INTERNATIONAL JOURNAL OF ACADEMIC RESEARCH IN PROGRESSIVE EDUCATION & DEVELOPMENT

OPEN ACCESS JOURNAL

Vol 13, Issue 4, (2024) E-ISSN: 2226-6348

Technological Innovations in Welding Education: A Review of Teaching and Learning Approaches

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To Link this Article: http://dx.doi.org/10.6007/IJARPED/v13-i4/23801 DOI:10.6007/IJARPED/v13-i4/23801

Published Online: 25 November 2024

Abstract

Welding education is undergoing a significant transformation due to the integration of advanced technologies such as virtual reality (VR), augmented reality (AR), and robotic automation, aligning with the demands of Industry Revolution 4.0 (IR 4.0). This study utilized a systematic review through the Scopus database to investigate the incorporation of these technological innovations into welding training. The focus was on identifying how these technologies enhance the learning experience beyond traditional methods, emphasizing practical skills in immersive, cost-effective environments without safety risks. The results from the review highlight that VR and AR not only revolutionize the way welding skills are taught by simulating realistic scenarios but also improve student engagement and understanding. Additionally, robotic systems prepare students for the automation prevalent in modern industries, while eLearning platforms extend educational reach beyond conventional classroom settings, promoting flexible, self-paced learning. The adoption of VR, AR, and automation in welding education enhances both the effectiveness of teaching and the quality of learning, ensuring students are well-prepared for a technologically advanced workforce. This shift towards technology-driven education is critical for developing a workforce capable of meeting the evolving needs of contemporary manufacturing sectors.

Keywords: Educational Technology, Welding Training, Welding Education, Literature Review

Introduction

Welding education has experienced a transformative shift, driven by rapid advancements in technology. Traditional teaching methods, which primarily relied on classroom-based instruction and hands-on practice (Fleischmann, 2021). There are being complemented and, in many cases, replaced by technological innovations such as virtual reality (VR), augmented reality (AR), robotic automation, and intelligent systems (Bassyouni & Elhajj, 2021). These innovations are not only making the teaching and learning process more engaging but also more aligned with the needs of modern industries, particularly in the context of Industry Revolution 4.0 (IR 4.0). IR 4.0 which emphasizes automation and smart technologies in manufacturing processes (Ahmadi et al., 2020). Welding, being a critical component of various

Vol. 13, No. 4, 2024, E-ISSN: 2226-6348 © 2024

industries, necessitates a workforce that is skilled in both traditional welding techniques and the use of advanced technologies.

VR and AR in welding education have revolutionized the way students acquire practical skills. VR simulators can provide immersive environments where students can practice welding in realistic virtual settings without the need for costly materials or safety risks (Heibel et al., 2023). This allows for repeated practice, immediate feedback, and the opportunity to simulate a wide range of welding techniques and scenarios. Research has shown that students trained using VR-based simulators demonstrate improved performance in actual welding tasks compared to those trained through traditional methods alone (Isham et al., 2021). Similarly, AR applications enhance learning by overlaying digital information on physical objects, helping students visualize welding processes in real-time, which significantly improves their understanding of complex concepts (Agrawal & Pillai, 2020; Papakostas et al., 2022).

Another significant innovation in welding education is the use of robotic automation. Robotic welding systems are becoming increasingly common in industrial settings due to their efficiency and precision (Hong et al., 2014). Welding education has adapted to include training on robotic systems, preparing students for the automation-driven demands of modern manufacturing industries. Studies have highlighted the importance of integrating robotic welding systems into educational curricula to ensure that students are proficient in the use of advanced automation technologies (Umachandran et al., 2021). This hands-on experience with robotic systems not only enhances students' technical skills but also their ability to adapt to emerging technologies in the workplace.

In addition to VR, AR, and robotic systems, eLearning platforms and mobile applications are playing a crucial role in making welding education more accessible and flexible (Prasetya et al., 2023). These platforms enable students to access learning materials, instructional videos, and simulations remotely, facilitating self-paced learning (Logan et al., 2021). The ability to learn outside the traditional classroom setting has been particularly beneficial in times of global disruptions, such as during the COVID-19 pandemic, where remote learning became essential. Mobile learning technologies are also increasing engagement by allowing students to practice welding concepts on their devices before applying them in a physical or virtual lab setting (Rusli et al., 2019).

The integration of technological innovations in welding education is not only enhancing the quality of teaching and learning but also ensuring that students are better prepared for the evolving demands of the industry. As welding processes become increasingly automated and complex, the need for highly skilled welders who are proficient in using advanced technologies is more pressing than ever. The shift toward technology-driven teaching and learning approaches in welding education is a necessary and beneficial response to these industry trends, promising a future workforce that is adaptable, skilled, and ready to meet the challenges of modern manufacturing environments.

Methodology

This research was conducted using the Scopus database. The search aimed to gather comprehensive insights on the intersection of technology and welding education, focusing on innovative teaching and learning methods. The initial search query was structured as follows:

TITLE-ABS-KEY ((technolog*) OR (innovation* OR integration* OR implementation*) AND (weld*) AND (education* OR train* OR instruction* OR pedagog*) AND (teaching) AND (learning) AND (approach* OR method* OR pedagog* OR strateg* OR technique*))

This query was designed to capture a broad spectrum of scholarly articles and conference papers that discussed technological advancements, integrations, and implementations within the context of welding education and its instructional methodologies. A total of 38 articles were initially identified on 20 September 2024. To refine the search and ensure relevance and focus, filters were applied to narrow down the results to specific document types and source types. Table 1 shows the selection criterion in searching.

Table 1
The Selection Criterion in Searching

Criteria	Inclusion	Exclusion
Year	All	-
Document type	Article, Conference	Book, Review
Source Type	Journal, Conference proceeding	Book series, trade journal
Publication Stage	Final	In Press

The refined search included only conference papers and research articles from document type. While journals and conference proceedings are selected in source type. This filter adjustment led to the identification of 22 pertinent documents. This systematic approach allowed for a focused review of contemporary educational practices in welding education, facilitating an analysis of various teaching and learning approaches. These findings are expected to contribute significantly to the development of enhanced pedagogical strategies within the field, aligning technological innovations with educational outcomes.

Results and Discussion

The transformation of teaching approaches in welding training through technology is not merely about adopting new tools. It is fundamentally enhancing the way education is delivered and experienced. These modern approaches leverage the power of integration, interaction, simulation, and personalization to meet the evolving demands of the industry and prepare students more effectively for their future careers. This ongoing evolution in teaching strategies, supported by technological advancements, promises to further elevate the standards and effectiveness of welding education. Table 2 provides a comprehensive overview of the methodologies, findings, teaching approaches, and technological innovations used in 22 articles related to the searching method.

Table 2
The Research Article's Findings

Article ID	Authors, Year	Teaching Welding Approach	Technology Innovations	Findings
A1	Kong et al. (2023)	Intelligent evaluation methods	Semantic segmentation and classification models	High performance in welding work evaluation
A2	Amiruddin et al. (2023)	Gamification as a teaching method	Gamification elements	Positive student perception towards gamification
A3	Amiruddin et al. (2021)	Robotic welding automation teaching	Robotic automation	Prototype is effective for theoretical and practical learning
A4	Jamal et al. (2021)	Computational thinking integrated with educational robotics	Educational robotics, Grounded Theory Analysis	Integration of CT in ER enhances problem-solving skills
A5	Lavrentieva et al. (2020)	Simulator-based teaching using VR and AR	VR and AR simulators	Simulators with VR and AR enhance training
A6	Jalinus et al. (2020)	Project-based and direct teaching models	Project-based learning environments	Different learning models affect hard and soft skills differently
A7	Ismail et al. (2020)	Teaching using educational kits	Magnetic test kit for welding teaching	Improved student interest and visualization abilities
A8	Vijay et al. (2020)	Knowledge-based AR teaching	Augmented reality with AI support	Effective learning of practical skills through AR
A9	Lai et al. (2020)	Virtual learning environments for welding	Mobile AR and VR applications	Effective integration of AR and VR in teaching
A10	Zulfabli et al. (2019)	Augmented reality for practical teaching	Augmented reality	AR technology is effective for 21st-century learning
A11	Kuchma et al. (2019)	Health and safety focused teaching	Survey tools and health assessments	Vocational training significantly impacts student health
A12	Junior (2018)	Creative project-based learning	Interdisciplinary project-based tools	Increased student creativity and teamwork
A13	Scotti (2017)	Active learning with audio-visual support	Audiovisual aids	Enhanced class effectiveness and

Article ID	Authors, Year	Teaching Welding Approach	Technology Innovations	Findings
				student engagement
A14	Erdem & Sirinterlikci (2015)	Integrated teaching, classroom and lab sessions	Computer assisted analysis with CastView™ software	Three-faceted approach improves learning objectives
A15	Lan et al. (2013)	Integrated teaching reform for welding robots	Welding robot teaching integration	Enhanced student learning initiative and engineering practice ability
A16	Engh (2012)	Integration of virtual technology and eLearning	Virtual welding equipment	Reduced costs and enhanced skill transfer
A17	Keitel & Ahrens (2011)	Blended and virtual training	Virtual Welding Trainer	Advanced training in welding skills
A18	Gray (2009)	Hands-on manufacturing integration in engineering education	Integration of practical applications in coursework	Enhances link between coursework and on-the-job tasks
A19	Hsieh & Hoermann (2009)	Virtual system training	Virtual PLC systems	Improved proficiency in PLC programming
A20	Genis et al. (2007)	Hands-on lab training with real-time video support	Internet-based videoconferencing for labs	Enhanced training effectiveness and accessibility
A21	Stav et al. (2006)	Distance training with video solutions	High-quality video streaming	Improved welding training with high-quality video solutions
A22	Ahlström & Christie (2005)	Teaching with computational tools	MATLAB for simulation exercises	Improved understanding of heat conduction during welding

Table 2 shows a review of teaching and learning approaches using technology in welding training reveals a significant shift towards the integration of advanced technological innovations, such as AR, VR, robotic automation, and intelligent evaluation systems, to enhance both theoretical knowledge and practical skills in welding education.

A. Teaching Approaches

The reviewed articles showcase a variety of teaching methods that integrate both traditional and innovative techniques. Notably, several studies emphasize the value of project-based learning models which that align closely with industry practices, thereby improving the practical skills of students. For instance, the use of project-based learning in combination with direct teaching models highlights the effectiveness of blending hard skills like welding techniques with soft skills such as teamwork, as discussed in the study on how these models affect teamwork and welding skills among students (Jalinus et al., 2020). Moreover, immersive teaching methodologies utilizing AR and VR are prominently featured, reflecting a shift towards high-engagement learning environments. The augmented reality approaches, for example, are shown not only to improve practical skills but also to significantly enhance student engagement and interest in learning complex welding techniques (Ahlström & Christie, 2005; Zulfabli et al., 2019). This is particularly evident in studies where AR was used to provide students with a more interactive and engaging learning experience, thereby deepening their understanding of theoretical concepts through practical application (Lai et al., 2020; Vijay et al., 2020).

The varied teaching approaches adopted in the reviewed studies reflect a transformative shift in educational strategies tailored to welding and similar technical disciplines. An integrated approach combining classroom theory with laboratory practice is prominently featured, providing a comprehensive learning experience that enhances students' understanding and application of welding processes. For instance, the use of an integrated teaching methodology for manufacturing processes (Erdem & Sirinterlikci, 2015) blends in-class theoretical lessons with hands-on laboratory experiences, significantly enhancing the students' ability to connect theoretical knowledge with practical applications. Active learning environments facilitated by non-passive audio-visual aids (Scotti, 2017) and gamification (Amiruddin et al., 2023) further exemplify the shift towards more engaging and interactive educational models. These methods not only stimulate student interest and involvement but also promote a deeper understanding of complex welding tasks through active participation and engagement. The gamification approach leverages the motivational dynamics of game-playing to enhance learning outcomes, which has proven effective in increasing student motivation and engagement, thereby potentially improving their academic performance and retention rates.

The shift towards immersive teaching methodologies, such as those involving augmented and virtual reality, introduces an element of realism and interactivity that was previously unattainable. This realism is crucial in technical education fields like welding, where the tactile and visual aspects of the craft are integral to mastering the skill. For instance, AR-enhanced teaching allows students to visualize welding processes in real-time, overlaying digital information that can guide techniques and correct errors instantaneously (Zulfabli et al., 2019). This method not only enhances the learning experience but also ensures higher levels of precision and understanding, which are critical in welding. Similarly, project-based learning, which has been increasingly adopted, supports a collaborative and problem-solving approach that mirrors real-world scenarios. Students engage in projects that require them to apply their welding skills to solve practical problems, thus bridging the gap between theoretical knowledge and practical application (Jalinus et al., 2020; Junior, 2018). This approach not only reinforces technical skills but also cultivates essential soft skills such as teamwork, communication, and critical thinking, making students well-rounded professionals.

B. Technological Innovations

The incorporation of advanced technological innovations plays a crucial role in the modernization of welding education. Semantic segmentation and classification models (Kong et al., 2023), as well as advanced VR and AR simulators (Lavrentieva et al., 2020), are highlighted as key tools in refining the educational processes. These technologies facilitate a more accurate and efficient evaluation of students' work and allow for real-time feedback, which is essential for mastering intricate welding tasks. The development of virtual learning tools and platforms also underscores a significant advancement in educational technologies, providing students with remote access to welding training modules that mimic real-world scenarios. The use of Virtual Welding Trainers (Keitel & Ahrens, 2011) and integration of virtual technology in eLearning contexts (Engh, 2012) exemplify how virtual platforms can be effectively used to transfer skills and knowledge, reduce training costs, and provide scalable learning opportunities.

Furthermore, the integration of AI into the learning environment has started to personalize the learning experience, adapting to individual student needs and pacing, which is particularly noted in the implementation of knowledge-based AR environments [8]. This personalization ensures that students receive tailored instruction that best fits their learning style and progress rate, thereby optimizing educational outcomes. Technological innovations continue to play a pivotal role in the evolution of welding education. The integration of semantic segmentation and AI in evaluating welding techniques (Kong et al., 2023) provides precision and objectivity in assessments, a previously labour-intensive process susceptible to subjective biases. Similarly, the implementation of AI and AR technologies (Vijay et al., 2020) offers a more nuanced and sophisticated approach to training, where complex welding techniques can be simulated and practiced without the material costs and safety risks associated with traditional welding training. Virtual and augmented reality technologies have particularly stood out as transformative tools in welding education. Virtual reality setups provide a safe, cost-effective, and scalable alternative to traditional welding training, allowing students to practice and hone their skills in a controlled, virtual environment that closely mimics real-world conditions (Lan et al., 2013; Lavrentieva et al., 2020). Augmented reality, on the other hand, overlays digital information onto the physical training environment, providing real-time guidance and feedback that enhances the learning process. These AR applications not only improve the accuracy and efficiency of welding training but also make it more accessible and engaging for students.

On the technological front, the integration of machine learning and AI into welding simulators and educational tools represents a significant leap forward. These technologies can analyze students' performance, provide tailored feedback, and adjust difficulty levels in real-time, catering to the individual learning pace of each student (Kong et al., 2023; Vijay et al., 2020). The data collected through these interactions can also be used to improve curriculum designs, teaching strategies, and even predict student outcomes, leading to a more efficient educational process. The development of virtual labs and simulation-based training platforms is another noteworthy innovation. These platforms enable unlimited practice without resource constraints, reduce the need for physical materials, and eliminate the risks associated with beginner-level training (Engh, 2012; Lavrentieva et al., 2020). The scalability of such solutions means that institutions can offer welding training to a larger number of students, including those in remote areas, thereby democratizing access to high-quality technical education.

Conclusion

Trend of technological innovation being integrated into welding education, improving both the learning outcomes and the efficiency of teaching methods. Traditional methods, while still in use, are being transformed by digital tools such as AR, VR, and AI-based systems that provide more engaging and effective ways for students to learn. These technologies not only support the theoretical understanding of welding processes but also facilitate practical skill development in a safe, controlled, and resource-efficient manner. The key to this transformation lies in the ability of eLearning platforms, mobile apps, and simulators to extend the learning environment beyond traditional classrooms, offering flexibility and accessibility that can meet the growing demands of both students and industry. Additionally, the shift towards automation technologies aligns welding education with IR 4.0 standards, ensuring that students are well-prepared for the future of manufacturing and industrial applications. The integration of technological innovations in welding education is proving to be a crucial factor in improving both the teaching approaches and learning outcomes for students. The continued exploration and adoption of VR, AR, intelligent systems, and robotic automation will likely pave the way for even more effective and industry-relevant welding training programs in the future.

Acknowledgement

This research was supported and funded by the Jabatan Perkhidmatan Awam Malaysia (JPA) through the Hadiah Latihan Persekutuan (HLP) scholarship.

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APPENDIX 1

Article ID	Authors, Year	Article Title
A1	Kong et al. (2023)	A Semantic Segmentation-based Method for Evaluating Students' Electronic Process Training Soldering Works
A2	Amiruddin et al. (2023)	Gamification in higher education: A study of the student's interest, motivation, and acceptance of gamification as a method of teaching welding technology
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A16	Engh (2012)	Integration of virtual welding technology, eLearning and activity based training in order to transfer skills, knowledge and competence in a life-long learning context
A17	Keitel & Ahrens (2011)	Latest developments in welding skills training
A18	Gray (2009)	The integration of hands-on manufacturing processes and applications within engineering disciplines; work in progress
A19	Hsieh & Hoermann (2009)	Integrated virtual learning system for programmable logic controller (Virtual PLC): Current progress and future directions

Article ID	Authors, Year	Article Title
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A21	Stav et al. (2006)	New models for pedagogical inclusion of high quality industrial video solutions within distance training practices
A22	Ahlström & Christie (2005)	Using a MATLAB exercise to improve the teaching and learning of heat conduction during welding