies in its dependence on technological advancements to conceive and explore novel applications. This inherent reliance injects an element of excitement into the field as it continually evolves in tandem with technological progress [46]. Undoubtedly, cobotics has achieved a level of maturity for welding tasks within various environments, a facet that the industry extensively leverages to bolster productivity.

The welding robot has control systems that reflect a significant evolution toward advanced automation and precision. Traditional control systems relied heavily on predefined trajectories and fixed parameters, limiting their adaptability to variations in welding conditions and workpiece geometries. However, recent advancements have revolutionized this landscape. Modern welding robot control systems incorporate sophisticated sensor technologies such as vision systems, laser scanners, and force/torque sensors, enabling real-time feedback and adaptive control. These systems utilize advanced algorithms, including machine learning and artificial intelligence, to optimize welding parameters and trajectories dynamically. Furthermore, cobots with advanced safety features have emerged as a prominent trend, allowing for human-robot collaboration in welding tasks [47]. Integration with cloud computing and data analytics facilitates remote monitoring, predictive maintenance, and continuous improvement of welding processes. Overall, the current state-of-the-art of welding robot control systems emphasizes flexibility, efficiency, and quality, paving the way for increased productivity and competitiveness in industries reliant on welding technology [48].

Traditional control methods in welding robot systems face several challenges that hinder their effectiveness in meeting the demands of modern manufacturing environments [47]. One significant challenge is their limited adaptability to variations in welding conditions, such as changes in material properties, joint geometries, or environmental factors like temperature and humidity. Traditional controllers often rely on predefined trajectories and fixed parameters, making them ill-equipped to handle the dynamic situations encountered in real-world welding applications. This rigidity can lead to issues such as poor weld quality, inconsistent bead profiles, and increased rework or scrap rates. Moreover, traditional controllers are unable to react to disturbances or anomalies in real-time during the welding process, leading to decreased productivity and efficiency. These methods also face difficulties in optimizing welding parameters for varying materials or techniques, resulting in less-than-optimal performance and higher operational costs. In conclusion, the limitations of traditional control approaches underscore the need for more adaptive, intelligent, and flexible control strategies for welding robots to effectively meet the complexities of modern manufacturing demands [49].

This chapter outlines the design of a control system for safe and effective human-robot interaction in welding. We first define the system's safety and performance requirements, followed by an overview of the control architecture, including sensors, controllers, and welding equipment integration. Key algorithms for motion planning and human-robot interaction are discussed, along with human detection and monitoring, to ensure safety.

3.2 System Requirement

The System Requirements section provides a comprehensive breakdown of the essential features that a control system must meet for safe human-robot collaboration in welding. These requirements include safety, performance, functionality, and usability aspects, which will guide the design and development of the system. This subsection will lay the foundation for understanding the architecture of the control system and its components.

3.2.1 Safety Requirements

Safety is a critical consideration in human-robot interaction, especially in hazardous environments such as welding. The control system must ensure that the robot operates in a manner that minimizes the risks to human workers and ensures their safety at all times.

- Human Detection and Proximity Awareness:

The control system must incorporate advanced sensing technologies, such as cameras, LIDAR, infrared, or ultrasonic sensors, to detect human presence within the robot's workspace. These sensors must continuously monitor the environment in real-time, enabling the system to track the location and movement of humans around the robot [50].

- Safety Zones and Robot Behavior:

In general, a key aspect of human detection feature is the establishment of distinct safety zones around the robot:

a) Free zone where normal operation is allowed,

b) A warning zone where the robot normally slows down to reduce the risk of injury,

c) Critical zone where the robot halts immediately to prevent collisions.

The system must ensure that the detection of humans and the corresponding robot response occur with minimal delay to mitigate risks effectively. Additionally, the detection and proximity system must be robust, work under various environmental conditions, and be capable of integrating data from multiple sensors to ensure redundancy and accuracy. This real-time, adaptive system enables safe and efficient collaboration between humans and robots in welding tasks, reducing the risk of accidents and maintaining productivity [21].

- Emergency stop mechanism

This mechanism must be designed to immediately halt the robot's operations when a safety breach occurs, such as a human entering a critical zone or a system malfunction. The emergency stop can be triggered by a controller system, manually by a human operator through accessible buttons, or remotely via a user interface. Additionally, the system must incorporate an automatic stop feature, which is activated when the control system detects a hazard, such as a sensor failure, unexpected object proximity, or sudden human movement in the robot's path. The system's response time is critical, with the robot required to cease all operations within 100 milliseconds of detecting an emergency condition to prevent harm. The emergency stop mechanism should be fail-safe, meaning that even if the system loses power or communication, it defaults to a safe, non-operational state. This redundancy ensures the system can handle unexpected events and guarantees the highest level of protection for human workers in the robot's vicinity [51].

- Compliance with Safety Standards

The control system must adhere to internationally recognized safety guidelines, such as ISO 10218 for industrial robots and ISO/TS 15066 for collaborative robots, which provide comprehensive frameworks for safe operation in shared workspaces. These standards define specific requirements for risk assessment, safe robot speeds, force limitations, and emergency stop mechanisms in environments where robots and humans work closely.

Additionally, the system must implement strict safety protocols, such as establishing defined safety zones, limiting robot speed and force based on proximity to humans, and ensuring real-time human detection and response. Verification of compliance is essential and should involve rigorous testing, including simulations and real-world trials, to confirm that the system's performance aligns with safety standards. Furthermore, documentation must be provided to demonstrate that the system meets all necessary regulatory requirements for welding and collaborative robotics, ensuring legal and operational safety in industrial applications. This adherence not only mitigates risks but also enhances trust in human-robot interaction by adhering to globally recognized safety benchmarks [10], [21].

3.2.2 Performance Requirements

The performance requirements of the control system focus on its ability to operate effectively in dynamic, real-world conditions while maintaining high levels of precision and safety. These requirements are critical to ensuring that the system can handle the complexities of human-robot collaboration in welding tasks without compromising performance. The key elements of performance include real-time control, precision and accuracy in welding, and robustness with fault tolerance.

- Real-Time Control

In a collaborative human-robot environment, especially in welding, real-time control is essential for maintaining safety and productivity. The control system must process data from various sensors (such as those monitoring human presence, robot motion, and the welding process) and react instantaneously to changes in the environment. The system needs to detect human presence, predict movements, and adjust robot actions in milliseconds to ensure safety. To meet this requirement, the control loop latency— the time taken to detect a change, process it, and adjust the robot's behaviour—must be kept to a minimum, ideally below 100 milliseconds. This responsiveness ensures that the robot can dynamically adjust its speed, path, and force to avoid collisions, react to human inputs, and synchronize seamlessly with the welding equipment in real-time. Any delay in control could result in safety risks or reduced efficiency, making real-time processing a critical requirement [52].

- Precision and Accuracy in Welding

Given the intricate nature of welding tasks, precision and accuracy in robot movements are vital for achieving high-quality welds while ensuring the safety of nearby human operators. The control system must be capable of guiding the robot with a high degree of spatial precision, ensuring that the welding tool follows the designated path accurately, even when human workers are interacting with or near the robot. The system should maintain a positional accuracy of less than 0.5 mm to prevent deviations that could compromise the weld quality or create safety risks. This precision becomes even more critical when performing detailed or complex welds in close proximity to human workers, where even minor errors could lead to safety hazards or defects in the welding process. In addition to precision, the control system must ensure consistent welding performance across different materials, task complexities, and environmental conditions, maintaining high-quality outcomes while allowing for real-time adjustments based on human interaction [53].

- Robustness and Fault Tolerance

To ensure continuous, safe operation, the control system must exhibit robustness and fault tolerance, allowing it to handle unexpected failures or changes in the operating environment without compromising human safety or task performance. The system should be designed to detect and respond to faults such as sensor malfunctions, communication breakdowns, or hardware failures. In the event of a fault, the control system must immediately switch to a safe operational state, such as reducing speed, stopping the robot, or activating emergency stop mechanisms. Redundancy is also crucial in ensuring fault tolerance—multiple sensors and safety mechanisms should be in place to provide backup functionality in case one component fails. For example, if a primary sensor fails to detect a human, a secondary sensor should take over to ensure safety. Furthermore, the control system should be able to operate effectively in different environmental conditions, such as changes in lighting, temperature, or workspace clutter, without degradation in performance. The ability to manage these contingencies ensures that the system remains reliable and safe, even under challenging conditions [54].

3.2.3 Functional Requirements Content

The functional requirements define the essential capabilities the control system must have to enable seamless, efficient, and safe collaboration between humans and robots in a welding setting. These features include path planning, collision prevention, adaptive human interaction, integration with welding equipment, and multitasking. Together, these capabilities ensure that the system not only fulfils its operational objectives but does so in a flexible, secure, and adaptable manner suitable for real-world scenarios.

- Robot Path Planning and Collision Avoidance

The robot must navigate a shared workspace where humans and objects are present, and its movements should be calculated to avoid any potential collisions. The system should utilize dynamic path-planning algorithms that can adjust the robot's trajectory in real-time based on sensor inputs, ensuring that the robot can move efficiently while avoiding obstacles and humans. This is especially important in welding tasks where precision in movement is crucial, and collisions could result in dangerous situations or task failure. The system should be able to predict potential collisions based on the speed and proximity of nearby objects or people and adjust the robot's speed and path to mitigate risks. The control system must also manage tight spaces and intricate welding tasks, ensuring that the robot moves smoothly along predetermined paths while adjusting to real-time changes in the environment, such as a human worker approaching [55].

- Adaptive Human-Robot Interaction

The system must support adaptive human-robot interaction, allowing the robot to respond intelligently to human presence, actions, and inputs. This means the robot should detect humans and adapt its behaviour based on their proximity and actions. For example, if a human operator gives a gesture or moves closer to a specific part of the welding area, the robot should be able to adjust its actions accordingly—either slowing down, changing its position or modifying the welding process to accommodate the human's movements. This adaptability enhances collaboration by making the robot more responsive to the needs and safety of human workers. The system should also incorporate mechanisms for real-time feedback, where the robot communicates its intentions or status to the human worker through visual or audible signals, reducing the likelihood of miscommunication or accidents. This interaction ensures a seamless workflow where humans and robots can safely and efficiently work side by side [56], [57].

- Integration with Welding Equipment

The control system must manage not only the robot's motions but also the operational parameters of the welding tools, such as heat, speed, and precision, to ensure a consistent and high-quality welding process. The system should facilitate real-time communication between the robot and the welding equipment, enabling the robot to adjust its path or speed based on the welding tool's current status or feedback. For example, the robot might slow down its movements if the welding equipment indicates an issue like overheating or irregular material deposition. This integration ensures that the welding process is not only automated but also optimized for quality, with the robot and welding tools working in harmony. Moreover, the control system should support various types of welding equipment, allowing for flexibility in different welding techniques (e.g., arc welding, spot welding) and materials [56], [58].

- Multi-tasking capabilities

In addition to handling welding operations, the control system must exhibit strong multi-tasking capabilities, enabling the robot to perform several functions simultaneously without compromising safety or performance. For instance, the robot might be required to weld while monitoring human presence, adjusting its path based on sensor inputs, and maintaining synchronization with the welding equipment—all at the same time. The control system should be designed to manage these concurrent tasks, ensuring that safety functions (such as human detection and collision avoidance) are prioritized while other tasks, like welding precision and path optimization, continue smoothly. The ability to multitask is crucial in collaborative environments where the robot needs to interact with both humans and complex machinery, handling multiple variables in real time. This functionality enables the robot to be both efficient and flexible, capable of handling dynamic work conditions without sacrificing performance or safety [58], [59].

3.2.4 Ergonomics and Usability

Ergonomics and usability are essential aspects of the control system, ensuring that human operators can interact with the robot in a safe, intuitive, and efficient manner. The design must prioritize ease of use, reduce the learning curve, and provide clear feedback to operators.

- User Interface (UI) Design

The control system must feature an intuitive and user-friendly "user interface (UI)" that allows operators to interact seamlessly with the robot. The UI should provide real-time information on the robot's status, including its position, speed, welding progress, and any safety alerts. It should be easy to navigate, even for non-technical users, with clear visual elements such as icons, graphs, and colour-coded indicators for different safety zones. The UI must also offer accessible control options, enabling operators to adjust the robot's behaviour, initiate tasks, or engage emergency stop functions as needed. The design should be adaptable to various platforms, such as touchscreens, handheld devices, or even wearable technology, ensuring that operators can interact with the system conveniently. Overall, the UI must minimize complexity while providing all necessary controls and status updates to ensure safe and efficient human-robot collaboration [60].

- Operator Training and Interaction

The control system should be designed to facilitate easy operator training and interaction, ensuring that even non-expert workers can quickly become proficient in working with the robot. The training process should be straightforward, with clear, step-by-step instructions that guide users through the system's functions, safety protocols, and emergency procedures. The system should include interactive training modes, allowing operators to simulate tasks or safety scenarios before working with the robot in a live environment. In terms of interaction, the robot should be capable of intuitive collaboration with human workers, where simple gestures or commands can trigger specific actions or adjustments in the robot's behaviour. The goal is to create a system that enables natural and fluid interaction, reducing the cognitive load on operators while maintaining safety and productivity. The training should be designed to take minimal time while ensuring that all safety and operational aspects of the system are clearly understood [51].

- Visual and Audible Feedback

Effective visual and audible feedback is crucial for ensuring that human operators are always aware of the robot's status and safety conditions. The control system should provide real-time visual cues, such as lights or on-screen indicators, to signal the robot’s operational mode, proximity to humans, or any potential hazards. For instance, color-coded lights (e.g., green for normal operation, yellow for warning zones, red for critical zones) can be used to communicate safety conditions at a glance. Additionally, the system should include audible signals, such as alarms or beeps, to notify operators of immediate safety concerns, system errors, or the activation of emergency stop protocols. This feedback should be clear, immediate, and easily interpretable by the operator, ensuring that even in noisy or visually cluttered environments, workers can quickly respond to any changes. By combining both visual and audible alerts, the system ensures a robust communication channel between the robot and its human collaborators, enhancing safety and efficiency [61].

3.3 Control Architecture

The control architecture forms the backbone of the collaborative human-robot system for safe welding applications. It provides a structured, modular approach to managing interactions between hardware components (robots, sensors, welding equipment) and software systems (control algorithms, human-machine interfaces). This section elaborates on the key components of the control system architecture, the communication protocols involved, and the integration of external devices to achieve the desired level of collaboration and safety.

3.3.1 High-Level Overview

The control system architecture is designed to manage multiple components and processes in real-time while maintaining safety and performance in collaborative welding environments. At the core of this architecture is a Central Processing Unit (CPU) or controller that coordinates the actions of the robot and welding equipment based on data from various sensors and human inputs. The system is organized into three key layers: the sensing layer, the control layer, and the execution layer. The sensing layer gathers data from human detection systems, environmental sensors, and robot status feedback. The control layer processes this data and makes decisions regarding robot movements, task execution, and safety measures. Finally, the execution layer handles the physical actions of the robot and welding equipment, ensuring that the robot behaves safely and efficiently during the collaborative welding process [62].

A diagram illustrating the system architecture can provide a clear visual representation of how these layers interact. The robot controller communicates with the welding equipment controller, the safety controller, and the human-robot interface through well-defined communication protocols. These connections allow the system to operate in real-time, ensuring that the robot can adapt to human presence and changes in the environment during welding operations.

3.3.2 Robot Controller

The robot controller is the central component of the control system, responsible for managing all aspects of robot motion and task execution. It receives inputs from the control algorithms that determine the robot's movements based on the current welding task and the location of the human collaborator. The controller ensures that the robot follows a pre-defined trajectory for welding operations while also adjusting in real time to avoid potential collisions with the human operator.

To achieve this, the controller uses a combination of path-planning algorithms and sensor data to dynamically adjust the robot's speed, direction, and force, ensuring both safety and precision. Additionally, the robot controller is designed to operate under constraints imposed by safety protocols, such as limiting the speed or force applied by the robot when a human is nearby. By integrating real-time feedback from sensors and welding equipment, the robot controller ensures continuous monitoring and adaptation to the evolving workspace environment [63].

3.3.3 Human-Robot Interface

The human-robot interface serves as the primary interaction point between the human operator and the control system. It allows human workers to communicate with the robot, issue commands, and receive feedback regarding the robot's status and intended actions. This interface must be intuitive and user-friendly to ensure that workers can easily understand the robot's behaviour and respond to any changes in the environment [60].

Nevertheless, it may incorporate visual feedback using displays or augmented reality systems, along with physical controls like joysticks or touch screens, allowing the operator to guide the robot or intervene during emergencies. Additionally, the interface could feature wearable devices, such as smart gloves or bracelets, that monitor the operator's movements and provide tactile alerts when they approach dangerous areas. By delivering clear and actionable information, the human-robot interface is essential for ensuring safe and efficient human-robot collaboration in welding tasks [64].

3.3.4 Communication Protocols

Reliable and real-time communication is essential for the smooth operation of the control system. Various components of the system, including the robot, sensors, and welding equipment, must continuously exchange data to maintain safety and efficiency during collaboration. The choice of communication protocols is, therefore, critical to ensure low latency, high reliability, and fault tolerance within the system [65].

In this control architecture, protocols such as Ethernet, CAN bus, and ROS (Robot Operating System) nodes are used to facilitate communication between system components. Ethernet or wireless protocols may be used for high-bandwidth data transfer between the robot and central controllers, while CAN bus can handle more localized communication between the robot and its internal sensors. ROS nodes allow for modular and scalable communication between software components, enabling the integration of various sensor inputs and control algorithms without the need for extensive rewiring [66], [67].

These communication protocols ensure that all components of the control system can respond in real-time to changes in the environment or human actions. In addition, redundancy mechanisms are often implemented to ensure that communication failures do not compromise safety. For instance, if one communication line fails, the system can switch to a backup protocol or stop the robot's movements entirely until the issue is resolved [65].

3.3.5 Integration of External Devices

The control system must also integrate seamlessly with external devices, particularly welding equipment, to ensure precise and synchronized task execution. Welding processes require precise timing and coordination between the robot and the welding machine, making integration a critical component of the system's architecture. This integration is typically achieved by linking the robot controller with the welding machine's control system through a dedicated communication interface [67].

The welding equipment must be able to send real-time status updates to the robot, including information about welding arc conditions, temperature, and the presence of any anomalies such as overheating. Conversely, the robot controller must synchronize its movements with the welding machine's operation, ensuring that welding occurs only when the robot is in the correct position and alignment. This bidirectional communication ensures that both the robot and welding equipment operate in harmony, reducing the risk of defects or safety hazards during the welding process [68].

In addition to welding equipment, the control system may need to integrate other external devices, such as safety sensors or environmental monitoring systems. These devices provide additional data that the system can use to make informed decisions about robot behaviour and human safety. By ensuring that all external devices are properly integrated, the control system can maintain a high level of safety and precision during collaborative human-robot welding operations [69].

3.4 Algorithm Development Content

The development of algorithms is central to the control system as it dictates how the robot will move, interact with humans, and perform welding tasks. These algorithms ensure that the system can respond dynamically to the environment and maintain safe collaboration while optimizing efficiency. This section presents the main algorithms that drive the robot's behaviour, focusing on path planning, human-robot collaboration, and the potential use of adaptive learning techniques [51], [70].

3.4.1 Path Planning and Motion Control

One of the key elements in collaborative human-robot workspaces, especially in welding applications, is ensuring precise and safe robot motion. Path-planning algorithms play a critical role in this context by guiding the robot's movements along predefined or dynamically generated paths. These paths must avoid obstacles, including humans while ensuring the robot's actions align with the welding task. The path-planning process typically involves algorithms such as Rapidly-Exploring Random Trees (RRT) or Probabilistic Roadmaps (PRM) to navigate complex environments. These algorithms ensure that the robot can reach its target position with minimal deviation while also dynamically avoiding moving obstacles, including humans.

In a welding environment, path planning must account for the spatial constraints imposed by the welding process, such as the robot's arm movement range, the workspace's geometry, and the precision required for the welding seam. Motion control algorithms complement path planning by ensuring that the robot follows its planned trajectory smoothly and accurately. These algorithms incorporate techniques like Proportional-Integral-Derivative (PID) control or Model Predictive Control (MPC), allowing for real-time adjustments to maintain safety and precision during welding operations. Moreover, they help minimize overshooting or drifting from the intended path, ensuring that the welding task is carried out with high accuracy.

3.4.2 Human-Robot Collaboration Algorithms

Human-robot collaboration algorithms are designed to facilitate real-time interaction between the robot and the human worker. These algorithms enable the robot to adjust its behaviour based on human actions, making the collaboration more natural and efficient. One crucial aspect of this is task sharing, where the robot and human may be working on different aspects of the same task or on separate tasks in close proximity. In welding applications, this might involve the robot handling heavy lifting and precise welding tasks while the human operator oversees quality control or manages components that the robot cannot handle.

To achieve this collaboration, algorithms must focus on shared control models, where both human and robot inputs are combined in decision-making processes. Techniques such as impedance control or force-based control can be employed, allowing the robot to respond to physical interactions initiated by the human worker. For example, if a human nudges the robot or physically redirects its motion, the control system can adjust the robot’s path in real-time without compromising safety. Additionally, gesture or voice recognition systems can be integrated into the collaborative framework, allowing humans to issue commands or provide feedback to the robot using intuitive methods, thus improving the overall workflow.

3.4.3 Learning and Adaptation

The introduction of adaptive learning mechanisms into the control system can enhance its efficiency and safety over time. Through Machine Learning (ML) or Reinforcement Learning (RL) Algorithms, the robot can learn from past interactions and continuously improve its performance in collaborative tasks. In a welding environment, adaptive learning could be used to optimize robot behaviour based on the particularities of each welding job or human worker's preferences. For instance, the robot could learn to recognize patterns in human movements and adjust its actions to better anticipate human intentions, reducing downtime and enhancing collaboration.

Reinforcement learning, in particular, is suited for developing intelligent control systems where the robot interacts with its environment to maximize a reward function. For welding, this reward could be based on factors like welding precision, task completion time, or safety compliance. The robot can gradually adjust its behaviour, learning which actions lead to better collaboration outcomes without compromising safety. In more advanced implementations, deep learning techniques could be applied for complex pattern recognition, such as predicting human gestures or identifying subtle variations in welding conditions that require adjustment in robot movements.

Moreover, these learning algorithms allow the system to adapt to environmental changes. For example, if the workspace layout or welding components change, the robot can adapt its path-planning and control strategies accordingly. This adaptability makes the control system more robust and scalable, ensuring that it can handle a variety of welding tasks and collaborative setups without requiring extensive manual reprogramming [49].

3.5 Integrating Human Detection, Monitoring, and Adaptive Control for Safe Collaborative Welding

The development of a robust and reliable control system is essential for ensuring both safety and efficiency in collaborative human-robot welding environments. Two key elements of such a system are human detection and monitoring and adaptive control. Human detection and monitoring utilize sensors and algorithms to track human presence and movement in real-time, enabling the robot to dynamically adjust its actions based on proximity. Technologies such as cameras, LIDAR, and infrared sensors define interaction zones that guide the robot's behaviour, helping to prevent accidents and promote smooth collaboration.

Adaptive control complements this by continuously optimizing the welding process and adjusting parameters based on real-time feedback. This not only improves the quality but also enhances human-robot interaction. By modifying the robot's actions in response to the human operator's movements and the welding environment, adaptive control ensures both operational safety and efficiency. Together, these technologies form the backbone of a safe and productive collaborative welding system, fostering a harmonious working relationship between humans and robots [51].

3.5.1 Human detection

Human Detection and Monitoring involves the use of sensors and algorithms to track human presence and movements in real-time, ensuring safety and efficient collaboration between humans and robots in shared workspaces. This process includes selecting appropriate sensors, developing tracking algorithms, defining interaction zones, and implementing real-time monitoring to adapt robot behaviour based on human proximity.

The following Table 2 summarizes the main points of each subsection, providing a quick reference for the key elements of human detection and monitoring:

Table 2: Main points of human detection subsection

Section	Key Points
Sensor Selection	- Use of cameras, LIDAR, infrared, and ultrasonic sensors for human detection.
	- Cameras for human gesture recognition, LIDAR for 3D mapping and proximity detection.
	- Infrared for low-visibility conditions, ultrasonic for short-range proximity.
Human Tracking Algorithms	- Algorithms for real-time human tracking based on sensor data (vision, LIDAR, etc.).
	- Deep learning for human recognition, predictive models for future movement.
	- Accurate multi-person tracking in collaborative welding tasks.
Interaction Zones	- Workspace divided into critical, warning, and free zones for dynamic safety management.
	- Critical zone: robot stop; Warning zone: robot speed reduction; Free zone: normal robot operation.
Real-Time Monitoring	- Continuous real-time data analysis for instant response to human movement.
	- Prevents accidents by dynamically adjusting robot speed and actions based on proximity.
	- Enables smooth human-robot collaboration through predictive and adaptive control.

3.5.2 Adaptive control in Welding

Adaptive control strategies in welding provide a dynamic approach to optimizing welding processes by continuously adjusting control parameters based on real-time sensor feedback and changing environmental conditions. These strategies allow welding robots to adapt rapidly to variations in workpiece geometry, material properties, and other factors influencing the welding process, thus improving overall process stability and robustness. By constantly monitoring key process variables such as arc voltage, welding current, and torch orientation, adaptive control systems can effectively compensate for disturbances and fluctuations during operations. This adaptability ensures that welding parameters remain optimized for specific conditions, resulting in enhanced weld quality and productivity.

Moreover, the incorporation of machine learning techniques and advanced sensing technologies, such as vision systems and thermal imaging cameras, further improves the adaptability and precision of these control systems by providing detailed feedback on the welding environment. In summary, adaptive control strategies mark a significant advancement in welding technology, offering the capability to produce consistently high-quality welds, increase efficiency, and reduce defects across a range of operating conditions.

Moreover, it is pivotal in optimizing the interaction between humans and welding robots, particularly in collaborative robotics or cobotics scenarios. In such setups, where humans and robots work together in shared spaces, adaptive control strategies are essential for ensuring safe and efficient collaboration. These strategies involve dynamically adjusting the robot's behaviour based on real-time feedback from sensors monitoring the human operator's movements, intentions, and safety. For instance, adaptive control systems can modulate the robot's speed, trajectory, and force exertion to prevent collisions or accidents, thus ensuring the safety of the human operator. Moreover, adaptive control allows the robot to adapt its behaviour to accommodate variations in the human operator's actions, preferences, and capabilities, enhancing the overall collaboration experience [71]. By continuously monitoring and analyzing the interaction between the human and the welding robot, adaptive control systems can optimize task execution, minimize errors, and maximize productivity. Additionally, adaptive control enables seamless switching between autonomous robot operation and collaborative modes, providing flexibility and versatility in various welding applications [72]. Overall, the use of adaptive control in optimizing human-robot interaction in welding environments not only enhances safety and efficiency but also fosters a more intuitive and harmonious working relationship between humans and robots [51]. Figure 5 illustrates the steps of controlling the welding robot to ensure not only human safety but also the quality of the production.

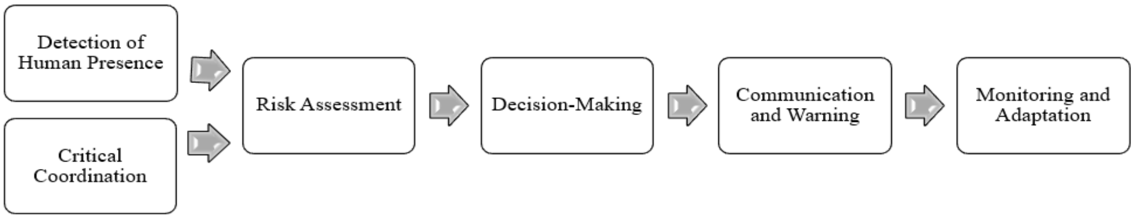


Figure 5: Safety and quality maintaining steps in welding robot controlling [49]

3.6 Conclusion

The current state of welding technology lacks extensive integration of advanced algorithms for optimizing parameters and identifying defects, which is evident from the limited accessible information. However, recent advancements have shown promising progress in utilizing neural networks to automate these processes, albeit in their early stages [47].

The application of machine learning in welding shows significant potential for progress, though further research and development are needed before implementation in industrial settings. Integrating machine learning into welding systems presents a valuable opportunity for advancement, offering improved parameter optimization and defect detection with greater precision and efficiency through the use of neural networks and other sophisticated algorithms. This automation potential could enhance productivity and weld quality and reduce reliance on manual adjustments and human inspection.

Based on this study, in the next chapter, we will simulate a developed intelligent control system that maintains not only the safety but also the efficiency of the welding application.

4 SIMULATION-BASED VALIDATION OF SAFETY AND EFFICIENCY IN HUMAN-ROBOT WELDING

4.1 INTRODUCTION

In the development of a control system for safe, collaborative human-robot work in welding applications, simulation plays a crucial role in evaluating and refining system performance before real-world deployment. Given the inherent risks associated with human-robot interaction in hazardous environments like welding, it is imperative to rigorously test the system's safety mechanisms, control algorithms, and collaborative efficiency in a controlled virtual setting. Simulations allow for the recreation of complex welding tasks, human movements, and robot responses, ensuring that all potential safety concerns are addressed before the system is implemented in an actual work environment [73], [74].

This chapter focuses on the use of simulation and modelling as tools to validate the proposed control system's effectiveness. The simulation process involves constructing a virtual environment that replicates real-world conditions, allowing the system to be tested under various scenarios, including different workspaces, robot movements, human interactions, and safety-critical situations. Key aspects such as human detection, proximity monitoring, robot path planning, and emergency stop mechanisms can be thoroughly evaluated in these simulated conditions.

The chapter will outline the simulation environment used, describe the modelling of the welding process, and provide an analysis of safety testing. The results from the simulations serve as an initial validation of the control system's performance, offering insights into its real-world applicability and identifying areas for further optimization. By providing a foundation for testing safety and collaborative workflows, simulation ensures the robustness and reliability of the control system before it is introduced into industrial welding applications.

4.2 Integrated control paradigm by enhancing welding robotics with operator Interaction and safety measures

A primary objective revolves around comprehending the operational behaviour of the welding robot, particularly in scenarios where an object, often a human, may inadvertently enter the robot's hazardous zone during its ongoing operation (Figure 6).

Understanding the intricacies of the robot's working mechanism is crucial for ensuring both safety and efficiency in industrial settings. In typical situations, potential risks arise when objects, including human operators, approach the designated danger zones while the robot operates. This necessitates a comprehensive understanding of the robot's response mechanisms and the implementation of effective safety measures to prevent accidents or injuries. By delving into the nuances of the welding robot's operational dynamics, engineers and operators can establish protocols and safeguards that mitigate risks associated with proximity to the robot during its active phases. This overarching goal aligns with the broader objective of creating a secure working environment where the welding robot seamlessly integrates with human activities without compromising safety standards. The continuous pursuit of this goal not only enhances the overall safety culture within industrial operations but also contributes to the optimization of the robot's performance in dynamic and potentially unpredictable workspaces [51].

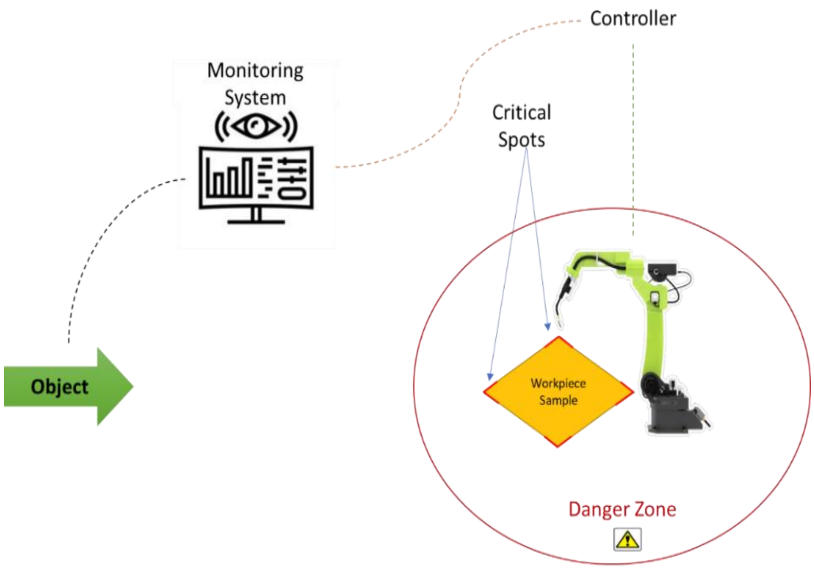


Figure 6: The general implementation of an object approaching the welding robot danger zone [51]

The implementation of the safety and quality requirement should pass as shown in the flowchart in Figure 7, where this system starts when a human comes closer to the danger zone. The monitoring system shall detect this action and provide an immediate response relative to the welding robot control system.

This manner could be included in the following setups:

1. The controller can press the "Stop" button.

2. The system checks if the robot works in a critical spot.

• If the robot is indeed working in a critical spot, it continues welding until it exits this spot, at which point it stops.

• If the robot is not working in a critical spot, it stops immediately.

3. If the operator doesn't press the "Stop" button, the robot continues welding.

4. An external emergency stop can be pressed at any time to trigger an immediate stop of the robot.

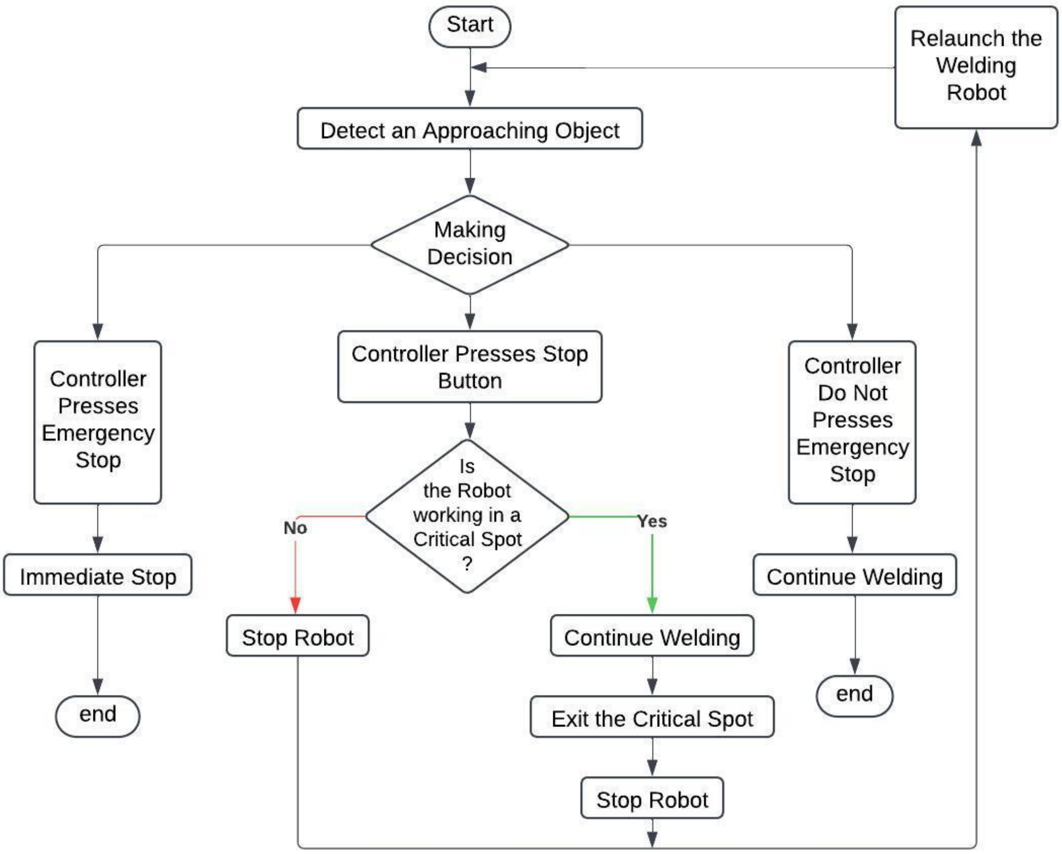


Figure 7: Flowchart of the decision-making process by the controller [51]

The presented flowchart outlines a comprehensive control system for a welding robot in an industrial environment, emphasizing safety, efficiency, and human-robot interaction. The clarity of the flowchart allows for a clear understanding of the decision-making process, showcasing the robot's immediate response to the operator's "Stop" button and ensuring prompt safety measures. Additionally, the flowchart illustrates the robot's intelligent behaviour in continuing welding when situated in a critical area, thus preventing production interruptions and optimizing the welding process. The incorporation of an emergency stop mechanism adds an extra layer of safety, ensuring the robot can be halted instantly in unforeseen circumstances.

Considering the potential integration of deep learning techniques into the fast and real-time control of the welding robot, several benefits and challenges should be considered. Deep learning algorithms can enhance the robot's decision-making capabilities by enabling it to learn and adapt to various scenarios, potentially improving its responsiveness to dynamic and complex environments. For instance, a deep learning model could be trained to recognize specific patterns or conditions in the welding environment and adjust the robot's behaviour accordingly.

However, the integration of deep learning into real-time control systems poses challenges. The process of training deep learning models typically demands substantial datasets and computational resources, and ensuring the safety and reliability of a deep learning-controlled system within an industrial context is paramount. The model must exhibit robustness to handle diverse operating conditions and possess the ability to generalize its learning to novel situations. The subsequent phases of incorporating deep learning techniques involve several key steps. First, comprehensive data collection and preprocessing are essential, encompassing various scenarios the welding robot may encounter. Subsequently, a deep learning model is developed and trained using the amassed dataset, implementing algorithms for real-time data processing and decision-making. The model's performance is rigorously evaluated through simulation and real-world testing, ensuring its accuracy and adaptability to dynamic conditions. Following successful validation, the model is seamlessly integrated into the existing control system. Robust safety measures, including fail-safe mechanisms and continuous system monitoring, are implemented to mitigate potential risks. The final steps encompass continuous optimization and fine-tuning of the deep learning model based on real-world performance, ensuring its adaptability to evolving conditions while maintaining a high level of accuracy [51].

By integrating deep learning techniques into the control system, the welding robot can potentially become more adaptive and intelligent, enhancing its overall efficiency and safety in dynamic industrial environments. However, careful consideration must be given to the challenges associated with training and deploying deep learning models in real-time control applications. Regular updates and improvements to the model, along with ongoing safety assessments, will be essential for successful implementation.

4.3 Intelligent Safety-Efficiency Control Scenario

To develop an effective Intelligent Safety-Efficiency Control Scenario, the first step is to identify the danger zone. In welding applications, the robot arm's operational zone- the area where the robot moves and performs tasks- can be considered the danger zone if it extends beyond the UV radiation area. In this situation, if a human enters this zone, the robot must stop immediately when the sensor detects its presence. The system prioritizes and achieves only safety without requiring risk assessment or critical coordination calculations. After stopping, the process must be restarted or resumed manually by the human operator.

Furthermore, in most industrial settings with welding robots, it's more common for the UV danger zone to be larger than the robot arm's operational zone. This is because UV radiation can spread widely during welding, covering a larger area than the arm's reach, which poses significant and serious harm, especially for prolonged exposure, to human health. One critical issue arises when a human inadvertently enters the hazardous UV zone of a welding robot during operation. Stopping the robot immediately may prevent harm, but it can also disrupt critical welding processes, as shown in Figure 8, resulting in production delays or material waste. The following study addresses the problem by developing an intelligent control system that prioritizes human safety while allowing for flexible decision-making based on the welding process and real-time risk assessment.

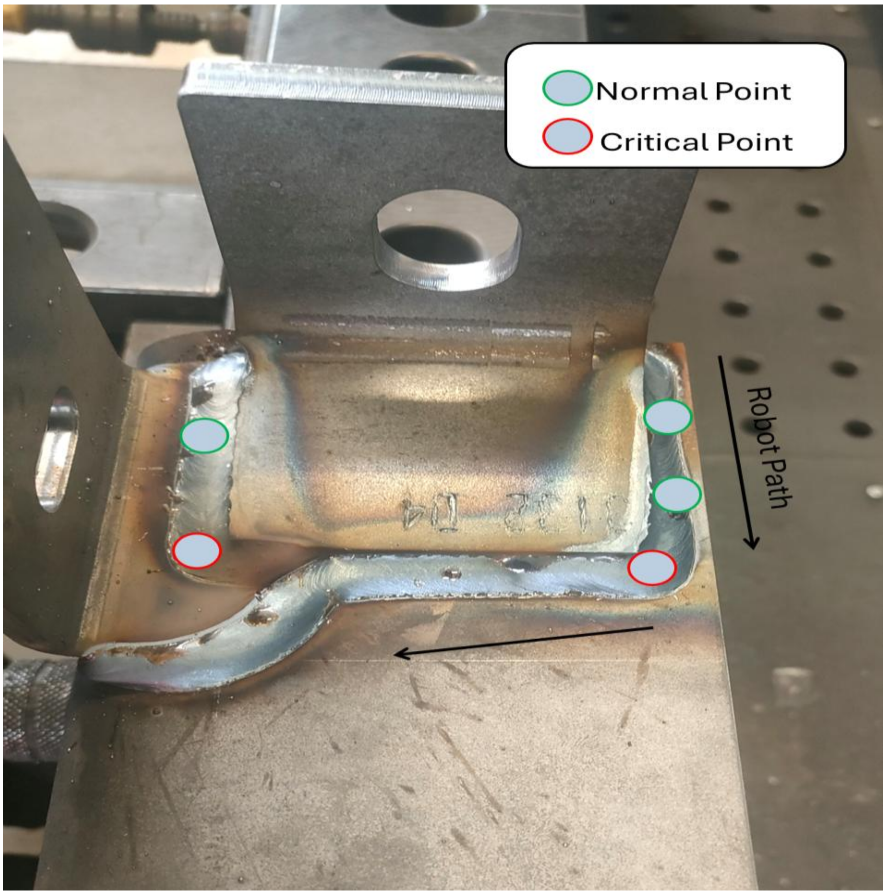


Figure 8: Workpiece with identification of critical and normal weld points

The annotated workpiece highlights the distinction between critical and normal points along the weld seam.

- Critical points (red): These are locations where welding must remain continuous to ensure metallurgical integrity and prevent defects such as cracks, porosity, or incomplete fusion. Any interruption at these points risks compromising weld quality and structural strength. Such zones typically correspond to corners, load-bearing transitions, or areas where heat distribution is most sensitive.
- Normal points (green): These are safer positions where the welding torch can pause or resume without negatively impacting the final weld quality. They often occur in relatively straight, uniform segments where localized thermal effects are less critical and the weld pool can be re-established consistently.

In relation to the decision logic of the control flowchart (Figures 7 and 8), the classification determines the robot's adaptive response when a human intrusion or safety event is detected. At normal points, welding can be safely paused and resumed once the workspace is secure, preserving operator safety without affecting efficiency. At critical points, however, the system prioritizes weld continuity, applying protective measures (e.g., maintaining a safety buffer or slowing the robot) to avoid interruptions that could degrade weld quality. This logic ensures that both safety and efficiency are dynamically balanced according to the welding context.This study [74] aims to advance human-robot collaboration in industrial environments, providing a balance between safety, efficiency, and productivity. Create a system that protects human workers, minimizes downtime, reduces material waste, and enhances workflow efficiency, offering a robust solution for integrating robots into hazardous workspaces such as welding applications.

In this research, we focused on the development of a safety-first control system for a collaborative human-robot working environment in welding applications. The system integrates Artificial Intelligence with a real-time monitoring and decision-making process, ensuring human safety while maintaining operational efficiency in the presence of unforeseen human intrusions in the UV zone generated by a welding robot. The goal was to balance safety, quality, and production rate by prioritizing human safety without compromising the welding process.

General Scenario:

The proposed system detects human presence in the UV zone of the welding robot, assesses the risk associated with the presence, and makes an intelligent decision based on the risk level and the stage of the welding process. The general scenario follows these steps [74]:

• Human Detection: The system detects when a human accidentally enters the dangerous UV zone.

• Risk Assessment: The AI system evaluates the risk to human health.

- If the risk level is unacceptable, the welding robot is immediately stopped, and the human is instructed to exit the zone, and for the next step and because the welding status in this case is unknown, it is necessary to relaunch or resume the process manually by human-operator who cooperate to evaluate the operated sample.

- If the risk level is acceptable, the system further evaluates the welding process.

• Welding Process Evaluation:

- If the robot is working at a normal point in the welding process (where stopping the process does not affect the quality), the robot is stopped, and the human is instructed to exit, in this case, since the workpiece is in known status, the next step, the robot will relaunch or resume the process automatically.

- If the robot is working at a critical point (where stopping the process could damage the sample), the robot continues welding. Simultaneously, warnings are issued to the human.

• Timeout Mechanism:

- If the human exits the UV zone before a preset timeout, the welding continues, and the robot moves to the next operation after finishing the current one.

- If the human remains in the zone beyond the timeout, the AI reassesses the risk level. If the risk level becomes unacceptable, the robot is stopped. If it remains acceptable, the robot continues the welding process.

The following presented workflow in Figure 8 ensures that safety protocols are followed while minimizing downtime or wastage during critical welding operations.

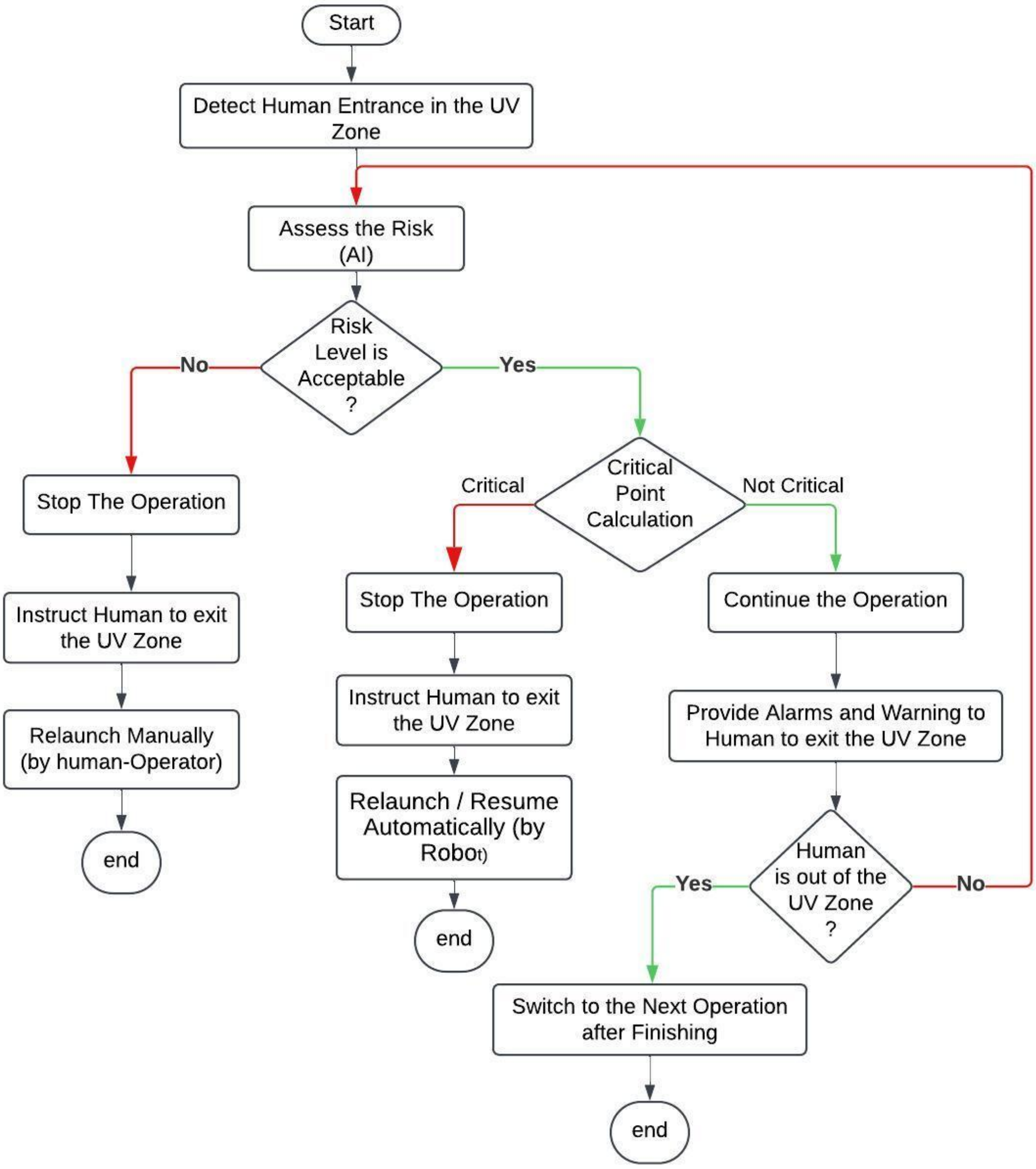


Figure 9: Figure: Workflow for Safety Control in Human-Robot Collaborative Welding Environments [74]

- The Python code for each scenario handles the decision-making logic using conditional checks, simulating the workflow discussed above. The system's operations depend on the real-time input from sensors (simulated in code) and the intelligent assessment by the AI module. Below is a brief explanation of the key components:

- detect_human_entry(): Simulates the sensor detecting a human entering the UV zone.

- assess_risk() / reassess_risk(): Simulates the AI evaluating the risk level based on various factors such as distance and exposure.

- determine_welding_point(): Identifies if the welding operation is at a critical or normal stage.

- does_human_exit_before_timeout(): Simulates the system waiting for the human to exit the dangerous zone.

- continue_welding() / send_stop_signal() / instruct_human_to_exit(): Functions that simulate the actual responses of the system based on the situation.

This simulation code ensures that all the potential scenarios are covered, where either the system stops the robot for safety reasons or continues the welding process when it is safe to do so.

To complement the simulation-based validation, a real-world experimental setup was developed in the laboratory environment to evaluate the proposed safety–efficiency control strategy. The setup consists of a collaborative welding robot, the workpiece, and the operator positioned outside of the designated risk area. In this configuration, the workspace is divided into two zones: the danger zone (UV intrusion zone), which surrounds the robot and welding torch during operation, and the operator zone, which represents the safe area where the human can stand without interfering with the welding process.

This visualization provides a direct mapping between the conceptual decision logic (Figures 7 and 9) and the physical experiment, ensuring that the system's responses to human presence are consistent with the simulated workflow.

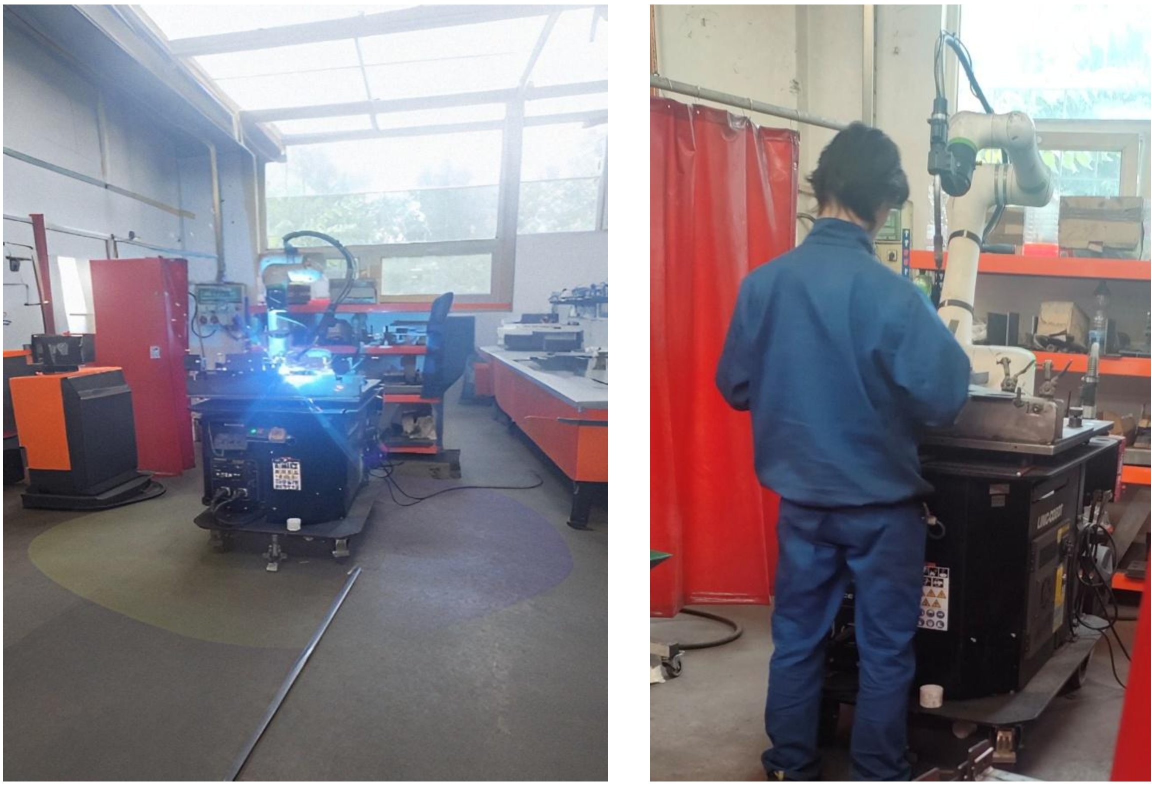


Figure 10: Real-world experimental setup illustrating the welding robot, operator position, and defined safety zones (danger zone and operator zone).

As shown in Figure 10, the danger zone highlights the area where both UV radiation and robotic motion pose risks, requiring immediate safety action when intrusions are detected. When the operator remains within the safe zone, the robot continues welding without interruption. However, if the operator enters the danger zone, the system applies the same logic as in the simulation: at normal weld points, welding is paused and resumes only once the area is cleared, whereas at critical weld points, welding continuity is preserved to avoid compromising joint integrity.

This experimental setup thus ensures a realistic validation of the proposed control strategy by demonstrating how safety and efficiency are dynamically balanced in practice. The results obtained from this setup are presented in the following section, where simulation outputs are compared with real-world performance indicators.

Results

The safety control system successfully demonstrates a flexible and robust decision-making process that guarantees human safety without significantly hindering the welding process. The integration of AI-based risk assessment with real-time monitoring provides an efficient solution to collaborative human-robot environments in welding applications.

Key Outcomes

- Safety First: The system prioritizes human safety in all scenarios, whether the risk is initially acceptable or not. The system ensures that if the risk level is unacceptable, the robot is immediately stopped.

- Efficiency in Critical Processes: For critical welding points where stopping would result in damage or waste, the system intelligently allows the robot to continue working while issuing warnings to humans.

- Adaptive Response: The system adapts based on real-time inputs and reassessments. If a human stays in the hazardous zone too long, the system re-evaluates the risk dynamically, ensuring continuous safety monitoring.

- Manual Control: After a safety stop, the robot can only be relaunched manually because the human operator decides whether the workpiece can be resumed or if it is already wasted, they need to launch another new operation.

- Automatic Control: After an efficiency stop, the current welding sample is at a normal stage where there is no need for human interaction to make the decision; instead, the robot relaunches the process by itself.

4.4 Conclusion

The research outlines a practical control system design for human-robot collaboration in welding applications, integrating real-time monitoring, AI-driven decision-making, and robust safety protocols. The Python code implementation successfully mimics the workflow, demonstrating the flexibility of the system under different risk scenarios. Future developments could integrate more advanced sensor technologies and AI models to further improve risk prediction accuracy and system reliability.

SUMMARY CONCLUSIONS

The use of collaborative robots in industrial welding has brought significant improvements in productivity, efficiency, and worker safety. However, ensuring a balance between safety and performance remains a challenge. This research focused on developing a real-time adaptive control system that integrates artificial intelligence (AI) and advanced sensors to implement a virtual barrier. The virtual barrier is an intelligent safety mechanism that replaces physical barriers while maintaining operational efficiency. This system provides a reliable solution for improving human-robot collaboration in welding applications by combining real-time monitoring, AI-driven decision-making, and adaptive control.

The key findings of this research confirm that an AI-driven control system significantly enhances worker safety without reducing productivity or weld quality. The virtual barrier prevents exposure to hazards such as UV radiation, excessive heat, and welding arcs, ensuring a safer work environment. The system dynamically responds to human movements, predicting and adjusting to potential risks in real-time. This proactive approach minimizes workplace accidents and improves overall operational stability.

One of the major contributions of this study is the optimization of welding parameters through adaptive control. By adjusting variables such as current, arc voltage, and torch orientation, the system ensures consistent welding quality, even when unexpected changes occur in the workspace. The use of machine learning models allows for continuous monitoring and improvement of safety measures, helping to prevent risks before they become dangerous. The combination of AI-based risk detection and real-time monitoring ensures compliance with industrial safety standards, making the virtual barrier a viable alternative to traditional safety methods.

The study emphasizes the significance of incorporating AI into quality assurance procedures. The virtual barrier not only ensures worker safety but also boosts the reliability of welding processes. Real-time defect detection and correction enhance production efficiency while minimizing waste. By continuously monitoring process data, the system helps sustain high-quality welds, which is crucial for industrial applications.

The findings of this dissertation have several broader implications. First, the proposed system introduces a more flexible and intelligent approach to workplace safety. Instead of relying on rigid physical barriers, manufacturers can implement AI-driven safety solutions that adapt to real-time conditions. This shift has the potential to influence future safety regulations and standards, leading to more advanced human-robot interaction frameworks. Additionally, the research contributes to the development of AI-driven robotics, paving the way for more intelligent and autonomous systems in manufacturing.

Despite its success, this study acknowledges some limitations. The computational demands of real-time AI processing can be high, which may affect system implementation in resource-limited environments. Additionally, the system has been tested in specific welding applications, and further research is needed to adapt it to different welding techniques and industrial scenarios. Future improvements could involve integrating the virtual barrier with physical safety measures creating a hybrid model for enhanced protection.

Future research directions should focus on enhancing AI capabilities for faster and more precise decision-making. Expanding the virtual barrier concept to other industrial applications, such as construction or medical robotics, could further validate its effectiveness. Integrating augmented reality (AR) for safety visualization and operator training could also improve worker awareness and response times. Additionally, large-scale industry testing will be necessary to refine the system and ensure its adaptability to real-world manufacturing conditions.

This dissertation has made significant contributions to the field of collaborative robotics in the welding area, industrial automation, and workplace safety. The development of an AI-integrated virtual barrier offers a new approach to protecting human workers while maintaining high welding performance. The results confirm that safety can be improved without sacrificing productivity, providing a foundation for future advancements in intelligent risk management systems. As industries continue to adopt automation, the insights from this research will help shape safer, more efficient, and more adaptive human-robot work environments.

New scientific results

Claim 1.

- **The intelligent virtual barrier system I have developed in this research ensures efficient collaborative robot welding without compromising the safety of human workers in its environment [7], [21].**

The intelligent virtual barrier developed in this research ensures efficient collaborative robot (cobot) welding without compromising the safety of human workers in its environment. This adaptive, AI-driven safety mechanism dynamically adjusts to human presence while maintaining welding quality and productivity. The virtual barrier is implemented through a combination of real-time sensor monitoring, AI-based risk assessment, and autonomous control strategies. It continuously scans the workspace, detects potential hazards, and activates appropriate safety protocols to prevent accidents such as UV radiation exposure, heat injuries, and physical contact with robotic components. The virtual barrier consists of several key components, including infrared sensors, depth cameras, proximity detectors, and AI-based predictive modeling algorithms. These elements work together to analyze the work environment and adjust the cobot's actions in real time. This innovative system eliminates the need for traditional physical safety barriers, thereby enhancing worker accessibility while maintaining a high level of protection in automated welding applications.

Claim 2.

- **The intelligent virtual barrier is an equivalent Alternative to Physical Safety Barriers in the cobot welding workplace [10], [51].**

The central scientific contribution of this dissertation is developing a real-time adaptive control system that integrates artificial intelligence and advanced sensors to implement a virtual barrier, ensuring a safer and more efficient collaborative human-robot welding environment. This research confirms that a virtual barrier—functioning as an AI-driven safety mechanism—can replace conventional physical barriers, ensuring synchronized collaboration while maintaining high productivity and welding quality. The system enhances safety by dynamically adapting to human presence and environmental variations, thereby establishing a novel framework for intelligent risk mitigation in welding applications.

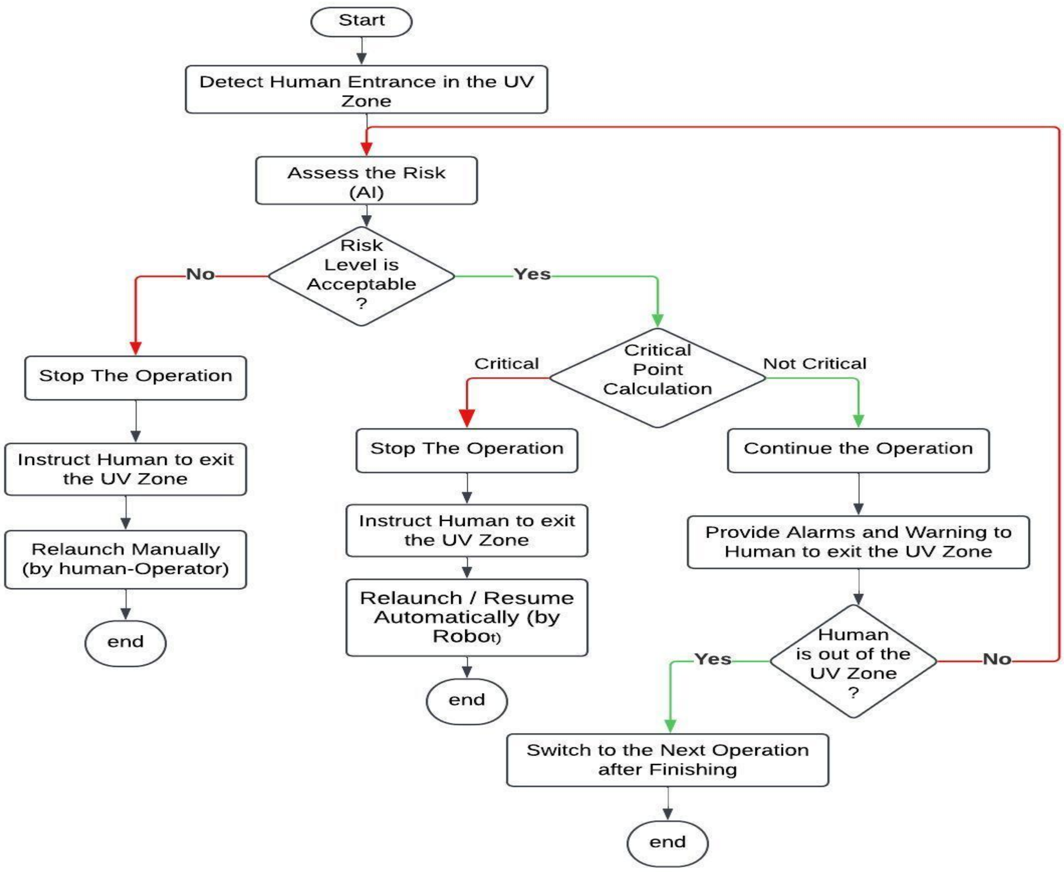
Claim 3.

- **By utilising real-time AI-driven monitoring, the system ensures precision in welding quality, even in the presence of environmental disturbances or human intervention [49], [70].**

Furthermore, experimental validation has demonstrated that the virtual barrier not only enhances safety but also directly contributes to weld quality assurance. The adaptive control strategy embedded in the virtual barrier continuously optimizes welding parameters such as arc voltage, current, welding speed, and torch orientation for a given shielding gas, ensuring process stability despite unpredictable disruptions. The control system's ability to optimize welding conditions while maintaining a responsive safety framework marks a significant advancement in adaptive robotic welding technologies.

Claim 4.

- **I developed an intelligent safety control system with AI, sensor technologies, and adaptive control for human-robot collaboration in welding, as submitted in the flowchart [49], [51], [74]:**



A key scientific result of this dissertation is the assertion that the fusion of AI-driven decision-making, advanced sensor technologies, and adaptive control strategies forms the foundation of an intelligent safety-assurance system for human-robot collaboration in welding. The virtual barrier, realized through this integration, continuously processes real-time sensory data to detect risks, predict hazardous conditions, and autonomously adjust welding parameters to preserve process stability and operator protection. This innovative approach effectively ensures that human workers remain safeguarded from welding hazards, not only UV radiation exposure but also heat and physical harm.

Summary

This dissertation establishes a conceptual and applied framework for implementing virtual barriers in collaborative welding environments, defining their properties, functional requirements, and effectiveness in enhancing both safety and process reliability. The integration of AI and sensor-based safety mechanisms within this framework introduces an advanced paradigm for intelligent safety systems, demonstrating their viability as an industry-ready alternative to traditional physical safeguards. The results of this research contribute to the evolution of human-aware, AI-assisted control systems, laying the groundwork for future innovations in industrial robotics and collaborative manufacturing. Thus, through these scientifically validated claims, this dissertation establishes a new standard in human-robot collaborative safety, redefining how AI-driven systems can enhance worker protection and welding efficiency in automated manufacturing environments.

Recommandation

- The intelligent control system I developed is highly suitable for industrial applications; however, further hardware and software innovations are required to enhance its efficiency and adaptability in diverse manufacturing environments.
- Expanding this intelligent control system to other high-risk industrial applications beyond welding, such as construction and healthcare robotics, could validate its effectiveness in broader collaborative environments.
- Future research should focus on reducing computational demands to make the system more feasible for industries with limited processing resources.
- A hybrid safety approach that combines physical and virtual barriers could be explored to further improve risk mitigation strategies in human-robot collaboration.

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LIST OF ABBREVIATIONS

Abbreviation	Meaning
HRC	Human Robot Collaboration
SMEs	Small and Medium Enterprises
UV	Ultraviolet
Cobot	Collaborative Robot
HRI	Human Robot Interaction
AI	Artificial Intelligence
OSHA	Occupational Safety and Health Administration
PPE	Personal Protective Equipment
IOT	Internet of Things
SA	Situational Awareness
VR	Virtual Reality
LVDTs	Linear Variable Differential Transformers
LOTO	Lockout/Tagout
UI	User Interface
CPU	Central Processing Unit
ROS	Robot Operating System
RRT	Rapidly-exploring Random Trees
PRM	Probabilistic Roadmaps
PID	Proportional Integral Derivative
MPC	Model Predictive Control
ML	Machine Learning Algorithm
RL	Reinforcement Learning Algorithm

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APPENDIX

The behaviour of the workflow for Safety Control in Human-Robot Collaborative Welding Environments presented in Figure 8 was modelled using Python. The scenarios outlined in the research were implemented as follows:

1. Scenario 1: The system detects a human, assesses an unacceptable risk level, and immediately stops the welding robot. The human is instructed to exit the UV zone, and the system waits for manual relaunch. The script is as follows:

```
#Python Code Scenaio 1:
def detect_human_entry():
    # Simulate detection of human entry in the UV zone : Return True if human is detected, False otherwise.
    return True  # Human is detected
def assess_risk():
    # Simulate AI assessing the risk level : Return True if risk level is acceptable, False otherwise.
    return False  # Risk level is not acceptable
def determine_welding_point():
    # Simulate determining if the welding point is normal or critical : Return True if welding at a normal point, False if at a critical point.
    return True  # This function will not be called in this scenario
def does_human_exit_before_timeout():
    # Simulate checking if the human exits the UV zone before timeout : Return True if human exits before timeout, False otherwise.
    return True  # This function will not be called in this scenario
def continue_welding():
    # Simulate continuing the welding operation.
    print("Welding continues.")  # This function will not be called in this scenario
def send_stop_signal():
    # Simulate sending a stop signal to the robot.
    print("Stop signal sent to the robot.")
def instruct_human_to_exit():
    # Simulate instructing the human to exit the UV zone.
```

```python
    print("Human instructed to exit UV zone.")
def wait_for_manual_relaunch():
    # Simulate waiting for manual relaunch of the robot.
    print("Waiting for manual relaunch.")
def wait_for_automatic_relaunch():
    # Simulate waiting for automatic relaunch of the robot.
    print("Waiting for automatic relaunch.")
def switch_to_next_operation():
    # Simulate switching to the next operation after finishing.
    print("Switching to the next operation after finishing")
def reassess_risk():
    # Simulate AI reassessing the risk level.
    print("Reassess the risk.")
def main():
    # Start of the workflow
    print("Workflow started.")
    if detect_human_entry():
        if not assess_risk():  # Risk level is not acceptable
            send_stop_signal()
            instruct_human_to_exit()
            wait_for_manual_relaunch()
        else:  # Risk level is acceptable
            if determine_welding_point():  # Welding at a normal point
                send_stop_signal()
                instruct_human_to_exit()
                wait_for_manual_relaunch()
            else:  # Welding at a critical point
                continue_welding()
                if does_human_exit_before_timeout():  # Human exited before timeout
                    continue_welding()
                else:  # Human did not exit before timeout, reassess risk level
                    if not assess_risk():  # Risk level is not acceptable after reassessment
                        send_stop_signal()
                        instruct_human_to_exit()
```

```python
                wait_for_manual_relaunch()
            else:  # Risk level is acceptable after reassessment
                continue_welding()
if __name__ == "__main__":
    main()
```

➢ Scenario 1 Response Result is as follows:

```
Workflow started.
Stop signal sent to the robot.
Human instructed to exit UV zone.
Waiting for manual relaunch.
```

2. **Scenario 2:** The system detects a human, assesses an acceptable risk level, and detects that the robot is working at a normal point. The robot is stopped, and the human is instructed to exit. The system then waits for automatic relaunch.

```python
#Python Code Scenaio 2:
def detect_human_entry():
    # Simulate detection of human entry in the UV zone: Return True if human is detected, False otherwise.
    return True  # Human is detected
def assess_risk():
    # Simulate AI assessing the risk level: Return True if risk level is acceptable, False otherwise.
    return True  # Risk level is acceptable
def determine_welding_point():
    # Simulate determining if the welding point is normal or critical: Return True if welding at a normal point, False if at a critical point.
    return True  # Welding at a normal point
def does_human_exit_before_timeout():
    # Simulate checking if the human exits the UV zone before timeout: Return True if human exits before timeout, False otherwise.
    return True  # This function will not be called in this scenario
def continue_welding():
    # Simulate continuing the welding operation.
```

```
    print("Welding continues.")  # This function will not be called in this scenario
def send_stop_signal():
    # Simulate sending a stop signal to the robot.
    print("Stop signal sent to the robot.")
def instruct_human_to_exit():
    # Simulate instructing the human to exit the UV zone.
    print("Human instructed to exit UV zone.")
def wait_for_manual_relaunch():
    # Simulate waiting for manual relaunch of the robot.
    print("Waiting for manual relaunch.")
def wait_for_automatic_relaunch():
    # Simulate waiting for automatic relaunch of the robot.
    print("Waiting for automatic relaunch.")
def switch_to_next_operation():
    # Simulate switching to the next operation after finishing.
    print("Switching to the next operation after finishing")
def reassess_risk():
    # Simulate AI reassessing the risk level.
    print("Reassess the risk.")
def main():
    # Start of the workflow
    print("Workflow started.")
    if detect_human_entry():
        if not assess_risk(): # Risk level is not acceptable
            send_stop_signal()
            instruct_human_to_exit()
            wait_for_manual_relaunch()
        else: # Risk level is acceptable
            if determine_welding_point(): # Welding at a normal point
                send_stop_signal()
                instruct_human_to_exit()
                wait_for_automatic_relaunch()
            else: # Welding at a critical point
                continue_welding()
```

```
        if does_human_exit_before_timeout(): # Human exited before timeout
            continue_welding()
        else: # Human did not exit before timeout, reassess risk level
            if not assess_risk(): # Risk level is not acceptable after reassessment
                send_stop_signal()
                instruct_human_to_exit()
                wait_for_manual_relaunch()
            else: # Risk level is acceptable after reassessment
                continue_welding()
if __name__ == "__main__":
    main()
```

- Scenario 2 Response Result is as follows:

```
Workflow started.
Stop signal sent to the robot.
Human instructed to exit UV zone.
Waiting for automatic relaunch.
```

3. **Scenario 3**: The system detects a human, assesses an acceptable risk level, and detects that the robot is working at a critical point. The robot continues working while warning the human. If the human exits the zone before the timeout, the robot continues welding.

```
#Python Code Scenaio 3:
def detect_human_entry():
    # Simulate detection of human entry in the UV zone : Return True if human is
detected, False otherwise.
    return True  # Human is detected
def assess_risk():
    # Simulate AI assessing the risk level : Return True if risk level is acceptable, False
otherwise.
    return True  # Risk level is acceptable
def determine_welding_point():
    # Simulate determining if the welding point is normal or critical : Return True if
welding at a normal point, False if at a critical point.
```

```python
    return False  # Welding at a critical point
def does_human_exit_before_timeout():
    # Simulate checking if the human exits the UV zone before timeout : Return True if human exits before timeout, False otherwise.
    return True  # Human exits before timeout
def continue_welding():
    # Simulate continuing the welding operation.
    print("Welding continues.")
def send_stop_signal():
    # Simulate sending a stop signal to the robot.
    print("Stop signal sent to the robot.")
def instruct_human_to_exit():
    # Simulate instructing the human to exit the UV zone.
    print("Human instructed to exit UV zone.")
def wait_for_manual_relaunch():
    # Simulate waiting for manual relaunch of the robot.
    print("Waiting for manual relaunch.")
def wait_for_automatic_relaunch():
    # Simulate waiting for automatic relaunch of the robot.
    print("Waiting for automatic relaunch.")
def switch_to_next_operation():
    # Simulate switching to the next operation after finishing.
    print("Switching to the next operation after finishing")
def reassess_risk():
    # Simulate AI reassessing the risk level.
    print("Reassess the risk.")
def main():
    # Start of the workflow
    print("Workflow started.")
    if detect_human_entry():
        if not assess_risk():  # Risk level is not acceptable
            send_stop_signal()
            instruct_human_to_exit()
            wait_for_manual_relaunch()
```

```
        else:  # Risk level is acceptable
            if determine_welding_point():  # Welding at a normal point
                send_stop_signal()
                instruct_human_to_exit()
                wait_for_manual_relaunch()
            else:  # Welding at a critical point
                continue_welding()
                if does_human_exit_before_timeout():  # Human exited before timeout
                    instruct_human_to_exit()
                    switch_to_next_operation()
                else:   # Human did not exit before timeout, reassess risk level
                    if not assess_risk():  # Risk level is not acceptable after reassessment
                        send_stop_signal()
                        instruct_human_to_exit()
                        wait_for_manual_relaunch()
                    else:  # Risk level is acceptable after reassessment
                        continue_welding()
if __name__ == "__main__":
    main()
```

- Scenario 3 Response Result is as follows:

```
Workflow started.
Welding continues.
Human instructed to exit UV zone.
Switching to the next operation after finishing
```

4. **Scenario 4**: The system detects a human, assesses an acceptable risk level, and detects that the robot is working at a critical point. Humans do not exist before the timeout, triggering a reassessment of the risk. If the risk becomes unacceptable, the robot is stopped; otherwise, it continues welding.

```
#Python Code Scenaio 4:
def detect_human_entry():
    # Simulate detection of human entry in the UV zone : Return True if human is
detected, False otherwise.
```

```
    return True  # Human is detected
def assess_risk():
    # Simulate AI assessing the risk level : Return True if risk level is acceptable, False
otherwise.
    return True  # Initial risk level is acceptable
def determine_welding_point():
    # Simulate determining if the welding point is normal or critical : Return True if
welding at a normal point, False if at a critical point.
    return False  # Welding at a critical point
def does_human_exit_before_timeout():
    # Simulate checking if the human exits the UV zone before timeout : Return True if
human exits before timeout, False otherwise.
    return False  # Human does not exit before timeout
def continue_welding():
    # Simulate continuing the welding operation.
    print("Welding continues.")
def send_stop_signal():
    # Simulate sending a stop signal to the robot.
    print("Stop signal sent to the robot.")
def instruct_human_to_exit():
    # Simulate instructing the human to exit the UV zone.
    print("Human instructed to exit UV zone.")
def wait_for_manual_relaunch():
    # Simulate waiting for manual relaunch of the robot.
    print("Waiting for manual relaunch.")
def wait_for_automatic_relaunch():
    # Simulate waiting for automatic relaunch of the robot.
    print("Waiting for automatic relaunch.")
def switch_to_next_operation():
    # Simulate switching to the next operation after finishing.
    print("Switching to the next operation after finishing")
def reassess_risk():
    # Simulate AI reassessing the risk level.
    print("Reassess the risk.")
```

```python
def main():
    # Start of the workflow
    print("Workflow started.")
    if detect_human_entry():
        if not assess_risk():  # Initial risk level is not acceptable
            send_stop_signal()
            instruct_human_to_exit()
            wait_for_manual_relaunch()
        else:  # Initial risk level is acceptable
            if determine_welding_point():  # Welding at a normal point
                send_stop_signal()
                instruct_human_to_exit()
                wait_for_manual_relaunch()
            else:  # Welding at a critical point
                continue_welding()
                if does_human_exit_before_timeout():  # Human exited before timeout
                    continue_welding()
                else:   # Human did not exit before timeout, reassess risk level
                    if not reassess_risk():  # Risk level is not acceptable after reassessment
                        send_stop_signal()
                        instruct_human_to_exit()
                        wait_for_manual_relaunch()
                    else:  # Risk level is acceptable after reassessment
                        continue_welding()
if __name__ == "__main__":
    main()
```

- Scenario 4 Response Result is as follows:

```
Workflow started.
Welding continues.
Reassess the risk.
Stop signal sent to the robot.
Human instructed to exit UV zone.
Waiting for manual relaunch.
```

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