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Review

AR Technologies in Engineering Education: Applications, Potential, and Limitations

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Abstract: Over the past decade, the use of AR has significantly increased over a wide range of applications. Although there are many good examples of AR technology being used in engineering, retail, and for entertainment, the technology has not been widely adopted for teaching in university engineering departments. It is generally accepted that the use of AR can complement the students' learning experience by improving engagement and by helping to visualise complex engineering physics; however, several key challenges still have to be addressed to fully integrate the use of AR into a broader engineering curriculum. The presented paper reviews the uses of AR in engineering education, highlights the benefits of AR integration in engineering curriculums, as well as the barriers that are preventing its wider adoption.

Keywords: augmented reality; AR; engineering education; mixed reality

1. Introduction

XR, also known as extended reality, refers to a combination of real and virtual environments where interaction between humans and machines is established through computer-generated technology and compatible hardware [1]. Currently, the most common "X" representations are virtual reality (VR), augmented reality (AR), and mixed reality (MR). VR creates a digital environment where the user is wholly immersed in a virtual world. AR overlays (augments) digital content into the user's real-world environment. MR aims to blend both virtual and real-world environments where both coexist and interact with each other [2].

In recent years, significant commercial and academic attention has been focused on the use of XR technologies across many different industries. These applications cover a wide range of sectors from retail [3] and gaming [4] to critical applications such as medical [5], manufacturing [1], and maintenance [6] where the health and safety of humans are often the primary concerns. This focus has also driven the research and development of XR technologies, potentially creating new opportunities in engineering education.

This paper reviews the development of AR technology and its application with a particular focus on engineering education to identify the main strengths, weaknesses, and potential future improvements. The main questions to be investigated are "How is AR presently used in engineering education?", "What are the benefits of AR for engineering education?" and "What are the barriers to the wider use of AR technology in engineering education?".

In engineering, the use of AR has been a key part of the industry 4.0 concept that focuses on advanced technologies in manufacturing systems and factories [7]. The use of AR has been utilised in many ways by industry including visualising complex assemblies, facilitating training programmes, and developing maintenance programmes and manufacturing lines [8].

In education, one of the early adopters of AR were researchers developing medical and surgical training technologies. AR is being used in surgical training for the automation of repetitive tasks needed to be perfected [5]. It has also been trialled in STEM subjects when

teaching K-12, higher education, and adult education [9], in science laboratories [10], and for initial teacher training [11]. The volume of academic publishing in AR in engineering education has been gradually increasing over the past 10 years.

For this review, Scopus and Google Scholar search engines were used. The search syntax for Scopus was: TITLE-ABS-KEY ("Augmented Reality" AND "Engineering Education") AND PUBYEAR > 2010 AND PUBYEAR < 2023 AND (LIMIT-TO (SUBJAREA, "ENGI")) AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (SRCTYPE, "*p*") OR LIMIT-TO (SRCTYPE, "j")) AND (LIMIT-TO (PUBSTAGE, "final")).

For Google Scholar, the syntax was:

Allintitle: Augmented reality engineering education.

In addition to the research syntax, inclusion and exclusion criteria were defined. The inclusion criteria included:

- Articles that include "Augmented reality" or "AR" and "Engineering Education" in their titles, keywords, or abstract.
- Articles written in English.
- Articles available in full text.
- Articles published in conferences and journals.
- Articles published between 2011 and April 2022
- Articles with focus on the use of augmented reality in engineering education.

The exclusion criteria included:

- Articles not written in English.
- Articles that mentioned AR but focused on VR technologies.
- Articles that mentioned engineering education but focused different subjects.
- Articles that mentioned university education but focused on any other level.
- Any duplicates among the searches were removed.

A total of 85 articles were reviewed, 55 articles described how AR was used to deliver teaching material to engineering students, and the remaining were reviews, frameworks, and evaluations. Figure 1 shows journal and conference proceedings articles published between 2011 and 2022 that meet the inclusion and exclusion criteria above. Santi et al. [7] reported that from 2017 to 2021, 26,621 articles included the keywords "Augmented Reality" on the Scopus database. Approximately 2500 of these articles also listed "Engineering" or "Education" in the keywords. After applying the inclusion and exclusion criteria for the same time period, the engineering education AR content was less than 2.6% of the engineering or education AR content.
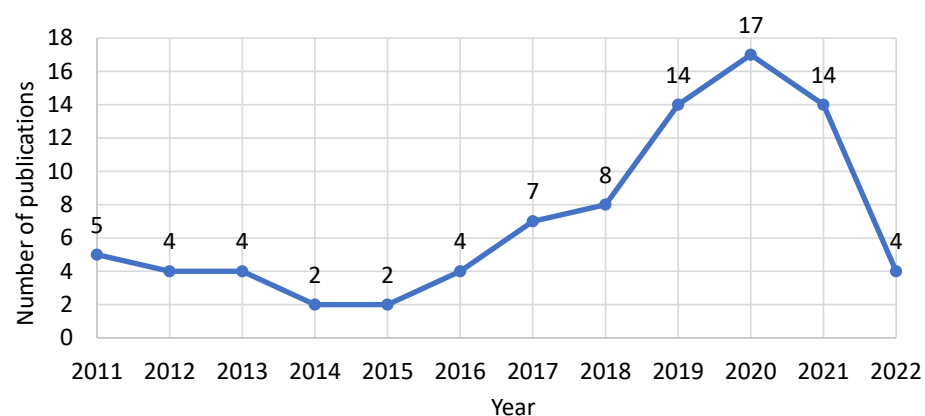
Figure 1. AR literature in engineering applications subjected to inclusion and exclusion criteria.

In engineering education, the use of AR is significantly increasing compared to other STEM subjects [12]. AR is being used as part of course material (i.e., [13,14]), to visualise engineering laboratories (i.e., [15,16]), in collaborative projects [17], for communication skills such as industry presentations [18], and to enhance students' spatial cognition [19,20].

In the past ten years, several forms of AR have been studied: using handheld (i.e., [21,22]), handsfree (i.e., [23,24]), and special hardware kits [25,26]. In addition, AR can be integrated with several digital technologies such as gamification [27,28], IOT [29,30], machine learning [31], FEA [32], and CFD [13] to produce more realistic, interactive, and scientifically credible AR experiences.

2. Augmented Reality: History

The first augmented reality system was developed by Sutherland [33] in 1967. The system consisted of an optical see-through head-mounted display, two 6DOF trackers, a mechanical tracker, and an ultrasonic tracker. In 1972, the first tablet computer was proposed by Kay [34] as a personal computing device for children. The term augmented reality that referred to "overlaying computer material on top of the real world" [35] was proposed by Thomas and David [36] in 1992. In 1994, Milagram and Kishino [37] defined the reality–virtuality continuum shown in Figure 2, which was a significant milestone in the AR development history. The continuum consists of a real environment, augmented reality, augmented virtuality (a higher level of virtuality than augmented reality used for the visualisation of new products [2]), and virtual environment. Arth et al. [35] documented these major milestones among others in the history of mobile augmented reality starting in 1967 and finishing in 2014. The report includes major achievements in the history of AR hardware and software. Edward-Stewart et al. [38] summarised the types of AR and then divided them into two categories: triggered and view-based (marker-less), and Pooja et al. [39] compared both categories' use in education. Triggered augmentation relies on using a "trigger" or stimuli to initiate the augmentation. The trigger can be a marker such as a 3D target or a 2D image. Two-dimensional targets are widely used in engineering education (i.e., [21,29,40,41]). Triggered augmentation can also be initiated using faces (i.e., Instagram filters), surfaces (i.e., Ikea AR), and location (Google Maps) [42]. View-based or marker-less AR includes real-time augmentation regardless of the location with no stored view to be triggered. It allows real-time interaction with the camera view [38].

Figure 2. Milgram and Kishino [37] reality–virtuality continuum.

Apple released the ARKit SDK [43] in 2017, quickly followed by Google releasing its ARcore [44] SDK in 2018. The release of these software development kits significantly improved the quality of AR experiences consumed by users through smart handheld devices (HHDs) and head-mounted devices (HMDs). Over the past decade, AR hardware components have become more portable with better performance and more accessibility [40]. This has led to an increase in the utilisation of AR-based technologies. Today, the most common ways to consume AR experiences are by using HHDs such as smartphones and HMDs such as the Microsoft HoloLens. The main difference between the two methods is the user input: an HHD uses multi-input touch, whereas an HMD uses gaze, eye, and finger tracking. Both systems share the use of screens, sound input/output cameras, and moving trackers [42].

3. AR in Engineering and Education: A Review

As augmented reality is being used over a wide range of applications, AR review articles have adopted different categorisation approaches. Alvarez-Marin et al. [45] reviewed AR in engineering education for 52 articles in terms of: engineering studies, educational activities, applications assessment, application characteristics, and degree of interactivity.

Garcia et al. [46] reviewed the use of augmented reality in engineering classrooms in Latin America; the review targeted: software, hardware, educational applications, advantages, disadvantages, and research, and their results were compared to international reviews. Merino et al. [47] reviewed mixed and augmented reality research for 458 papers in six categories: publisher, type of paper (i.e., technique, design), topic (i.e., tracking, application, display technology), evaluation scenario (i.e., user experience and user scenario), cognitive aspects, and configurations. Santi et al.'s [7] review of AR in Industry 4.0 used categories of application, software, hardware, and limitations. Di Lanzo et al. [48] reviewed the use of VR in engineering education for 17 studies in six categories: class format, justification of use, learning outcomes, evaluation metrics, teaching discipline, and software and hardware used. Doolani et al. [1] reviewed the use of AR for training, particularly in manufacturing. The article focused on defining XR usage at different manufacturing phases, XR technologies implemented for these phases, and the gaps and limitations of the used technologies. Diao et al. [49] reviewed the use of AR in civil and architecture engineering education. They reviewed 21 papers and focused on application domains, software, hardware, learning outcome, user feedback, advantages, and challenges.

This review article focuses on the use of augmented reality-based technologies in engineering education applications. The structure of this article is shown in Figure 3. The review categories are the application of use, continuity and commercialisation, software, hardware, and evaluation methods.
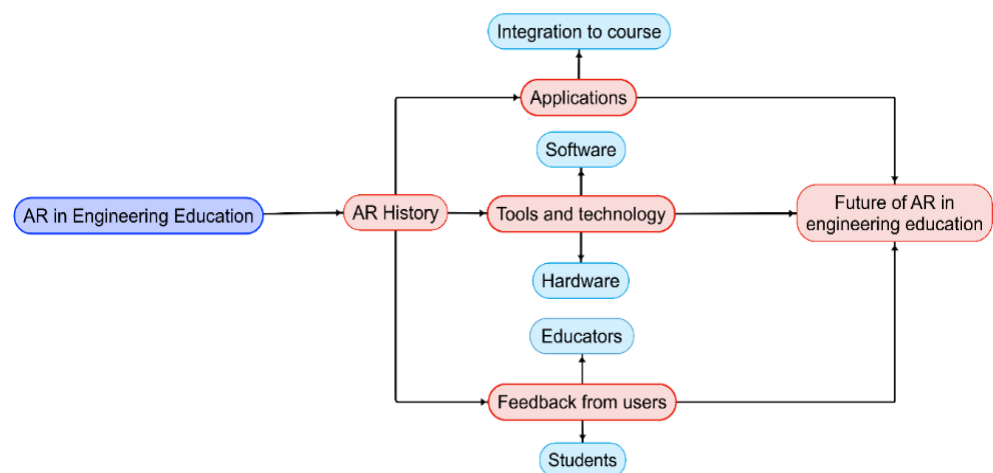

Figure 3. Review article structure.

4. AR in Engineering Education Applications

Figure 4 shows the engineering fields where AR has been implemented in an engineering curriculum. Most of the uses were in mechanical, electrical, and civil engineering. Table 1 summarises the use of AR in engineering education. The use of AR to date can be divided into three categories: first, delivering principles of engineering in selected topics within the curriculum, for example, HVAC systems [50,51], hydraulic transmission [52], Unified Modelling Language (UML) [53], hydraulics laboratory [29], CAD design [20,41,54–57], manual material handling (MMH) laboratories [23,24], oscilloscope training [58,59], or circuit analysis [28,31]. Such studies focus on developing AR experiences and then finding the impact the experience has on the student's understanding. AR also allows users to observe an internal structure that cannot be observed in standard laboratory environments such as the simulation of electron movements [60] or the behaviour inside a nuclear core that students would usually have to imagine from limited observable data [14].
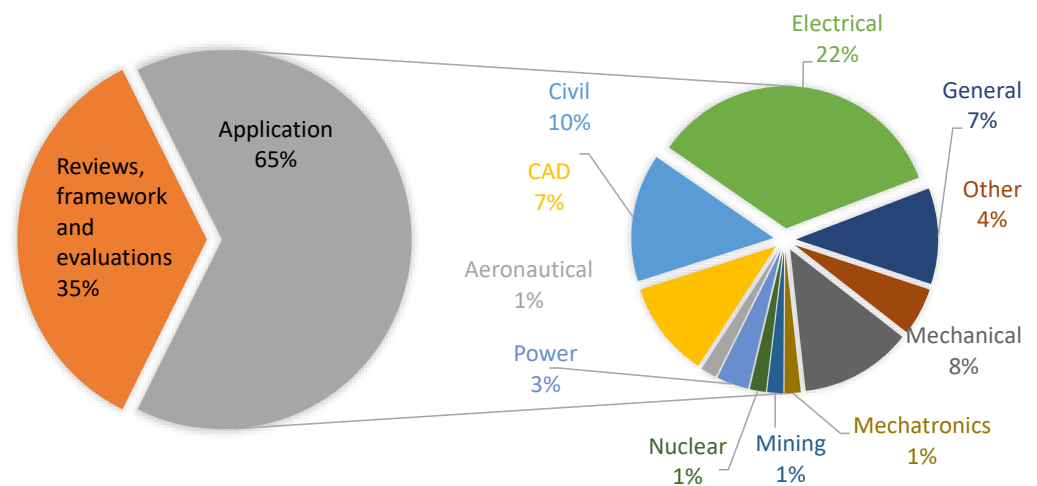
Figure 4. AR applications in engineering education.

Table 1. Applications of AR in engineering education.

Author	Field	Topic
Borrero and Marquez [15]	Electrical	Electrical engineering labs
Dinis et al. [21]	Civil	Design AR experiences for younger students
Gutierez and Fernandez [61]	General	Learning industrial elements
Gutierez et al. [62]	General	AR textbooks
Neges et al. [29]	Mechanical	Virtual labs
Opris et al. [63,64]	Power	Laboratories
Sahin et al. [30]	Electrical	Wireless communications
Tsujita et al. [14]	Nuclear	Reactor core simulation
Yuzuak and Yigit [60]	Electrical	N-Type MOSFET
Zoghi et al. [50]	Mechanical	HVAC
Behzadan and Kamat [65]	Civil	Construction management
Borgen et al. [66]	Aeronautical	Cockpit simulator
Theodossiou et al. [25]	Civil	Hydrology
Louis and Lather [26]	Civil	Mass haul diagrams
Waters et al. [67]	Civil	Fundamentals, soil, and hydrology
Alanis and Tejeda [40]	Industrial	Decision trees
Alptkien and Temmen [58]	Electrical	Oscilloscope training
Alptkien and Temmen [68]	Electrical	Lab training
Calderon et al. [69]	Mechatronics	Industry 4.0 applications
Pan et al. [22]	Mechanical	Mechanical manufacturing
Pogodaev et al. [70]	Electrical	Asynchronous electric motor
Solmaz and Gerven [13]	Mechanical	Computational fluid dynamics
Yazykova et al. [16]	Electrical	Electrical engineering labs
Guo and Kim [23]	General	Manual material handling
Guo et al. [24]	General	Manual material handling
Reuter et al. [53]	Software	Unified modelling language
Daling et al. [71]	Mining	Mixed reality books
Cukovic et al. [41]	CAD/CAM	Visualise 3D CAD models
Alvarez-Marin et al. [72]	Electrical	Digital current (DC)
Criollo-C et al. [73]	Network	Various topics
Schiffeler et al. [17]	General	Project management
Liu et al. [52]	Mechanical	Hydraulic transmission
Xie and Yang [51]	Civil	HVAC
Hung and Weinman [57]	CAD	Technical drawing
Matsutomo et al. [32]	Electrical	Magnetic field
Alvarez-Marin et al. [74]	Electrical	DC current
Tumkor and El-Sayed [55]	CAD	Drawings visualisation
Bairaktarova et al. [75]	General	Freshmen engineering course
Liu et al. [76]	Mechanical	Lathe turning
Odeh et al. [77]	Electrical	Remote labs
Wang et al. [56]	CAD	Assembly training
Kaur et al. [78]	Electrical	Linear control systems
Urbano et al. [28]	Electrical	DC circuits
Shirazi and Behzadan [79]	Civil	Interactive books
Singh et al. [59]	Electrical	Oscilloscope and function generator
Phade et al. [80]	Electrical	Personal electronics components
Kumar et al. [81]	Electrical	Embedded systems
Dong et al. [82]	Civil	Collaborative visualisation
Chen et al. [83]	CAD	Visualisation and assembly
Topal and Sener [18]	General	AR Industry presentations
Tirado-Morueta et al. [84]	Electrical	Remote Lab
Alhalabi et al. [31]	Electrical	Circuits solver
Dakeev et al. [20]	CAD	Design and spatial skills
Jacob et al. [85]	Electrical	Interactive books
Shretha [86]	Mechanical	Car engine model

Unlike VR, the use of AR allows students to simultaneously interact with real-world objects. This makes explicit the relationship between virtual augmentations and the real

devices or phenomena under consideration. It also avoids the risk of collisions with real world objects as the digital data are directly augmented to the physical objects [87] as opposed to the student operating within a virtual environment. Secondly, AR experiences can be used to visually enhance the engineering learning material and make the laboratory components and some equipment more portable and accessible [71,88–90]. These studies tend to focus on enhancing the teaching material and evaluating the students' interest and motivation towards the lectures. Thirdly, AR can be used to display digital instructions to physical spaces to teach students how to complete a task using hands-free mixed-reality AR devices [23,24,66,91].

Integration to Taught Course and Continuity

Most of the papers listed in Table 1 contain an introduction to AR in education or their respective industry, and details about the developed augmented reality followed by students' feedback/ performance measures for the time when the technology was used in the classroom. While extensive data have been generated on the short-term usage of AR for a particular test group, there is very little literature investigating the long-term integration of AR-based technologies into engineering education. Urbano et al. [28] taught their AR experience for 3 consecutive years and reported feedback from 440 students in total. Zoghi et al. [50] suggested that the "WOW factor" can affect users' reaction to technology and that these effects might wear out over time. Thus, it is essential that long-term effects of the use of AR be tested over longer periods and with full integration in the curriculum. Arashpour and Aranda-Mena [92] and Vassigh et al. [93] proposed the use of AR to visualise Building Information Modelling (BIM) for engineering and construction education. Arashpour and Aranda-Mena [92] concluded that the use of AR + BIM will make BIM more relevant to on-site operations and improve collaboration and communication at different project stages that employ architecture and engineering BIM models.

One main success factor for any technology to grow is continuity. Most of the available research by the authors did not continue after the development of their first AR experience. Approximately six authors [23,24,55,58,63,64,68,72,74,94–97] from this review produced follow-up studies after publishing their first works on implementing AR experiences in an engineering education context. One of the reasons behind this observation might be the lack of distribution of the AR applications on application stores and the lack of data on how much time, effort, and knowledge are required from non-experienced educators to develop a usable AR experience and then integrate it into the teaching plan. Another factor is the technical challenges associated with the integration of AR-based technologies into university data management systems and the technical difficulties for developing the digital assets [92,98].

The relative sparsity of current data on the long-term integration of AR into engineering courses suggests the need for further research to determine how content, learners, and the learning context affect, and are affected by, the use of AR technology. AR in STEM research addressed some questions raised in Mystakidis et al. [12] such as the most relevant STEM topics, and the most frequent instructional methods to be used with AR in higher education. Still, a number of research questions may be posed: "Is AR most effectively utilised when new content is first introduced or to consolidate existing knowledge and skills?", "To what degree should AR experiences be scaffolded to enable students to address learning objectives?", "Is the knowledge gained from the use of AR easily translated to other contexts and tasks or are supporting activities required to achieve this?", and "What is the role of formative assessment, group work, and discussion before, after, and during AR experiences?". Answers to these questions would better allow educators to successfully integrate AR experiences and tools into existing and future courses and to assist those developing these tools to adapt them for educational use. Not only may this allow for the better achievement of current learning outcomes, but also, as AR expands the available modes of assessment, the intended outcomes may themselves be reimagined.

5. Tools and Technology

Table 2 shows a list of the software and hardware used to create AR experiences for engineering education. Out of 55 AR application articles, 52 included the software/hardware tools used in developing the experiences. For software, the options for developing AR experiences in an engineering context can be divided into three categories: (i) the use of mobile application development and 3D modelling tools [99] (such as Unity, Vuforia, Arkit, or ARcore), (ii) the use of in-house development tools, and (iii) the use of already developed AR experiences [90]. For hardware, the use of AR experiences can also be divided into three categories: (i) handheld smart devices shown in Table 2, (ii) head mounted devices [23,24,50,53,66], and (iii) special hardware kits [14,25,26,77,78,81–83,100].

Table 2. Software and hardware used of AR experiences in engineering education.

Author	Software	Hardware	AR Type	IOT
Borrero and Marquez [15]	Unknown	Unknown	Image marker	No
Dinis et al. [21]	Unity	Handheld	Image marker	No
Gutierez and Fernandez [61]	Build AR	Handheld	Image marker	No
Gutierez et al. [62]	Build AR	Handheld	Image marker	No
Neges et al. [29]	Unknown	Handheld	Various	Yes
Opris et al. [63,64]	APRE	Handheld	Various	No
Sahin et al. [30]	Unity/Vuforia	Handheld	Image marker	Yes
Tsujita et al. [14]	Unknown	Hardware Kit	Image marker	No
Yuzuak and Yigit [60]	Unity/Vuforia	Handheld	Image marker	No
Zoghi et al. [50]	Unity	HoloLens	Hologram	No
Behzadan and Kamat [65]	Unknown	Hardware Kit	Image marker	No
Borgen et al. [66]	Unity	HoloLens	Hologram	Yes
Theodossiou et al. [25]	In-house	Hardware kit	Surface marker	No
Louis and Lather [26]	In-house	Hardware Kit	Surface marker	No
Alanis and Tejeda [40]	Unity/Vuforia	Handheld	Surface marker	No
Alptkien and Temmen [58]	Unknown	Handheld	Unknown	No
Alptkien and Temmen [68]	Unknown	Handheld	Unknown	No
Calderon et al. [69]	Unknown	Handheld	Image marker	Yes
Pan et al. [22]	Unity/Vuforia	Handheld	Image marker	No
Pogodaev et al. [70]	Unknown	Handheld	Image marker	No
Solmaz and Gerven [13]	Unity/Vuforia	Handheld	Image marker	Yes
Yazykova et al. [16]	EV Toolbox	Handheld	Image marker	No
Guo [24]	Unknown	HoloLens	Hologram	No
Guo and Kim [23]	Unknown	HoloLens	Hologram	No
Reuter et al. [53]	Unity	HoloLens	Hologram	No
Daling et al. [71]	Unknown	Handheld	Image marker	No
Cukovic et al. [41]	Unity/UbiTrack	Handheld	Image marker	No
Alvarez-Marin et al. [72]	Unity/Vuforia/Blender	Handheld	Image marker	No
Criollo-C et al. [73]	Unity/Vuforia	Handheld	Image marker	No
Schiffeler et al. [17]	Vuforia	Handheld	Image marker	No
Liu et al. [52]	Unity/Vuforia	Handheld	Image marker	No
Xie and Yang [51]	Unity/EasyAR/OpenCV	Handheld	Unknown	No
Hung and Weinman [57]	Autodesk/ENTiti	Handheld	Image marker	No
Alvarez-Marin et al. [74]	Unity/Vuforia	Handheld	Image marker	No
Tumkor and El-Sayed [55]	SolidWorks/Google SketchUP	Handheld	Image marker	No
Bairaktarova et al. [75]	Spatial Vis/Vuforia	Handheld	Image marker	No
Liu et al. [76]	Unity/Vuforia	Handheld	Image marker	No
Odeh et al. [77]	Lab server/Web browser	Hardware Kit	Unknown	No
Wang et al. [56]	Unity 3D	Handheld	Image marker	No
Kaur et al. [78]	Unity/Vuforia	Hardware kit	Image marker	No
Urbano et al. [28]	Blender	Handheld	Image marker	No
Shirazi and Behzadan [79]	Unknown	Handheld	Image marker	No
Singh et al. [59]	Unity/ARLE	Handheld	Image marker	No
Phade et al. [80]	Unknown	Handheld	Image marker	No
Kumar et al. [81]	Unity Vuforia	Hardware Kit	Image marker	No
Dong et al. [82]	ARToolKit/ARvita	Hardware Kit	Image marker	No
Chen et al. [83]	Unknown	Hardware kit and handheld	Image marker	No
Topal and Sener [18]	Metiao Creator/Juniao Browser	Handheld	Image marker	No
Alhalabi et al. [31]	Unknown	Handheld	Unknown	No
Dakeev et al. [20]	Unity/Vuforia/Creo	Handheld	Unknown	No
Jacob et al. [85]	Unity/Vuforia/Blender	Handheld	Image marker	No
Shrestha [86]	Unity/Vuforia/C#	Handheld	various	No

5.1. Software

Most of the presented literature relied on the use of free software to develop AR experiences, as shown in Table 2. These tools are easy to access, offer plenty of educational material, and are accessible to end users due to their compatibility with most common operating systems including HHDs and HMDs. It should be noted that none of the reviewed papers mentioned commercialising the AR tools developed or using them outside the context of academic research. Another way is to develop in-house AR experiences that make use of applications such sandbox AR [25,26,67] or the image tracking graphics visualisation system developed in C# by Aher et al. [101]. Using third-party applications

is another way to access AR experiences. Fuchsova and Korenova [90] tested the Brain iExplore and Anatomy 4D with students in the classroom. Although there are several commercially available applications on the Apple App Store and Google Play Store for AR, there are no reports in the literature that these applications have been used in engineering education.

Around 67% of the analysed literature used image markers to implement their augmentations. These augmentations either use a barcode to launch the AR experience or are in the form of AR textbooks. This is due to how easy it is to use and support image markers with all commercial AR SDKs. The use of surface markers and holograms (images produced using holography, which is a photographic method that records the light dispersed from a body to produce realistic images in 3D [102]) is less common compared to image markers and, in this context, was mostly used with HMDs or special hardware kits, as shown in Figure 5. HHDs can support different types of targets such as surface recognition targets [40] and model targets that detect edges and the construction of physical 3D models and then adds the 3D augmentation to the physical surface [103]. Several commercial SDKs do support these types of more advanced tracking such as Unity 3D, Vuforia, ARKit, and ARcore.
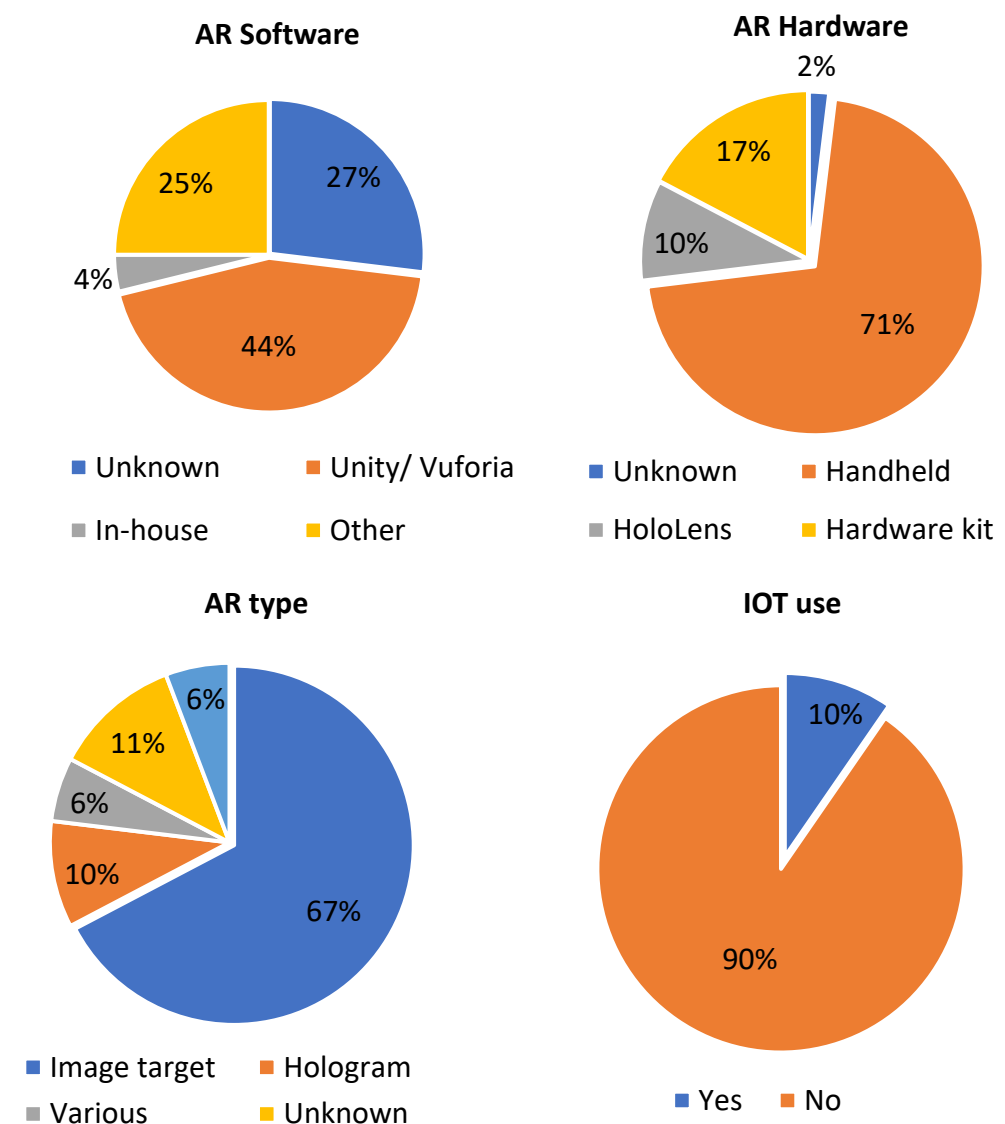

Figure 5. Tools and technology used for AR in engineering education.

Although the use of AR mainly focuses on visually enhancing the student learning experience, recently, the use of AR is being associated with another industry 4.0 technology, the internet of things (IOT). Around 10% of the analysed literature [13,29,30,66,69] added an IOT element to their AR experiences. Apart from Sahin et al. [30], who published in 2016, all other IOT/AR works were published after 2019. The attention to the AR-IOT in engineering education is consistent with the attention these two technologies are receiving in the industry for various applications [104–107]. A summary of the software technologies used in this review is shown in Figure 5.

5.2. Hardware

The hardware technology used to experience AR content has significantly improved over the past decade. Experiences constructed between 2010 and 2012 [15,100] required several trackers, an HMD, a personal computer (PC), and a camera to view an image marker experience. Today, users can view high-quality image marker experiences only using their smart devices. While the use of handheld smart devices is most common among AR education applications, as shown in Figure 5, the use of hands-free AR is becoming more popular as the Microsoft HoloLens 2 availability is increasing. Guo et al. [23,24] used the Microsoft HoloLens 2 to develop AR modules for manual material handling as part of an ergonomics class. The AR experience consisted of a job analysis work sheet, main animated hologram, and a contents blackboard where the students can view and interact with the course material and complete tasks via the AR technology. Borgen et al. [66] used a HoloLens device combined with IOT to display a flight deck hologram to start an auxiliary power unit (APU) and compared the procedure with the traditional paper-based teaching.

The use of AR HMDs has shown great benefits in terms of safety, cost, and engineering training. In the aviation industry, for example, the use of HMDs can save manufacturers significant amounts of money and provide an updated safe training experience. However, in engineering education, the use of AR HMDs can still be considered expensive especially if more than one headset is needed for each laboratory session. The augmented reality sandbox [25,26,67] is an example of using specialist hardware to generate a mixed reality experience. The sandbox hardware [25,26,67] consists of a computer with a high-end graphics card running Linux, a Microsoft Kinect 3D camera, a digital video projector with a digital video interface, and a sandbox with a Kinect camera mounted above the box. Theodossiou et al. [25] used the sandbox to teach concepts of hydrology to civil engineering students. The use of the hardware and the continuous development of the software allowed the students to better understand concepts of watershed, flooding, and the impact of constructions on rainwater management.

6. Users' Feedback

6.1. Feedback from Students

Feedback from students is a key factor to assess the success of the implementation of AR experiences as they are the primary users of the proposed technology. In the literature the students' feedback has been assessed from different perspectives. The studies assessed the motivation to learn [108], performance after using AR, and cognitive load [23,59].

To analyse the effect of using AR-based technologies, two approaches are generally used: first and foremost is the use of surveys to collect the student's feedback on their experiences. This approach covers a wide range of questions and allows the researchers to seek suggestions for enhancements and to evaluate the impact of AR technology from different perspectives, such as the motivation to learn [108,109], ease of use, and entertainment value. The second approach is the evaluation of the students' performance with and without the use of AR. Guo et al. [24] observed that 53% of the students who had an AR-based lecture received a perfect mark compared to only 23.3% of students without the use of AR. Borgen et al. [66] evaluated the effectiveness of an AR experience based on the time required by students to complete certain tasks, with and without AR support. Although the use of AR helped the students to complete the tasks quicker, the authors

acknowledged that the students required a significant period of time to learn how to use the AR technology. Liu et al. [52], Bairaktarova et al. [75], and Shrestha [86] integrated quizzes into their AR application. Dakeev et al. [20] assessed the amount of time required by students to perform tasks with and without AR. While these methods quantify to some extent the impact of AR in terms of a student performance and understanding, they do not provide any evaluation of the overall learning experience, motivation, or cognitive load associated with the use of hands-free or hand-held AR devices.

Borrero and Andujar [15], Gutierez et al. [95,96], and Omar et al. [110] used both surveys and marking to evaluate the use of AR. Shirazi et al. [79] tested the students' knowledge one month after the AR experience was used to analyse their ability to remember the material compared to a control group who did not use AR. In addition to questionnaires and evaluations, Reuter [53] conducted personal interviews with the students to collect feedback on the use of the AR technology. The interviewees were mainly asked about their opinions on the use of AR, any suggestions for further development, and to rate their own performance out of 100 on the performed AR task. The surveys developed to garnish the feedback presented in the STEM education literature were diverse and focused on the school level. For example, Da Silva et al. [111] proposed general guidelines for the educational evaluation of AR tools at the school level; Marin et al. [72] used the technology acceptance model, first proposed by Davis [112]; Reuter et al. [53] used taxonomy SOLO by Biggs [113] and Brabrand [114] for self-assessment and the MUSIC model of academic motivation [115]; Criollo et al. [73] used the IBM computing system usability questionnaire (CSUQ); and Schiffeler et al. [17] used both the technology acceptance model [112] and the task technology fit model [116]. However, there are no reported guidelines or standards to evaluate AR content for higher education. As shown in Table 3, 29 articles used surveys to evaluate the students' reaction to the use of the AR experience. For most papers, the survey questions can be categorised as follows:

- Motivation and interest: how did the AR material affect the student motivation toward the presented material?
- Learning material: is the presented material suitable for AR and does it improve the student's understanding?
- Ease of use for the whole AR experience in classroom and remotely.
- Educational added value.
- Overall experience, and positive/negative attitude toward the use of the technology.

In addition to the previously listed categories, particular attention to other aspects of the AR experience was given by authors. These survey elements could significantly enhance the overall evaluation methods for AR-based technologies. These categories are as follows:

- Previous knowledge: questions to indicate users' familiarisation with the proposed technology [15,60].
- UI/UX: to test interface appearance [15], on-screen dimensions [61], navigation and interaction [50].
- Software solutions: installation and running [15], third-party providers [90], application stability [61].
- Digital Assets: feedback on the produced AR media [15,41,90,108].
- Hardware used: hands-free, hand-held, and eco-system.
- Comparative analysis between hands-on and AR lab [77].

In addition to the survey questions throughout the reviewed literature, the data sample size was variable and there was no clear measure of how many students/educators should test AR to evaluate the use of the technology. The average number of participants for studies was 100. For the case where handheld AR devices were used, the average number of participants was approximately 110, which is significantly higher than the average number of participants for the cases where a mixed reality glass was used, which was approximately 27, as shown in Figure 6. This is likely due to hands-free AR being more

available and affordable. It also suggests that the use of hands-free AR might be a better option for teaching larger groups, whereas the use of mixed reality devices might be more suitable for teaching small groups.

Table 3. Methods of evaluation.

Author	Evaluation Method	Performance Measure	Number of Participants
Borrero and Marquez [15]	Performance measures and survey	Marks	20 students 10 teachers
Dinis et al. [21]	Survey	N/A	14 students
Gutierez and Fernandez [61]	Performance measures and Survey	Marks	47 students
Gutierez et al. [62]	Performance measure	Marks	47 students
Opris et al. [63,64]	Survey	N/A	34 student 14 teachers
Sahin et al. [30]	Survey	N/A	55 students
Yuzuak and Yigit [60]	Survey and students' evaluation	N/A	51 students
Zoghi et al. [50]	Survey	N/A	10 students
Behzadan and Kamat [65]	Survey	N/A	63 students
Borgen et al. [66]	Performance measure	Experiment time	36 students
Alanis and Tejeda [40]	Survey	N/A	39 students
Alptkien and Temmen [58]	Survey	N/A	44 students
Alptkien and Temmen [68]	Test by [111]	N/A	Unknown
Reuter et al. [53]	Survey, performance measures and Interviews	Various elements	14 students
Daling et al. [71]	Survey	N/A	120 students
Alvarez-Marin et al. [72]	Survey	N/A	173 students
Criollo-C et al. [73]	Survey	N/A	80 students
Schiffeler et al. [17]	Survey	N/A	13 students
Guo [24]	Performance measure	Test score	32 students
Guo and Kim [23]	Performance measure	Work loads	45 students
Mohammed et al. [89]	Survey	N/A	7 teachers
Liu et al. [52]	Performance measure	In application quizzes	Unknown
Xie and Yang [51]	Survey	N/A	Unknown
Hung and Weinman [57]	Survey	N/A	13 students
Alvarez-Marin et al. [74]	Survey	N/A	124 students
Bairaktarova et al. [75]	Performance measure	In application quizzes	119 students
Liu et al. [76]	Survey	N/A	1417 students
Odeh et al. [77]	Survey	N/A	Unknown
Urbano et al. [28]	Survey	N/A	440 students
Shirazi and Behzadan [79]	Survey	N/A	166 students
Singh et al. [59]	Survey and performance measure	Marks	
Kumar et al. [81]	Survey	N/A	20 teachers
Dong et al. [82]	Survey	N/A	Unknown
Tirado-Morueta et al. [84]	Survey	N/A	98 students
Dakeev et al. [20]	Performance measure	Time to perform task	39 students
Jacob et al. [85]	Survey and performance measure	Marks	180 students 30 teachers
Shrestha [86]	Survey and performance measure	In application quizzes	34 students 2 educators 11 Industry professional 1 other
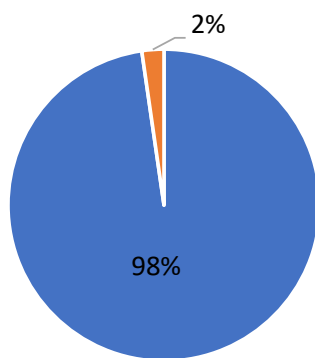
(a)
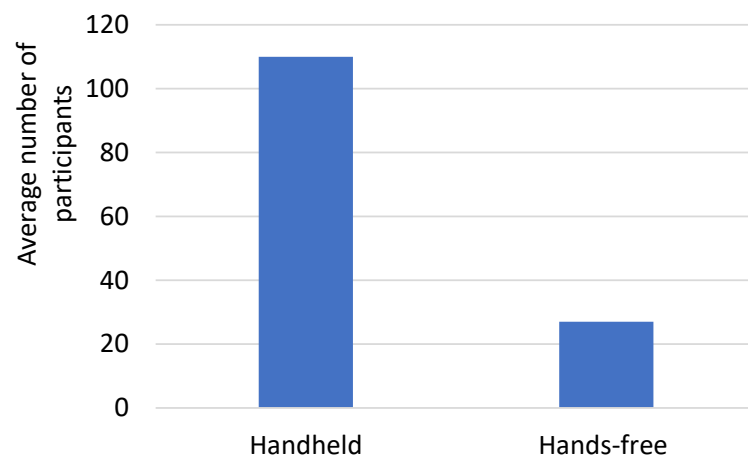
(b)

Figure 6. Feedback on the use of AR from students and educators: (**a**) students vs. educators and (**b**) hardware used to consume the AR experiences.

6.2. Feedback from Educators

The literature reports only limited feedback from educators, as shown in Figure 6. Around 2% of the participants reported in the literature were educators, and most of the

educators' feedback was recorded from a student's perspective when using the technology and not from an educator's point of view. For example, Borgen et al. [66] and Opris et al. [64] surveyed 10 and 14 teachers, respectively. For every case, the teacher performed the same tasks as the students and recorded their feedback. Mohammed et al. [89] conducted a survey for educators to study their responses on using AR in electrical engineering courses in terms of the effect of using AR on the lecture process. The survey included questions about their background in terms of their years of experience as an educator, awareness or previous knowledge on AR, usability, and interest in such technology. The survey was given to seven educators, of which more than 50% were familiar with AR technologies. The educators were as excited as the students about the use of AR technologies. Although the overall reaction to the technology was positive, the educators were concerned about the AR content loading time and video quality. Jacob et al.'s [85] teachers survey included questions for teachers to evaluate the quality of their teaching after using AR and to evaluate their students' satisfaction levels after using AR. The authors conducted the experiment for 11 weeks and the teachers' scores significantly improved by the end of the trial. Kumar et al. [81] conducted an AR application usability test with educators and collected feedback from 20 teachers using a questionnaire that included questions on: application ease of use, need for technical support, application functions, and prerequisite knowledge required to use the AR application. There remain many unknowns when it comes to the use of AR technology in education including "How much time does it take a lecturer to develop an AR experience [91]?", "What previous knowledge is required to develop an AR experience?", "How much testing, debugging, and optimisation does an AR experience require", and "How does the use of AR affect lecturers' work and cognitive loads?".

7. The Future of AR in Engineering Education

The adoption of augmented reality-based technology could help tackle several challenges in engineering education [117]; namely student engagement, customisation of the learning experience, visualisation of physics, encouragement of self-learning, access to dangerous environments, and language barriers.

7.1. Student Engagement: Motivation, Engagement, and Achievement

The relationship between student engagement and achievement has been well documented [61,108,109]. Learning strategies such as problem and project-based learning have been considered pedagogies of engagement for many years because they require students to be actively involved in their learning [118]. It is hypothesised here that AR technology could increase the engagement of students by adding a sense of fun to their studies and provide a nonthreatening path for the students to find information and explanation.

7.2. Customisation of the Learning Experience: Learning at Your Own Pace

It is apparent to many educationalists that students learn in different ways. There has been a general movement in engineering education toward active learning techniques, which can broadly be described as learning by doing. This has led to engineering courses using a mixed delivery approach with the most popular elements being lectures, laboratories, tutorials, and self-learning resources, such as textbooks. AR introduces the potential for learners undertaking laboratory sessions to receive supporting information during the laboratory through links that signpost them directly to documents or multi-media files obtained from the integration of other engineering technologies (i.e., IOT data, CFD/FEA simulations).

7.3. Visualisation: Seeing the Invisible

Mathematics provides tools to engineers for modelling fluid flows, heat transfer, and stress in materials. AR technology has the potential to visualise these parameters and overlay them directly onto laboratory experiments. Tsujita et al.'s [14] nuclear reactor core simulator and Solmaz and Gerven's [13] use of AR to teach Computational Fluid Dynamics

(CFD) are both good examples that demonstrate the visualisation principle. In addition to enhanced visualisations, the use of AR technology can provide virtual access to dangerous environments via simulating dangerous laboratory or real-life situations. Several papers reported the use of AR-based technologies for safety training purposes. Examples of these include: construction safety [119], fire safety [120], and occupational safety in industrial environments [121].

7.4. Self-Learning: Success for All

As a greater number of people enter further and higher education, courses will continue to grow, and the diversity of the student's academic capabilities, educational backgrounds, and cultural backgrounds will likely increase. This is exemplified by the number of entry points into many engineering degrees—students who have studied school exams in the home country, students who have studied other educational paths such as vocational qualifications, students with overseas qualifications, or mature students with qualifications and work experience. One trusted approach that helps students, whatever their profile, on entering a course is for an educational establishment to facilitate and encourage a self-discovery path. AR platforms have the potential to provide visually impressive material that may encourage students to ask questions, collaborate with each other and be active in their learning.

7.5. Language Barriers: Overcome Educational Difficulties

Language differences in combination with generational gaps between lecturer and student can often lead to communication challenges. Tools such as AR that help students to investigate phenomena and physics on their own will help to overcome some of these barriers [122,123]. In recent years, augmented reality has been widely used in learning languages. Indeed, Parmaxi and Demetriou [124] reviewed 54 papers published between 2014 and 2019, which made use of AR technologies to teach foreign languages. AR was employed successfully to help teach vocabulary, reading, speaking, and writing. Therefore, it is hypothesised that applying this approach to engineering education could significantly improve the overall experience of international students, particularly in the early years of study.

8. Future Research Directions

From reviewing the growing body of literature, several trends become apparent for the future direction of research into the use of AR technology in engineering education.

8.1. Developing AR Experiences

The availability of AR experiences continues to be the principal barrier to the testing and adoption of AR technology. The equipment and software needed to develop realistic and high-quality experiences is often expensive and requires expertise. However, it is essential to develop affordable experiences to encourage educationalists to test and adopt the technology. An AR platform that allows lecturers to develop their own experiences for a low cost may enable an accelerated uptake of the technology. It would also facilitate students to participate in the development of the educational AR experiences [125,126]. Nesterov et al. [127] highlighted the importance of training learners and educators to model, construct, and build AR experiences from different aspects and fields so they integrate AR over a diverse range of subjects and restructure the educational process to be more visual and interactive. Anastassova et al. [128] suggested that improvements could be made to AR experiences by encouraging more user involvement in the design of the learning experience and the evaluation of digital prototypes. They also suggested improving the feedback obtained from users with more in-depth interviews, observations, and extended questionnaires, such as the way AR technologies are being evaluated in industry. Mystakidis et al. [129] developed an online professional development program for K-12 teachers, which included AR and VR modules. Training educators in developing

educational AR content can significantly ease the integration of the technology into the engineering curriculum [130].

8.2. Developing Engineering Courses with Embedded AR Experiences That Have Meaning

While there is some work underway to develop AR experiences for engineering education, little has been reported on the advantages of these experiences to support a wider curriculum. As has been discussed in this review paper, AR technologies have the potential to be engaging; however, a greater value is required if they are to become a permanent fixture in engineering courses. The AR experiences need to add to the curriculum content as well as the experience of the student.

8.3. Measuring the Impact of AR Technology on the Student Experience and Learning Outcomes

In the field of engineering education, very little evidence has been reported in the literature on the long-term impact of AR technology on the student experience and learning outcomes. Some researchers have surveyed students and staff to gather qualitative data focused on the individual's experience and the perceived value of the AR technology as an educating tool. However, large, long-term trials [28,76] are needed to discover if AR experiences motivate students to self-learn, continue to engage students after the novelty has waned, and facilitate deep learning. Measuring these factors will be difficult; however, a combination of surveys, quizzes and practical tests could be used to add to the growing body of evidence.

9. Conclusions

This paper has presented an overview of the use of AR in engineering education. This section summarises the findings in the form of a SWOT analysis.

Strengths

- AR technology uniquely provides students the ability to observe internal structure, complex engineering physics (such as fluid flows, heat distributions, currents, and magnetic fields), guidance to complete hands-on tasks, and link real-world applications with taught material in a safe interactive environment.
- Affordable software and hardware that can be used to develop and consume AR experiences are increasingly available.
- The 'WOW factor' associated with the use of these technologies encourages student engagement.

Weaknesses

- There is a lack of AR digital assets for engineering principals developed by educators.
- There has been very little integration of AR experiences into engineering curricula.
- There have been very few studies on the long-term educational impact on both students and educators.

Opportunities

- Student achievement could be improved because of better engagement, motivation, enhanced visualisations, and improving the students overall learning experiences.
- AR technology could be a vehicle for other industry 4.0 concepts to be included in education.
- AR offers a means to customise the learning experience for students based on their capabilities and their learning preferences.

Threats

- Lack of skills to develop AR experiences from engineering students and educators.
- Limited commercialisation of developed AR engineering applications.
- Educators not adopting the AR applications, due to the lack of AR digital assets.

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