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RESEARCH ARTICLE

The Application of Artificial Intelligence in Engineering Education: A Systematic Review

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ABSTRACT Artificial Intelligence (AI) is increasingly impacting the environment, pedagogy, and management practices in engineering education. However, literature reviews that provide a systematic review and analysis of AI in engineering education remain limited. To address this research gap and gain a comprehensive understanding of AI applications in engineering education, this study conducts a systematic review based on 161 studies on AI applications in engineering education. Using VOSviewer, this paper analyzes the research hotspots of AI in engineering education, as well as the top ten organizations, countries, cited sources, and cited authors. Furthermore, the study categorizes the application of AI technologies in engineering education into seven distinct categories: Virtual Experiment Environments, Learning Prediction, Learning Analytics, Engineering Education Robots, Intelligent Tutoring Systems, Automatic Evaluation, and Assisted Learning. The study reveals that these technologies have already been widely adopted. Moreover, this paper summarizes the influence of AI technologies on engineering education, along with the implications and challenges, providing a foundation for further exploration of the integration of AI technologies into educational systems.

INDEX TERMS Artificial intelligence, engineering education, systematic review, VOSviewer.

I. INTRODUCTION

In recent years, Artificial Intelligence (AI) technologies have been widely applied in the field of education [1], [2]. Research on AI in Education (AIED) has garnered widespread attention. Examples of AIED applications include intelligent tutoring systems, automatic scoring, sentiment analysis, and related areas [3], [4]. Engineering Education refers to the training of professionals in the engineering field, encompassing the development of foundational theoretical knowledge as well as abilities in design, analysis, innovation, and solving complex engineering problems [5]. AI technologies not only offer efficient tools but also enhance students' practical skills in solving complex engineering problems [6], [7].

Systematic reviews help researchers identify gaps in the field, which is crucial for advancing related areas of study [8]. Although relevant review studies already exist in the field of AIED [9], [10], [11], [12], the primary distinction between engineering education and general education lies in its emphasis on developing the skills necessary to solve complex engineering problems. This involves not only mastering theoretical knowledge but also cultivating hands-on practical abilities [5].

Given the growing significance and potential of AI technologies in engineering education, this study seeks to close the research gap by reviewing and synthesizing relevant studies. It examines the current landscape of AI in

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engineering education, research hotspots, application areas, educational effects, and the associated implications and challenges.

II. LITERATURE REVIEW

AI in engineering education, as a subfield of AIED, is playing an increasingly important role in engineering education [13]. Engineering education emphasizes experiential learning and laboratory experience. The application of AI technologies can enhance the teaching processes in engineering education and provide new resources [2], such as intelligent learning management systems and virtual laboratories, which assist in solving complex engineering problems [14]. Multiple studies have demonstrated the potential of AI in improving teaching effectiveness, student engagement, and learning outcomes in the field of engineering education [15], [16], [17], [18]. Overall, AI is reshaping various facets of engineering education, including teaching methodologies, resource availability, and student outcomes.

Currently, there are only a limited number of studies specifically focusing on AI in engineering education. Bahroun et al. [19] employed a bibliometric analysis method to examine 207 research papers on the application of generative AI in education, particularly in medical and engineering education. However, this study primarily focuses on the overall application of generative AI and lacks in-depth analysis of its specific applications and impacts in engineering education. Núñez and Lantada [2] reviewed how AI supports engineering education in teaching processes, exploring its potential and challenges. This provides readers with insights into the application of AI in engineering education. However, it does not offer a specific classification of AI applications in engineering education and lacks an in-depth analysis of the literature.

To address the research gap on the application of AI in engineering education, this systematic review aims to provide a comprehensive understanding of the applications and impacts of AI technologies in engineering education. The research questions are listed as follows:

RQ1: What is the general status of AI in engineering education?

RQ2: What are the top ten organizations, countries, cited sources, and cited authors related to AI in engineering education?

RQ3: What are the application categories of AI in engineering education?

RQ4: What are the effects of AI in engineering education?

RQ5: What are the implications and challenges of AI in engineering education?

III. RESEARCH METHODS

We conducted a systematic review of the application of AI in engineering education, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) [20].

A. DATABASE SEARCH

On October 25, 2024, the researchers conducted a search in the Web of Science (WOS) database utilizing the Science Citation Index Expanded (SCI-EXPANDED), Social Sciences Citation Index (SSCI), and Arts & Humanities Citation Index (A&HCI). The following search strategy was developed: "artificial intelligence" OR AI OR "AIEd" OR "translation machine" OR "chatbot" OR "robot" OR "intelligent tutoring system" OR "virtual agent" OR "conversational agent" OR "machine learning" OR "deep learning" OR "expert system" OR "recommended system" OR "recommendation system" OR "feedback system" OR "personalized learning" OR "adaptive learning" OR "prediction system" OR "student model" OR "learner model" OR "data mining" OR "learning analytics" OR "prediction model" OR "automated evaluation" OR "automated assessment" OR "algorithm" OR "natural language processing" AND "engineering educat*". Researchers restricted the time frame to 2004–2024 and excluded review articles, early access publications, and non-English articles. A total of 377 results were obtained. During the literature screening process, two researchers independently and systematically reviewed all candidate literature according to the predetermined inclusion and exclusion criteria (see Table 1). For articles with discrepancies in the review process, the researchers reached consensus through in-depth discussions. Finally, 161 articles meeting the criteria were included in this systematic review (see Figure 1).

B. DATA SELECTION

Researchers established inclusion and exclusion criteria based on the PRISMA guidelines. The studies will be included if they meet these criteria: (1) Studies related to AI in engineering education; (2) be high-quality peer-reviewed journal articles; (3) were written in English. Studies were excluded if they met any of the following criteria: (1) are not written in English; (2) Studies that are not relevant to the research question; (3) Articles from conference proceeding, book chapters, magazines, news, and posters.

The data screening approach used in this study is shown in Fig. 1. After extracting the data from WOS, a snowballing method was used for further acquisition of relevant articles. The filtering process involved the following steps: (1) Removal of duplicate articles; (2) Screening titles and abstracts to exclude irrelevant articles based on the inclusion and exclusion criteria; (3) Full-text reading to further exclude irrelevant articles; (4) Extracting relevant data from the final set of articles.

C. DATA ANALYSIS

This study utilized bibliometric analysis to examine the literature meeting the established inclusion criteria, followed by content analysis for article classification. To ensure analytical credibility, two researchers conducted thorough verification of the article categorization. Subsequently, in-depth analysis of the categorized articles was performed to determine the research questions for this study.

TABLE 1. Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
1.Studies focus on AI in engineering education.	1.Studies not directly related to AI in engineering education.
2.Articles be published in peer-reviewed journals.	2.Non-journal publications including conference proceedings, book chapters, magazines, news articles, and posters.
3.Research demonstrating the practical implementation and outcomes of AI in engineering education contexts.	3.Theoretical papers or conceptual frameworks without empirical evidence.
4.Articles must be published in English.	4.Studies that only describe AI systems without reporting their educational outcomes.
5.Full text of the articles must be accessible.	5.Papers focusing solely on technical aspects of AI without educational applications.

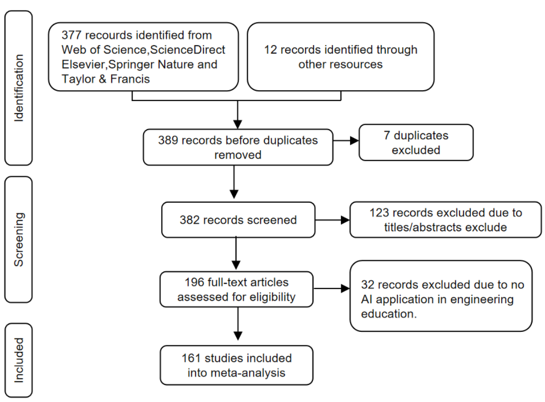

FIGURE 1. A flow chart of literature research.

IV. RESULTS

To address the research questions, the researchers conducted a systematic analysis of the current state of AI research in engineering education, its application categories, effects, and the associated implications and challenges.

A. WHAT IS THE GENERAL STATUS OF AI IN ENGINEERING EDUCATION?

To address this, the researchers analyzed 161 publications, examining trends in publication years and citation counts, the co-occurrence of keywords, and the mediums and environments where AI is applied in engineering education.

1) THE YEAR-BASED TREND OF INCLUDED PUBLICATIONS AND CITATIONS

A detailed analysis of the 161 included publications shows a clear upward trend in AI-related research in engineering education. From 1990 to 2000, the number of related studies was relatively low. However, as AI technologies have advanced and research has deepened, studies on the application of AI in engineering education have steadily increased. This growth has been especially pronounced in recent years, with the number of publications peaking in 2022. This trend indicates that research on AI in engineering education is expanding rapidly and attracting widespread attention. Regarding the citation counts of these 161 publications, they remained nearly unchanged between 1991 and 2007, fluctuated between 2008 and 2017, and then surged sharply from 2018, peaking in 2023. Although 2024 data is incomplete, it is anticipated that both research output and citation counts will reach new highs by the end of the year(see Fig. 2).

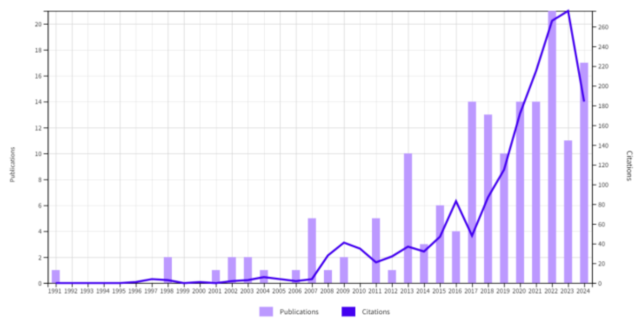

FIGURE 2. The year-based trend of included publications and citations.

2) THE RESEARCH HOTSPOTS RELATED TO AI IN ENGINEERING EDUCATION

In order to visualize the research hotspots related to AI in engineering education, researchers used co-occurrence analysis using VOSviewer. This method considered all keywords as individual units of analysis and used full counting to measure co-occurrences. To ensure relevance, only keywords that appeared at least 8 times were included. Out of 836 keywords, 13 met this threshold.

For each of these 13 keywords, researchers computed the cumulative strength of co-occurrence connections with other keywords. The keywords exhibiting the highest total link strength were then chosen. In this visualization, the size of each node indicates the volume of related publications, while color signifies thematic clusters. The proximity and total link strength between nodes unveil underlying correlations. Notably, closely intertwined subjects are positioned in closer proximity(see Fig. 3).

The keywords and heated topics with the strongest total strength were engineering education(Link = 62, Occurrences = 66), education(Link = 24, Occurrences = 21), data mining(Link = 21, Occurrences = 11), educational data mining(Link = 18, Occurrences = 11), students(Link = 17, Occurrences = 13), learning analytics(Link = 16, Occurrences = 14), machine learning(Link = 15, Occurrences = 9), performance(Link = 13, Occurrences = 9), system(Link = 12,Occurrences = 9),design (Link = 11, Occurrences = 9), systems(Link = 11, Occurrences = 12), artificial intelligence(Link = 9, Occurrences = 14), e-learning (Link = 9, Occurrences = 8).

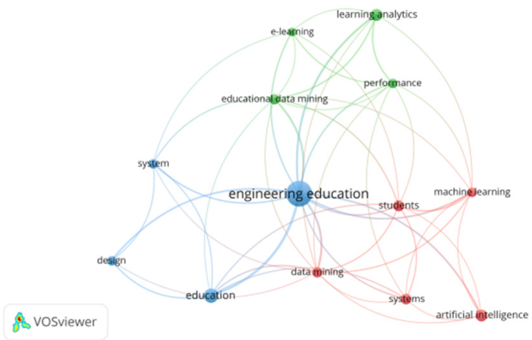

FIGURE 3. Visualization of the co-occurrence of keywords in the studies.

Based on the link strength and occurrences of each keyword, researchers constructed the keyword distribution related to AI in engineering education (see Fig. 4). The keyword distribution indicates that in terms of AI technology applications in engineering education, Learning Analytics, Data Mining, and Educational Data Mining play crucial roles in optimizing educational outcomes, personalizing learning experiences, and evaluating student performance. Furthermore, student behavior analysis, system design, and AI-driven e-learning have emerged as significant focal points, reflecting a trend toward enhancing pedagogical experiences through intelligent systems. These research hotspots demonstrate that AI is facilitating the transformation of engineering education from traditional paradigms toward data-driven and intelligent approaches.

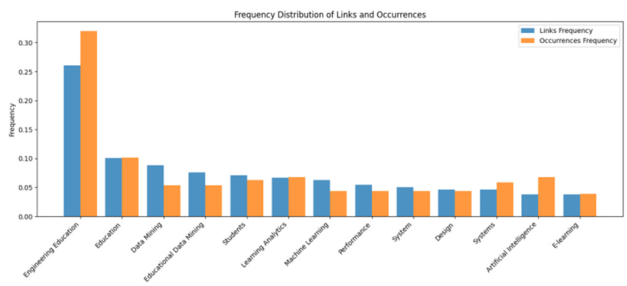

FIGURE 4. Visualization of the keyword distribution.

3) THE MEDIUM AND ENVIRONMENT OF AI IN ENGINEERING EDUCATION

Medium refers to the educational mediums mentioned in studies related to AI in engineering education. Among the 161 included publications, 139 discuss the educational mediums used, which include computer system resource (95), entity resource (25), online resource (14), mobile phone resourc (4), and paper resource (1). Among all these educational mediums, computer system resource are the most frequently used, followed by entity resources and online resources, while mobile phone resources and paper resources are used relatively less frequently (see Table 2).

TABLE 2. Educational medium of AI in engineering education research (N = 39).

Dimension	Category	Number(%)
Educational Medium	Computer system resource	95(67.38%)
	Entity resource (e.g., robot, experimental instrument)	25(17.73%)
	Online resource	14(9.93%)
	Mobile phone resource	4(2.84%)
	Paper resource	1(0.71%)

Environment refers to the educational environments mentioned in studies related to AI in engineering education. Among the 161 included publications, 118 discuss the educational environments used, including online learning environment (52), experimental learning environment (35), virtual reality/augmented reality learning environment (18), and face-to-face learning environment (12). Online learning environments are the most frequently used, while face-to-face environments are the least utilized(see Table 3).

TABLE 3. Educational medium of AI in engineering education research (N = 139).

Dimension	Category	Number(%)
Educational Medium	Online learning environment	52(44.4%)
	Experimental environment (i.e., lab)	35(29.9%)
	Virtual reality/augmented reality learning environment	18(15.4%)
	Face-to-face learning environment	12(10.3%)

B. WHAT ARE THE TOP TEN ORGANIZATIONS, COUNTRIES, CITED SOURCES, AND CITED AUTHORS RELATED TO AI IN ENGINEERING EDUCATION ?

To identify the top ten organizations, countries, cited sources, and authors related to AI in engineering education, researchers used VOSviewer to compute the rankings (see Table 4). Based on citation counts, the top ten cited organizations are University of Maribor, University of Málaga, Wuhan University, Clemson University, Universidad Carlos III de Madrid, IMDEA Networks Institute, Guru Nanak Dev University, Texas A&M University, JdeRobot Organization, Universidad Rey Juan Carlos. The top ten countries are Spain, USA, People's Republic of China, India, Mexico, Turkey, Taiwan, Malaysia, Australia, Saudi Arabia. These countries show significant variation in citation counts, with Spain, USA, and People's Republic of China collectively accounting for over 60% of all citations. The top ten cited sources are IEEE Transactions on Education, Computers & Education, Computer Applications in Engineering Education, International Journal of Engineering Education, Journal of Engineering Education, IEEE Access, Computers in Human Behavior, IEEE Transactions on Industrial Electronics, IEEE Robotics and Automation Magazine, IEEE Transactions on Learning Technologies. The top ten cited author are Romero, C., Lei, Z. C., Ohland, M. W., Casini, M., Baker, R. S. J. D., Lord, S. M., Maiti, A., Mayer, R. E., McLurkin, J., Michaud, F.

TABLE 4. Top ten organizations, countries, cited sources, cited author.

No.	Organization	Citation	Link
1	University of Maribor	126	0
2	University of Málaga	96	0
3	Wuhan University	93	4
4	Clemson University	83	2
5	Universidad Carlos III de Madrid	79	3
6	IMDEA Networks Institute	67	3
7	Guru Nanak Dev University	55	0
8	Texas A&M University	51	2
9	JdeRobot Organization	40	2
10	Universidad Rey Juan Carlos	40	2
No.	**Country**	**Citation**	**Link**
1	Spain	499	3
2	USA	362	7
3	People's Republic of China	177	4
4	India	72	1
5	Mexico	56	1
6	Turkey	45	0
7	Taiwan	38	2
8	Malaysia	23	2
9	Australia	16	2
10	Saudi Arabia	12	2
No.	**Cited Sources**	**Citation**	**Link**
1	IEEE Transactions on Education	175	1167
2	Computers & Education	160	1368
3	Computer Applications in Engineering Education	135	815
4	International Journal of Engineering Education	90	782
5	Journal of Engineering Education	67	609
6	IEEE Access	63	445
7	Computers in Human Behavior	58	598
8	IEEE Transactions on Industrial Electronics	45	335
9	IEEE Robotics and Automation Magazine	42	366
10	IEEE Transactions on Learning Technologies	37	333
No.	**Cited authors**	**Citation**	**Link**
1	Romero, C.	23	16
2	Lei, Z. C.	11	22
3	Ohland, M. W.	11	81
4	Casini, M.	10	3
5	Baker, R. S. J. D.	9	11
6	Lord, S. M.	9	81
7	Maiti, A.	9	19
8	Mayer, R. E.	9	0
9	McLurkin, J.	9	0
10	Michaud, F.	9	0

C. WHAT ARE THE APPLICATION CATEGORIES OF AI IN ENGINEERING EDUCATION ?

Two researchers independently analyzed the 161 relevant publications. When disagreements arose, they discussed and resolved them. This process led to the identification of seven categories of AI applications: Virtual Experiment Environment, Learning Prediction, Learning Analytics, Engineering Education Robot, Intelligent Tutoring System, Automatic Evaluation, and Assisted Learning (see Table 5).

1) VIRTUAL EXPERIMENT ENVIRONMENT

The first category of AI applications in engineering education is the Virtual Experiment Environment. Among the 161 relevant publications, 25 mention Virtual Experiment Environments. This category includes two subcategories: intelligent experimental environment and remote-controlled experiment. AI-based virtual simulation experiment teaching systems can provide intelligent experimental environment [30]. For example, the Web-based modular virtual laboratory system, by integrating an Intelligent Tutoring System (ITS) and animated demonstrations, can adjust the experimental content in real time based on students' learning progress and feedback. This intelligent environment not only enhances students' learning outcomes but also provides teachers with more flexible teaching tools, enabling them to more effectively monitor and guide the learning process [22]. One prominent example of an AI-enhanced virtual experimental tool is the Webots simulator, widely used in engineering education. By leveraging AI technology, Webots simulates complex robotic operations and provides real-time feedback, facilitating a deeper understanding of operational principles and control strategies in robotics [33]. Furthermore, Gulec et al developed a virtual reality environment that simulates the software development process, providing students with a highly interactive and immersive learning platform [21]. The gamified robotic simulator strengthens students' hands-on abilities by turning learning content into a game. This combination of virtual simulation and gamified learning not only increases student engagement but also enhances their understanding and application of complex engineering concepts [25]. In terms of remote-controlled experiment, AI technology enables students to monitor and operate experiments in real-time remotely. This allows them

TABLE 5. The categories of AI applications in engineering education.

Category	Sub-category	Articles
1.Virtual Experiment Environment	1.a Intelligent experimental environment	[21]; [22]; [23]; [24]; [25]; [26]; [27]; [28]; [29]; [30]; [31]; [32]; [33]; [34]; [35]
	1.b Remote-controlled experiment	[36]; [37]; [38]; [39]; [40]; [41]; [42]; [6]; [43]; [44]
2.Learning prediction	2.a Learning performance prediction	[45]; [46]; [47]; [48]; [49]; [50]; [51]; [52]; [53]
	2.b Innovation capability and student status prediction	[54]; [55]; [56]; [57]; [58]; [59]; [60]
3.Learning analytics	3.a Learning behavior analysis	[61]; [62]; [63]; [64]; [65]; [66]; [67]; [17]; [68]; [69]; [70]; [71]; [72]; [73]; [74]; [75]; [76]; [77]; [78]; [79]; [80]; [81]; [82]
	3.b Teaching methods and quality optimization	[83]; [84]; [85]; [86]; [87]; [88]; [89]; [90]
4.Engineering Education Robot	4.a Programming robots	[91]; [92]; [93]; [94]; [95]; [96]; [97]; [98]; [99]; [100]; [101]; [102]; [103]; [104]; [105]; [106]
	4. b Robotics competition	[107]; [108]; [109]; [110]; [111]; [112]; [113]; [114]; [115]; [116]
5.Intelligent turtoring system	5.a Adaptive learning platform	[117]; [118]; [119]; [120]; [121]; [122]; [123];
	5.b Interactive feedback system	[124]; [125]; [126]; [127]; [128]; [129];
	5.c Expert system-based teaching and assessment	[130]; [131]; [132]; [133]
6. Automatic evaluation	6.a Programming and code quality assessment	[134]; [135]; [136]; [137];
	6.b Student performance evaluation	[138]; [139]; [140]; [141]; [142]; [143]; [144]; [145]; [7]
7.Assisted learning	7.a Assisted learning	[13]; [146]; [147]; [148]; [149]; [150]; [151]; [152]; [153]; [16]; [154]; [155]

to access experimental equipment from any location and perform actual control system design and debugging [39]. The online laboratory framework enabled by AI technology can support large-scale online engineering experiments [41]. The application of virtual experimental environments in engineering education manifests in three technical aspects: (1) Web-based remote laboratory architectures, such as the front-end and back-end separation framework proposed by Lei et al., which enables online control algorithm design through JointJS interface and dedicated algorithm servers; [41] (2) VR-integrated immersive learning environments, exemplified by the VR-SODEF framework developed by Gulec et al., which provides comprehensive software development experience through AI-driven virtual characters and situational simulations; [21] (3) Intelligent teaching support systems, like the IVLS system designed by Hsieh et al., which integrates intelligent tutoring and animated demonstrations to enhance PLC technology learning [22]. Practical evidence demonstrates the effectiveness of these integrated technologies, as shown in Lee et al.'s study, where gamified robotic simulators outperformed traditional methods in inquiry learning and reflective thinking [25]. In summary, the application of AI technology not only overcomes the limitations of traditional laboratories but also provides enriched and diversified learning environments for engineering education.

2) LEARNING PREDICTION

The second category of AI applications in engineering education is Learning prediction. Of the 161 relevant studies, 16 specifically address Learning Prediction. This category is further divided into two subcategories: learning performance prediction and innovation capability and student status prediction. The first subcategory, learning performance prediction, involves analyzing data from students' interactions with e-learning platforms to forecast their academic outcomes in engineering courses [49]. By leveraging AI models, educators can more accurately predict students' academic performance, allowing for early intervention to improve overall learning outcomes. Commonly used models include Fuzzy Inference Systems (FIS) [45], [46], the Generalized Linear Autoregressive (GLAR) model [47], the D-vine copula model [52], and tree-based models [53]. For example, Bressane et al. developed a fuzzy AI-based model achieving 94% accuracy in training and 91.9% generalization capability for predicting student performance, identifying course review (34.6%), reference reading (25.6%), class attendance (23.5%), and emotional control (16.3%) as key learning factors [45]. The second subcategory, Innovation Capability and Student Status Prediction, uses AI technologies to assess students' creativity, cognitive development, and emotional states. This allows for more personalized support of individual learning needs and helps inform teaching strategies. For example, by analyzing students' discussion logs during creative activities, the Support Vector Machine (SVM) model can predict creativity in engineering education, promoting innovative thinking [54]. In the context of skill acquisition, integrating Mixed Reality (MR) with deep learning models can accurately identify students' interaction challenges and assess their cognitive development levels [59]. In graduate software engineering education, Support Vector Regression (SVR) techniques can predict individual productivity among graduate students [57]. Additionally, combining Long Short-Term Memory (LSTM) networks with Convolutional Neural Networks (CNN) enables precise prediction of students' emotional states during the learning process [57]. These studies demonstrate that by thoroughly analyzing student status, it is possible to predict factors such as learning performance, academic standing, and emotional well-being, allowing educators to provide personalized guidance tailored to each student's needs.

3) LEARNING ANALYTICS

The first category of AI applications in engineering education is learning analytics. Among the 161 relevant studies, 31 have mentioned learning analytics. This category is divided into two subcategories: learning behavior analysis and teaching methods and quality optimization. The first subcategory is learning behavior analysis, which involves an in-depth examination of students' behavioral data during the learning process. This analysis can reveal students' learning patterns, habits, engagement levels, and individual differences, thereby providing a foundation for personalized instruction and the optimization of learning pathways. For instance, in engineering education, AI technology can classify students' behavioral patterns by analyzing their interactions with educational software [79]. By analyzing student behaviors in online open courses, interventions can be made to provide personalized guidance tailored to each student's needs [65]. By analyzing classroom learning behaviors and emotional states, teachers can gain a deeper understanding of students' learning conditions [17]. Analyzing language and behaviors within team collaborations can swiftly identify and intervene in instances of marginalization within the team [66]. In teaching optimization, the implementation focuses on data-driven decision making. For instance, Vargas et al. proposed a comprehensive competency assessment framework that enables continuous monitoring and improvement through learning analytics, achieving successful implementation across 15 courses in eight different university degrees [88]. The second subcategory is Teaching Methods and Quality Optimization, which primarily focuses on improving teaching methods and strategies, optimizing teaching quality, and enhancing the learning experience through AI technologies. For example, teachers can use AI to analyze students' learning behavior data to refine flipped classroom approaches, thereby improving student learning efficiency [84], [87]. Utilizing data mining techniques to analyze students' learning outcomes in engineering education can significantly enhance the quality of education [86]. A competency assessment framework can be employed to monitor and evaluate teaching quality [88]. Data mining methods can be used to analyze learning objectives and outcomes in engineering education, providing insights that optimize teaching decisions [90]. However, some learners believe that the risks associated with using AI technologies for learning analytics outweigh the benefits [69]. In summary, learning behavior analysis and teaching methods and quality optimization can help both teachers and students enhance the learning experience and improve learning outcomes.

4) ENGINEERING EDUCATION ROBOT

The fourth category of AI applications in engineering education is engineering education robots. Among the 161 relevant studies, 25 have mentioned engineering education robots. This category is divided into two subcategories: programming robots and robotics competitions. The first subcategory, programming robots, refers to the use of robots as practical platforms and tools for students to engage in hands-on activities and programming, thereby enhancing their engineering application skills. For example, Robot platforms such as Lego Mindstorms and Mitsubishi are commonly used in programming and control courses [91], [93], [98],Additionally, the low cost and scalability of these platforms have made their use in education increasingly widespread, allowing them to meet diverse teaching needs. These platforms can accommodate various levels of instruction, ranging from basic C language programming [97] to complex control system design [100]. Technologically, many studies utilize ROS (Robot Operating System) as a development platform, such as the open-source educational tool developed by Canas et al. (2020), which integrates 3D simulation and Python programming environments to support training in various real-world application scenarios [160]. The second subcategory, robotics competitions, involves using robotics competitions and projects to spark students' interest in learning. By designing, building, and testing robots, students develop the ability to solve complex engineering problems. For example, competition-based learning environments like the RoboWaiter competition [107] and drone programming competitions [109],foster project-based learning that enhances students' overall competencies and professional skills. In summary, these two applications complement each other in engineering education, collectively advancing the development of students' engineering capabilities and professional skills.

5) INTELLIGENT TUTORING SYSTEM

The fifth category of AI applications in engineering education is the Intelligent Tutoring System. Of the 161 relevant studies, 18 mention the Intelligent Tutoring System. This category includes three subcategories: adaptive learning platforms, interactive feedback systems, and expert system-based teaching and assessment. The first subcategory, adaptive learning platforms utilize AI technology to tailor learning content and difficulty levels based on students' individual needs and learning styles. For example, adaptive platforms can help identify areas where students struggle and provide teachers with recommendations for instructional adjustments [117],Personalized Learning Environment (PLE) systems not only enhance students' motivation to learn but also enable teachers to more effectively monitor and guide students' learning progress [118]. In flipped classrooms, the integration of adaptive learning systems has a positive impact on students' motivation and learning outcomes [119]. For Java programming practice, adaptive learning systems dynamically adjust the learning content based on students' performance during their activities [120]. Additionally, adaptive learning can be integrated with virtual reality technology to continuously optimize and adjust the learning environment, thereby enhancing students' learning outcomes [122]. AI-driven personalized learning recommendation systems can also assist students in setting learning goals and recommending optimal learning pathways [123]. In terms of adaptive learning platforms, research indicates that the core technical principles are based on learner modeling and content adaptation. For instance, the ADEPT platform developed by Al-Othman et al. identifies learning challenges and adjusts teaching strategies by analyzing student performance [117]. Regarding implementation details, Clark et al. demonstrated that combining adaptive learning with flipped classrooms during COVID-19 significantly improved students' perception of the classroom environment and independent learning motivation [119]. The second subcategory, interactive feedback system, refers to the use of interactive feedback to help students promptly correct errors and gain a deeper understanding of the learning material. For example, the Mechanix sketch recognition tool uses AI algorithms to identify and analyze students' drawings, providing immediate feedback [124]. RoboREIT, an interactive robotic tutor, can enhance students' interview skills by simulating interview scenarios and providing real-time feedback [125]. Additionally, an emotional feedback system can perform real-time analysis of students' emotional states and provide feedback and guidance accordingly [126]. The third subcategory, expert system-based teaching and assessment, refers to the use of expert systems' reasoning and decision-making capabilities to provide automated instructional guidance and assessment. This approach is particularly effective in addressing the learning needs of large groups of students. For example, In computer science, expert system knowledge bases can for undergraduate computer networking courses [130]. In the field of manufacturing engineering, intelligent tutoring systems are used to efficiently develop instructional content [131]. In power engineering education, expert systems are used to simulate emergency scenarios, enhancing students' operational skills [132], [133]. In summary, the integration of these three applications can support complex engineering instruction and significantly enhance the quality of engineering education.

6) AUTOMATIC EVALUATION

The fifth category of AI applications in engineering education is automatic evaluation. Of the 161 relevant studies, 13 mention automatic evaluation. This category is divided into two subcategories: programming and code quality assessment and student performance evaluation. The first subcategory, programming and code quality assessment, focuses on evaluating the quality of programming and code, both of which are critical in engineering education. The core technical principles include black-box testing (based on input-output comparison) and white-box testing (based on source code property checking). For instance, the semi-automatic assessment system developed by Insa et al. automatically completed over 48% of the evaluation workload in practical applications, significantly improving assessment efficiency [135]. Automated programming assessment systems (APAS) analyze code quality to assess individual contributions within team projects and the overall quality of programming assignments [134]. Semi-automated code assessment methods have been widely applied to Java programming tasks, enabling rapid and objective evaluation of both code functionality and quality [135]. Tools like CodeLabeller enhance the efficiency of labeling source code files in large-scale annotation tasks [136]. Additionally, GPTSniffer can effectively detect AI-generated code, helping safeguard academic integrity in engineering education [137]. The second subcategory, student performance evaluation, involves using AI technology to analyze students' learning progress and professional skills, allowing educators to assess academic performance and project management capabilities [138], [141], [145]. Furthermore, automatic evaluation tools designed specifically for engineering education can assist students in mastering essential engineering skills. For example, automated assessment tools based on CAD models [139], as well as tools that support practice and automated evaluation in online learning environments [142], are commonly used. In fields like production scheduling within mechanical engineering, the application of these tools helps students acquire solid practical skills [7]. In summary, automatic evaluation tools designed for specific areas in engineering education allow students to quickly acquire specialized skills, contributing to their overall professional development.

7) ASSISTED LEARNING

The sixth category of AI applications in engineering education is Assisted Learning, which refers to the use of AI to support teaching and enhance the student learning process. Of the 161 relevant studies, 12 mention Assisted Learning. For example, in engineering education, AI tools can be used to generate interface design wireframes, helping students develop and visualize user interfaces [13]. In software development, the application of genetic algorithms to optimize group learning structures improves the effectiveness of software engineering education [146]. Similarly, in fields such as control engineering [150], architectural engineering [153], and civil engineering [155], students can enhance their learning outcomes by using AI tools. In summary, AI technology not only assists students in their learning but also optimizes teaching processes, significantly improving the effectiveness of engineering education.

D. WHAT ARE THE EFFECTS OF AI IN ENGINEERING EDUCATION ?

From an educational perspective, 40 of the 161 relevant studies have discussed the impact of AI techniques on engineering education. These impacts include improvements in learning performance, learning perception, and the overall ability to apply AI techniques within the field of engineering education.

1) THE EFFECT OF LEARNING PERFORMANCE

Among the 40 studies on the educational impact, 14 specifically focused on its influence on students' learning performance. These studies found that AI techniques not only enhance students' academic performance in engineering education but also positively influence their skill acquisition and overall learning outcomes. For instance, the Mechanix system, which combines AI with real-time error feedback, has been shown to significantly improve students' learning performance [124]. The Virtual Programmable Logic Controller, through intelligent tutoring, helps students better understand and master complex concepts in manufacturing engineering [23]. In practical applications, the introduction of short-term courses and fluid simulation tools using AI technology enhances students' knowledge acquisition in fluid mechanics [156]. Additionally, the use of low-cost robots and experimental platforms in automation education greatly improves students' hands-on skills [105]. In summary, AI technology in engineering education not only boosts students' academic performance but also significantly enhances their practical skills.

2) THE EFFECT OF LEARNING PERCEPTION

Among the 40 studies on the educational impact, 11 specifically highlight its influence on students' learning perception, focusing primarily on interest, motivation, and engagement. The interactivity and real-time feedback offered by AI can boost students' interest and motivation in learning. For example, the introduction of LEGO robots in introductory programming courses has been shown to increase students' enthusiasm for learning [91]. Similarly, the RoboWaiter competition sparks greater interest in engineering design [107]. The use of intelligent tutoring systems and virtual reality technology also contributes to improved learning perception. For instance, the edX-LIS system enhances students' motivation, persistence, and engagement by providing regular learning feedback [65]. Moreover, learning environments that combine AI with virtual reality technology further increase students' motivation [122]. In summary, through the interactivity and feedback provided by AI technology, students' interest, motivation, and engagement in learning can be significantly enhanced.

3) THE EFFECT OF COMPREHENSIVE ABILITY

Among the 40 studies on the educational impact, 15 have addressed the influence on students' comprehensive abilities, focusing on how AI technology affects communication skills, teamwork, creativity, computational thinking, and problem-solving abilities in engineering education. Regarding teamwork and communication skills, the Automatic Programming Assessment System (APAS) aids in identifying "free-riding" behavior within teams by evaluating code quality and team participation, thereby promoting students' teamwork abilities and contributions to projects [134]. The RoboREIT system, by simulating real-world requirements-gathering interview scenarios, enhances students' communication and expression skills in software engineering [125]. In terms of computational thinking and problem-solving abilities, personalized learning recommendation systems can effectively enhance students' computational thinking skills [123]. In fostering students' creativity, models that predict creativity by analyzing discussion records can enhance students' engagement and innovativeness throughout the learning process [54]. In summary, the application of AI technology can effectively enhance students' problem-solving abilities in engineering.

E. WHAT ARE THE IMPLICATIONS AND CHALLENGES OF AI IN ENGINEERING EDUCATION ?

In this section, we summarize the benefits and challenges of AI in engineering education.

1) IMPLICATIONS OF AI IN ENGINEERING EDUCATION

A diversified learning environment. In the field of engineering education, the advancement of AI technology has significantly contributed to the creation of diversified learning environments. By integrating virtual reality (VR) and augmented reality (AR) with AI, educators can design complex and varied learning scenarios that enable students to intuitively grasp intricate engineering principles within virtual environments. For instance, the fusion of AI algorithms with VR/AR technologies greatly enhances the user experience in virtual learning settings [157]. Additionally, combining classroom instruction with hands-on practice through mobile robotic production lines offers students exposure to a wide array of practical environments [6]. Moreover, web-based virtual and remote laboratory environments can replicate real experimental conditions, providing opportunities to reduce the costs associated with physical laboratories [31]. In summary, these diverse practical environments not only enrich the content and delivery methods of engineering education but also offer students more flexible and varied learning pathways.

Personalized learning guidance. AI enables the provision of personalized learning paths and resource recommendations by analyzing each student's learning habits, knowledge proficiency, and obstacles. For example, by collecting and analyzing classroom performance data, teachers can identify areas where students may struggle and provide targeted guidance accordingly [88]. Furthermore, personalized learning recommendation systems can analyze skill requirements from online job postings to offer students tailored learning objectives that align with the demands of the future job market [123]. In conclusion, with the support of AI technology, students can discover learning methods and paces that best suit their individual needs, thereby laying a solid foundation for the intelligent evolution of engineering education.

2) CHALLENGES OF AI IN ENGINEERING EDUCATION

Privacy and data security. In the process of collecting and analyzing student data, AI systems must manage significant amounts of sensitive information. If not properly handled, this data could result in privacy violations. For example, when predicting learners' emotional states, the use of audio, video, and biosensors may risk privacy breaches [60]. With the widespread use of generative AI tools like ChatGPT in programming education, students may inadvertently expose learning data during code generation, leading to potential data security issues [137]. In summary, as AI becomes more integrated into engineering education, concerns related to privacy and data security are becoming increasingly prominent. It is crucial for technology providers to collect and store data responsibly, ensuring the protection of student privacy.

Technology training and teacher support. The rapid development of AI technology places higher demands on educators, presenting challenges to its application in engineering education, particularly in contexts where teachers lack technical expertise. For instance, AI tools like ChatGPT offer significant potential in teaching, but both teachers and students must undergo training to use these tools effectively [16]. Moreover, some educators in engineering fields adopt a conservative attitude toward AI technology, hindering its widespread adoption in engineering education [151]. Technical challenges also arise in the adaptability of AI to various environments. For example, gamified learning technologies require not only interdisciplinary technical support for teachers but also additional environmental and technological infrastructure [158]. Although AI technology holds great potential in engineering education, it imposes higher demands on educators, making additional technical support and training essential. This assistance is crucial to helping teachers overcome technical challenges, thereby ensuring more effective application of AI in education.

V. DISCUSSION

Although Artificial Intelligence in Education (AIED) has garnered widespread attention in the educational community, research on the application of AI technology in engineering education remains limited. To address this research gap, this study systematically reviews and synthesizes 161 relevant studies, providing a comprehensive overview of AI applications in engineering education and answering the following five research questions: (1) general status of AI in engineering education, (2) the top ten organizations, countries, cited sources, and authors related to AI in engineering education, (3) the application categories of AI in engineering education, (4) the effects of AI in engineering education, and (5) the implications and challenges of AI in engineering education.

A. GENERAL STATUS OF AI IN ENGINEERING EDUCATION?

Firstly, an analysis of the number of relevant publications, citation counts, and their trends reveals significant growth in the application of artificial intelligence (AI) in engineering education. It is anticipated that the number of related publications and citations will reach new peaks by 2024. Utilizing co-occurrence analysis with VOSviewer, this study identifies key research hotspots in AI in engineering education, focusing on areas such as engineering education, data mining, learning analytics, and machine learning. By reviewing and summarizing discussions on 'The medium and environment of AI in engineering education' in relevant publications, this study finds that most research relies on computer system resources and experimental learning environments. The widespread application of computer system resources provides a solid foundation for integrating AI technologies into engineering education. Additionally, the use of online learning platforms and virtual reality/augmented reality (VR/AR) environments has been increasing, primarily because VR/AR technologies offer enhanced learning experiences, enabling students to better comprehend complex engineering principles [157].

B. THE APPLICATION OF AI IN ENGINEERING EDUCATION

After summarizing and analyzing 161 relevant studies, it was found that the application of AI in engineering education is not identical to that in general AIEd (Artificial Intelligence in Education). These similarities include areas such as learning analytics and learning prediction. However, this study identifies several unique applications of AI specifically in engineering education. The first category involves the use of virtual laboratory environments, where AI technologies simulate real experimental conditions, providing students with a safe, repeatable, and flexible experimental platform. For example, virtual and remote laboratory environments enhance students' learning experiences and practical skills [31]. The second category involves engineering education robots. Educational robots simulate human teachers to interact with students [159], while engineering education robots provide a platform that bridges learning and practical application, fostering students' hands-on abilities [100]. Additionally, when students design and program robots, they are exposed to real engineering environments, further enhancing their engineering practice skills [115]. The third category involves intelligent tutoring systems, which primarily emphasize using AI technology to enhance students' skills in engineering education. For instance, these systems can diagnose students' issues in power systems courses [133] and recommend acquiring specific skills based on the job market demands [62]. The fourth category involves automated assessment, focusing on specific areas such as evaluating programming and code quality in engineering practice [134] and assessing learning and project management skills [138], [141], [145]. In summary, as AI technology continues to advance, integrating it with engineering education to fully harness its potential represents a crucial direction for future research.

C. THE EFFECTS OF AI IN ENGINEERING EDUCATION

Enhancing students' learning performance. Providing personalized learning paths and real-time feedback can significantly enhance students' learning performance. For instance, tree-based machine learning algorithms can predict students' academic performance in undergraduate courses, enabling the rapid identification of academic risks and timely interventions, thereby improving overall performance [53]. A personalized learning recommendation system can analyze the demand for professional skills and suggest relevant learning content, helping students acquire targeted competencies. This approach enhances the effectiveness of engineering education by aligning student learning with industry needs [123].

Enhancing students' learning perception. Students generally hold a positive attitude toward AI tools like ChatGPT. The use of AI technology can enhance student engagement and improve learning attitudes [16], [155]. In virtual reality learning environments, AI enhances the immersion and interactivity of the learning experience. These enriched experiences can increase students' interest and motivation in learning [32].

In terms of students' overall competencies, AI tools can assist learners in understanding and applying knowledge in programming and engineering design, thereby fostering their problem-solving abilities in engineering contexts [89]. AI-based practical platforms can significantly enhance students' overall competencies. For example, intelligent manufacturing training systems can develop critical thinking and problem-solving skills.

D. IMPLICATIONS AND CHALLENGES OF AI IN ENGINEERING EDUCATION

In engineering education, it is crucial to address privacy and data security concerns associated with AI technology. While the widespread adoption of generative AI offers convenience in student programming, it also elevates data security risks, which must be mitigated through a combination of technological and managerial strategies. Additionally, educators need adequate training and technical support to navigate these challenges. In summary, it is essential to consider various factors, including technology, policy, and practice, to ensure that AI can positively impact engineering education.

VI. CONCLUSION AND LIMITATION

The application of AI technology is profoundly influencing engineering education. While AI offers numerous advantages and opportunities in this field, it also encounters challenges, including privacy protection and the need for technical support. This paper provides a systematic review of the current research on AI in engineering education, covering its application categories, impacts, and associated challenges. However, this review has several limitations: First, the study retrieved data exclusively from the Web of Science (WOS) database. Future research should consider including additional databases, such as Taylor & Francis, ScienceDirect, Elsevier, and Springer, to broaden the scope. Additionally, potential biases in the search and screening processes could be mitigated by refining the search strategy in future studies. Second, this study was limited to a systematic review. Future research could conduct a meta-analysis to more deeply explore the impact of AI technology on engineering education.

Data included in this article:

https://docs.google.com/spreadsheets/d/19j5brKG7eSGxFIy7FuPBPjwwEt1o3XsnTsU6nQ7JJuM/pubhtml

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

DECLARATIONS

CONFLICT OF INTEREST/COMPETING INTERESTS

We have no conflicts of interest to declare that are relevant to thecontent of this article.

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AUTHOR CONTRIBUTIONS

Cong Liu and Guang-Chao Wang Rong collected data, analyzed data, edited, revised, and confirmed the article; Cong Liu and Hong-Feng Wang conceptualized and supervised the research process.

COMPETING INTERESTS

The authors declare no competing interests.

ETHICAL APPROVAL

This article does not contain any studies with human participants conducted by any of the authors.

INFORMED CONSENT

This article does not contain any studies with human participants performed by any of the authors.

REFERENCES

[1] H. Luan, P. Geczy, H. Lai, J. Gobert, S. J. H. Yang, H. Ogata, J. Baltes, R. Guerra, P. Li, and C.-C. Tsai, "Challenges and future directions of big data and artificial intelligence in education," *Frontiers Psychol.*, vol. 11, Oct. 2020, Art. no. 580820, doi: 10.3389/fpsyg.2020.580820.

[2] J. L. M. Naez and A. D. Lantada, "Artificial intelligence aided engineering education: State of the art, potentials and challenges," *Int. J. Eng. Educ.*, vol. 36, no. 6, pp. 1740–1751, 2020.

[3] X. Chen, D. Zou, H. Xie, G. Cheng, and C. Liu, "Two decades of artificial intelligence in education," *Educ. Technol. Soc.*, vol. 25, no. 1, pp. 28–47, 2022.

[4] B. K. Prahani, I. A. Rizki, B. Jatmiko, N. Suprapto, and A. Tan, "Artificial intelligence in education research during the last ten years: A review and bibliometric study," *Int. J. Emerg. Technol. Learn. (iJET)*, vol. 17, no. 8, pp. 169–188, Apr. 2022.

[5] R. S. Adams, J. Turns, and C. J. Atman, "Educ.ating effective engineering designers: The role of reflective practice," *Design Stud.*, vol. 24, no. 3, pp. 275–294, May 2003.

[6] S. Wang, L. Jiang, J. Meng, Y. Xie, and H. Ding, "Training for smart manufacturing using a mobile robot-based production line," *Frontiers Mech. Eng.*, vol. 16, no. 2, pp. 249–270, Jun. 2021, doi: 10.1007/s11465-020-0625-z.

[7] K. J. Woo, "A job shop scheduling game with GA-based evaluation," *Appl. Math. Inf. Sci.*, vol. 8, no. 5, pp. 2627–2634, Sep. 2014, doi: 10.12785/amis/080562.

[8] J. Paul and A. R. Criado, "The art of writing literature review: What do we know and what do we need to know?" *Int. Bus. Rev.*, vol. 29, no. 4, Aug. 2020, Art. no. 101717, doi: 10.1016/j.ibusrev.2020.101717.

[9] K. Guo, Y. Li, Y. Li, and S. K. W. Chu, "Understanding EFL students' chatbot-assisted argumentative writing: An activity theory perspective," *Educ. Inf. Technol.*, vol. 29, no. 1, pp. 1–20, Jan. 2024, doi: 10.1007/s10639-023-12230-5.

[10] O. Zawacki-Richter, V. I. Marín, M. Bond, and F. Gouverneur, "Systematic review of research on artificial intelligence applications in higher education-where are the educators?" *Int. J. Educ. Technol. Higher Educ.*, vol. 16, no. 1, pp. 1–27, Dec. 2019, doi: 10.1186/s41239-019-0171-0.

[11] K.-Y. Tang, C.-Y. Chang, and G.-J. Hwang, "Trends in artificial intelligence-supported e-learning: A systematic review and co-citation network analysis (1998–2019)," *Interact. Learn. Environments*, vol. 31, no. 4, pp. 2134–2152, May 2023, doi: 10.1080/10494820.2021.1875001.

[12] C. Perrotta and N. Selwyn, "Deep learning goes to school: Toward a relational understanding of AI in education," *Learn., Media Technol.*, vol. 45, no. 3, pp. 251–269, Jul. 2020, doi: 10.1080/17439884.2020.1686017.

[13] D. Gudoniene, E. Staneviciene, V. Buksnaitis, and N. Daley, "The scenarios of artificial intelligence and wireframes implementation in engineering education," *Sustainability*, vol. 15, no. 8, p. 6850, Apr. 2023.

[14] A.-J. Pan, Y.-C. Huang, and C.-F. Lai, "Constructing hands-on distance labs: The development and implementation of an intelligent learning management system (ILMS-d) in undergraduate IoT courses," *Interact. Learn. Environments*, vol. 32, no. 10, pp. 6413–6429, Nov. 2024, doi: 10.1080/10494820.2023.2263061.

[15] M. Chan, J. Chan, C. Gelowitz, and C. Chan, "Application of video game artificial intelligence techniques for design of a simulation software systemfor transportation engineering education," *Int. J. Eng. Educ.*, vol. 32, no. 1, pp. 542–552, Jan. 2016.

[16] T. Pham, T. B. Nguyen, S. Ha, and N. T. Nguyen Ngoc, "Digital transformation in engineering education: Exploring the potential of AI-assisted learning," *Australas. J. Educ. Technol.*, vol. 39, no. 5, pp. 1–19, Dec. 2023, doi: 10.14742/ajet.8825.

[17] J. Hu, Z. Huang, J. Li, L. Xu, and Y. Zou, "Real-time classroom behavior analysis for enhanced engineering education: An AI-assisted approach," *Int. J. Comput. Intell. Syst.*, vol. 17, no. 1, p. 15, Jun. 2024.

[18] B. Ramos and R. Condotta, "Enhancing learning and collaboration in a unit operations course: Using AI as a catalyst to create engaging problem-based learning scenarios," *J. Chem. Educ.*, vol. 101, no. 8, pp. 3246–3254, Aug. 2024, doi: 10.1021/acs.jchemed.4c00244.

[19] Z. Bahroun, C. Anane, V. Ahmed, and A. Zacca, "Transforming education: A comprehensive review of generative artificial intelligence in educational settings through bibliometric and content analysis," *Sustainability (Basel)*, vol. 15, no. 17, p. 12983, 2023, doi: 10.3390/su151712983.

[20] D. Moher, "Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement," *Ann. Internal Med.*, vol. 151, no. 4, p. 264, Aug. 2009, doi: 10.7326/0003-4819-151-4-200908180-00135.

[21] U. Gulec, M. Yilmaz, V. Isler, and P. M. Clarke, "Applying virtual reality to teach the software development process to novice software engineers," *IET Softw.*, vol. 15, no. 6, pp. 464–483, Dec. 2021, doi: 10.1049/sfw2.12047.

[22] S. Hsieh, "Animations and intelligent tutoring systems for programmable logic controller education," *Int. J. Eng. Educ.*, vol. 19, pp. 282–296, Jan. 2003.

[23] S.-J. Hsieh and P. Y. Hsieh, "web-based modules for programmable logic controller education," *Comput. Appl. Eng. Educ.*, vol. 13, no. 4, pp. 266–279, Jan. 2005, doi: 10.1002/cae.20052.

[24] W. Hu, Z. Lei, H. Zhou, G.-P. Liu, Q. Deng, D. Zhou, and Z.-W. Liu, "Plug-in free web-based 3-D interactive laboratory for control engineering education," *IEEE Trans. Ind. Electron.*, vol. 64, no. 5, pp. 3808–3818, May 2017, doi: 10.1109/TIE.2016.2645141.

[25] J.-V. Lee, Z. Taha, H. J. Yap, and A. Kinsheel, "Constructivist game-based robotics simulator in engineering education," *Int. J. Eng. Educ.*, vol. 29, no. 4, pp. 1024–1036, Jan. 2013.

[26] M. S. D. S. Lopes, I. P. Gomes, R. M. P. Trindade, A. F. da Silva, and A. C. D. C. Lima, "web environment for programming and control of a mobile robot in a remote laboratory," *IEEE Trans. Learn. Technol.*, vol. 10, no. 4, pp. 526–531, Oct. 2017, doi: 10.1109/TLT.2016.2627565.

[27] C. Losada-Gutiérrez, F. Espinosa, C. Santos-Pérez, M. Marrón-Romera, and J. M. Rodríguez-Ascariz, "Remote control of a robotic unit: A case study for control engineering formation," *IEEE Trans. Educ.*, vol. 63, no. 4, pp. 246–254, Nov. 2020, doi: 10.1109/TE.2020.2975937.

[28] C. Martin-Villalba and A. Urquia, "An approach to develop collaborative virtual labs in modelica," *IEEE Access*, vol. 10, pp. 58938–58949, 2022, doi: 10.1109/ACCESS.2022.3179712.

[29] T. D. Murphey, "Teaching rigid body mechanics using student-created virtual environments," *IEEE Trans. Educ.*, vol. 51, no. 1, pp. 45–52, Feb. 2008, doi: 10.1109/TE.2007.900019.

[30] Y. Shen, P. Yu, H. Lu, X. Zhang, and H. Zeng, "An AI-based virtual simulation experimental teaching system in space engineering education," *Comput. Appl. Eng. Educ.*, vol. 29, no. 2, pp. 329–338, Mar. 2021, doi: 10.1002/cae.22221.

[31] S. Solak, Ö. Yakut, and E. Dogru Bolat, "Design and implementation of web-based virtual mobile robot laboratory for engineering education," *Symmetry*, vol. 12, no. 6, p. 906, Jun. 2020.

[32] S. K. Sood and K. D. Singh, "An Optical-Fog assisted EEG-based virtual reality framework for enhancing E-learning through educational games," *Comput. Appl. Eng. Educ.*, vol. 26, no. 5, pp. 1565–1576, Sep. 2018, doi: 10.1002/cae.21965.

[33] H. Yue, J. Miao, J. Zhang, C. Fan, and D. Xu, "Simulation for senior undergraduate education of robot engineering based on webots," *Comput. Appl. Eng. Educ.*, vol. 29, no. 5, pp. 1176–1190, Sep. 2021, doi: 10.1002/cae.22377.

[34] Z. Jinfang, "Research on chemistry experiment instruction system based on 3D simulation," *Agro Food Ind. Hi-Tech.*, vol. 28, no. 1, pp. 2626–2630, 2017.

[35] X. Zhou, G.-P. Liu, W. Hu, and Z. Lei, "M2PLab: A pocket laboratory with unified and flexible framework applied in engineering education," *IEEE Trans. Ind. Electron.*, vol. 71, no. 3, pp. 1–10, Mar. 2023, doi: 10.1109/TIE.2023.3270544.

[36] M. Casini, D. Prattichizzo, and A. Vicino, "Operating remote laboratories through a bootable device," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3134–3140, Dec. 2007, doi: 10.1109/tie.2007.907026.

[37] J. Marín Garcés, C. Veiga Almagro, G. Lunghi, M. Di Castro, L. R. Buonocore, R. Marín Prades, and A. Masi, "MiniCERNBot educational platform: Antimatter factory mock-up missions for problem-solving STEM learning," *Sensors*, vol. 21, no. 4, p. 1398, Feb. 2021.

[38] D. Heer, R. L. Traylor, T. Thompson, and T. S. Fiez, "Enhancing the freshman and sophomore ece Student experience using a platform for learning/sup TM," *IEEE Trans. Educ.*, vol. 46, no. 4, pp. 434–443, Nov. 2003, doi: 10.1109/te.2003.818752.

[39] D. Hercog, B. Gergic, S. Uran, and K. Jezernik, "A DSP-based remote control laboratory," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3057–3068, Dec. 2007, doi: 10.1109/TIE.2007.907009.

[40] Y. Rae Kim, J. Yang, Y. Lee, and B. Earwood, "Assessing cybersecurity problem-solving skills and creativity of engineering students through model-eliciting activities using an analytic rubric," *IEEE Access*, vol. 12, pp. 5743–5759, 2024, doi: 10.1109/ACCESS.2023.3348554.

[41] Z. Lei, H. Zhou, W. Hu, and G.-P. Liu, "Unified and flexible online experimental framework for control engineering education," *IEEE Trans. Ind. Electron.*, vol. 69, no. 1, pp. 835–844, Jan. 2022.

[42] Z. Lei, H. Zhou, S. Ye, W. Hu, G.-P. Liu, and Z. Wei, "Interactive and visualized online experimentation system for engineering education and research," *J. Visualized Experiments*, vol. 13, no. 177, p. 63342, Nov. 2021.

[43] S. Wang, J. Meng, Y. Xie, L. Jiang, H. Ding, and X. Shao, "Reference training system for intelligent manufacturing talent education: Platform construction and curriculum development," *J. Intell. Manuf.*, vol. 34, no. 3, pp. 1125–1164, Mar. 2023, doi: 10.1007/s10845-021-01838-4.

[44] L. Xue, W. Hu, and G. Liu, "Learning with remote laboratories: Designing control algorithms with both block diagrams and customized c code schemes," *Comput. Appl. Eng. Educ.*, vol. 30, no. 5, pp. 1561–1576, Sep. 2022, doi: 10.1002/cae.22544.

[45] A. Bressane, M. Spalding, D. Zwirn, A. I. S. Loureiro, A. O. Bankole, R. G. Negri, I. de Brito Junior, J. K. S. Formiga, L. C. D. C. Medeiros, L. A. P. Bortolozo, and R. Moruzzi, "Fuzzy artificial intelligence—Based model proposal to forecast Student performance and retention risk in engineering education: An alternative for handling with small data," *Sustainability*, vol. 14, no. 21, p. 14071, Oct. 2022.

[46] P. Jiao, F. Ouyang, Q. Zhang, and A. H. Alavi, "Artificial intelligence-enabled prediction model of Student academic performance in online engineering education," *Artif. Intell. Rev.*, vol. 55, no. 8, pp. 6321–6344, Dec. 2022, doi: 10.1007/s10462-022-10155-y.

[47] Z. Kanetaki, C. Stergiou, G. Bekas, S. Jacques, C. Troussas, C. Sgouropoulou, and A. Ouahabi, "Grade prediction modeling in hybrid learning environments for sustainable engineering education," *Sustainability*, vol. 14, no. 9, p. 5205, Apr. 2022.

[48] C. Li, K. Zhao, M. Yan, X. Zou, M. Xiao, and Y. Qian, "Research on the big data analysis of MOOCs in a flipped classroom based on attention mechanism in deep learning model," *Comput. Appl. Eng. Educ.*, vol. 31, no. 6, pp. 1867–1882, Nov. 2023, doi: 10.1002/cae.22678.

[49] S. L. S. López, R. P. D. Redondo, and A. F. Vilas, "Predicting Students' grade based on social and content interactions," *Int. J. Eng. Educ.*, vol. 34, no. 3, pp. 940–952, Jan. 2018.

[50] V. L. Miguéis, A. Freitas, P. J. V. Garcia, and A. Silva, "Early segmentation of students according to their academic performance: A predictive modelling approach," *Decis. Support Syst.*, vol. 115, pp. 36–51, Nov. 2018, doi: 10.1016/j.dss.2018.09.001.

[51] M. Naseer, W. Zhang, and W. Zhu, "Early prediction of a team performance in the initial assessment phases of a software project for sustainable software engineering education," *Sustainability*, vol. 12, no. 11, p. 4663, Jun. 2020.

[52] T. Nguyen-Huy, R. C. Deo, S. Khan, A. Devi, A. A. Adeyinka, A. A. Apan, and Z. M. Yaseen, "Student performance predictions for advanced engineering mathematics course with new multivariate copula models," *IEEE Access*, vol. 10, pp. 45112–45136, 2022, doi: 10.1109/ACCESS.2022.3168322.

[53] W. Zhang, Y. Wang, and S. Wang, "Predicting academic performance using tree-based machine learning models: A case study of bachelor students in an engineering department in China," *Educ. Inf. Technol.*, vol. 27, no. 9, pp. 13051–13066, Nov. 2022, doi: 10.1007/s10639-022-11170-w.

[54] Y.-C. Chien, M.-C. Liu, and T.-T. Wu, "Discussion-record-based prediction model for creativity education using clustering methods," *Thinking Skills Creativity*, vol. 36, Jun. 2020, Art. no. 100650.

[55] H. S. Chigne, J. E. L. Gayo, M. E. A. Obeso, P. O. de Pablos, and J. M. C. Lovelle, "Towards the implementation of the learning analytics in the social learning environments for the technology enhanced assessment in computer engineering education," *Int. J. Eng. Educ.*, vol. 32, no. 4, pp. 1637–1646, 2016.

[56] X. Li, R. Younes, D. Bairaktarova, and Q. Guo, "Predicting spatial visualization Problems' difficulty level from eye-tracking data," *Sensors*, vol. 20, no. 7, p. 1949, Mar. 2020.

[57] C. López-Martín, R. L. Ulloa-Cazarez, and A. García-Floriano, "Support vector regression for predicting the productivity of higher education graduate students from individually developed software projects," *IET Softw.*, vol. 11, no. 5, pp. 265–270, Oct. 2017, doi: 10.1049/iet-sen.2016.0304.

[58] J. A. Méndez and E. J. González, "A control system proposal for engineering education," *Comput. Educ.*, vol. 68, pp. 266–274, Oct. 2013, doi: 10.1016/j.compedu.2013.05.014.

[59] O. Ogunseiju, A. Akinniyi, N. Gonsalves, M. Khalid, and A. Akanmu, "Detecting learning stages within a sensor-based mixed reality learning environment using deep learning," *J. Comput. Civil Eng.*, vol. 37, no. 4, p. 17, Jul. 2023, doi: 10.1061/jccee5.cpeng-5169.

[60] S. R. Rathi and Y. D. Deshpande, "Course complexity in engineering education using E-learner's affective-state prediction," *Kybernetes*, vol. 52, no. 9, pp. 3197–3222, Sep. 2023, doi: 10.1108/k-09-2021-0806.

[61] A. V. Bengesai and J. Pocock, "Patterns of persistence among engineering students at a south African university: A decision tree analysis," *South Afr. J. Sci.*, vol. 117, no. 3, pp. 62–70, Mar. 2021.

[62] C. Yinying, J. Li, and B. Wang, "Data mining techniques and machine learning algorithms in the multimedia system to enhance engineering education," *ACM Trans. Asian Low-Resource Lang. Inf. Process.*, vol. 21, no. 6, pp. 1–21, Nov. 2022.

[63] L. M. Cruz Castro, A. J. Magana, K. A. Douglas, and M. Boutin, "Analyzing Students' computational thinking practices in a first-year engineering course," *IEEE Access*, vol. 9, pp. 33041–33050, 2021, doi: 10.1109/ACCESS.2021.3061277.

[64] T. Chiang, "Estimating the artificial intelligence learning efficiency for civil engineer education: A case study in Taiwan," *Sustainability*, vol. 13, no. 21, p. 11910, Oct. 2021.

[65] R. Cobos and J. C. Ruiz-Garcia, "Improving learner engagement in MOOCs using a learning intervention system: A research study in engineering education," *Comput. Appl. Eng. Educ.*, vol. 29, no. 4, pp. 733–749, Jul. 2021, doi: 10.1002/cae.22316.

[66] D. A. Dickerson, S. Masta, M. W. Ohland, and A. L. Pawley, "Is Carla grumpy? Analysis of peer evaluations to explore microaggressions and other marginalizing behaviors in engineering Student teams," *J. Eng. Educ.*, vol. 113, no. 3, pp. 603–634, Jul. 2024, doi: 10.1002/jee.20606.

[67] C. Fernández, M. A. Vicente, and M. O. Martínez-Rach, "Implementation of a face recognition system as experimental practices in an artificial intelligence and pattern recognition course," *Comput. Appl. Eng. Educ.*, vol. 28, no. 3, pp. 497–511, May 2020, doi: 10.1002/cae.22218.

[68] A. Ivanov, "Decision trees for evaluation of mathematical competencies in the higher education: A case study," *Mathematics*, vol. 8, no. 5, p. 748, May 2020.

[69] A. Johri and A. Hingle, "Students' technological ambivalence toward online proctoring and the need for responsible use of educational technologies," *J. Eng. Educ.*, vol. 112, no. 1, pp. 221–242, Jan. 2023, doi: 10.1002/jee.20504.

[70] C. Lacave and A. I. Molina, "Using Bayesian networks for learning analytics in engineering education: A case study on computer science dropout at UCLM," *Int. J. Eng. Educ.*, vol. 34, no. 3, pp. 879–894, 2018.

[71] C. Lacave, A. I. Molina, and J. A. Cruz-Lemus, "Learning analytics to identify dropout factors of computer science studies through Bayesian networks," *Behaviour Inf. Technol.*, vol. 37, nos. 10–11, pp. 993–1007, Nov. 2018, doi: 10.1080/0144929x.2018.1485053.

[72] M. Liz-Domínguez, M. Llamas-Nistal, M. Caeiro-Rodríguez, and F. A. Mikic-Fonte, "Profiling Students' self-regulation with learning analytics: A proof of concept," *IEEE Access*, vol. 10, pp. 71899–71913, 2022, doi: 10.1109/ACCESS.2022.3187732.

[73] S. M. Lord, M. W. Ohland, M. K. Orr, R. A. Layton, R. A. Long, C. E. Brawner, H. Ebrahiminejad, B. A. Martin, G. D. Ricco, and L. Zahedi, "MIDFIELD: A resource for longitudinal Student record research," *IEEE Trans. Educ.*, vol. 65, no. 3, pp. 245–256, Aug. 2022, doi: 10.1109/TE.2021.3137086.

[74] A. J. Magana, S. Elluri, C. Dasgupta, Y. Y. Seah, A. Madamanchi, and M. Boutin, "The role of simulation-enabled design learning experiences on middle school Students' self-generated inherence heuristics," *J. Sci. Educ. Technol.*, vol. 28, no. 4, pp. 382–398, Aug. 2019, doi: 10.1007/s10956-019-09775-x.

[75] M. Maphosa, W. Doorsamy, and B. S. Paul, "Student performance patterns in engineering at the university of johannesburg: An exploratory data analysis," *IEEE Access*, vol. 11, pp. 48977–48987, 2023, doi: 10.1109/ACCESS.2023.3277225.

[76] N. Merayo and A. Ayuso, "Identifying beliefs about the gender gap in engineering professions among university students using community detection algorithms and statistical analysis," *Comput. Appl. Eng. Educ.*, vol. 32, no. 4, p. 18, Jul. 2024, doi: 10.1002/cae.22751.

[77] P. J. Muñoz-Merino, J. A. Ruipérez-Valiente, C. D. Kloos, M. A. Auger, S. Briz, V. de Castro, and S. N. Santalla, "Flipping the classroom to improve learning with MOOCs technology," *Comput. Appl. Eng. Educ.*, vol. 25, no. 1, pp. 15–25, Jan. 2017, doi: 10.1002/cae.21774.

[78] A. Roy and K. E. Rambo-Hernandez, "There's so much to do and not enough time to do it! A case for sentiment analysis to derive meaning from open text using Student reflections of engineering activities," *Amer. J. Eval.*, vol. 42, no. 4, pp. 559–576, Dec. 2021.

[79] L. Stern, C. Burvill, J. Weir, and B. W. Field, "Metrics to facilitate automated categorization of Student learning patterns while using educational engineering software," *Int. J. Eng. Educ.*, vol. 32, no. 5, pp. 1888–1902, Jan. 2016.

[80] H. J. Teo, A. Johri, and V. Lohani, "Analytics and patterns of knowledge creation: Experts at work in an online engineering community," *Comput. Educ.*, vol. 112, pp. 18–36, Sep. 2017, doi: 10.1016/j.compedu.2017.04.011.

[81] W. Villegas-Ch, X. Palacios-Pacheco, D. Buenaño-Fernández, and S. Luján-Mora, "Comprehensive learning system based on the analysis of data and the recommendation of activities in a distance education environment," *Int. J. Eng. Educ.*, vol. 35, no. 5, pp. 1316–1325, Jan. 2019.

[82] A. Aleem and M. M. Gore, "The choice is yours: The effects of optional questions in engineering examinations," *Comput. Appl. Eng. Educ.*, vol. 27, no. 5, pp. 1087–1102, Sep. 2019, doi: 10.1002/cae.22138.

[83] Y. Do, "Self-selective multi-objective robot vision projects for students of different capabilities," *Mechatronics*, vol. 23, no. 8, pp. 974–986, Dec. 2013, doi: 10.1016/j.mechatronics.2012.11.003.

[84] I. M. Estévez-Ayres, J. A. Fisteus, L. Uguina, C. Alario-Hoyos, and C. D. Kloos, "Uncovering flipped-classroom problems at an engineering course on systems architecture through data-driven learning design," *Int. J. Eng. Educ.*, vol. 34, no. 3, pp. 865–878, Nov. 2017.

[85] P. A. López, F. J. Martínez-Solano, V. S. Fuertes, and P. L. Iglesias, "Computational models calibration: Experiences in environmental engineering studies," *Comput. Appl. Eng. Educ.*, vol. 19, no. 4, pp. 795–805, Dec. 2011, doi: 10.1002/cae.20366.

[86] K. Mahboob, S. A. Ali, and U. Laila, "Investigating learning outcomes in engineering education with data mining," *Comput. Appl. Eng. Educ.*, vol. 28, no. 6, pp. 1652–1670, Nov. 2020, doi: 10.1002/cae.22345.

[87] A. Rubio-Fernández, P. J. Muñoz-Merino, and C. D. Kloos, "A learning analytics tool for the support of the flipped classroom," *Comput. Appl. Eng. Educ.*, vol. 27, no. 5, pp. 1168–1185, Sep. 2019, doi: 10.1002/cae.22144.

[88] H. Vargas, R. Heradio, G. Farias, Z. Lei, and L. de la Torre, "A pragmatic framework for assessing learning outcomes in competency-based courses," *IEEE Trans. Educ.*, vol. 67, no. 2, pp. 224–233, Apr. 2024, doi: 10.1109/TE.2023.3347273.

[89] S. E. Wilson and M. Nishimoto, "Assessing learning of computer programing skills in the age of generative artificial intelligence," *J. Biomechanical Eng.*, vol. 146, no. 5, p. 6, Mar. 2024.

[90] A. A. Yahya and A. Osman, "A data-mining-based approach to informed decision-making in engineering education," *Comput. Appl. Eng. Educ.*, vol. 27, no. 6, pp. 1402–1418, Nov. 2019, doi: 10.1002/cae.22158.

[91] A. Álvarez and M. Larrañaga, "Experiences incorporating lego mindstorms robots in the basic programming syllabus: Lessons learned," *J. Intell. Robotic Syst.*, vol. 81, no. 1, pp. 117–129, Jan. 2016, doi: 10.1007/s10846-015-0202-6.

[92] R. V. Aroca, R. B. Gomes, D. M. Tavares, A. A. S. Souza, A. M. F. Burlamaqui, G. A. P. Caurin, and L. M. G. Goncalves, "Increasing Students' interest with low-cost CellBots," *IEEE Trans. Educ.*, vol. 56, no. 1, pp. 3–8, Feb. 2013, doi: 10.1109/TE.2012.2214782.

[93] M. Crneković and D. Zorc, "Kinematic controller for a mitsubishi RM501 robot," *Trans. FAMENA*, vol. 36, no. 1, pp. 69–77, Jan. 2012.

[94] C. Deniz and M. Cakır, "A novel designed interactive training platform for industrial robot offline programming and robotics education," *Int. J. Robot. Autom.*, vol. 32, no. 6, pp. 665–672, 2017, doi: 10.2316/journal.206.2017.6.206-5139.

[95] E. Fabregas, G. Farias, S. Dormido-Canto, M. Guinaldo, J. Sánchez, and S. Dormido Bencomo, "Platform for teaching mobile robotics," *J. Intell. Robotic Syst.*, vol. 81, no. 1, pp. 131–143, Jan. 2016, doi: 10.1007/s10846-015-0229-8.

[96] J. Fernandez, R. Marin, and R. Wirz, "Online competitions: An open space to improve the learning process," *IEEE Trans. Ind. Electron.*, vol. 54, no. 6, pp. 3086–3093, Dec. 2007, doi: 10.1109/TIE.2007.907013.

[97] O. O. Ortiz, J. Á. Pastor Franco, P. M. Alcover Garau, and R. Herrero Martín, "Innovative mobile robot method: Improving the learning of programming languages in engineering degrees," *IEEE Trans. Educ.*, vol. 60, no. 2, pp. 143–148, May 2017, doi: 10.1109/TE.2016.2608779.

[98] N. Ç. Özuorçun and H. Bicen, "Does the inclusion of robots affect engineering Students' achievement in computer programming courses?" *EURASIA J. Math., Sci. Technol. Educ.*, vol. 13, no. 8, pp. 4779–4787, Jul. 2017, doi: 10.12973/eurasia.2017.00964a.

[99] M. Rahnavard, S. M. H. Alavi, S. Khorasani, M. Vakilian, and M. Fardmanesh, "Educ.ational robot for principles of electrical engineering," *Scientia Iranica*, vol. 10, no. 1, p. 26, Aug. 2017, doi: 10.24200/sci.2017.4369.

[100] A. Rengifo, F. E. Segura-Quijano, and N. Quijano, "An affordable set of control system laboratories using a low-cost robotic platform," *IEEE/ASME Trans. Mechatronics*, vol. 23, no. 4, pp. 1705–1715, Aug. 2018, doi: 10.1109/TMECH.2018.2843888.

[101] A. Araujo, D. Portugal, M. S. Couceiro, and R. P. Rocha, "Integrating arduino-based educational mobile robots in ROS," *J. Intell. Robotic Syst.*, vol. 77, no. 2, pp. 281–298, Feb. 2015, doi: 10.1007/s10846-013-0007-4.

[102] C. A. Chung, "A cost-effective approach for the development of an integrated PC-PLC-robot system for industrial engineering education," *IEEE Trans. Educ.*, vol. 41, no. 4, pp. 306–310, Nov. 1998, doi: 10.1109/13.728266.

[103] H.-J. Lee and H. Yi, "Development of an onboard robotic platform for embedded programming education," *Sensors*, vol. 21, no. 11, p. 3916, Jun. 2021.

[104] J. McLurkin, J. Rykowski, M. John, Q. Kaseman, and A. J. Lynch, "Using multi-robot systems for engineering education: Teaching and outreach with large numbers of an advanced, low-cost robot," *IEEE Trans. Educ.*, vol. 56, no. 1, pp. 24–33, Feb. 2013, doi: 10.1109/TE.2012.2222646.

[105] S. Sahin and Y. Isler, "Microcontroller-based robotics and SCADA experiments," *IEEE Trans. Educ.*, vol. 56, no. 4, pp. 424–429, Nov. 2013, doi: 10.1109/TE.2013.2248062.

[106] M. Tedder, D. Chamulak, L. Chen, S. Nair, A. Shvartsman, I. Tseng, and C. Chung, "An affordable modular mobile robotic platform with fuzzy logic control and evolutionary artificial neural networks," *J. Robotic Syst.*, vol. 21, no. 8, pp. 419–428, Aug. 2004, doi: 10.1002/rob.20023.

[107] D. J. Ahlgren and I. M. Verner, "Socially responsible engineering education through assistive robotics projects: The RoboWaiter competition," *Int. J. Social Robot.*, vol. 5, no. 1, pp. 127–138, Jan. 2013, doi: 10.1007/s12369-011-0137-4.

[108] J. C. Cada, "From classroom to mobile robots competition arena: An experience on artificial intelligence teaching," *Int. J. Eng. Educ.*, vol. 27, no. 4, pp. 813–820, 2011.

[109] J. M. Cañas, D. Martín-Martín, P. Arias, J. Vega, D. Roldán-Álvarez, L. García-Pérez, and J. Fernández-Conde, "Open-source drone programming course for distance engineering education," *Electronics*, vol. 9, no. 12, p. 2163, Dec. 2020.

[110] R. M. Crowder and K.-P. Zauner, "A project-based biologically-inspired robotics module," *IEEE Trans. Educ.*, vol. 56, no. 1, pp. 82–87, Feb. 2013, doi: 10.1109/TE.2012.2215862.

[111] L. Fernandez-Samacá, N. W. B. Rico, L. A. M. Mesa, and W. J. P. Holguín, "Engineering for children by using robotics," *Int. J. Eng. Educ.*, vol. 33, no. 1, pp. 389–397, Jan. 2017.

[112] A. Friesel, "Learning robotics by combining the theory with practical design and competition in undergraduate engineering education," *Intell. Autom. Soft Comput.*, vol. 13, no. 1, pp. 93–103, Jan. 2007.

[113] J. M. Gomez-de-Gabriel, A. Mandow, J. Fernandez-Lozano, and A. J. García-Cerezo, "Using LEGO NXT mobile robots with LabVIEW for undergraduate courses on mechatronics," *IEEE Trans. Educ.*, vol. 54, no. 1, pp. 41–47, Feb. 2011, doi: 10.1109/TE.2010.2043359.

[114] S. Jung, "Experiences in developing an experimental robotics course program for undergraduate education," *IEEE Trans. Educ.*, vol. 56, no. 1, pp. 129–136, Feb. 2013, doi: 10.1109/TE.2012.2213601.

[115] F. Michaud, "Engineering education and the design of intelligent mobile robots for real use," *Intell. Autom. Soft Comput.*, vol. 13, no. 1, pp. 19–28, Jan. 2007, doi: 10.1080/10798587.2007.10642947.

[116] A. Nagchaudhuri, S. Kuruganty, and A. Shakur, "Introduction of mechatronics concepts in a robotics course using an industrial SCARA robot equipped with a vision sensor," *Mechatronics*, vol. 12, no. 2, pp. 183–193, Mar. 2002, doi: 10.1016/s0957-4158(01)00059-9.

[117] M. A. Al-Othman, J. H. Cole, C. B. Zoltowski, and D. Peroulis, "An adaptive educational web application for engineering students," *IEEE Access*, vol. 5, pp. 359–365, 2017, doi: 10.1109/ACCESS.2016.2643164.

[118] B. Balakrishnan, "Motivating engineering students learning via monitoring in personalized learning environment with tagging system," *Comput. Appl. Eng. Educ.*, vol. 26, no. 3, pp. 700–710, May 2018, doi: 10.1002/cae.21924.

[119] R. M. Clark, A. K. Kaw, and R. Braga Gomes, "Adaptive learning: Helpful to the flipped classroom in the online environment of COVID?" *Comput. Appl. Eng. Educ.*, vol. 30, no. 2, pp. 517–531, Mar. 2022, doi: 10.1002/cae.22470.

[120] N. Gavrilović, A. Arsić, D. Domazet, and A. Mishra, "Algorithm for adaptive learning process and improving learners' skills in Java programming language," *Comput. Appl. Eng. Educ.*, vol. 26, no. 5, pp. 1362–1382, Sep. 2018, doi: 10.1002/cae.22043.

[121] L. A. González, A. Neyem, I. Contreras-McKay, and D. Molina, "Improving learning experiences in software engineering capstone courses using artificial intelligence virtual assistants," *Comput. Appl. Eng. Educ.*, vol. 30, no. 5, pp. 1370–1389, Sep. 2022, doi: 10.1002/cae.22526.

[122] Y. Lin, S. Wang, and Y. Lan, "The study of virtual reality adaptive learning method based on learning style model," *Comput. Appl. Eng. Educ.*, vol. 30, no. 2, pp. 396–414, Mar. 2022, doi: 10.1002/cae.22462.

[123] M. Tavakoli, A. Faraji, J. Vrolijk, M. Molavi, S. T. Mol, and G. Kismihók, "An AI-based open recommender system for personalized labor market driven education," *Adv. Eng. Informat.*, vol. 52, Apr. 2022, Art. no. 101508.

[124] O. Atilola, S. Valentine, H.-H. Kim, D. Turner, E. McTigue, T. Hammond, and J. Linsey, "Mechanix: A natural sketch interface tool for teaching truss analysis and free-body diagrams," *Artif. Intell. Eng. Design, Anal. Manuf.*, vol. 28, no. 2, pp. 169–192, May 2014, doi: 10.1017/s0890060414000079.

[125] B. Görer and F. B. Aydemir, "RoboREIT: An interactive robotic tutor with instructive feedback component for requirements elicitation interview training," *J. Software, Evol. Process*, vol. 36, no. 5, p. 28, May 2024, doi: 10.1002/smr.2608.

[126] S. Jiménez, R. Juárez-Ramírez, V. H. Castillo, G. Licea, A. Ramírez-Noriega, and S. Inzunza, "A feedback system to provide affective support to students," *Comput. Appl. Eng. Educ.*, vol. 26, no. 3, pp. 473–483, May 2018, doi: 10.1002/cae.21900.

[127] J. Khalfallah and J. B. H. Slama, "The effect of emotional analysis on the improvement of experimental e-learning systems," *Comput. Appl. Eng. Educ.*, vol. 27, no. 2, pp. 303–318, Mar. 2019, doi: 10.1002/cae.22075.

[128] S. Salcedo-Sanz, S. Jiménez-Fernández, J. M. Matías-Román, and J. A. Portilla-Figueras, "An educational software tool to teach hyper-heuristics to engineering students based on the bubble breaker puzzle," *Comput. Appl. Eng. Educ.*, vol. 23, no. 2, pp. 277–285, Mar. 2015, doi: 10.1002/cae.21597.

[129] H. Sung, M. A. Rau, and B. D. Van Veen, "Development of an intelligent tutoring system that assesses internal visualization skills in engineering using multimodal triangulation," *IEEE Trans. Learn. Technol.*, vol. 17, no. 6, pp. 1585–1598, Apr. 2024, doi: 10.1109/tlt.2024.3396393.

[130] W. Chen, "Teaching problem solving in engineering education: Expert systems construction," *Int. J. Eng. Educ.*, vol. 25, no. 4, pp. 723–728, Sep. 2009.

[131] S. J. Hsieh and P. Y. Hsieh, "Intelligent tutoring system authoring tool for manufacturing engineering education," *Int. J. Eng. Educ.*, vol. 17, no. 6, pp. 569–579, 2001.

[132] M. Negnevitsky, "A knowledge based tutoring system for teaching fault analysis," *IEEE Trans. Power Syst.*, vol. 13, no. 1, pp. 40–45, Feb. 1998, doi: 10.1109/59.651611.

[133] B. Valiquette, G. L. Torres, and D. Mukhedkar, "An expert system based diagnosis and advisor tool for teaching power system operation emergency control strategies," *IEEE Trans. Power Syst.*, vol. 6, no. 3, pp. 1315–1322, Aug. 1991, doi: 10.1109/59.119283.

[134] H.-M. Chen, B.-A. Nguyen, and C.-R. Dow, "Code-quality evaluation scheme for assessment of Student contributions to programming projects," *J. Syst. Softw.*, vol. 188, Jun. 2022, Art. no. 111273.

[135] D. Insa, S. Pérez, J. Silva, and S. Tamarit, "Semiautomatic generation and assessment of Java exercises in engineering education," *Comput. Appl. Eng. Educ.*, vol. 29, no. 5, pp. 1034–1050, Sep. 2021, doi: 10.1002/cae.22356.

[136] N. Nazar, N. Chen, and C. Y. Chong, "CodeLabeller: A web-based code annotation tool for Java design patterns and summaries," *Int. J. Softw. Eng. Knowl. Eng.*, vol. 33, no. 7, pp. 993–1009, Jul. 2023, doi: 10.1142/s0218194023500213.

[137] P. T. Nguyen, J. Di Rocco, C. Di Sipio, R. Rubei, D. Di Ruscio, and M. Di Penta, "GPTSniffer: A CodeBERT-based classifier to detect source code written by ChatGPT," *J. Syst. Softw.*, vol. 214, Aug. 2024, Art. no. 112059.

[138] K. E. Chapman, M. E. Davidson, N. Azuka, and M. W. Liberatore, "Quantifying deliberate practice using auto-graded questions: Analyzing multiple metrics in a chemical engineering course," *Comput. Appl. Eng. Educ.*, vol. 31, no. 4, pp. 916–929, Jul. 2023, doi: 10.1002/cae.22614.

[139] A. Eltaief, S. Ben Amor, B. Louhichi, N. H. Alrasheedi, and A. Seibi, "Automated assessment tool for 3D computer-aided design models," *Appl. Sci.*, vol. 14, no. 11, p. 4578, May 2024.

[140] J. M. García-Gorrostieta, A. López-López, and S. González-López, "Automatic argument assessment of final project reports of computer engineering students," *Comput. Appl. Eng. Educ.*, vol. 26, no. 5, pp. 1217–1226, Sep. 2018, doi: 10.1002/cae.21996.

[141] I. Menchaca, M. Guenaga, and J. Solabarrieta, "Learning analytics for formative assessment in engineering education," *Int. J. Eng. Educ.*, vol. 34, no. 3, pp. 953–967, Jan. 2018.

[142] G. M. Nicholls and S. L. Restauri, "Instituting and assessing the effectiveness of focused e-learning modules in engineering education," *Int. J. Eng. Educ.*, vol. 31, no. 2, pp. 461–475, 2015.

[143] S. K. Sood and K. D. Singh, "Optical fog-assisted smart learning framework to enhance students' employability in engineering education," *Comput. Appl. Eng. Educ.*, vol. 27, no. 5, pp. 1030–1042, Sep. 2019, doi: 10.1002/cae.22120.

[144] Y. Ugurlu, "Smart e-learning: Enhancement of human-computer interactions using head posture images," *Int. J. Eng. Educ.*, vol. 29, no. 3, pp. 568–577, Jan. 2013.

[145] P. Verma, S. K. Sood, and S. Kalra, "Smart computing based Student performance evaluation framework for engineering education," *Comput. Appl. Eng. Educ.*, vol. 25, no. 6, pp. 977–991, Nov. 2017, doi: 10.1002/cae.21849.

[146] A. Hazeyama, N. Sawabe, and S. Komiya, "Group organization system for software engineering group learning with genetic algorithm," *IEICE Trans. Inf. Syst.*, vol. 85, no. 4, pp. 666–673, Apr. 2002.

[147] T. A. Khan, M. Alam, S. A. Rizvi, Z. Shahid, and M. S. Mazliham, "Introducing AI applications in engineering education (PBL): An implementation of power generation at minimum wind velocity and turbine faults classification using AI," *Comput. Appl. Eng. Educ.*, vol. 32, no. 1, p. 28, Jan. 2024, doi: 10.1002/cae.22691.

[148] I. E. Khuda, S. Ahmad, and A. Ashraf Ateya, "STEM-based Bayesian computational learning model-BCLM for effective learning of Bayesian statistics," *IEEE Access*, vol. 12, pp. 91217–91228, 2024, doi: 10.1109/ACCESS.2024.3420731.

[149] T. Kosar, D. Ostojić, Y. D. Liu, and M. Mernik, "Computer science education in ChatGPT era: Experiences from an experiment in a programming course for novice programmers," *Mathematics*, vol. 12, no. 5, p. 629, Feb. 2024.

[150] J. Lisowski, "Computational intelligence in marine control engineering education," *Polish Maritime Res.*, vol. 28, no. 1, pp. 163–172, Mar. 2021, doi: 10.2478/pomr-2021-0015.

[151] M. Z. Naser, "An engineer's guide to explainable artificial intelligence and interpretable machine learning: Navigating causality, forced goodness, and the false perception of inference," *Autom. Construct.*, vol. 129, Sep. 2021, Art. no. 103821.

[152] A. Neyem, L. A. González, M. Mendoza, J. P. S. Alcocer, L. Centellas, and C. Paredes, "Toward an AI knowledge assistant for context-aware learning experiences in software capstone project development," *IEEE Trans. Learn. Technol.*, vol. 17, no. 5, pp. 1599–1614, Apr. 2024, doi: 10.1109/tlt.2024.3396735.

[153] J. Olayiwola, A. Yusuf, A. Akanmu, N. Gonsalves, and Y. Abraham, "Efficacy of annotated video-based learning environment for drawing Students' attention to construction practice concepts," *J. Construct. Eng. Manage.*, vol. 150, no. 1, p. 15, Jan. 2024, doi: 10.1061/jcemd4.coeng-13778.

[154] L. M. Sánchez-Ruiz, S. Moll-López, A. Nuñez-Pérez, J. A. Moraño-Fernández, and E. Vega-Fleitas, "ChatGPT challenges blended learning methodologies in engineering education: A case study in mathematics," *Appl. Sci.*, vol. 13, no. 10, p. 6039, May 2023.

[155] S. M. J. Uddin, A. Albert, M. Tamanna, A. Ovid, and A. Alsharef, "ChatGPT as an educational resource for civil engineering students," *Comput. Appl. Eng. Educ.*, vol. 32, no. 4, p. 18, Jul. 2024, doi: 10.1002/cae.22747.

[156] M. Rodríguez-Martín, P. Rodríguez-Gonzálvez, A. Sánchez-Patrocinio, and J. R. Sánchez, "Short CFD simulation activities in the context of fluid-mechanical learning in a multidisciplinary Student body," *Appl. Sci.*, vol. 9, no. 22, p. 4809, Nov. 2019.
[157] K. D. Singh and P. D. Singh, "QoS-enhanced load balancing strategies for metaverse-infused VR/AR in engineering education 5.0," *Comput. Appl. Eng. Educ.*, vol. 32, no. 3, p. 10, May 2024, doi: 10.1002/cae.22722.
[158] J. A. Ruipérez-Valiente, P. J. Muñoz-Merino, and C. D. Kloos, "Detecting and clustering students by their gamification behavior with badges: A case study in engineering education," *Int. J. Eng. Educ.*, vol. 33, no. 2, pp. 816–830, Sep. 2017.
[159] P. Ponce, A. Molina, E. O. L. Caudana, G. B. Reyes, and N. M. Parra, "Improving education in developing countries using robotic platforms," *Int. J. Interact. Design Manuf. (IJIDeM)*, vol. 13, no. 4, pp. 1401–1422, Dec. 2019.
[160] J. M. Cañas, E. Perdices, L. García-Pérez, and J. Fernández-Conde, "A ROS-based open tool for intelligent robotics education," *Appl. Sci.*, vol. 10, no. 21, p. 7419, Oct. 2020, doi: 10.3390/app10217419.

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