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DOKTORAL (PHD) THESIS BOOKLET

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

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Contents

Summary

My PhD thesis presents a comprehensive study on developing an intelligent control system for safe collaborative human-robot interaction in welding applications. The research addresses the growing need for adaptive safety solutions as collaborative robots (cobots) become increasingly integrated into industrial environments, particularly in hazardous processes such as welding. While automation has improved productivity and precision, welding tasks still require human expertise for complex or customized operations. This creates a critical challenge: ensuring worker safety while maintaining operational efficiency in shared workspaces.

The dissertation begins by exploring the historical and technological evolution of robotics and collaborative systems, emphasizing their role in modern industrial production. It highlights the unique risks associated with welding, including exposure to ultraviolet (UV) radiation, extreme heat, toxic fumes, and potential physical injuries. These hazards make it essential to establish advanced safety mechanisms beyond traditional fixed barriers and manual protective equipment.

A mixed-methods research approach was employed, combining theoretical analysis with experimental validation. Through literature reviews, risk assessments, and real-world measurements, the study evaluates the safety gaps in collaborative welding environments. A key outcome of this work is the introduction of a virtual barrier system, a novel adaptive control concept that dynamically monitors and manages danger zones without relying on physical fences or curtains. This system uses real-time sensor data and artificial intelligence to identify human presence, predict potential hazards, and adjust robot behavior to prevent accidents while supporting continuous workflow.

The experimental results confirm that the virtual barrier can effectively reduce risks associated with welding activities while preserving weld quality and productivity. Furthermore, the research demonstrates that integrating advanced sensing technologies and AI-driven control strategies establishes a safer and more flexible collaborative workspace, setting a foundation for next-generation industrial robotics.

In conclusion, this dissertation provides a robust framework for enhancing human-robot collaboration in hazardous industries. By addressing safety and efficiency together, it contributes to the development of innovative industrial practices that protect workers while advancing the capabilities of collaborative robotic systems.

Summary in Hungarian Languag be – Magyar nyelvű összefoglaló

Doktori disszertációm egy intelligens vezérlőrendszer kidolgozását mutatja be, amely célja a biztonságos együttműködés megvalósítása emberek és robotok között hegesztési alkalmazásokban. A kutatás a kollaboratív robotok (cobotok) ipari környezetben történő egyre növekvő elterjedéséből indul ki, különösen az olyan veszélyes folyamatokban, mint a hegesztés. Bár az automatizálás jelentősen növelte a termelékenységet és a pontosságot, számos hegesztési feladat továbbra is emberi szakértelmet igényel, különösen az összetett vagy egyedi műveletek esetében. Ez a helyzet komoly kihívást jelent: hogyan lehet biztosítani a munkavállalók biztonságát anélkül, hogy csökkenne a termelés hatékonysága a közösen megosztott munkaterületeken.

A disszertáció bemutatja a robotika és az együttműködő rendszerek történeti és technológiai fejlődését, hangsúlyozva azok szerepét a modern ipari termelésben. Részletesen tárgyalja a hegesztéssel kapcsolatos egyedi kockázatokat, többek között az ultraibolya (UV) sugárzásnak való kitettséget, az extrém hőhatást, a mérgező füstöket és a fizikai sérülések lehetőségét. Ezek a veszélyek szükségessé teszik a hagyományos fizikai védőeszközökön és védőfüggönyökön túlmutató, fejlett biztonsági mechanizmusok kialakítását.

A kutatás során vegyes módszertant alkalmaztam, amely ötvözi az elméleti elemzést és a kísérleti validációt. Az irodalmi áttekintések, kockázatértékelések és valós mérési adatok segítségével azonosítottam azokat a biztonsági hiányosságokat, amelyek a kollaboratív hegesztési környezetekben fennállnak. A kutatás egyik legfontosabb eredménye egy virtuális biztonsági határ koncepciójának kidolgozása, amely dinamikusan figyeli és kezeli a veszélyzónákat fizikai akadályok alkalmazása nélkül. Ez a rendszer valós idejű szenzoradatokat és mesterséges intelligenciát használ az emberi jelenlét észlelésére, a potenciális veszélyek előrejelzésére, valamint a robot viselkedésének azonnali szabályozására a balesetek megelőzése érdekében, mindezt a folyamatos munkafolyamat fenntartása mellett.

A kísérleti eredmények megerősítik, hogy a virtuális biztonsági határ hatékonyan képes csökkenteni a hegesztési tevékenységekhez kapcsolódó kockázatokat, miközben megőrzi a hegesztési minőséget és a termelékenységet. A kutatás továbbá bebizonyítja, hogy a fejlett érzékelési technológiák és a mesterséges intelligencia által vezérelt irányítás integrálása biztonságosabbá és rugalmasabbá teszi az ember-robot együttműködést, és alapot teremt a jövő ipari robotikai rendszerei számára.

Összefoglalva, ez a disszertáció átfogó keretrendszert kínál a kollaboratív hegesztési folyamatok biztonságának növelésére. A biztonság és a hatékonyság egyidejű kezelésével hozzájárul az olyan innovatív ipari gyakorlatok kialakításához, amelyek egyszerre védik a munkavállalókat és fejlesztik a kollaboratív robotrendszerek képességeit.

1 Introduction

My doctoral research stems from a strong academic foundation in electronics and automation engineering. I earned my Bachelor's degree in Electronics Engineering and Master's degree in Electrical Engineering with a specialization in Electrical Control from Ahmed Draya African University, Algeria. During my Master's studies, I focused on control systems and advanced industrial automation, which provided me with the expertise to address complex challenges in robotics and manufacturing systems.

Currently, I am pursuing a PhD in Automation Engineering at the Doctoral School on Safety and Security Sciences, Óbuda University, Budapest, Hungary, with a research focus on AI-supported automation, human-robot collaboration, and intelligent control systems. My experience includes implementing collaborative robot applications, optimizing workflows through mixed-reality systems, and integrating advanced safety mechanisms into industrial environments. This interdisciplinary background serves as the foundation for the research presented in this dissertation.

1.1 Welding

Welding remains one of the most essential industrial manufacturing processes, as it enables the permanent joining of metal components into reliable structures. Despite its importance, welding is inherently hazardous, exposing operators to several serious risks such as [1], [2]:

- Ultraviolet (UV) radiation causing burns and eye damage.
- Extreme heat and molten metal spatter leading to thermal injuries.
- Toxic fumes and gases with harmful long-term health effects.
- Physical strain due to repetitive motion and awkward postures.

To meet the increasing demands for precision and durability, industries employ advanced welding techniques that improve quality while addressing safety concerns. The most widely used welding methods include [1], [3], [4] :

1) Gas Tungsten Arc Welding (GTAW/TIG): Delivers highly precise welds for critical components.
2) Gas Metal Arc Welding (GMAW/MIG): Preferred for its speed and adaptability to various materials.
3) Shielded Metal Arc Welding (SMAW): Commonly used for fieldwork and structural repairs.

4) Laser Welding: Produces accurate, clean joints with minimal heat distortion.
5) Friction Stir Welding (FSW): Ideal for joining aluminum and other non-ferrous metals without defects.

Although these techniques have enhanced production quality, manual welding remains physically demanding and high-risk [5], [6]. These challenges underline the importance of developing automated solutions to improve worker safety and productivity simultaneously.

1.2 Robotics

Robotics has revolutionized modern manufacturing by increasing productivity, precision, and repeatability. Traditionally, industrial robots operated in isolated environments separated by physical barriers to ensure worker safety [7], [8], [9]. However, the rise of collaborative robots (cobots) has shifted this paradigm, allowing humans and robots to share the same workspace [11], [10].

Cobots are equipped with advanced sensors and control algorithms that enable them to detect human presence and adapt their actions to avoid accidents [12], [13]. This capability makes them particularly valuable for hazardous operations such as welding [14], [15]. By assigning repetitive and high-risk tasks to robots while allowing humans to focus on skilled and adaptive activities, collaborative systems enhance both efficiency and safety [16], [17], [18].

Despite their advantages, collaborative welding environments face a significant challenge [19], [20], [21]: traditional safety barriers, such as curtains or fences, can limit workflow flexibility. To address this, my research introduces an intelligent virtual safety barrier, a dynamic, intelligent system designed to define and monitor danger zones without interrupting production flow [10], [22].

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 1) [14]. 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 [15]. 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 [14].

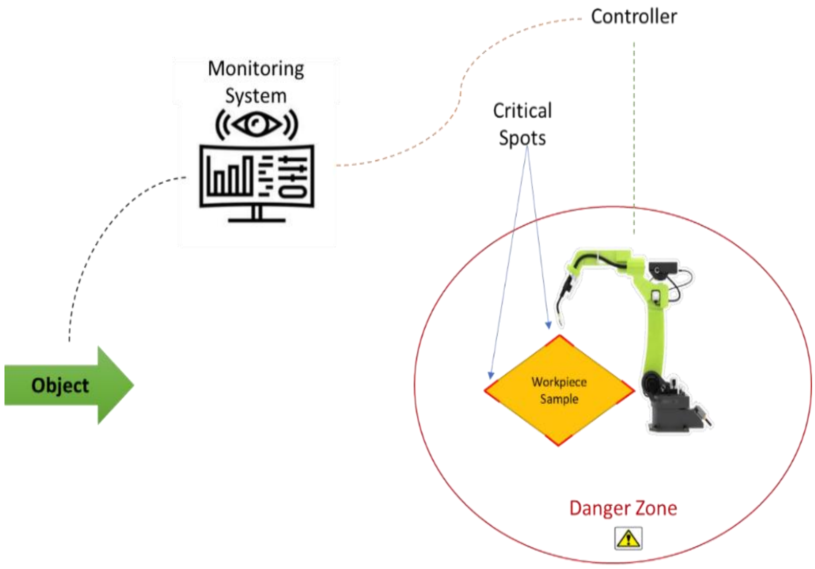

Figure 1: The general implementation of an object approaching the welding robot danger zone [14]

The implementation of the safety and quality requirement should pass as shown in the flowchart in Figure 2, 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 does not 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.

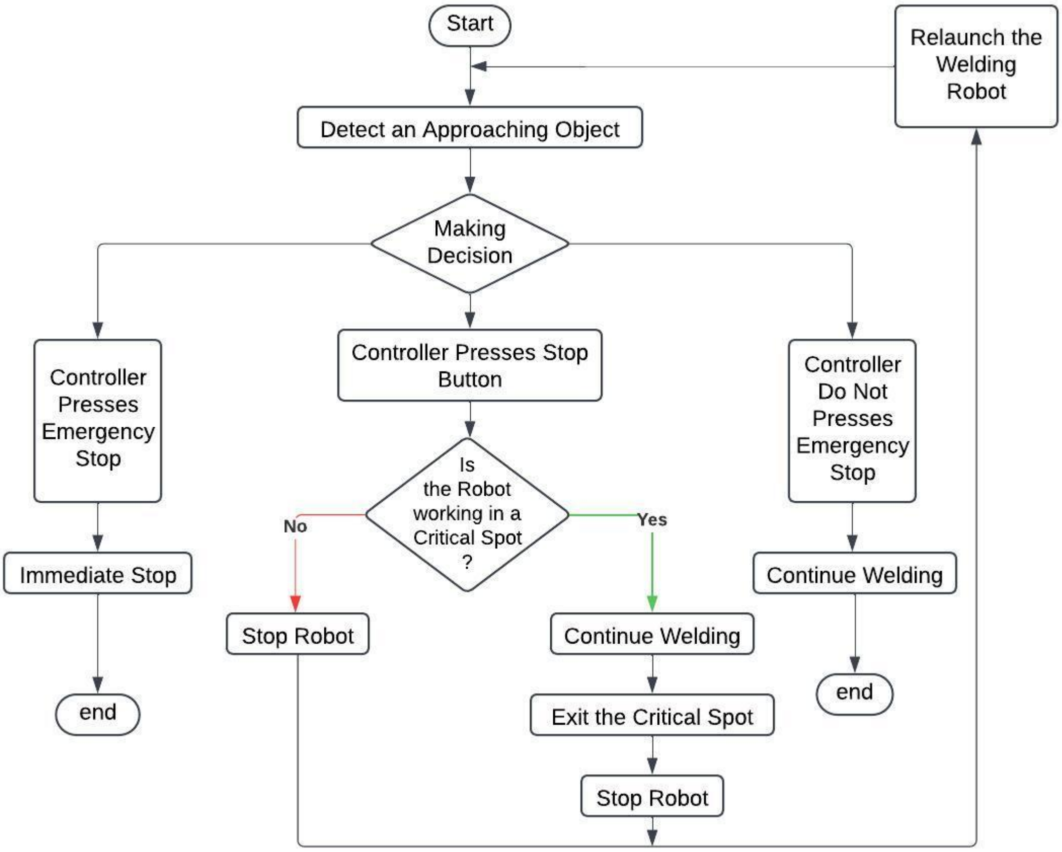

Figure 2: Flowchart of the decision-making process by the controller [14]

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.

2 Goals of the research

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.

The ultimate objective of this research is to create a safer, smarter, and more efficient collaborative welding environment, where humans and robots can work side-by-side without physical barriers, maintaining both worker protection and operational excellence. This work contributes to the advancement of industrial safety practices and provides a foundation for future intelligent control systems in collaborative robotics.

3 Methods of the research

The research methodology outlines the systematic approach used to design, implement, and validate the intelligent control system for safe collaborative welding. It includes the design of experiments, data collection techniques, and analytical methods required to address the research objectives presented in the previous chapter.

Given the complexity of collaborative welding environments and the dual focus on both safety and productivity, a mixed-methods approach was adopted. This combines qualitative methods, which provide insights into safety requirements and risk assessment, and quantitative methods, which offer measurable, data-driven evaluation of the system's performance.

3.1 Qualitative Methods

The qualitative component focused on understanding the human-robot interaction context and identifying the hazards that workers face in collaborative welding environments. This step provided the foundation for defining the parameters of the virtual safety barrier.

Key activities included:

Literature review

An extensive review of standards, regulations, and previous research was conducted to identify gaps in existing safety practices for welding robots [16], [17]. Special attention was given to studies addressing UV radiation hazards, toxic fume exposure, and robotic collision risks.

Workplace risk assessment

Observational analysis was performed to evaluate real-world welding processes, identifying common hazards and assessing the effectiveness of current safety measures such as protective clothing and physical barriers.

Expert consultations

Discussions with welding professionals and robotics specialists provided practical insights into safety challenges and operational needs in collaborative environments [18].

Outcome

This phase produced a clear understanding of the dangers present in collaborative welding environments and guided the conceptual design of the virtual barrier system.

3.2 Quantitative Methods

The quantitative part of the research focused on measurement, testing, and validation. It was essential for evaluating whether the proposed virtual barrier system could reliably detect hazards and ensure operator safety.

Research design

- Experimental research was chosen to generate real-world data under controlled welding conditions.
- The experiments were conducted in a dedicated collaborative welding cell developed specifically for this study.

Sampling technique

- A non-probability sampling approach was used, selecting representative scenarios and welding configurations based on hazard exposure and task complexity.

Data collection methods

- UV radiation measurements: Specialized sensors were employed to measure UV intensity at different distances and angles around the welding area to define the safe operating boundary.
- Proximity detection tests: Depth cameras and infrared sensors were tested for their ability to detect human presence and motion in real time.
- Robot motion tracking: Data on the robot's path, speed, and positioning were recorded to evaluate its adaptive behavior within the virtual barrier framework.

Data analysis techniques

- Statistical analysis was applied to identify correlations between environmental hazards, robot movement, and system performance.
- Control system validation was achieved by comparing experimental data against safety thresholds established by international standards.

3.3 Research Plan

The research was structured in sequential stages to ensure a logical progression from concept to validation:

1) Literature and standard review to identify welding hazards and relevant safety limits, particularly those related to UV exposure.
2) Risk assessment to classify hazards and determine the most critical threats requiring real-time monitoring.

3) Design and implementation of the virtual barrier control system using AI algorithms and sensor integration.
4) Experimental setup of the collaborative welding cell, incorporating both robotic and human elements.
5) System testing and validation through controlled experiments measuring both safety and welding performance.
6) Analysis and refinement of the system based on experimental feedback.

3.4 Summary of the Research Methodology

This mixed-methods approach ensured a comprehensive understanding of both the human factors and technical performance required for safe collaborative welding.

- The qualitative phase established the hazard framework and guided system design.
- The quantitative phase provided measurable data for validating the system's effectiveness.

The methodology was carefully structured to ensure that the final solution meets industrial requirements, combining theoretical rigor with practical applicability. Through this approach, the research delivers a scientifically validated, industry-ready control system for enhancing safety in collaborative welding environments.

4 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], [20].**

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], [14].**

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 [12], [23].**

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, and torch orientation, 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.

- **AI, sensor technologies, and adaptive control are the foundation of an intelligent safety control system for human-robot collaboration in welding, as submitted in the flowchart that I have developed [12], [14], [27]:**

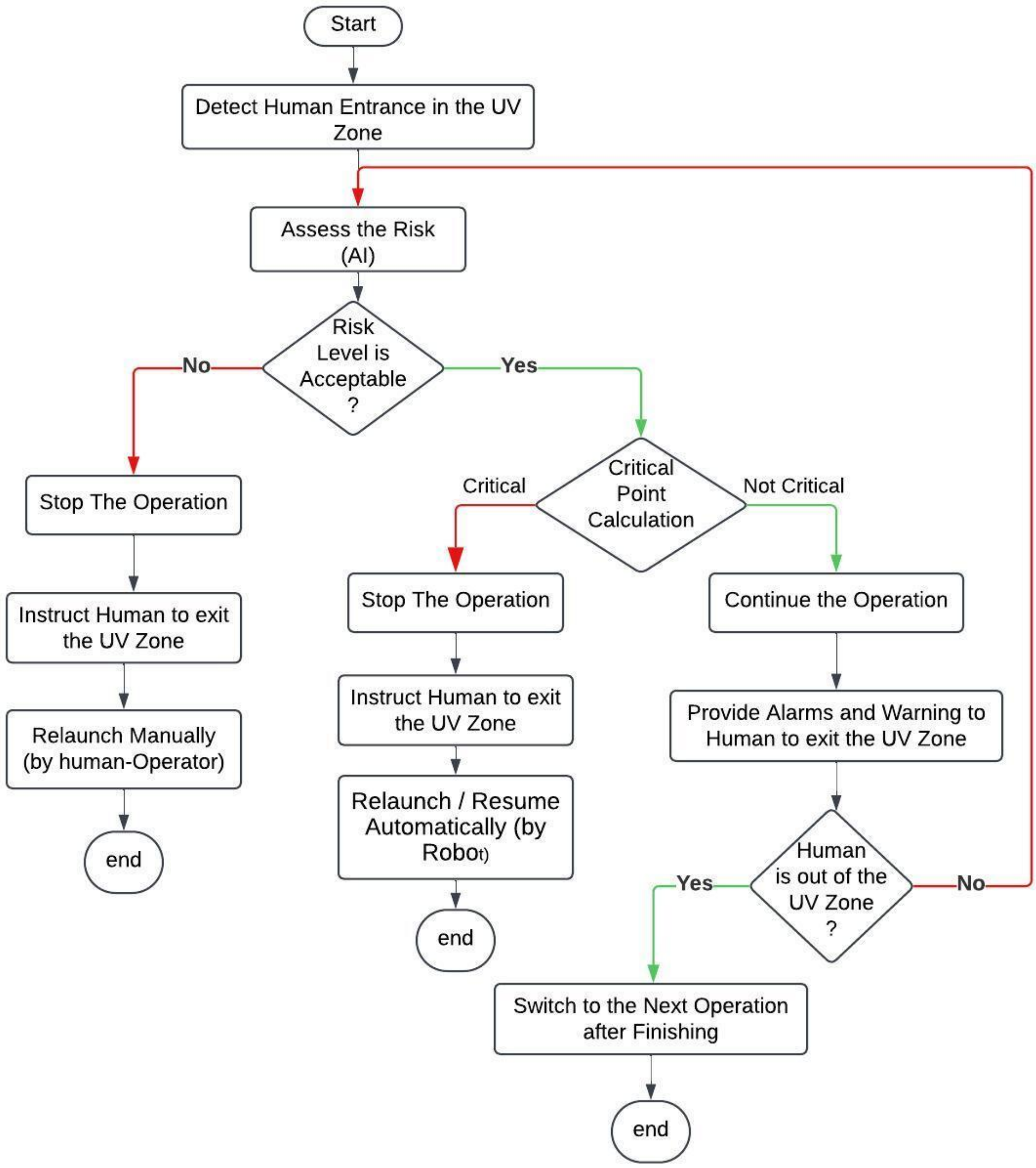

Figure 3: Workflow for Safety Control in Human-Robot Collaborative Welding Environments [27]

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.

5 Recommendations

- 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.

6 References

[1] H. Altin and M. Pedaste, “Learning approaches to applying robotics in science education,” J. Balt. Sci. Educ., vol. 12, no. 3, p. 365, 2013.

[2] T. PALE, “La robotique collaborative.. Promouvoir un outil de développement en jugulant la faiblesse des infrastructures physiques en Afrique,” Commun. Technol. Dév., no. 8, 2020, Accessed: Mar. 05, 2025. [Online]. Available: https://journals.openedition.org/ctd/2628

[3] M. Gurgul, Industrial robots and cobots: Everything you need to know about your future co-worker. Michał Gurgul, 2018. Accessed: Mar. 05, 2025. [Online]. Available: https://books.google.com/books?hl=en&lr=&id=n-2BDwAAQBAJ&oi=fnd&pg=PT5&dq=Gurgul+M+Industriel+robots+and+cobots&ots=jqoWM5laqO&sig=Pi-wZPMRyVEqoBC5QJYIOSRDN3M

[4] S. Czudek, “Robotic surgery–a taste of Hollywood?,” Videosurgery Miniinvasive Tech., vol. 8, no. 2, pp. 95–98, 2013.

[5] L. Gualtieri, E. Rauch, and R. Vidoni, “Emerging research fields in safety and ergonomics in industrial collaborative robotics: A systematic literature review,” Robot. Comput.-Integr. Manuf., vol. 67, p. 101998, 2021.

[6] L. D. Evjemo, T. Gjerstad, E. I. Grøtli, and G. Sziebig, “Trends in Smart Manufacturing: Role of Humans and Industrial Robots in Smart Factories,” Curr. Robot. Rep., vol. 1, no. 2, pp. 35–41, Jun. 2020, doi: 10.1007/s43154-020-00006-5.

[7] N. E. Y. Aichaoui and Z. Nyikes, “Collaborative Robots in the Critical Infrastructure Area Review,” in Security-Related Advanced Technologies in Critical Infrastructure Protection, T. A. Kovács, Z. Nyikes, and I. Fürstner, Eds., in NATO Science for Peace and Security Series C: Environmental Security. , Dordrecht: Springer Netherlands, 2022, pp. 185–194. doi: 10.1007/978-94-024-2174-3_16.

[8] J. Saenz, “Méthodologie pour la conception d’espaces de travail sûrs, avec la collaboration de robot humain,” PhD Thesis, Ecole nationale supérieure d’arts et métiers-ENSAM, 2019. Accessed: Mar. 01, 2025. [Online]. Available: https://pastel.hal.science/tel-02736291/

[9] N. E. Y. Aichaoui and T. A. Kovács, “Integrating Collaborative Robots and IoT-

Enabled SCADA Systems for Enhanced Greenhouse Automation and Sustainable Precision Agriculture," in Springer, 2025th ed.

[10] N. E. Y. Aichaoui, "Enhancing Safety Protocols for Human-Robot Collaboration in Welding Environments: Investigation Review into Augmenting Worker Safety within Robot Hazard Zones," in 2024 IEEE 22nd World Symposium on Applied Machine Intelligence and Informatics (SAMI), IEEE, 2024, pp. 000035–000040. Accessed: Mar. 02, 2025. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10432922/

[11] A. Rout, B. Deepak, and B. B. Biswal, "Advances in weld seam tracking techniques for robotic welding: A review," Robot. Comput.-Integr. Manuf., vol. 56, pp. 12–37, 2019.

[12] N. E. Y. Aichaoui and T. A. Kovács, "Optimization and Adaptive Control Strategies for Welding Robot Systems," in Müszaki Tudományos Közlemenyek (EN) 21 pp. 1-6, p. 2024.

[13] B. Wang, S. J. Hu, L. Sun, and T. Freiheit, "Intelligent welding system technologies: State-of-the-art review and perspectives," J. Manuf. Syst., vol. 56, pp. 373–391, 2020.

[14] N. El Yasmine Aichaoui and T. A. Kovács, "Enhancing Safety and Efficiency: Human–Cobot Interaction in Critical Infrastructure," in The Impact of the Energy Dependency on Critical Infrastructure Protection, T. A. Kovács, R. G. Stadler, and N. Daruka, Eds., Cham: Springer Nature Switzerland, 2025, pp. 77–86. doi: 10.1007/978-3-031-78544-3_6.

[15] J. Arents and M. Greitans, "Smart industrial robot control trends, challenges and opportunities within manufacturing," Appl. Sci., vol. 12, no. 2, p. 937, 2022.

[16] S. I. Wahidi, S. Oterkus, and E. Oterkus, "Robotic welding techniques in marine structures and production processes: A systematic literature review," Mar. Struct., vol. 95, p. 103608, 2024.

[17] G. D. Putnik, P. B. Petrovic, and V. Shah, "Spatial Visual Feedback for Robotic Arc-Welding Enforced by Inductive Machine Learning," J. Manuf. Sci. Eng., vol. 146, no. 4, 2024, Accessed: Mar. 05, 2025. [Online]. Available: https://asmedigitalcollection.asme.org/manufacturingscience/article/146/4/040902/1171645

[18] Y. Chu et al., "Structural design and adaptive tracking control of automatic welding

robot for liquefied natural gas containment system," Discov. Appl. Sci., vol. 6, no. 3, p. 118, Mar. 2024, doi: 10.1007/s42452-024-05764-x.

[19] S. Panagou, W. P. Neumann, and F. Fruggiero, "A scoping review of human robot interaction research towards Industry 5.0 human-centric workplaces," Int. J. Prod. Res., vol. 62, no. 3, pp. 974–990, 2024.

[20] N. E. Y. Aichaoui and T. A. Kovács, "Risk Assessment of Industrial Collaborative Welding Robots: A Critical Review of Methodologies and Limitations," in Critical Infrastructure Protection in the Light of the Armed Conflicts, T. A. Kovács, Z. Nyikes, T. Berek, N. Daruka, and L. Tóth, Eds., in Advanced Sciences and Technologies for Security Applications. , Cham: Springer Nature Switzerland, 2024, pp. 149–159. doi: 10.1007/978-3-031-47990-8_14..

[21] A. Vigil et al., "Enhanced Weld Defect Categorization via Nature-Inspired Optimization-Driven Neural Networks," SN Comput. Sci., vol. 5, no. 8, pp. 1–14, 2024.

[22] S. Mian Qaisar, D. Say, M. Krichen, and S. Zidi, "Artificial Intelligence Assistive Non-Destructive Testing of Welding Joints: A Review," Artif. Intell. Assist. Non-Destr. Test. Weld. Jt. Rev., Accessed: Mar. 05, 2025. [Online]. Available: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5074702

[23] N. E. Y. Aichaoui and T. A. Kovács, "Exploring the Intersection of Human Movement and Collaborative Robotics: Challenges and Opportunities in Computational Modeling," in NATO International Conference, pp. 1-10. Dordrecht: Springer Netherlands, 2024.

[24] C. C. Doumanidis and D. E. Hardt, "Multivariable adaptive control of thermal properties during welding," 1991, Accessed: Mar. 02, 2025. [Online]. Available: https://asmedigitalcollection.asme.org/dynamicsystems/article-abstract/113/1/82/394954

[25] E. Aldalur, A. Suárez, D. Curiel, F. Veiga, and P. Villanueva, "Intelligent and adaptive system for welding process automation in T-shaped joints," Metals, vol. 13, no. 9, p. 1532, 2023.

[26] J. T. Kahnamouei and M. Moallem, "Advancements in control systems and integration of artificial intelligence in welding robots: A review," Ocean Eng., vol. 312, p. 119294,

2024.

[27] N. E. Y. Aichaoui and T. A. Kovács, "AI-driven control system for safe and adaptive human-robot collaboration in welding applications," Biztonságtudományi Szemle, vol. 7, no. 1, p. 1-13, 2025.

Publication list of the author

1. N. E. Y. Aichaoui and Z. Nyikes, "Collaborative Robots in the Critical Infrastructure Area Review," in *Security-Related Advanced Technologies in Critical Infrastructure Protection*, T. A. Kovács, Z. Nyikes, and I. Fürstner, Eds., in NATO Science for Peace and Security Series C: Environmental Security. , Dordrecht: Springer Netherlands, 2022, pp. 185–194. doi: 10.1007/978-94-024-2174-3_16.

2. N. E. Y. Aichaoui and T. A. Kovács, "Integrating Collaborative Robots and IoT-Enabled SCADA Systems for Enhanced Greenhouse Automation and Sustainable Precision Agriculture," in *Springer*, 2025th ed.(accepted)

3. N. E. Y. Aichaoui, "Enhancing Safety Protocols for Human-Robot Collaboration in Welding Environments: Investigation Review into Augmenting Worker Safety within Robot Hazard Zones," in *2024 IEEE 22nd World Symposium on Applied Machine Intelligence and Informatics (SAMI)*, IEEE, 2024, pp. 000035–000040. Accessed: Mar. 02, 2025. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/10432922/

4. N. E. Y. Aichaoui and T. A. Kovács, "Risk Assessment of Industrial Collaborative Welding Robots: A Critical Review of Methodologies and Limitations," in *Critical Infrastructure Protection in the Light of the Armed Conflicts*, T. A. Kovács, Z. Nyikes, T. Berek, N. Daruka, and L. Tóth, Eds., in Advanced Sciences and Technologies for Security Applications. , Cham: Springer Nature Switzerland, 2024, pp. 149–159. doi: 10.1007/978-3-031-47990-8_14.

5. N. E. Y. Aichaoui and T. A. Kovács, "Optimization and Adaptive Control Strategies for Welding Robot Systems," in *Müszaki Tudományos Közlemenyek (EN) 21 pp. 1-6, p.* 2024.

6. N. El Yasmine Aichaoui and T. A. Kovács, "Enhancing Safety and Efficiency: Human–Cobot Interaction in Critical Infrastructure," in *The Impact of the Energy Dependency on Critical Infrastructure Protection*, T. A. Kovács, R. G. Stadler, and N. Daruka, Eds., Cham: Springer Nature Switzerland, 2025, pp. 77–86. doi: 10.1007/978-3-031-78544-3_6.

7. N. E. Y. Aichaoui and T. A. Kovács, "Exploring the Intersection of Human Movement and Collaborative Robotics: Challenges and Opportunities in Computational

Modeling," in *NATO International Conference*, pp. 1-10. Dordrecht: Springer Netherlands, 2024.

8. N. E. Y. Aichaoui and T. A. Kovács, "AI-driven control system for safe and adaptive human-robot collaboration in welding applications," *Biztonságtudományi Szemle*, vol. *7*, no. 1, p. 1-13, 2025.