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TOPICAL REVIEW

Augmented Reality and Its Applications in Education: A Systematic Survey

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ABSTRACT The use of technology, especially mobile phones, has significantly increased over the past few decades and has become an essential element in our daily lives. Mobile and desktop applications based on Augmented Reality (AR) proved to be a revolutionary step in different areas, especially in the educational sector. AR provides an improved and extended version of reality with the superimposition of a virtual object in the real-world environment. These objects can be interacted with and visualized in many ways to provide full AR experiences. By interacting with augmented virtual objects, students can visualize and completely understand various difficult concepts during their studies rather than traditional learning, allowing collaborative learning and hence improving learnability, motivation, and focus. This survey paper discusses the concept of AR and its types, the need for AR applications in education, analysis of various state-of-the-art AR applications in terms of platform, augmented virtual content, interactions, usability, usefulness, performance, effectiveness, and ease-of-use under a single taxonomy. Although applications of AR in education for learning, teaching, and simulating have proven quite effective in delivering the concepts via interactive study, there are also several limitations in terms of complexity and availability of hardware, platforms, internet connections, portability, computational, and rendering speed. This study offers insights into potential trends and directions that AR technology might take in education, furnishing readers with a glimpse of forthcoming developments. This comprehensive perspective equips educators, researchers, and practitioners with valuable insights into the pedagogical implications, technological aspects, and practical considerations related to AR.

INDEX TERMS Augmented reality, education, taxonomy, virtual reality, collaborative learning.

I. INTRODUCTION

With the advancement of emerging technologies, the ability to observe, interact, and hear virtual objects coexisting in the real-world environment is possible with the introduction of AR. Applications based on AR have proven quite an attention, interest, and attraction in many areas, including education, medical, automation, e-commerce, tourism, interior design, building architecture, and construction, as well as in entertainment [1], [2]. Traditional educational styles and classrooms have been replaced with more interactive methods of teaching and learning with the help of various AR-based applications. In the medical and healthcare sector, with the help of AR, the interactive study of human anatomy is possible; also, surgeons can perform medical procedures on the virtual body before actually performing the same procedures on real human bodies. A variety of mediums can explore educational material. Traditionally, students learn through interaction with peers and teachers, which use traditional face-to-face communication to understand the educational content and non-interactive mediums like video, notebooks, and images [3]. In the last few years, digital media has been continuously involved in learning and educational activities and provides opportunities to learn with educational

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games and interactive simulations [4]. Educational content can be enhanced by using AR technology in the educational medium, where AR combines virtual information in the user's real world and allows the users to interact with all body parts with the virtual content. AR experience can be explored through smartphone-based and web-based applications that allow the users to capture the educational content by using the webcam and smartphone's camera and display its augmentation on the screen like a monitor and projector [5]. By using AR in education, some interesting advantages were perceived. Martin-Gutierrez et al. [6] found that using AR in education increases self-learning among students, which provides the teacher with more time to explain complex topics. According to Fonseca et al. [7], AR tools continuously enhance the spatial perceptions of the students, which helps the students to learn or memorize complex content quickly. Kiyokawa et al. [8] proposed that collaborative tasks can be enhanced by using AR in education. It is possible to design innovative computer interfaces that integrate real and virtual worlds to enhance remote and face-to-face collaboration. It helps the students to memorize the educational content more easily. Internet and web applications are widely used, but still, practical people prefer reading books and textbooks for learning instead of using internet technologies. One of the most interesting applications of AR technology is AR textbooks.

AR can enhance the learning experience and motivation among students. Yuen et al. [9] classified AR technologies into five groups that can be used for educational purposes. AR can also be used in discovery-based learning. Such applications are used in historical places, museums, and astronomy education [10], [11], [12], [13]. In these applications, a user can interact with the objects of his interest. In object modeling applications, AR can also be used, where a user receives visual feedback of images from different directions. Such applications also allow users to plot virtual objects and find physical properties and interactions between two or more objects. Such applications are mostly used in architectural education. AR books are also used in education, which is printed as normal, but in AR books, a webcam can generate visualization and interactions from the book [14]. It is achieved by special software in the computer or with special applications or websites designed for such purpose. This software technology allows all existing books to generate augmentation after publication. Using 3D objects and modeling and simulations with various interactions is the best way to connect two isolated worlds. Using AR in education or printed books can become a dynamic source of information. In such a way, the people who have no computer experience can still use the technology and have an interactive experience [15]. Skill training applications that are used in airplane maintenance in which all repairing parts are being augmented on the screen are the application of AR technology. AR gaming, like video games, provides new chances for students to learn that have been ignored for many years [16]. Now, AR games are being used in education. It provides a highly interactive and visual form of learning. Many papers discuss that the use of AR in education has increased and have proved that AR technologies enhance motivation and participation between teachers and students in educational institutes. When AR is integrated with the study, students become more involved in learning, explaining in more detail, and interacting with real objects in a virtual environment [17], [18]. AR can not only be used in a formal learning environment like classrooms but it can also be implemented in informal learning like parks, museums, etc [19], [20]. Empowering AR in such an environment as a museum proves that motivating the user to learn about the presented resources.

Improving learning skills and motivation among the students at AR can also be applied to create, plan, distribute, and provide access to learning resources [21]. AR is also facilitating users with disabilities. For example, visually impaired users can interact with the help of music and sounds. Albums-Perrois et al. [22] proposed a tool named the paper AR toolkit, which is used to interact with maps using e-boards with sound. In general, AR helps the user to have better knowledge and experience as it provides access to relevant information, which enhances participants' knowledge and learning skills about the different contents. Radu [4] discussed that AR is a new technology in education, and few participants know how to use it. According to the study by Tzima et al. [23], AR is not popular among students and teachers, and its use is difficult; while implementing the 3D content, they have to face difficulties. The use of mobile devices can be harmful to students because these devices could become a distraction and can be a reason for time wastage in installing the tasks as it includes virtual information that cannot be related to the user's tasks and can be a hurdle in learning [24].

The main contributions of this paper are as follows:

- This paper provides a comprehensive overview of the evolution, advancement, and applications of AR in education. This overview is traced from its origins to its current state, highlighting the key milestones and trends in AR adoption in the educational landscape.
- This paper presents a structured taxonomy that categorizes the diverse applications of AR in education. This taxonomy enables readers to navigate through different aspects of AR integration effectively, facilitating a deeper understanding of the potential benefits of AR in various learning contexts.
- The paper delves into various learning categories and educational objectives that benefit from AR integration, showcasing how AR can enhance engagement and outcomes across disciplines and levels of education. By providing concrete examples of how AR can be used to improve teaching and learning, the paper contributes to the evidence base for AR adoption in education.
- This paper discusses different augmentation types and the devices used to deliver AR experiences, offering insights into the technical aspects of AR implementation

and its impact on educational practices. This information is valuable for educators and policymakers who are considering implementing AR in their schools and classrooms.

- The paper highlights the software tools utilized in creating AR experiences for education and discusses the methods employed in designing effective AR-based learning activities. This practical guidance is essential for educators who want to start developing their own AR-enhanced learning resources.
- This paper explores a wide range of educational applications developed using AR technology, demonstrating how AR is used to enrich learning experiences in diverse domains. This showcase provides readers with a glimpse into the innovative and transformative potential of AR in education.
- This paper presents insights into the methodologies used to evaluate the effectiveness of AR applications in education, encompassing both quantitative and qualitative evaluation criteria. This information is essential for researchers and developers who are designing and assessing AR-based learning interventions.
- The survey paper contributes to the advancement of educational technology by consolidating and synthesizing information on the state of AR in education, fostering informed decision-making and innovation in teaching and learning. By providing a comprehensive and authoritative overview of AR in education, the paper helps to pave the way for the widespread adoption of this transformative technology in educational settings.

The rest of the paper is arranged as follows: Section II discusses the basic concept of Augmented Reality. The inclusion criteria for the paper are briefly discussed in Section III. A brief history of Augmented Reality is discussed in Section IV. Section V discusses the complete paper under a single taxonomy. The summary of the taxonomy is presented in Section VI. The limitations of applications of AR in Education are discussed in Section VII. Finally, the paper is concluded in Section VIII with potential future research directions.

II. AUGMENTED REALITY

Various researchers define the term "Augmented Reality" in different ways. The standard definition of AR is a system with three characteristics: (a) it overlays virtual objects in the real-world environment. (b) it provides real-time user interaction with the augmented virtual object. (c) three-dimensional (3D) virtual objects are accurately registered on real-world objects [2]. It is important to understand three aspects of the definition of AR. Firstly, AR device technologies are not only restricted to Head-Mounted Displays (HMD); there could be different types of displaying technologies. Secondly, perception through AR is not only limited to the sense of sight only, as AR could be perceived by the sense of hearing, touch, and smell. Finally, overlaying virtual environments on real objects by completely removing the reality is also considered

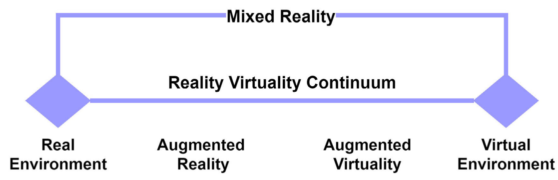

FIGURE 1. Pipeline of reality-virtuality continuum.

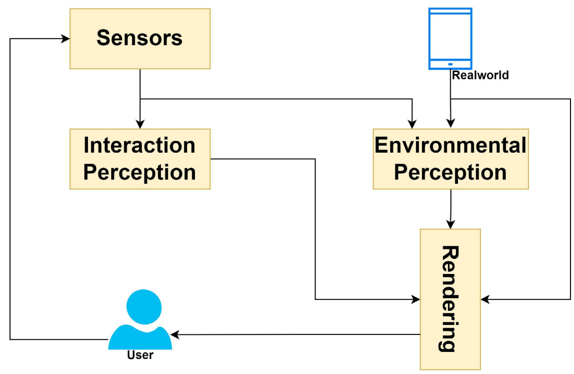

FIGURE 2. Basic AR process.

part of AR, also referred to as mediated or diminished reality. Fig. 1 shows a reality-virtuality continuum proposed by Demitriadou et al. [25], which tells that AR is the subpart of Mixed Reality (MR) where virtual objects are integrated with real objects in a real-world environment. Augmented Virtuality (AV) and Virtual Reality (VR) are on the same continuum. The comparison of AR, VR, and Mixed Reality (MR) is summarized in Table 1.

AR enhances the perception of the real-world environment with the integration of one or more computer-generated virtual objects or graphics, allowing interaction with the virtual objects with the help of various sensory modalities including sound, haptic, visual, or gestural. The typical process of AR is shown in Fig. 2. The device takes perception from the environment and interactive perceptions are fetched by the sensors provided by the user. The interaction perception refers to the ability of the AR system to recognize and respond to user actions and inputs within the virtual environment it creates. It involves the seamless integration of computer-generated virtual objects or graphics into the real-world environment, allowing users to interact with these virtual elements using various sensory modalities, including sound, haptic feedback (touch or tactile sensations), visual cues, or gestural commands. These two inputs are rendered together into a single display and finally, the user can see an enhanced version of the reality in terms of AR.

III. INCLUSION CRITERIA FOR THE PAPERS

The paper provides a systematic literature survey on the application of AR, more specifically in education. Several research papers from the year 2000 to 2023 that are published in impact factor journals and reputed conferences are part

TABLE 1. Comparison of AR, VR, and MR.

Virtual Reality (VR)	Augmented Reality (AR)	Mixed Reality (MR)
Digital environments completely shut out the real world.	Virtual objects are overlaid in the real-world environment.	Virtual environment combined with the real world.
Fully artificial environment.	Enhancement of the real world with digital objects.	Interaction with both real-world and virtual environments.
Complete immersion in the virtual environment.	Virtual content is placed on top of the real world.	Digital content interacts with the real world.
Offers Freedom of movement in the digital atmosphere with sound effects.	Special AR handsets can be used wherein the digital content is displayed on small screens.	The user remains in the real world, and digital content is appended i.e., Microsoft Hololens.
Special Head-Mounted Displays (HMD) can be utilized for the enhanced experience.	Example: Pokémon Go. People around the globe rush with their smartphones in search of small virtual creatures.	It is also possible that mixed reality starts with the virtual world, and the digital environment replaces the real one but remains connected.
Example: VR games		Example: Windows mixed reality headsets.

of the survey. Keywords such as "Augmented Reality," "Augmented Reality in Education," "Application of AR in education," etc. are utilized to search for the latest and most relevant papers in Google Scholar, Springer, PubMed, PubMed Central, and Science Direct, etc.

The inclusion criteria for the papers to be a part of the survey are as follows:

1. The research paper must directly address the utilization of augmented reality (AR) technology in an educational context. The content should focus on AR's impact, benefits, challenges, or outcomes within various educational settings.

2. Only peer-reviewed and published research papers are considered. This ensures the quality and credibility of the information presented in the survey paper.

3. Research papers published within the last ten years will be included unless they offer significant foundational insights that remain relevant to the current state of AR in education.

4. Papers focusing on AR applications across diverse educational levels (e.g., primary, secondary, tertiary, lifelong learning) are included. The papers should demonstrate how AR enhances learning experiences for different age groups and learning objectives.

5. Empirical studies, including quantitative, qualitative, and mixed-methods research, are encouraged. Case studies demonstrating the practical implementation of AR in real-world educational scenarios are also relevant.

6. Papers should discuss the impact of AR on learning outcomes, including measures of engagement, retention, comprehension, and skill development. Studies that provide evidence of AR's efficacy in enhancing educational goals are prioritized.

7. Papers should delve into the technical aspects of AR implementation in education, including software, hardware, usability, user experience, and design considerations.

By adhering to these inclusion criteria, the primary objective of this study is to conduct an in-depth systematic literature survey by discussing applications of Augmented Reality (AR) within the educational context. Although numerous systematic reviews and meta-analyses exist on the topic of AR in education and related subjects, examples include the works of Akçayır and Akçayır [26], as well as Garzón [27], these reviews are characterized by their limited scope. They tend to focus on a small subset of articles published in the field and within a confined time frame. Notably, certain analyses have extended their scope to encompass a 25-year span (1995-2020) of AR research [28]. There are also several survey papers that spotlight various applications of AR in education, exploring its advantages, disadvantages, limitations, and prospects for future research directions. For instance, Garzón et al. [29] conducted a survey that accentuates the trends in AR applications across a quarter-century by categorizing them into three distinct generational phases. Moreover, the survey delves into the limitations associated with AR implementation. Interestingly, there is a noticeable absence of studies that delve into the tools, technologies, and evaluation criteria employed in the development of AR-based applications, as well as the assessment of their usability and practicality [30]. While certain surveys have restricted their inquiry to specific sub-subjects or domains concerning AR's application in education, such as medical education [31], biomedical applications [32], history education and heritage visualization [33], engineering education [34], and mathematics [35], the present study takes a broader stance. It covers a more extensive array of AR applications across various educational domains, thereby offering a comprehensive perspective on augmented reality's potential impact.

IV. BRIEF HISTORY

In the 1960s, Ivan Sutherland, collaborating with his team, designed the first augmented reality prototypes named"Sword of Damocles" at the University of Utah and Harvard University created by computer graphics pioneers that used head-mounted devices to augment 3D graphics [36]. From the 1970s to the 1980s, mobile devices like digital watches and PDAs were presented by a small research group of the United States Air Force Armstrong Laboratory, NASA Ames research center with the collaboration of the University of North Carolina [36], [37]. In the 1980s, Steve Mann introduced wearable computing devices. In 1984, beginning computers contained the Psi-on I. In 1993, the Apple Newton MessagePad was introduced. In 1996, the Palm Pilot was presented in the world. In the 1990s, Boeing researchers Tom Caudell and Mizell formulated the term "*Augmented Reality*" [38] while progressing with the experiment of an AR system that helps users set up wiring harnesses. Cell phones with AR technology were still away from common users, but after some years [39], a GPS-based outdoor system was proposed, which provides navigational help to visually impaired persons with the help of geospatial overlays. With the passage of time tracking and computing devices become more efficient and sufficiently small to handle geographical sheathing in mobile phones. Feiner et al. [40] designed a prototype of the Mobile Augmented Reality System (MARS) which has the capability to capture 3D graphical tour images and information with its historical buildings and objects so that visitors can entertain by this. In the late 1990s, when AR emerged as the trending research field, many conferences on AR started. AR applications have started to be developed with freely available ARToolKit. NASA designed a compound synthetic vision system in 1990 for X-38 spacecraft. This system works on AR applications that provide navigational support during the test flight [41]. In 2013, Volkswagen designed the MARTA application, which provides technical support and repair instructions. In the same way, AR technology was applied in many other industries. In 2014, Google presented its Google Glass devices that users wear for its immersive experience. In 2016, Microsoft released its AR wearable device named Holo-lens with high cost, which is more powerful than Google Glass. It allows the user to scan the surrounding environment and generate an AR experience [42]. In 2017, IKEA introduced an AR application named IKEA Place that changed the retail industry forever. It allows the user to decorate the home virtually before purchasing the accessories. In the near future, every consumer will start to use AR applications and technologies.

V. TYPES OF AUGMENTED REALITY

AR-based applications are usually categorized into three different types to display augmented content on the screens, these are; marker-based, markerless, and geographical. Each type of AR has its strengths and weaknesses. Marker-based also known as recognition-based or image recognition AR uses different sets of predefined markers or images in order to display augmented virtual content in real-world environments. These markers are the distinct patterns that the camera of displaying devices captures and processes that later act as a trigger for the augmented reality experience. Markers are usually in the form of a Quick Response code (QR code) or Microsoft Tags. These markers act as an anchor point for the virtual content to be displayed on the screen. By moving either marker or displaying devices, overlaid objects can be seen from different viewpoints. Unlike marker-based, marker-less AR applications are more flexible types of AR that do not require any predefined markers or targets. Here, virtual content can be augmented as per the needs of the user by allowing the integration of virtual objects at any place in the real-world environment. These marker-less ARs are dependent on mobile cameras, accelerometers, Global Positioning System (GPS), or compass to gather positional information for the object. The technique of imposing content at a 3D pace is referred to as the Simultaneous Localization and Mapping (SLAM) algorithm. Here, "mapping" typically refers to the construction of a map that represents the real-world environment. This map is a digital representation of the physical world, which may include features, objects, and landmarks, without the use of predefined markers. It is used to provide a reference for the augmentation of digital content into the real environment, ensuring accurate alignment and interaction. Geographical or locational AR is an extension of marker-less AR where it uses a device GPS, accelerometer, gyroscope, or compass that acts as a sensor, and virtual contents are anchored on a specified location based on the user's input and requirements. A very popular game 'Pokemon Go' is an example of a locational-based AR application that is shown in Fig. 3 for mobile devices that fetches a user's location to display different Pokemons in the real environment, on the user's mobile screen. Other applications that use locational AR are travel guides and maps [43].

FIGURE 3. 'Pokemon Go', an example of locational-based AR.

VI. TAXONOMY FOR AUGMENTED REALITY IN EDUCATION

This section discusses the taxonomy for AR in Education, as shown in Fig. 4. The section is divided into nine different categories: (a) Learning categories, (b) Objectives, (c) Augmentation types, (d) Devices, (e) Content, (f) Interaction, (g) Software Tools, (h) Applications, and (i) Testbeds.

A. LEARNING CATEGORIES

The use of technology has changed the way of learning for students, especially in the field of education. Nowadays, different types of learning categories are being used in education. This section discusses different learning categories widely used and practiced in the education sector.

1) ELECTRONIC LEARNING (E-LEARNING)

E-learning refers to the use of electronic technology, primarily the Internet, to deliver and facilitate learning. Unlike traditional learning systems of student-teacher interactions within the classrooms, it encompasses a wide range of learning activities that can be conducted using various digital platforms, including computers, laptops, and tablets. E-learning can involve synchronous (real-time) or

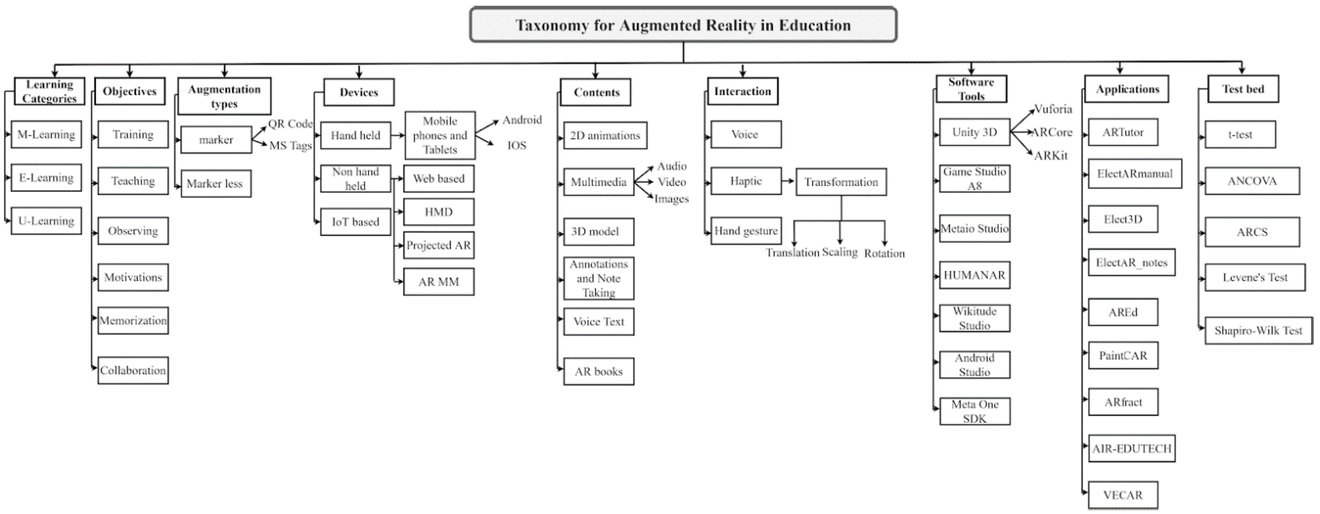

FIGURE 4. **Taxonomy for augmented reality in education.**

asynchronous (self-paced) interactions between learners and instructors or content. It is not limited to a specific device and can be accessed through different technologies [44], [45].

2) MOBILE LEARNING (M-LEARNING)

The use of mobile phones has increased rapidly in everyday life. There are various applications of mobile: chatting, calling, gaming, social networking, educational and office use, etc. M-learning refers to learning that is conducted using mobile devices, such as smartphones, tablets, and wearable devices. It leverages the mobility and ubiquity of these devices to provide learners with access to educational content anytime and anywhere. M-learning takes advantage of features like touchscreens, cameras, and sensors to create interactive and context-aware learning experiences. It's often used for short, bite-sized lessons or micro-learning [6], [45] [46], [47].

3) UBIQUITOUS-LEARNING (U-LEARNING)

Ubiquitous-Learning (U-Learning) is a new learning paradigm. As we move from E-learning to M-learning, we are now moving to U-learning. U-learning is "anywhere and anytime learning." U-learning is a subset of mobile learning that focuses on seamless and continuous learning experiences across various devices, contexts, and environments. It goes beyond just using smartphones and includes a wider range of technologies such as sensors, RFID (Radio-Frequency Identification) tags, and smart environments. U-learning aims to integrate learning into everyday activities and surroundings, blurring the boundaries between formal and informal learning [44]. Lin et al. [48] proposed an interactive AR-based picture E-book to study the life cycle of insects for kindergarten students. The goal of this picture AR book was to improve U-learning.

Major Difference: While there is some overlap between these categories, they each have distinct focuses and characteristics. E-learning encompasses a broad range of electronic-based learning, M-learning specifically refers to learning through mobile devices, and U-learning extends the concept of mobile learning to create ubiquitous and context-aware learning experiences.

B. OBJECTIVES

AR applications have proven to be quite effective, especially in the education sector, as these applications promote the student's learning capability, increase motivation to study, enhance learnability, easily understand difficult concepts, and provide interactive study, thus increasing learning. Many cross-platform AR applications have been designed and developed by various researchers. The primary objective of all applications is the same. This section discusses different objectives and reasons behind the development of AR applications for education.

1) TRAINING

The basic purpose of training is to train the students and teachers about technology like AR and model-based VR. Training includes how to use the specific real device and training for process, operation, and equipment rather than implementing and designing the applications [47].

2) TEACHING

The main goal of AR technology in education is to prepare students to teach difficult and abstract concepts that cannot be taught in the classrooms. AR technology extracts the information from the content and represents it in a 3D model, and teachers can use this to explain it efficiently. This concept is more helpful for visual learners who learn through images and videos more easily and convert the theoretical content into real concepts. With the help of 3D models, teachers can teach the same topic from different perspectives and students retain such content more easily than in traditional ways [45], [49], [50].

3) OBSERVING

In traditional learning styles, students primarily engage with books and 2D animations, often facing difficulties in comprehending complex diagrams and topics, particularly within medical groups. However, AR provides an environment where students can explore content and intricate diagrams in 3D views. By employing full-body interaction, students can manipulate AR content [51], [52].

4) MEMORIZATION

The purpose of using AR technology in education is to enhance students' memorization. It is experienced that students who learn through AR tools and technologies have stronger long-term memory retention than those who learn through books and videos. Different studies analyzed that students learn more through visual interaction rather than books. So instead of theory, students visualize the content through AR technology and retain it [53].

5) COLLABORATION

One of the main objectives of using AR technology in education is to enhance collaboration among teachers and students. The main purpose is to create a shared environment where different students can collaborate with peers and enhance their learning skills. Collaboration helps the student learn the knowledge gained more easily by training [54]. Moreover, interactive lessons, in which all the students are simultaneously involved in the learning process, help them enhance their teamwork skills [45].

C. AUGMENTATION TYPES

Two types of augmentation are used to extract the information from the educational content: Marker-based and the other one is Marker-less.

1) MARKER-BASED

Marker-based augmentation types recognize the code or AR content when the camera is triggered on it. Quick Response (QR) codes, Microsoft tags, and latitude, longitude, and altitude (LLA) are the common types of marker-based augmentation type [55]. In this type, the marker must be detectable and recognizable using a camera or other detectable device for the successful result of the QR marker, where the AR marker represents the 3D content that can be displayed on the screen. The AR marker system uses the AR Toolkit to generate and detect the region. Using image detection techniques, the captured image is transformed into a binary image, and with the help of a threshold, the edge and corner of the marker are extracted from the image. After successfully detecting the marker from the image, the marker is verified from the marker library, and its relevant information is displayed on the screen [4]. Typical QR codes and MS tags are shown in Fig. 5.

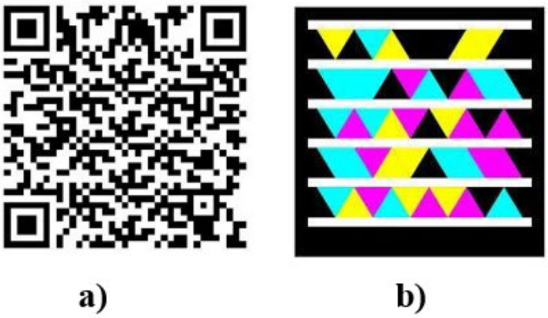

FIGURE 5. Illustration of two markers, a) QR code and b) MS tags.

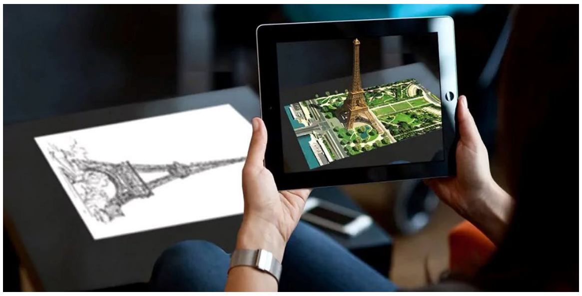

FIGURE 6. Illustration of marker-based AR.

Marker-based AR is an approach that heavily utilizes image recognition. Marker-based augmented reality experiences require a stationary image, often referred to as a trigger photograph, which individuals can view through their mobile devices using an augmented reality application. The act of scanning this image on the mobile device will activate supplementary content such as videos, animations, 3D elements, or other materials previously prepared, causing them to superimpose on to the marker. The recognition of markers can occur either locally or through cloud-based methods, implying that databases containing marker information can be housed on the device itself, and the recognition process can also take place directly on the device. An example of such 3D element marker-based AR can be seen in Fig. 6.

2) MARKER-LESS

Unlike Marker-based AR, the marker-less augmentation type detects planes where virtual objects are to be augmented. Locational or geographical AR is also an example of markerless AR, where they fetch data from a global positioning system (GPS) to retain the user's location and a compass to detect the object orientation, and with the help of infrared light depth, the image can be produced. Using this, we can create augmentation of virtual content in desired locations and real and static environments [56]. The Aurasma eco-system was used to recognize marker-less images, which are free and easy to use and do not require any programming experience. The AR content can be created by creating a channel like a YouTube channel for teachers, and

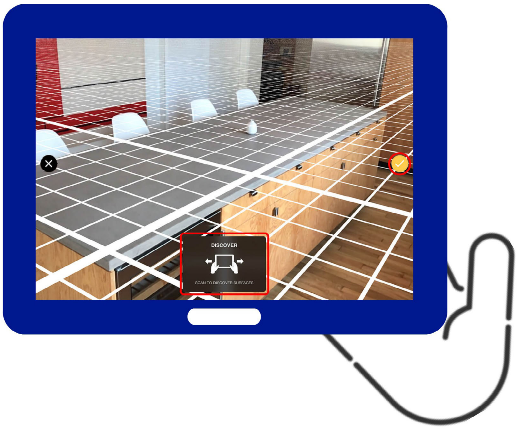

FIGURE 7. Illustration of marker-less AR.

they add educational content to their channels. After creating the channel, the teacher uploads the triggered images, which are AR educational content images. After the upload, the final step is aura creation, that is, 3D animation and AR action images that appear when a camera is triggered on the real-world image. Aura stored that image and students can learn from this augmentation at any time. The example of marker-less AR is given in Fig. 7.

D. DEVICES

AR and VR use the same hardware devices that provide the advantages of virtual scenes, 3D objects, and interaction. The common devices of AR are display screens like monitors, projectors, and computer input and output devices. AR devices are mainly distributed into three categories: handheld, non-handheld, and IoT-based.

1) HANDHELD

All the computing devices that have a display and can be held are categorized under handheld devices [15]. Handheld devices are portable and ubiquitous. Handheld devices include smartphones, tablets, and personal digital assistants (PDAs). Smartphones and tablets continuously increase the power of processing, which helps to integrate mobile platforms into education. Smartphones and tablets allow users to travel in their real-world environment while looking at their augmentation on their smartphone display screen. AR applications are developed for both Android and IOS Operating systems (OS) [57]. The use of smartphones and tablets continuously decreases AR applications' costs. Using such devices in education can improve the quality of education, monitoring, and control of the storage process [58]. But such devices came with one disadvantage: the users have to hold them in their hand all the time, i.e., during the capture of the image and the creation of the augmentation [15].

2) NON-HANDHELD

Devices that cannot be held are categorized under non-hand-held devices. Some non-handheld devices where an AR-based application can run are explained in this section.

FIGURE 8. HMD for AR and VR-based applications.

FIGURE 9. Optical see-through AR glass.

- **Web-based:** In web-based infrastructure, the AR content is represented on the webpage without extra installation. In marketing and advertisement of the products, companies create augmentation of their products and paste them on their web pages. The application uses Adobe Flash software to present the video and image data on the website by using a webcam [59]. These types of applications use the webcam to capture images. It allows the users to use their hands to interact with augmented content. Kinect and Wii platforms are primarily sensor-based technologies that can be used in conjunction with web-based AR applications. These applications use large augmented spaces like classrooms, allowing users to use their whole body to control the virtual experience, where virtual content is placed in the real world [15].
- **Head Mounted Display (HMD):** HMD is an AR device that the users wear on their heads like a helmet. It has two optical lenses in front of each other, with an attached video camera and an internal display. Typical HMD is shown in Fig. 8. If we want to experience something remotely like an image enhancement system, then these devices play an important role. HM devices combine computer-created resources with glass images in the real-world environment. For this purpose, a small partially transparent glass is used as shown in Fig. 9. The mirror technology allows the user to capture a real-world image and pass it through an optical lens, and the optical see-through device reflects that image in front of the user's eye [15]. HM devices allow users to have complete control of augmented space and use their hands to manipulate the AR experience. The benefit of using HMD in educational activities is that the display stays in front of the user's eye, and the user can move in any direction without manipulating the augmented object. Google Glass is the most common example of an HMD device [56].
- **Projected AR:** Projected AR devices usually use projectors or big screens to show augmentation on the screen. Images are captured through the camera

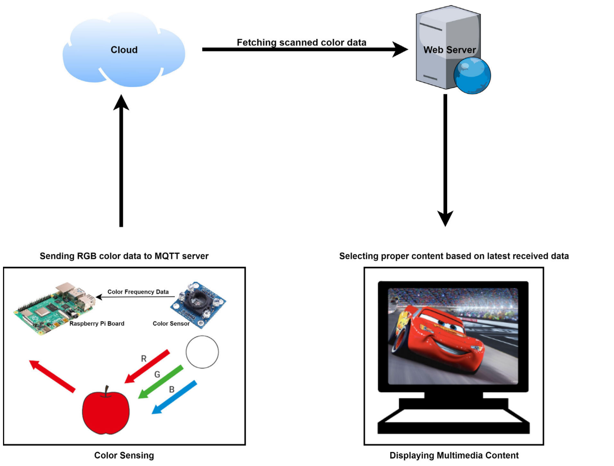

FIGURE 10. **Overall architecture of color sensing AR-IoT based embedded system.**

and projected on the projector's screen to enhance the augmentation experience. Work-based on [60] and [61] used projected AR technology to protect and augment virtual content via projector.

- **AR Magic Mirror (MM):** AR MM uses a mirror as a display screen. In this case, any virtual object is augmented on a mirror. Bork et al. [57] proposed Reversing and Non-Reversing Magic Mirrors (RMM and NR-MM) for the study of human anatomy.
- **IoT-based:** The platforms of AR applications are not restricted to mobile phones and desktops only, but they can also be developed using embedded systems consisting of different hardware like Raspberry Pi, Sensors, etc. The Internet of Things (IoT) in AR has proved effective and useful, especially in education. Mahmoudi et al. [62] proposed an AR-IoT-based embedded system for the study of colors in the Spanish Language. The embedded system consists of a Raspberry Pi board and a color sensor. By providing sensory input of colors from a book, an MQTT code of the RGB channel is generated. On the basis of this code, different markers for various colors are fetched from the cloud server which is then provided to the student where different multimedia content and animations are provided to the students in the form of augmentation. Finally, the Spanish translation for the detected color is shown in the Fig. 10. The only limitation of IoT-based AR applications is that they are not cost-friendly, which makes the availability of these types of applications a bit challenging.

E. CONTENTS

Applications based on AR take fiducial markers, planes, or GPS location that acts as an input, recognize them, and then augment virtual objects on top of it, keeping the user in a real-world environment hence providing an AR experience. There is no limit to the types of virtual content to be augmented. This section discusses types of various virtual content that can be augmented on real-world objects to get an enhanced version of reality.

1) 2D ANIMATIONS

Some AR-based applications use 2D animations as video clips or animated 2D models to be augmented on the tracked marker or plane on the device's screen. These animated videos are smaller in size; therefore, AR applications do not take a longer time to process and render to visualize on the screen. It can be said that a student's learning capability and experience increase with video clips instead of mere texts and images [56]. Arfract is a hybrid-based AR application developed by Oh et al. [61] to study the physical phenomena of reflection and refraction of light. They designed game-based and non-game-based simulation content in their application. The game-based simulation was designed in animated 2D content with which students can interact with the content to understand the concepts via gaming [50].

2) MULTIMEDIA

Different multimedia content such as (audio, video, and image) can be used as virtual objects to be augmented on the screen. This multimedia content increases a student's learning, motivation to study, and concepts. When a student has difficulty understanding any topic, they usually watch YouTube videos and consult other websites to get an idea and better understand concepts. AR-based applications can store all the multimedia content in a single cloud storage and superimpose it concerning any marker or plane. Gutiérrez et al. [63] proposed various AR applications to study Electrical Engineering. ElectAR notes used several multimedia contents like images, recorded video by their instructor, and audio to be augmented to learn complex Electromechanical concepts.

3) 3D MODEL

The 3D model is the product obtained using a technique in 3D Computer Graphics (CG) in which different 3D modeling software tools are used to form a 3D representation of an object utilizing advanced mathematics that is then rendered to form a final product. These models are usually stored in film box (FBX) format in which the model's polygonal structure and their baked textures and animations (if any) are stored. This prefab in FBX is used by game engines or other AR development software during application development. 3D models are especially used in AR-based and gaming applications. Some of the advantages of using 3D models are that, compared to the 2D demonstration of an object, it gives a detailed visualization of an object, and the user can view the model from different angles and viewpoints. It is noted that the greater the number of polygons (vertex and edges) of a 3D model, the more realistic an object will be. Proper and detailed texturing on a 3D model also plays an important role in determining how realistic a 3D model is [62], [64]. In AR-based applications, a corresponding virtual 3D object is augmented on the screen after receiving sensory input. The user can see and interact with the model to enhance their learning skills and understand the concept easily [57]. Studies in [46], [47], [48], [51], [63], and [65] used 3D models in their application for the study of Electrical Engineering, Chemistry, human anatomy, biology, buoyancy, atoms, English culture and places respectively. Another application, ARTutor was proposed for distance learning and one-to-one interaction between students and teachers. Teachers provide different markers from the textbook along with their respective 3D content via the Web application. Students can download the models and markers from their mobile application for their study.

4) ANNOTATIONS AND NOTE-TAKING

Another way to interact with augmented objects is by utilizing annotations and note-taking. Annotations are labels of the various parts of the model. The need for annotation is usually required in learning to identify and use different human anatomy. Annotations are usually defined using different 3D modeling software [59]. These annotated 3D models are used as virtual objects in AR applications for educational purposes. Usually, learners can interact with these annotated models using different gestures (usually finger tapping) to understand the behavior, uses, or structure of different parts of the model. Instead of predefined annotations, students can also add custom annotations and notes on the augmented 3D model for their learning. This process is termed note-taking. The advantage of note-taking is that students can formulate and save their notes. It also allows self-assessment and evaluation of the student and how well they have learned after studying. Yang and Liao [66] work is based on an AR-based mobile application for note-taking on 3D content employing finger-tip recognition, tracking, and movement. The application allows the students to formulate their notes and annotations around the augmented 3D content concerning their curriculum by moving their fingertips on the surroundings of the augmented object. This application allows the learner to write notes around the augmented object on a physical tabletop and embed these notes on a corresponding augmented 3D object in a 3D space. Khalid et al. [47] proposed a mobile-based AR application to study human anatomy. 3D modeling software tool [67] was used to model human organs and provide annotation to various parts of the organ. As shown in Fig. 11 the anatomy of these annotated models was augmented and studied.

5) VOICE TEXT

One of the ways to interact with augmented virtual objects is by utilizing speech. The application uses the device's microphone as sensory input to fetch voice commands given by the user and performs operations based on given instructions. Voice-text uses the user's voice as input,

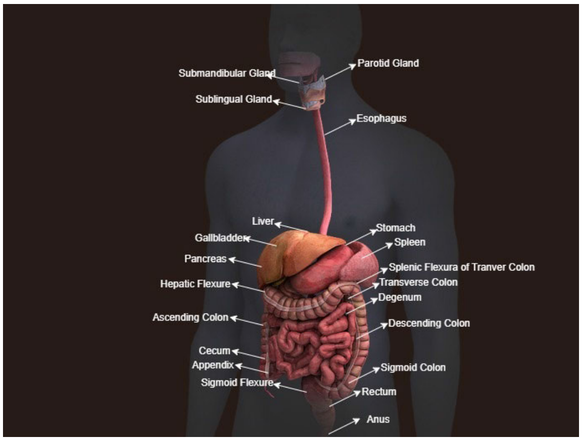

FIGURE 11. **Annotated 3D model of the human digestive system, proposed in study.**

translates the imputed audio, and generates text on the screen. It also allows one-to-one interaction between students and teachers. Lytridis et al. [45] proposed ARTutor, a cross-platform (Web and Mobile) AR application for interactive distance learning between students and teachers. ARTutor provides a voice command feature where students can interact with the augmented objects. This feature was mainly provided to facilitate visually impaired students. Once an object is augmented on the screen, a button is pressed to record the voice. This inputted voice command is matched with the predefined active asset, and then transformation is applied to the augmented object concerning the inputted command. This audio voice recognition button is also used to ask questions and receive answers concerning the augmented content.

6) AR BOOKS

AR book is an Android-based application similar to the printed textbook, but bookmarkers are added to each page to refer to additional content in the AR. When the marker is scanned through the camera of a smartphone, 3D images and videos are rendered in the textbook. The rotation, scaling, and translation of the 3D content depend on the camera-scanned view of the marker [44]. Lin et al. [48] proposed an AR-based picture E-book to study the life cycle of various insects. Picture E-book was designed merely for the students in kindergarten, where they require pictorial and visual representations of concepts rather than texts. The primary goal of this AR book was to enhance the imaginative capability of the students.

F. INTERACTION

AR applications superimpose additional information (2D images, text, audio, 2D animated video, 3D models and animations, etc.) on the device's screen within the real-world environment and allow the user to interact fully with these virtual objects. Students learn and perceive better when they can visually see and interactively experience different phenomena and concepts of their studies. Interaction of users with augmented content is not restricted to sight only, but they can also be perceived through the senses of touch, hearing, and smell. This section discusses different ways users can interact with the augmented object to increase interest and improve the learning experience.

1) VOICE

One of the ways to interact with augmented virtual objects is by means of speech. The application uses the device's microphone as sensory input to fetch voice commands given by the user and performs operations based on given instructions. For example, some of the AR-based applications provide different features like transformations (rotation, scaling, and translation), annotations, and note-taking by means of voice commands. Lytridis et al. [45] proposed ARTutor, a cross-platform (Web and Mobile) AR application for interactive distance learning between students and teachers. Teachers provide markers that act as a target and corresponding virtual content (audio, 3D model, image, etc.) on the web interface that is downloadable to the students on their mobile interface. Once downloaded, they can interact with the augmented content. Android application of ARTutor provides a feature of voice command, where students can interact with the augmented objects. This feature was mainly provided to facilitate visually impaired students. Once an object is augmented on the screen, a button appears, which is then pressed to record the voice. This inputted voice command is matched with the pre-defined active asset and then transformation is applied to the augmented object with respect to the inputted command. This audio voice recognition button is also used to ask questions and receive answers to them with respect to the augmented content.

2) HAPTIC

Haptic is defined as the sense of touch. It is the most basic feature that an AR-based mobile application provides. Once the virtual content is augmented on the device's screen either by marker-based or marker-less augmentation, users can interact with this content via the movement of fingers in a specific way [45], [47], [65]. This motion of virtual objects is termed transformation. Transformations are a measure of the movement of an object in any direction. Fig. 12 shows three basic types of transformations.

1) **Translation:** movement of objects in either horizontal (along the x-axis) or vertical (along the y-axis) directions.
2) **Scaling:** growing and shrinking the size of an object.
3) **Rotation:** movement of an object in a circular direction concerning the center of the axis. It is a measure of the degree to which an object rotates. By rotating an object, a complete 360-degree view of the augmented object can be seen, thus enhancing the object's viewpoints.

3) HAND GESTURES

Another way to interact with augmented 3D objects is by using different hand gestures. Gestures are nonverbal communication in which various bodily actions convey information. Hand gestures are the movement of hands via different interpretations of hands to convey a message. AR application takes sensory inputs like fiducial markers, plane, image, or geographical location from the surroundings utilizing a device's camera, GPS, accelerometer, compass, etc., and integrates virtual contents. Different Computer Vision (CV) algorithms are used for hand recognition, segmentation, finger-tip, and hand and finger motion tracking for different predefined and learned hand gestures. Fig. 13 shows a state diagram of different hand gestures used in one of the education AR applications [51]. Fig. 14 shows the freehand gesture-based AR application process from the projected AR screen to the tabletop. The user first placed their palm on the augmented object projected on the projector screen, and the camera recognized the hand and detected the corresponding gesture to pick an object. The next fist is closed and is moved towards the tabletop. Once the hand is reached toward the tabletop, a fist is opened again to place an object on the tabletop.

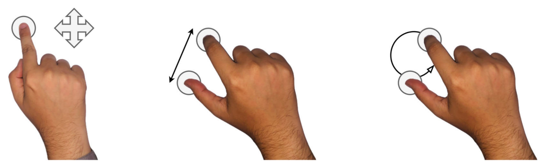

FIGURE 12. Finger movement for different transformations; a) translation, b) scaling, c) rotation.

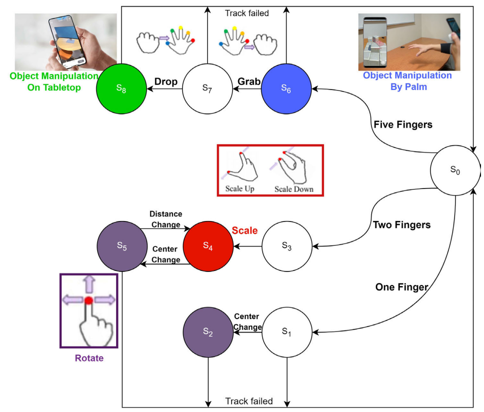

FIGURE 13. State diagram of different hand gestures.

G. SOFTWARE TOOLS

Different open-source and paid software tools and their Software Development Kit (SDK) are available for developing web-based and mobile-based AR applications. Each software tool and SDK has its strengths and weaknesses. These software tools are easy to use; however, some require programming skills in various programming languages like Java or C# to develop AR applications. This section discusses detailed descriptions of different software tools used by

FIGURE 14. Gestural movement to translate 3D object from projected screen to tabletop.

different research studies. Finally, this section is concluded with a comparison of various SDKs available by Unity, as shown in Table 2.

1) UNITY 3D

Unity 3D [66] is a cross-platform game engine software developed by Unity technologies to develop 2D/3D, AR, and VR games and applications. It uses the C# programming language for scripting and provides multiple APIs, packages, and plugins to ease the developers' access and usability. Unity provides open access ARCore and ARKit [68] SDK engines provided by AR-Foundation developed by Google and Apple, respectively, for developing Android and IOS-based AR applications. Despite their complexity, the advantages of using ARCore and ARKit are that these plugins can augment almost all the 3D objects in any real-world environment. Both provide motion tracking, plane detection, smooth rendering, automatic light detection, automatic anchor positioning, and interactive user engagement. The limitations of these plugins are that they are device-dependent. It means that a few advanced devices support ARCore and ARKit to experience AR applications fully. Vuforia SDK is another paid plugin provided by Unity for developing either Android or IOS-based AR applications. Vuforia has its image and object-tracking mechanisms. It uses predefined markers either in the form of QR codes or images along with their respective virtual components to be augmented for each marker already stored in a cloud database provided by Vuforia. The advantage of Vuforia over ARCore or ARKit is that Vuforia is a cross-platform SDK that can support lower and higher specifications mobile devices to provide an AR experience. However, Vuforia is less stable and a user's interaction with augmented objects on mobile screens is not that smooth compared to AR applications developed via ARCore or ARKit.

ARED [47] is an Android-based AR application for the study of human anatomy. It was developed using Vuforia SDK. ARED is a marker-based application that uses predefined markers. Modeling and annotations of 3D virtual objects were done in 3Ds Max (3D modeling software tool) provided by Autodesk [69]. AIR-EDUTECH [46] is a cross-platform educational AR application designed and developed using Vuforia SDK. It is a marker-based AR application that uses fiducial markers as a trigger to display virtual content on the screen.

2) GAME STUDIO A8

Game studio (Gamestudio Game Development System (Homepage)) is an interactive 2D/3D game engine for developing multiple games, AR/VR applications, simulations, multimedia tools, or other software programs. Their single package provides three levels of access: beginner, advanced, or professional, depending upon application requirements. The professional package of Gamestudio provides Gamestudio's A8 engine that supports C++, C#, or Delphi Programming Languages. It also provides 3D modeling tools like Autodesk Maya or 3Ds Max to create 3D models and save them in FBX format to be used within the Gamestudio A8 engine. An AR application for the study and practice of installation of electrical machines known as ElectARmanual [6] was developed using Gamestudio A8. For the modeling and animations of 3D models, 3D studio software was used, and animated models were saved in MDL format that Gamestudio A8 only supported.

3) METAIO STUDIO

Metaio is a free and open-source software product designed to create AR applications by taking any image as a target and overlaying any virtual content like videos, images, or 3D models on top of the selected target. It has its SDK for developing mobile, web, Personal Computer (PC), or custom platform-based AR applications. It uses the latest image recognition and visual search methodology to create an AR experience. The software is user-friendly; it just uses a drag-and-drop option to create AR software and applications without needing to learn any programming languages. Elect3D [6] is an AR application developed for Electrical Engineering students for the study of various symbols used in the subject of Electrical Engineering. It is a markerless AR application developed using Metaio SDK. Metaio Studia was preferred over other AR development tools for the following reasons.

- Any PNG image can act as a target to augment virtual content on the image, not just the predefined ones.
- It allows customized tracking as detection of the target image is done via a cloud of points. This feature allows customizable adjustment of the application sensitivity.
- The software has good speed and stability.
- The software is very easy to learn as no programming language is required to be known to develop AR applications.

The mobile application of ElectAR_notes [6] for both Android and IOS platforms was also developed in Metaio studio.

4) HUMANAR

HUMANAR is a software library tool developed by Martín-Gutiérrez et al. [6]. It is based on the Computer Vision (CV) technique for calculating camera viewpoints for the marker present in the real world. That is responsible for calculating the real-time integration of 3D objects systematized by the camera. Whenever the marker detects the plane and is shown on the entire surface from the device's screen, any virtual content can be augmented concerning the marker. This technique captures and relates the real environment and virtual objects on a single coordinate point. The key challenges for developing such a system are that it requires carefully done marker detection, marker positioning and orientation calculation, fine-tuning of the camera, and lastly, augmentation of virtual objects. The windows application of ElectAR notes [6] was developed using the HUMANAR software library tool.

5) WIKITUDE STUDIO

Wikitude [70] is a cross-platform mobile augmented reality-based applications development software developed by Wikitude GmbH. Initially, it was designed for the development of locational-based WebAR applications. Later, they provided their SDK. The framework provides image recognition, tracking, model rendering, video overlay, and geographical-based AR technologies. One of the limitations of Wikitude is that it shows watermarks on the applications created by non-commercial free trial versions of Wikitude. Wikitude SDK for developers is freely available to develop AR applications only for educational purposes. In academic applications, Wikitude SDK displays a splash screen and Wikitude logo. Wikitude SDK can explore AR learning activities. In locational-based projects, Wikitude SDK can be used to implement radar points. We can also recognize the target image and interchange it in 2D and 3D information on the top of Wikitude SDK. In this SDK, there is an option to combine image recognition and geographical-based AR. However, working on Wikitude SDK required programming experience and knowledge.

6) ANDROID STUDIO

Android Studio [70] is an Integrated Development Environment (IDE) widely used to develop Android mobile applications. Google and JetBrains developed it. This IDE supports Java, C++, and Kotlin programming languages. Applications built via Android Studio are capable of supporting all Android devices. IDE has its Android emulator where the developer can run and test-built applications. ARTutor [45] was developed for both IOS and Android-based mobile devices. Android Studio and XCode were used to develop this application for Android and IOS devices, respectively. The main objective of the ARTutor was to recognize targeted images and superimpose virtual content on top of them to create an AR experience. The Kudan SDK provided by Unity was used for that purpose. Kudan was preferred over other SDKs mainly due to the following reasons.

- Kudan is a cross-platform AR solution capable of running AR-based applications on a wide range of both Android and IOS-based mobile devices.
- Unlike Vuforia, ARToolkit, or Wikitude, Kudan is not restricted to predefined markers already saved in their respective database for image recognition.
- Kudan SDK is open-access and free to use for non-commercial and educational purposes.

7) METAONE SDK

Meta is a package provided by Unity designed to experience AR content on the wearable optical see-through headset. The very first release of Meta was Metaone SDK [70]. A new release of the Meta series known as Meta 2 is available. This package provides its assets and prefabs to be used in custom-developed AR applications. Arfract a simulation environment is a game-based and non-game-based AR application designed by Oh et al. [61] to study the physics concept of incident and refraction of light along with the propagation of lights through different mediums. They used an optical see-through meta one headset that can see 23-degree viewpoints having a resolution of 960 $\times$ 540. These AR glasses provide 360-degree head tracking with 9-axis inertial movement and a 3D depth time-of-flight camera to get inputs via hand gestures. The development and rendering of Arfract were done using Meta One SDK and Unity 3D.

H. APPLICATIONS

This section discusses various AR applications developed in different studies for education, learning, simulation, and teaching.

1) ARTutor

Lytridis et al. [45] proposed ARTutor, a cross-platform (Web and Mobile) AR application for interactive distance learning between students and teachers. Teachers provide markers that act as a target and corresponding virtual content (audio, 3D model, image, etc.) on the web interface that is downloadable to the students on their mobile interface. Once downloaded, they can interact with the augmented content. Android application of ARTutor provides multiple features like transformation (translation, scaling, and rotation) of augmented objects and voice command, where students can interact with the augmented objects. This feature was mainly provided to facilitate visually impaired students. Once an object is augmented on the screen, a button is pressed to record the voice. This inputted voice command is matched with the predefined active asset, and then transformation is applied to the augmented object for the inputted command.

TABLE 2. Comparison of different available SDKs for the development of AR applications.

	Vuforia	ARCore	ARKit	Wikitude	Kudan
	vuforia™	ARCore by Google	ARKit 3	wikitude	kudan
Platforms	Android, IOS, UPW and Unity Editor	Android 7.0+, IOS 11+	IOS 11+	Android, IOS and Windows for tablets	Android and IOS
License Type	Free, commercial	Free	Free	Commercial	Free, commercial
Smart Glass Support	+	+	+	+	+
Cloud Storage	+	+	+	+	+
3D Recognition	+	+	+	+	+
Geolocation	+	+	+	+	+

This audio voice recognition button is also used to ask questions and receive answers for augmented content [3].

2) ElectAR MANUAL

Martín-Gutiérrez et al. [6] developed an educational AR application to provide training for understanding the installation and assembling of parts of various electromechanical machines. The application was designed to facilitate the students of Electrical Engineering in their lab practical, where they are being taught to assemble various components (coil, resistor, wires, magnets, etc.) to install specialized electrical and mechanical machines. Continuous live demonstration with proper monitoring of all the students simultaneously in the laboratory is impossible for the teacher. Therefore, ElectAR_ manual was developed to provide guidance, step-by-step instructions, and tutorials on the lab manual for assembling various mechanical parts. By using this application, students can easily understand and practice assembling without being directly in contact with that machine.

3) ELECT3D

Students of Electrical Engineering have to memorize Elect3D [6], an AR application developed for Electrical Engineering students to study various symbols used in the subject of Electrical Engineering.

4) ElectAR NOTE

To understand complex theoretical concepts of Electrical Engineering, an AR application named ElectAR notes was developed [6]. The main goal of this project was to enable the students to learn and understand difficult theoretical concepts of generation and behavior of electrical and mechanical fields in the electrical-mechanical machines by inducing more realistic and easy-to-understand virtual visual components in the textbook. They also developed a custom-built notebook on the subject of'Basic Electrical Machines' that includes various electromagnetism, ferromagnetism, and similar topics because they are difficult to understand by mere theory and 2D diagrams. The application augments the book's 3D models and animations on text and images to better visualize and understand the concepts mentioned above.

5) ARED

Fatima et al. [47] developed a mobile AR application, AR in Education (AREd), to study human organs' anatomy. The application camera captures an image from AREd website that acts as a target and augments the 3D model of the respective captured organ on the mobile device's screen. Users can interact with the overlaid 3D model by zooming or rotating with their fingers. annotation and note-taking of the 3D human organ parts can also be seen. The application also plays audio that tells detailed descriptions of the organ.

6) PaintCAR

Bacca et al. [60] proposed an AR mobile application for Vocational Education Training (VET) known as PaintCAR to study car maintenance, repair, and painting. This application allows peer-to-peer interaction with students and teachers on a single platform. Teachers provide markers as targets and their respective augmented content like text, image, video, and audio for each marker, which will later be downloaded and utilized by the students. The application guides help and, finally, evaluate the students to perform a couple of steps to paint a car.

7) ARFRACT

Physics concepts of the incident phenomenon and refraction of light on any surface medium through any incident light are explained by an AR simulation environment called Arfract developed by Oh et al. [61]. Most students face difficulty in visualizing and mapping the concepts in their mindset by mere 2D drawings or physical experimentations. Arfract was developed to overcome this problem. It uses hybrid AR-based technologies for simulation environments. The system was developed for game-based and non-game-based simulation to teach the refraction of light and relevant concepts through user interactions via hybrid AR technology.

8) AIR-EDUTECH

Educational application based on Augmented Immersive Reality (AIR), known as AIR-EDUTECT, was developed by Cen et al. [46] to study the Chemistry concepts of the molecular structure of various elements and the occurrence of chemical reactions between them. These concepts are complicated to perceive by the mere imagination of the students. The basic goal of this application was to focus the student's interest and motivation in studying chemistry by allowing them to grasp complex chemistry concepts and chemical reactions with the addition of an interactive-based AR mobile application. The scope of AIR-EDUTECH is limited only to the study of chemical reactions between four basic elements: Hydrogen (H2), Oxygen (O2), Chlorine (Cl2), and Sodium (Na) and the study of Organic Chemistry involving structure, properties, and uses of Carbon (C) atoms and compounds.

9) VECAR

Yang and Liao [66] proposed an AR application for English culture and language learning by incorporating algorithms of Computer Vision (CV) and AR for a single Virtual English Classroom application known as VECAR. The basic objectives of this application were to enable the students to learn English Culture and Language from various perspectives. The application uses free hand gestures and provides an interactive AR experience using wearable HMD.

I. TESTBEDS

This section discusses the performance analysis of state-of-the-art AR applications using various evaluation parameters and tests. For the performance evaluation of each application, various surveys and questionnaires were conducted for specific targeted audiences (students). Usability, usefulness, reliability, adaptability, ease of access, performance, speed, stability, accuracy, flexibility, dependability, portability, effectiveness, quality, attraction, intuition and novelty, clarity, and relevance were the evaluation parameters on which the effectiveness of the proposed solution for most of the studies was measured and evaluated.

1) T-TEST

In Statistics, the t-test is widely used to test the hypothesis that checks significant differences in the mean value of two more groups. The T-test can be used to check the origin of a group of samples by analyzing whether groups of samples came from the same population set.

The performance evaluation of the AR-IOT-based system to teach the children various color schemes in Spanish through sensory input embedded in a Raspberry Pi was done by Mahmoudi et al. [62]. Their proposed methodology was evaluated using paired t-tests to evaluate the system's effectiveness in improving the learning experience. A total population of 35 students participated in the experience. Pre and Post tests were conducted to determine the level of knowledge each student has for the level of knowledge they gained after using the device. The result showed significant improvement in the post-test with an increase in mean value ($\mathscr{M} = 3.11$) to the multiples of three. Mahmoudi et al. [62] applied the T-test to analyze the effect of AR content in educational activities. In this experiment, half of the participants interacted with traditional-based learning approaches, and the remaining half with AR-based learning techniques. To evaluate the effectiveness of VECAR [53], questionnaires for pre-test and post-test were designed. Paired t-test was conducted to evaluate the difference in learning outcomes between the two tests. The results showed that the p-value was less than 0.05 for the difference between the average score of both the post-test and pre-test. Hence the use of VECAR for cultural knowledge proved to be significant.

2) ANCOVA

Analysis of Covariance (ANCOVA) is a Statistical measure to determine what additional information can be obtained for one independent variable over time. ANCOVA blends Analysis of Variance (ANOVA) and regression. Like regression, ANCOVA observes the behavior of independent variables for dependent variables by removing the covariate effect (variables that are not understudied. There are two applications of ANCOVA [71].

- Control of covariates that are irrelevant to the study.
- Act as predictors to calculate possible combinations of continuous and categorical variables on a single scale.

A statistical test ANCOVA was performed in the study to identify the presentation order of learning outcomes on the use of ARfract [61]. They applied ANCOVA by setting the variables of Scores of the pre-test and post-test as independent and dependent, respectively. The results obtained by ANCOVA showed a significant difference in non-Game First (NF) and Game First (GF) groups that proved that the performance of participants who used game-based simulation first is much higher than those of participants who used non-game-based simulation, thus providing higher learning gain in GF groups.

3) ARCS

The Attention Relevance Confidence Satisfaction (ARCS) model of motivational design [72], [73] was proposed by Keller in 1987 as the measure of a student's learning outcome and motivation after the use of technology during their learning process. ARCS model is categorized into four components, as shown in Fig. 15, and each component is further divided into subsections. This model is mainly used for E-learning, where students use various electrical

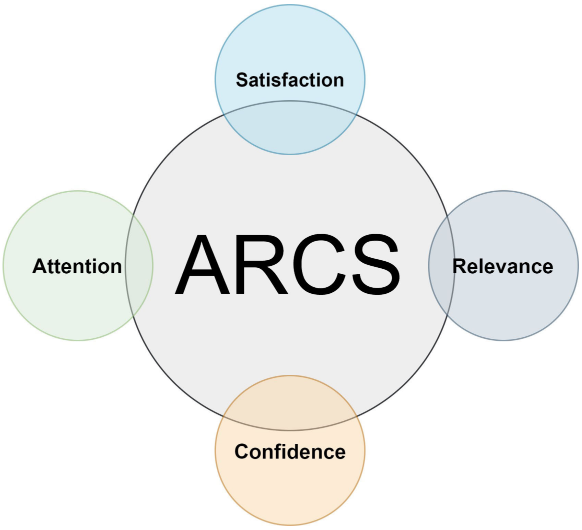

FIGURE 15. **ARCS components.**

and technological equipment during their learning, making it important and difficult to ensure student motivation throughout their learning process rather than student-teacher face-to-face live interaction in normal classrooms [73]. The questionnaire was designed in [49] to evaluate students' motivation levels after using an AR-based picture E-book to study insects. The answers to various questions that measure the level of motivation were analyzed. The values of Cronbach's α for Attention, Relevance, Confidence, and Satisfaction were 0.955, 0.930, 0.980, and 0.987, respectively. These results proved significant for measuring students' motivations using AR-based picture E-books, contrary to the traditional educational teaching styles.

4) LEVENE'S TEST

Levene's test is a statistical test used to calculate the homogeneity in variances of samples taken from different distributions of groups. Levene's test validates that the variances of k samples across different test groups are equal. It checks the null hypothesis that if the value of $p <= $ some constant (usually 0.05), the difference in variances of sample populations is unlikely to cause the selection of samples randomly from populations of similar kinds [74]. Levene's test is usually conducted to check the equal distribution of error variances among independent variables.

5) SHAPIRO-WILK TEST

Samuel Sanford Shapiro and Martin Wilk proposed the Shapiro-Wilk test in 1965 [75]. The Shapiro-Wilk test is used to test the normal distribution of data samples. The data distribution is considered normal if the value of the Shapiro-Wilk test is less than a specific alpha threshold (usually alpha = 0.05). On the contrary, data samples do not follow a normal distribution if the value of the Shapiro-Wilk test is greater than 0.05. The assumption of the Normality of ARfract was confirmed by using the Shapiro-Wilk test in the study [61]. The test result confirmed that the data was sampled from a normally distributed sample population. The teacher Communication Behavior Questionnaire (TCBQ) [76] comprises five attributes: Challenging, Encouragement, Praise, Non-Verbal Support, Understanding, and Friendly were generated to evaluate student-teacher interpersonal communication via VECAR. TCBQ contained 40 questions from the above five subclasses. The Shapiro-Wilk test was applied to five classes to calculate the distribution of samples between classes. The results showed that the distribution of samples was subjected to the normal distributions due to a higher value of p (typically 0.05).

VII. SUMMARY OF TAXONOMY

The taxonomy of the paper has been summarized in this section. Table 3. compares state-of-the-art AR technologies and their applications for various areas of education. Purpose, types of AR, platform, types of available content, level of interaction between user and the augmented objects, and strengths and weaknesses are the attributes on which the effectiveness, usability, and reliability of existing AR applications are being compared.

It has been observed that the majority of the studies, such as work done in [6], [45], [46], [47], and [60] preferred marker-based augmentation type as compared to the marker-less augmentation [61], [77], [78]. Marker-based and marker-less AR are two distinct approaches to creating AR-based applications, each with its own set of advantages and benefits. When considering the development of AR-based applications for educational purposes, both approaches offer unique features that can contribute to enhanced learning experiences. However, there are some key advantages and benefits of using marker-based augmentation compared to marker-less augmentation. Marker-based AR relies on predefined markers or images as reference points, allowing for highly accurate tracking of the real world. This precision is particularly beneficial in educational scenarios where accuracy is essential, such as in medical simulations or architectural visualizations. Secondly, since marker-based AR relies on the recognition of specific markers, the virtual content tends to remain stable and well-aligned with the real-world markers. This stability is advantageous in educational contexts where learners need consistent and reliable visual cues. Additionally, Markers provide a tangible interaction point for users. Learners can easily trigger AR content by directing their devices towards the marker, facilitating intuitive and straightforward interaction. Lastly, Marker-based AR can augment complex 3D models onto relatively simple markers, enabling a deeper understanding of intricate concepts. This is valuable in fields such as biology, where learners can interact with detailed 3D models of microscopic organisms. In the case of devices, most of the studies opted for mobile phones for the development and deployment of AR-based applications. These devices are handy, easy to use, easily available, and relatively cheaper than AR-specific devices such as HMD, Google Glass, and other hardware devices. In addition, the majority of the software frameworks, and AR Toolkits support developing AR-based applications for mobile phones only. Lastly, it has been observed that the despite strengths/ advantages of several AR-based applications that have been developed, they have some limitations as well. AR-NRMM, and AR-RMM [78] have poor user interactions and perception in RMM. Similarly, ElectAR manual, Elect3D, and ElectAR notes [6] are not portable despite their usability. In addition, both AIR-EDUTECH [46] and AREd [47] have limited project scope. Some applications have poor interfaces and designs that reduce the usability of the application to some extent [60]. Lastly, due to the usage of marker-less AR technology and expensive hardware components such as AR glasses, ultra-short throw AR projectors, Webcam, HMD monitors and projectors, etc., both ARfract [61] and VICAR [77] are very expensive to purchase for students, highly device dependent and has high complexity in setup the hardware components.

VIII. LIMITATIONS OF APPLICATIONS OF AR IN EDUCATION

AR has evolved in education through the use of mobile phones. The implementation of AR in education proves significant in the students' learning process. AR depends on the advancement of technology and digital networks, but some limitations of AR applications in education still need to be overcome.

- AR applications are device-dependent. The applications using ARCore and ARKit did not operate on all kinds of devices.
- AR applications are unique and developed for specific fields of education which means not everyone can benefit from all applications.
- Training of the students and teachers is required for those groups who did not belong to computer science groups before using the AR applications in education.
- AR applications require a constant and stable internet connection. Without the internet, we cannot run such applications.
- AR applications require more time to render the image into useful information or superimposition the image from 2D to 3D.
- AR applications work well on mobile phones, but in the case of 2D matrix cards, it depends on the webcam and other computer hardware.
- Some AR applications using HMD and goggle lenses are costly and out of the range of students.
- Marker-based AR applications require additional cloud storage to fetch the data on the track.
- Sometimes, users have to interact with multi-user AR environments where all the educational contents are mixed, which can provide a complex learning style for the students.
- AR-based applications are expensive to develop and require more cost to maintain.

Despite these limitations, AR is limited in technology, and it will take time to come to everyday tasks. The challenges AR faces include social acceptance of the application, the privacy of the content, and the business's profitability. Although we can overcome these challenges and hope AR applications become part of the everyday tool one day.

IX. CONCLUSION AND FUTURE RESEARCH DIRECTIONS

This survey paper discusses a detailed discussion on AR, its uses, and its applications in the education field. This study analyzed applications of AR in different fields of education, which shows that AR technology can improve students' learning performance. The features and advantages of AR applications engage students in technological learning. These features help students and prove beneficial for the teachers who help them explain complex topics more efficiently. The various tests applied to several participants from different fields show their interest in using AR technologies. As AR is a new field in education, there are some limitations, but this survey paper indicates that these limitations are due to technical and cost issues that may be overcome with time.

The future directions of augmented reality in education encompass a broad spectrum of interdisciplinary applications, personalized learning experiences, collaborative pedagogies, and ethical considerations. As researchers and educators continue to explore and innovate, the potential for AR to enhance teaching and learning across diverse contexts remains a topic of profound interest and significance. Here are some major areas where AR can be implemented and integrated into education for collaborative learning.

- **Integration of AR Across Disciplines:** Scholars have recognized the cross-disciplinary applicability of AR in education. While initial implementations have primarily focused on STEM (Science, Technology, Engineering, and Mathematics) subjects, there is growing interest in integrating AR into the humanities, social sciences, and arts. Researchers emphasize the importance of developing AR applications that cater to diverse educational domains, enabling learners to interact with content in contextually relevant ways.
- **Personalized and Adaptive Learning:** The future of AR in education involves tailoring learning experiences to individual students' needs and preferences. Adaptive AR applications can dynamically adjust content complexity, pacing, and interaction levels based on learners' performance and learning history. This approach enhances engagement and ensures that each student receives a customized learning journey.
- **Collaborative and Social Learning:** Emerging research highlights the potential of AR to facilitate collaborative and social learning experiences. Shared AR spaces can enable students to collaboratively solve problems, conduct virtual group projects, and engage in peer-to-peer learning regardless of their physical locations. The integration of social interaction features within

TABLE 3. Summary of taxonomy.

Method	Application(s)	Purpose	AR-type	Devices	Content	Interaction	Strengths	Weaknesses
[80]	AR-NRMM, AR-RMM	Anatomy learning	Marker-less	Kinect, video camera and mirror	3D model of human anatomy	Visual and haptic	Better performance than RMM due to design	Poor user interaction and perception in RMM
[6]	ElectARmanual, Elect3D, ElectAR notes	Study of Electrical Engineering	Marker	Mobile phone	3D model	Visual and haptic	Easy to use, usable	Not portable
[61]	Paint-cAR	Training for automobile paint repairing	Marker	Mobile phone	2D images and text	Visual and haptic	Increase the motivation of students in VET.	Poor design
[47]	AIR-EDUTECT	Study of molecular and Organic Chemistry	Marker	Mobile phone	3D animated model, Multimedia	Visual and haptic	Better visualization of chemical components and reactions	Limited project scope
[48]	AREd	Study of the anatomy of the human digestive system	Marker	Mobile phone (Android)	3D annotated model	Visual and haptic	Better visualization of human anatomy with annotated content	Limited project scope
[46]	ARTutor	Distance learning	Marker	Web and Mobile (Android and IOS)	3D model, multimedia content	Visual, haptic, voice	Ease of access, voice command, usable for visually impaired students, instant augmented content access, cross-platform	The search algorithm for answers retrieval
[62]	ARfract	Study of refraction of light, traveling of light in a medium	Marker-less	AR glass, ultra-short-throw AR projector	Game-based and non-game-based simulations	Visual, haptic, and hand gesture	Hybrid AR, egocentric and exocentric viewpoint	Costly, highly device-dependent, complexity in hardware setup
[79]	VICAR	Study of English culture	Marker-less	Webcam, HMD, monitor, projector	3D model	Visual, Gesture interaction	Combination of AR and CV	Highly device-dependent

AR platforms can foster knowledge exchange and cooperation among learners.

- **Expanding Access and Equity:** As AR technologies advance, efforts are being made to ensure equitable access for all learners. Researchers are exploring cost-effective AR solutions, including smartphone-based AR applications, to overcome barriers related to hardware limitations and financial constraints. The future direction involves bridging the digital divide and ensuring that AR-enhanced learning is inclusive and accessible to diverse student populations.
- **Enhancing Teacher Training and Professional Development:** AR is not limited to student learning; it also holds promise for teacher training and professional development. Educators can use AR tools to practice pedagogical strategies, simulate classroom scenarios, and develop innovative teaching approaches. Future

research may focus on designing AR-based training programs that empower educators to harness the technology effectively.

- **Seamless Integration with Curriculum:** Integrating AR into curricular frameworks poses both opportunities and challenges. Scholars stress the need for aligning AR experiences with learning objectives and curricular goals. Future directions include the development of guidelines and frameworks that facilitate the seamless integration of AR into existing educational structures while maintaining pedagogical coherence.
- **Ethical and Privacy Considerations:** As AR collects and processes real-world data, ethical and privacy concerns are paramount. Scholars emphasize the need to address issues related to data security, consent, and user privacy within AR educational applications. Future research should explore ethical frameworks and best practices to guide the responsible use of AR technology in educational contexts.
- **Advancements in AR Hardware:** The evolution of AR hardware, including wearables, smart glasses, and haptic interfaces, opens up new possibilities for immersive learning experiences. Researchers anticipate that hardware advancements will drive the development of more sophisticated AR applications, enabling learners to interact with digital content in more intuitive and immersive ways.

Augmented Reality other than Education

Augmented reality has already made significant strides in various fields, from entertainment and gaming to education and industrial applications. As technology continues to evolve, there are several exciting future directions that augmented reality could take:

- **Wearable AR Devices:** The development of more advanced and user-friendly AR glasses or headsets will likely be a key direction. These devices would seamlessly blend digital information with the real world, enhancing everyday experiences.
- **Spatial Computing:** AR systems are moving towards a better understanding of physical spaces, enabling more precise and dynamic interactions with the environment. This could lead to improved navigation, object recognition, and context-aware information display.
- **5G Integration:** The rollout of 5G networks will significantly enhance AR experiences by reducing latency and increasing bandwidth. This will enable real-time collaboration, high-quality content streaming, and more immersive multiplayer AR gaming.
- **AR Cloud:** The concept of an "AR Cloud" involves creating a shared digital layer over the real world that multiple users can access. This would allow for persistent AR experiences that are location-based and can be interacted with by multiple people simultaneously.
- **Digital Twins and Simulations:** AR could be used to create digital twins of real-world objects, spaces, or systems. This can have applications in architecture, engineering, maintenance, and more, allowing for simulations and testing in virtual environments.
- **Healthcare and Medical Training:** AR could revolutionize medical training by offering realistic simulations of surgeries and procedures. It could also aid surgeons by providing real-time visualizations of patient data during operations.
- **Remote Assistance and Collaboration:** AR can enable experts to provide real-time assistance to remote users through guided instructions and annotations overlaid on their field of view. This has applications in industries like manufacturing, maintenance, and field services.
- **Entertainment and Storytelling:** AR could create entirely new forms of entertainment where users participate in interactive and immersive narratives that unfold around them.
- **Advertising and Marketing:** AR could transform how brands engage with consumers by allowing them to interact with products and experiences in their own environment.
- **Cultural Heritage and Tourism:** AR could enhance the way we experience historical sites, museums, and cultural landmarks by providing contextual information and immersive reconstructions.
- **Ethical and Privacy Considerations:** As AR becomes more integrated into daily life, there will be important discussions about data privacy, surveillance, and the potential for information overload.
- **Customization and Personalization:** AR could enable highly personalized experiences based on individual preferences, such as personalized shopping experiences or tailored travel guides.
- **Gesture and Voice Interaction:** Advancements in natural user interfaces like gesture control and voice recognition could make interacting with AR environments more intuitive and seamless.
- **Cross-Platform Integration:** AR experiences that seamlessly transition between different devices, such as smartphones, tablets, and AR glasses, will likely become more common.

Overall, the future of augmented reality is promising and holds vast potential for transforming various aspects of our lives. However, realizing this potential will depend on continued technological innovation, user adoption, and addressing challenges related to usability, privacy, and ethical considerations.

DECLARATIONS

AVAILABILITY OF DATA AND MATERIALS

Not applicable

COMPETING INTEREST

The authors declare that they have no competing interest to report regarding the present study.

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