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XR Pedagogical Framework: Leveraging Augmented Reality for Effective Learning in Industrial Training Using CDIO

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Abstract. Knowledge acquisition in engineering education, particularly in hands-on disciplines like electrical drawing, faces challenges such as prolonged learning durations, low engagement, and limited real-time competency assessment. Traditional methods rely on physical apparatus and static experimentation, which often fail to address these issues effectively. This paper proposes an XR pedagogical framework integrating augmented reality (AR) with the Conceive-Design-Implement-Operate (CDIO) standards to enhance learning experiences. The framework merges constructivist learning theories, social collaboration, and competency-based assessment to create immersive industrial training. To demonstrate its application, we developed a Minimum Viable Product (MVP) AR prototype. It features interactive 3D circuit simulations aligned with CDIO Standard 7 (experiential learning), self-assessment quizzes for competency tracking (Standard 11), and real-time collaborative troubleshooting workspaces (Standard 8). By simulating electrical drawing tasks in a risk-free virtual environment, the prototype enables learners to practice complex concepts, receive immediate feedback, and refine problem-solving skills—key competencies for modern engineering practice. The framework empowers educators to design AR-enhanced curricula bridging theoretical knowledge with industry-driven skill development. Preliminary insights suggest that AR integration enhances engagement, accelerates skill acquisition, and fosters critical thinking. The prototype's interactive simulations reduce cognitive load by visualizing abstract electrical principles spatially, while collaborative modules mirror real-world engineering teamwork. This work contributes to the evolving discourse on immersive learning by aligning XR technologies with globally recognized educational standards.

Keywords: Augmented Reality (AR), XR Pedagogy, Industrial Training, CDIO Framework, Immersive Learning.

1 Introduction

The demand for industry-ready engineers in STEM disciplines like electrical engineering highlights critical gaps in traditional education, where hands-on training is often constrained by cost, safety risks, and scalability. Extended Reality (XR) technologies, particularly Augmented Reality (AR), offer transformative solutions by enabling immersive, risk-free simulations that bridge theoretical knowledge and practical skill development. However, the adoption of XR in STEM remains fragmented, prioritizing technological novelty over structured pedagogical alignment with industry standards. Without frameworks that integrate immersive tools into competency-driven curricula, educators struggle to ensure equitable access, measurable skill acquisition, or relevance to workforce demands [1, 2].

This paper addresses these gaps by proposing an XR pedagogical framework that aligns immersive learning with the Conceive-Design-Implement-Operate (CDIO) initiative, a global benchmark for engineering education. While XR encompasses diverse technologies, the framework emphasizes AR for its ability to overlay digital guidance on physical environments—ideal for disciplines like electrical drawing, where learners must interact with real tools while receiving virtual support. Grounded in constructivist and social learning theories, the framework was developed by mapping AR-driven simulations, collaborative problem-solving modules, and competency assessments to CDIO's industry-aligned pillars [3, 4].

A Figma-based AR prototype for electrical drawing demonstrates the framework's practicality, enabling learners to troubleshoot circuits iteratively, receive real-time feedback, and refine designs in collaborative virtual workspaces. By embedding XR within a structured pedagogy, this work empowers educators to deliver scalable, engaging training that mirrors professional engineering environments while adhering to globally recognized standards [5, 6].

The paper begins with a review of XR's role in STEM education, followed by an analysis of CDIO standards, the framework's approach, and the prototype's design. Conclusions outline future directions for scaling the framework across STEM disciplines.

2 Literature Review

Immersive technologies, particularly XR, have revolutionized education by creating interactive, hands-on learning environments that enhance engagement and comprehension. However, their effective integration requires robust pedagogical frameworks to guide implementation. This review examines XR's role in education, evaluates existing frameworks like TPACK, SAMR, and CDIO, and identifies the need for a systematic approach to align XR with CDIO standards for industrial training [2, 6].

2.1 XR in Education

Extended Reality (XR), encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), has emerged as a transformative tool in education, offering immersive and interactive environments that enhance learning outcomes. AR, in particular, has been recognized for its potential to simulate real-world scenarios and provide risk-free environments for learners to practice complex tasks. XR technologies also foster collaborative and social learning spaces, which are critical for developing teamwork and problem-solving skills, especially in engineering contexts [1, 2, 5].

In industrial training, XR allows learners to visualize abstract concepts and interact with 3D models in real-time, aligning with constructivist approaches where knowledge is built through experience. XR addresses challenges such as limited access to physical resources and the need for scalable training solutions. However, barriers like high implementation costs and the lack of pedagogical frameworks that align XR technologies with educational objectives remain significant [7, 8].

2.2 Pedagogical Frameworks

The integration of XR technologies into education requires robust pedagogical frameworks to ensure effective and meaningful learning experiences. Several existing frameworks, such as TPACK (Technological Pedagogical Content Knowledge), SAMR (Substitution, Augmentation, Modification, Redefinition), and CDIO (Conceive-Design-Implement-Operate), offer distinct approaches for integrating technology into teaching and learning processes. Table 1 provides a comparative benchmark of these frameworks, highlighting their key features, strengths, and limitations [9, 10].

Table 1. Benchmark of pedagogical frameworks.

Framework	Focus	Strengths	Limitations
TPACK	Integration of technology, pedagogy, and content knowledge.	Comprehensive understanding of how to use technology effectively in teaching; emphasizes the interplay of knowledge domains.	Complex to implement; requires extensive teacher training.
SAMR	Levels of technology integration in education (Substitution, Augmentation, Modification, Redefinition).	Simple and practical for assessing technology use; focuses on transforming learning experiences through technology.	Limited focus on pedagogy and content; lacks depth in addressing interdisciplinary teaching needs.
CDIO	Engineering education reform based on real-world practices (Conceive, Design, Implement, Operate).	Strong emphasis on hands-on learning and professional skills development; aligns with industry	Primarily focused on engineering disciplines; less adaptable to non-engineering contexts.

		needs; integrates active and experiential learning methods.

The TPACK framework emphasizes the integration of technological, pedagogical, and content knowledge to create effective teaching strategies. It is particularly useful for educators seeking a holistic approach to technology integration but can be challenging to implement without adequate training. On the other hand, the SAMR model provides a straightforward method for evaluating and enhancing the use of technology in classrooms. While it is practical for assessing the level of technology integration, it does not address the interplay between pedagogy and content knowledge as comprehensively as TPACK.

The CDIO framework stands out for its alignment with real-world engineering practices. By focusing on project-based learning and experiential activities, it prepares students for professional environments. However, its applicability is largely confined to engineering disciplines, making it less versatile compared to TPACK or SAMR. Despite this limitation, CDIO's emphasis on hands-on learning makes it an ideal foundation for integrating XR technologies into industrial training programs [11].

2.3 Research Gap

While the potential of XR technologies in education has been widely explored, there remains a significant gap in understanding how to systematically implement these technologies within structured pedagogical frameworks. Specifically, the integration of AR into the CDIO framework for industrial training is underexplored. The CDIO framework, with its emphasis on hands-on, experiential learning and alignment with industry needs, provides a robust foundation for engineering education. However, what is missing is a clear approach for implementing XR technologies, particularly AR, to enhance these experiential learning opportunities in a way that aligns seamlessly with CDIO standards [2, 6].

Existing research often focuses on either the technological capabilities of XR or the pedagogical principles of frameworks like CDIO but rarely addresses their intersection. For example, while studies have demonstrated how XR can improve engagement and comprehension through immersive simulations, they do not provide detailed guidance on how these simulations can be integrated into CDIO-aligned curricula to achieve specific learning outcomes. Similarly, while the CDIO framework emphasizes active learning and competency development, it lacks explicit strategies for incorporating emerging technologies like AR into its implementation [3, 4].

This study aims to fill this gap by proposing an XR pedagogical framework that leverages AR to align with CDIO standards. By focusing on practical implementation, this work seeks to demonstrate how AR can bridge theoretical knowledge and practical skills in industrial training contexts. The framework not only addresses the need for immersive learning experiences but also provides educators with a structured approach to designing AR-enhanced curricula that meet industry-driven educational objectives [6, 12].

3 XR Pedagogical Framework: A Theoretical Foundation

The proposed XR pedagogical framework integrates multiple learning theories, developmental approaches, and assessment methods to create a comprehensive structure for immersive learning in engineering education. This framework is built upon four key pillars that work together to support effective XR-based learning experiences.

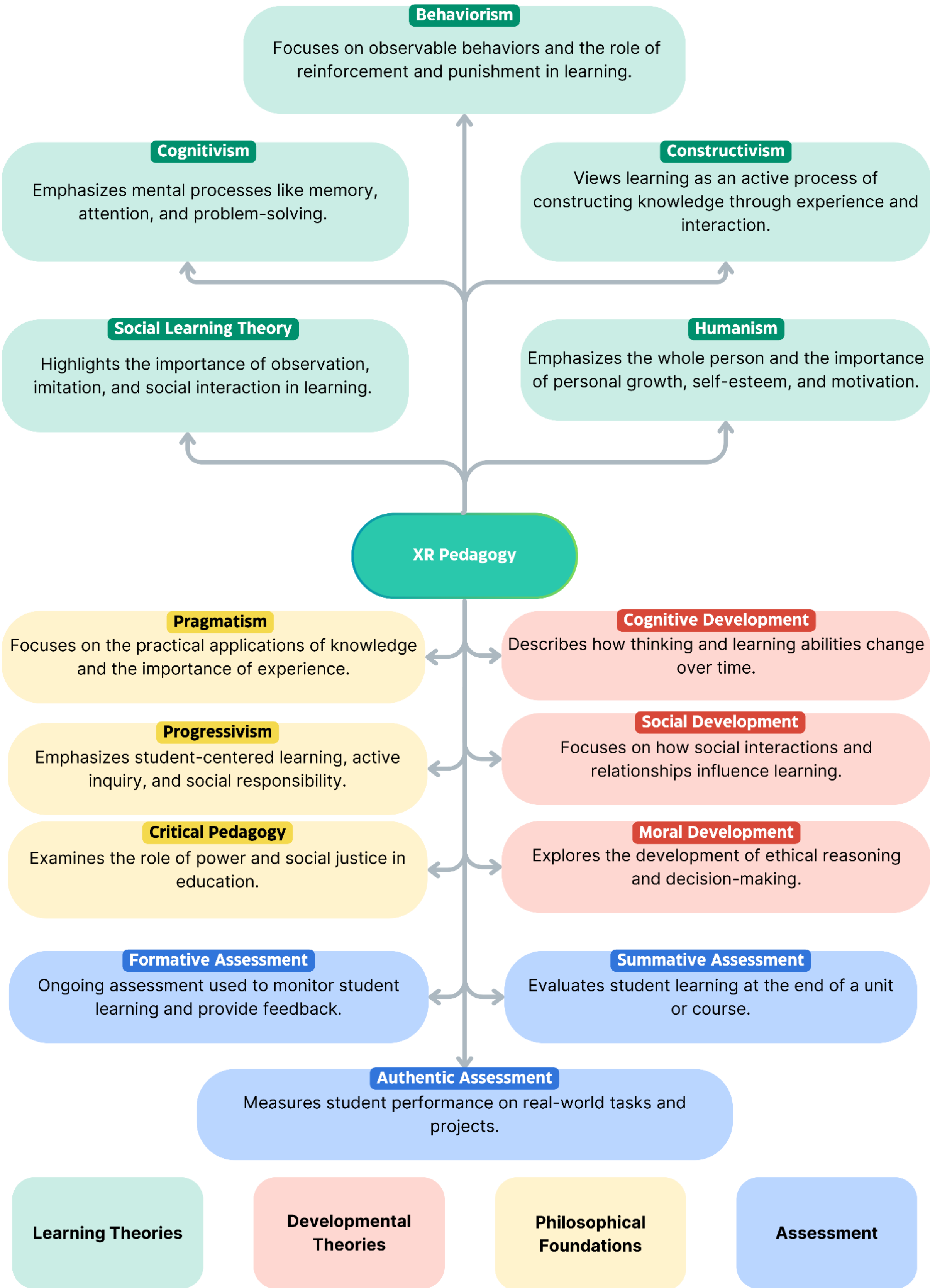

Fig. 1. XR Pedagogy Framework integrating Learning Theories, Developmental Theories, Philosophical Foundations, and Assessment Methods for engineering higher education.

3.1 Learning Theories Integration

The framework incorporates five fundamental learning theories that complement each other in the XR environment:

1. Behaviorism: focuses on observable behaviors and reinforcement in learning, guiding the design of immediate feedback mechanisms in AR simulations1.
2. Cognitivism: emphasizes mental processes, informing how AR applications support memory, attention, and problem-solving through interactive 3D visualizations2.
3. Constructivism: views learning as an active process of knowledge construction, aligning with AR's ability to enable hands-on experimentation3.
4. Social Learning Theory: highlights observation and interaction, reflected in the collaborative features of AR environments2.
5. Humanism: emphasizes personal growth and motivation, incorporated through self-paced learning pathways.

3.2 Developmental Theories

The framework incorporates three developmental perspectives:

1. Cognitive Development: guides the sequencing of learning experiences, ensuring content complexity matches learner capabilities.
2. Social Development: informs the design of collaborative features and peer learning opportunities.
3. Moral Development: considers ethical decision-making in engineering contexts.

3.3 Philosophical Foundations

Three philosophical approaches underpin the framework:

1. Pragmatism emphasizes practical applications, reflected in the focus on real-world engineering tasks.
2. Progressivism promotes student-centered learning and active inquiry, supported by interactive AR simulations.
3. Critical Pedagogy examines power dynamics in education, ensuring equitable access to learning resources.

3.4 Assessment Integration

The framework implements three assessment types:

1. Formative Assessment provides ongoing feedback through interactive quizzes and performance tracking.
2. Summative Assessment evaluates overall competency achievement through comprehensive evaluations.
3. Authentic Assessment measures real-world task performance through practical AR simulations.

This theoretical foundation aligns with CDIO standards while leveraging XR technologies to create engaging, effective learning experiences. The framework's structure ensures that technological implementation serves pedagogical goals rather than driving them, addressing a key gap identified in current research (see Fig. 1) [13, 14].

4 Framework Implementation

The XR pedagogical framework has been operationalized through a Minimum Viable Product (MVP) AR application called ScanLab, designed specifically for electrical drawing education. This implementation demonstrates how theoretical principles can be translated into practical learning tools while maintaining alignment with CDIO standards [8, 15–17].

4.1 Authentication and User Management

The application begins with a secure authentication system featuring login and signup capabilities, ensuring personalized learning experiences and progress tracking. This implementation reflects the framework's humanistic approach by providing individualized learning pathways and maintaining user privacy (see Fig. 2, Fig. 3, Fig. 4, Fig. 5).

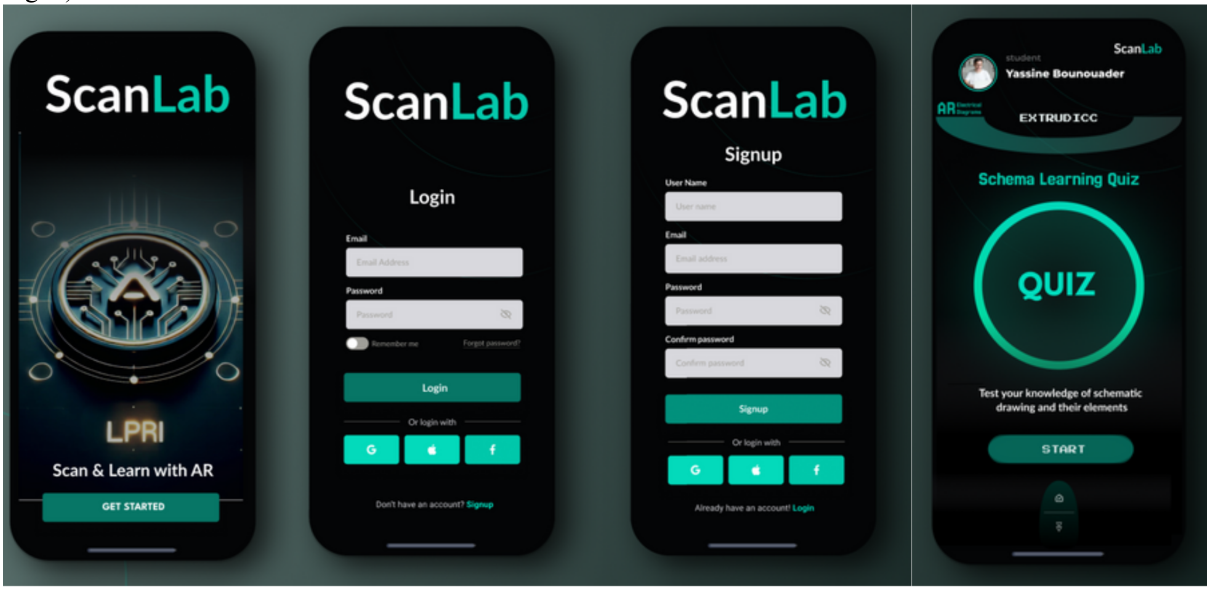

Fig. 2. Login and Signup interfaces.

4.2 Authentication and User Management

The framework's assessment integration is realized through an interactive quiz system that evaluates learners' understanding of electrical components and schemas. This module implements:

- Formative assessment through immediate feedback on component identification
- Competency tracking with detailed performance metrics
- Adaptive difficulty levels based on user progress, aligning with cognitive development theory

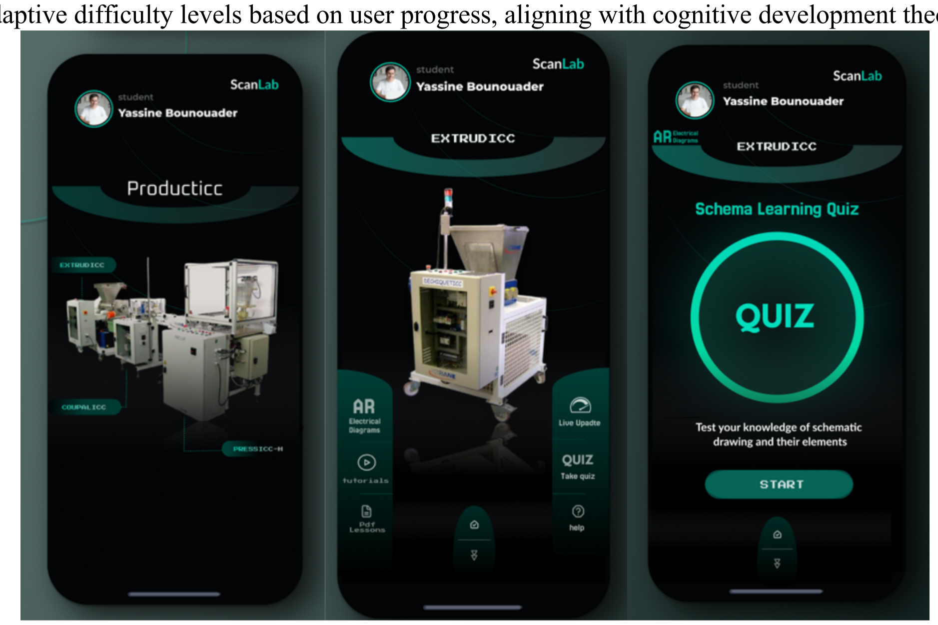

Fig. 3. Quiz assesment to measure the user level of understanding.

4.3 AR-Enhanced Learning Environment

The core functionality demonstrates the framework's constructivist principles through AR-based visualization and interaction:

- Real-time overlay of 3D electrical components on physical schemas.
- Interactive manipulation of virtual circuit elements.
- Collaborative workspace features enabling peer learning and expert guidance.

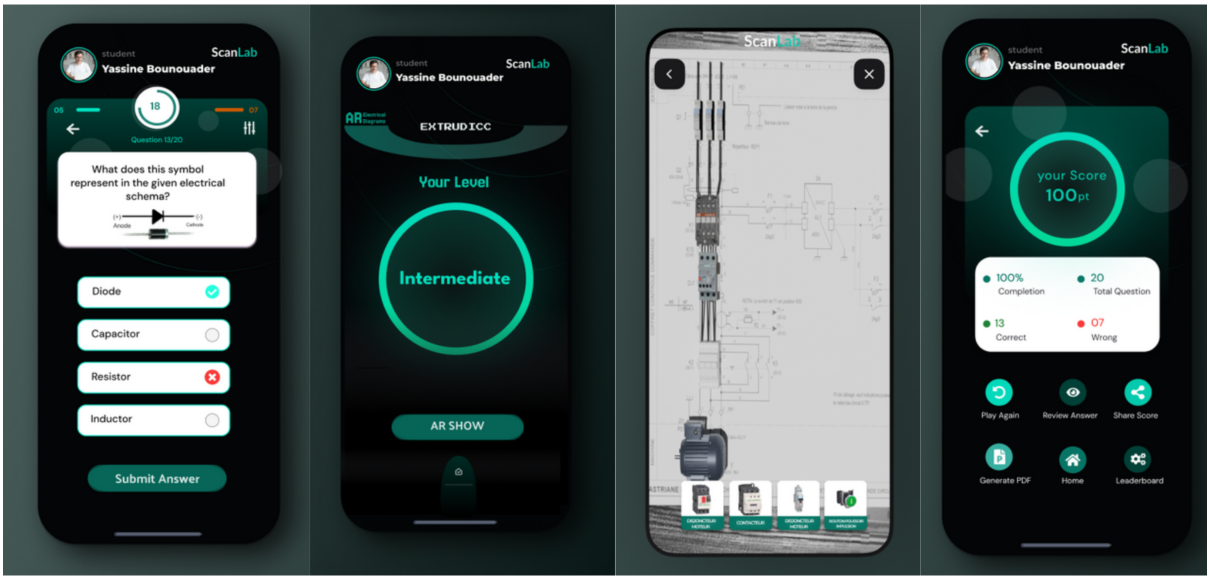

Fig. 4. AR visualization and interaction in electrical drawing schemas.

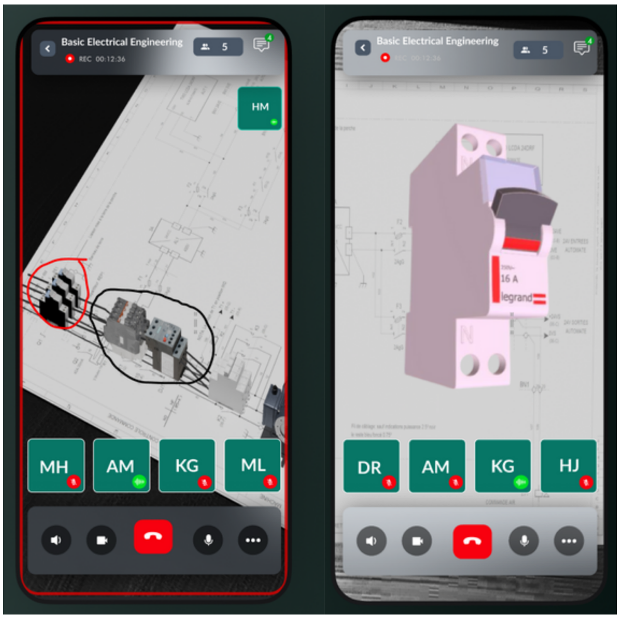

Fig. 5. Peer learning and expert guidance experience overview.

This implementation demonstrates how the theoretical framework can be translated into practical tools that support experiential learning while maintaining alignment with CDIO standards. The AR application serves as a bridge between theoretical knowledge and practical skills, enabling learners to engage with complex electrical concepts in an immersive, risk-free environment. The prototype's features directly map to specific framework components:

- Learning Theories: Interactive 3D visualizations support cognitive and constructivist learning.
- Developmental Theories: Progressive difficulty levels align with cognitive development principles.
- Philosophical Foundations: Practical, hands-on experiences reflect pragmatic approaches.
- Assessment Methods: Integrated evaluation tools provide continuous feedback and authentic assessment.

Through this implementation, the framework demonstrates its potential to enhance engineering education by creating engaging, effective learning experiences that align with industry standards while supporting individual learner needs.

5 Approach

The development of the ScanLab AR application follows a systematic approach to implement the XR pedagogical framework while maintaining alignment with CDIO standards. This section details the methods used to translate theoretical principles into a practical learning tool for electrical drawing education.

5.1 Research Design

The study employs a design-based research approach to develop and validate the AR application. This approach ensures the integration of theoretical insights with practical requirements, creating an effective tool for industrial training in electrical drawing. The design process incorporates constructivist and experiential learning theories mapped to CDIO standards, particularly focusing on Standards 7, 8, and 11 [2, 3].

5.2 Framework Operationalization

The XR pedagogical framework has been operationalized through the development of specific AR features aligned with CDIO standards. Standard 7 (Integrated Learning Experiences) is addressed through interactive 3D simulations that enable learners to visualize and manipulate electrical circuits in a risk-free environment. Standard 8 (Active Learning) is implemented via collaborative troubleshooting workspaces where learners can engage in real-time problem-solving with peers. Standard 11 (Learning Assessment) is realized through integrated self-assessment quizzes that provide immediate feedback and track competency development [4, 6].

5.3 Technical Implementation

The AR application was developed using Unity 3D and Vuforia SDK, chosen for their robust capabilities in creating interactive AR experiences. The user interface was designed using Figma to ensure intuitive navigation and accessibility. The development process focused on creating realistic 3D models of electrical components and implementing marker-based AR recognition for schema visualization. The application incorporates real-time tracking capabilities to enable precise overlay of virtual components on physical electrical drawings [12, 15].

5.4 Content Development

The educational content within ScanLab was carefully structured to support progressive skill development. Electrical circuit diagrams and 3D models were created based on standard curriculum requirements for electrical drawing courses. The content includes various difficulty levels to accommodate different learning capabilities and provides comprehensive coverage of essential electrical components and schemas [8, 16].

5.5 Assessment Design

The assessment system was developed to provide continuous feedback and track learner progress. It includes knowledge evaluation modules that assess understanding of electrical components and schemas through interactive quizzes. The system generates detailed performance metrics and allows for progress tracking through an intuitive interface. Performance data can be exported as PDF reports for documentation and reflection purposes [13, 17].

By following this structured approach, the study shows how the XR pedagogical framework can be operationalized through an AR application to enhance industrial training in engineering education. The next phase of development will focus on user testing and refinement based on feedback from engineering students and educators.

6 Discussion

The development and implementation of the XR pedagogical framework through the ScanLab AR application demonstrates significant potential for enhancing engineering education, particularly in electrical drawing training. The framework's integration of multiple learning theories with CDIO standards addresses several key challenges in traditional engineering education while providing a structured approach to implementing immersive technologies [18, 19].

The framework's emphasis on constructivist learning principles, realized through interactive AR simulations, enables students to engage with complex electrical concepts in a risk-free environment. This approach particularly addresses the safety concerns and resource limitations often associated with traditional hands-on training methods. The implementation of real-time feedback mechanisms and adaptive difficulty levels supports personalized learning pathways, addressing the diverse needs of learners while maintaining alignment with CDIO Standard 11[20].

The collaborative features of ScanLab, including peer learning and expert guidance capabilities, reflect the framework's incorporation of social learning theory and align with CDIO Standard 8. These features mirror real-world engineering practices where collaboration and communication are essential skills. The integration of formative and summative assessment methods provides educators with comprehensive tools to track learner progress and ensure competency development [21].

However, several limitations must be acknowledged. The current implementation focuses primarily on electrical drawing education, and further research is needed to validate the framework's applicability across other engineering disciplines. Additionally, the effectiveness of the AR application in enhancing learning outcomes requires empirical validation through user testing, which is planned for the next phase of development [22, 23].

The framework's alignment with CDIO standards demonstrates a promising approach to structuring XR-enhanced educational experiences. By mapping specific AR features to CDIO standards, the implementation provides a replicable model for integrating immersive technologies into engineering education while maintaining pedagogical rigor. This structured approach addresses the gap identified in current literature regarding the systematic implementation of XR technologies within established educational frameworks.

Future developments of the framework should consider the integration of artificial intelligence to enhance the adaptivity of learning pathways and provide more sophisticated feedback mechanisms. Additionally, expanding the framework to accommodate other XR technologies could provide greater flexibility in addressing diverse learning objectives across engineering disciplines.

7 Conclusion

This paper presents a novel XR pedagogical framework that integrates AR technology with CDIO standards to enhance engineering education, particularly in electrical drawing training. The framework successfully merges established learning theories, developmental approaches, and assessment methods to create a comprehensive structure for immersive learning experiences. Through the implementation of ScanLab, an MVP AR application, we demonstrate how theoretical principles can be effectively translated into practical educational tools [18, 24].

The framework's alignment with CDIO standards, particularly Standards 7, 8, and 11, provides a structured approach to implementing XR technologies in engineering education while maintaining pedagogical rigor. The integration of interactive 3D simulations, collaborative workspaces, and comprehensive assessment tools addresses critical challenges in traditional engineering education, including limited access to resources, safety concerns, and the need for real-time competency assessment [14, 25].

Future work will focus on empirical validation through user testing with engineering students and educators, exploring the integration of artificial intelligence to enhance adaptive learning pathways, and expanding the framework's application across other engineering disciplines. This research contributes to the evolving discourse on immersive learning by providing a systematic approach for aligning XR technologies with globally recognized educational standards, ultimately advancing the quality and effectiveness of engineering education.

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