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Mobile Augmented Reality Framework in STEM Education: A Systematic Literature Review

Nur Fatin Razlieya Binti Mohd Razali [1], Danakorn Nincarean Eh Phon [2],

[1,2]Faculty of Computing, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600, Pekan, Malaysia

*Corresponding Author: Danakorn Nincarean Eh Phon

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ABSTRACT: There is a growing concern with preparing a sufficient number of highly qualified professional in areas of Science, Technology, Engineering and Mathematics (STEM). However, the number of students to reach proficiency and pursue in STEM majors seems to be decreasing. Augmented Reality (AR) is one of the evolving technologies that have potential and effect on learning, especially in STEM education. The aim of this paper is to review and analyze existing works that are related to AR in STEM Education. In this study, the common design elements, components or features for designing educational AR framework in STEM education were analyzed. This paper determined a literature review which included 67 studies from scientific journals and papers. The findings indicated that there were many components which played an important role to construct a mobile AR framework in STEM education. By reviewing existing research, the study identified key components for designing effective AR frameworks, including AR systems, multimedia elements, teaching methods, and learning outcomes. The findings suggested that AR could enhance student motivation, understanding, and development of practical skills in STEM subjects. With these reviewed, understanding on how to develop the educational AR apps in STEM education could be enhanced.

Keywords: Mobile Augmented Reality; STEM curriculum; Educational Technology

1. INTRODUCTION

The increasing availability of Augmented Reality (AR) applications reflects advancements in Information Technology (IT). AR seamlessly blends virtual objects, like 3D computer-generated information, with the real world [1]. This interactive technology fulfils three key principles: (a) combining virtual and real environments, (b) real-time interaction with virtual information, and (c) 3D registration of virtual objects [1]. AR allows users to experience a convergence of the physical and digital worlds. By integrating real and virtual environments, AR creates opportunities to interact with computer-generated objects in real time.

Studies have shown the positive impact of AR on education, particularly in improving learning, motivation, interaction, and collaboration [2]. These benefits suggest that incorporating AR into classrooms can enhance learning experiences. Research also highlighted the potential of AR in providing students with valuable opportunities in STEM education [2]. A strong STEM curriculum fosters a deeper understanding of fundamental factors, impacting student performance throughout the learning cycle. This approach aims to cultivate STEM-literate students who are prepared for careers in scientific and technical fields. However, a decline in student enrolment in STEM programmes has become a major concern [2].

AR has potential to revolutionize education by offering interactive features that can enrich the teaching and learning experience, ultimately reinforcing the learning process [3]. Furthermore, integrating AR into STEM education equips students with opportunities to develop and strengthen practical skills, while boosting their engagement, motivation, and overall learning satisfaction [3]. These advantages underscore the importance of emphasizing AR utilization in education, particularly within STEM fields [3].

Mobile AR leverages widely accessible technology platforms like smartphones and tablets. Essentially, mobile AR refers to the hardware needed to run AR experiences at anywhere and anytime. These applications enhance interaction by overlaying digital elements over the real world, primarily through smartphone cameras [4]. Mobile devices are keys to maximize the effectiveness of AR in educational settings [4].

While neither mobile learning nor AR is a novel concept in education, the potential of AR to collaborate with STEM fields remains highly relevant [5, 6]. AR technology can significantly enhance the learning experience and improve comprehension of STEM subjects, ultimately increasing student interest [5, 6]. Additionally, AR capabilities can transform classrooms into more interactive environments, simplifying complex information for easier understanding. By visualizing concepts within the real world, AR empowers teachers to provide more effective explanations of

*Corresponding author: danakorn@umpsa.edu.my

intricate and abstract ideas [7, 8]. Research suggested that AR offers valuable educational opportunities, including fostering spatial visualization skills, developing hands-on practical abilities, enhancing content comprehension, and promoting scientific inquiry learning – all are crucial aspects of STEM education [7, 8].

The findings of elements and components will be analyzed from related articles or papers of previous research works. On the other hand, there is lack of research on elements and components in designing the MAR apps in the field of education, especially in STEM education. Therefore, studies in different pedagogical approaches and features in developing the AR educational apps are less [9] [10]. Previous studies emphasized on exploring more into pedagogical approaches and what method was used to improve learning. Most studies did not apply the design concepts or elements from learning theory to their performance analysis [11]. However, the main concern in this study is lack of research in AR framework which focuses on STEM education in Malaysia. Until now, only a limited set of common design guidelines exist. Clearly, there is a need for more design guidelines research in the field of AR that would facilitate the development of easy-to-use MAR applications. Therefore, this study aims to investigate the essential elements and components for designing a framework for educational Mobile Augmented Reality (MAR) applications. The framework will serve as a guide for developing effective AR educational tools, specifically for STEM education. Consequently, the following research questions were formulated:

1. How many studies on AR frameworks were conducted?
2. What are the components or features to develop an effective MAR framework?
3. What are the types of AR used for STEM Education?
4. What are the multimedia elements used in AR for STEM learning?
5. What are the teaching approaches used in AR for STEM learning?
6. What are the STEM learning outcomes in AR?
7. What are the impacts of AR on student emotional state?

2. LITERATURE REVIEW

Augmented Reality (AR) has emerged as a powerful technology with the potential to revolutionize education. By seamlessly blending virtual elements with the real world, AR creates engaging and interactive learning experiences. This literature review explored the current state of research on AR in education, with a particular focus on its application in STEM subjects. the study aimed to identify the key benefits of AR in STEM education, analyses existing frameworks for educational AR applications, and ultimately highlight a critical gap that this study seeks to address.

2.1 AR IN EDUCATION

Studies have consistently demonstrated the positive impact of AR on various aspects of education. Research suggests that AR can enhance student motivation, engagement, and collaboration in the learning process [2]. The interactive nature of AR applications encourages active participation, fostering a more student-centered learning environment [9]. Additionally, AR can cater for different learning styles by providing visual, auditory, and kinesthetic elements [12].

2.2 BENEFITS OF AR IN STEM EDUCATION

Beyond its general advantages in education, AR offers unique benefits specifically tailored to STEM subjects. Here, some key advantages were explored:

Improved Spatial Skills: AR allows students to visualize complex 3D objects and concepts in real-world settings [13]. This visual representation enhances spatial reasoning and problem-solving abilities, which are crucial for STEM disciplines [14].

Enhanced Practical Learning: AR applications can simulate real-world experiments and procedures, providing students with safe and accessible hands-on learning experiences [15]. This approach can be particularly beneficial for subjects like chemistry or biology, whereby laboratory work is often limited.

Deeper Content Comprehension: AR can help students to visualize abstract concepts and processes in STEM subjects. For instance, AR simulations can depict the microscopic world in biology or the workings of an engine in physics [16]. This visualization can significantly improve comprehension and knowledge retention.

Promoted Inquiry-Based Learning: AR applications can be designed to encourage students to explore and investigate scientific phenomena independently [17]. By interacting with virtual elements in the real world, students can conduct virtual experiments and analyses data, and thus fostering critical thinking and scientific inquiry skills.

2.3 EXISTING FRAMEWORKS FOR EDUCATIONAL AR

Several researchers had proposed frameworks for developing educational AR applications. These frameworks typically outlined the key components, such as the type of AR technology used (marker-based or markerless), multimedia elements (text, graphics, audio, video), and pedagogical approaches (inquiry-based learning, problem-based learning) [18, 19]. However, some limitations exist in current frameworks. Studies suggested that the existing frameworks often priorities technical aspects over pedagogical considerations [20]. There is a need for frameworks that integrate sound learning theories into effective AR design principles to ensure optimal learning outcomes.

The reviewed literature highlighted the immense potential of AR in enhancing STEM education. However, in this context a critical gap exists regarding frameworks which were designed specifically to promote inquiry-based learning (IBL). While some studies touched upon IBL within the AR frameworks, a comprehensive framework tailored for this pedagogical approach is lacking [21]. IBL requires students to actively investigate, analyses, and solve problems, fostering critical thinking and scientific reasoning skills – the core competencies in STEM education.

This study aimed to address the critical gap by developing a framework for educational MAR applications that is specifically designed to promote IBL in STEM education. This framework will incorporate effective AR design principles into well-established IBL methodologies, providing educators with a valuable tool to create engaging and inquiry-oriented learning experiences for STEM subjects.

3. RESEARCH METHODOLOGY

This study presented existing literature which have focused on designing the MAR framework in STEM education. To ensure a comprehensive and reproducible search strategy, the following methods for selecting relevant articles were employed:

Search Terms: A combination of keywords related to AR, education, STEM, and framework development was utilized. Some specific examples were:

- "Augmented Reality" OR "AR"
- "Education" OR "Educational" OR "Learning"
- "STEM" OR "Science" OR "Technology" OR "Engineering" OR "Mathematics"
- "Framework" OR "Model" OR "Design"

Databases: Articles were searched in several reputable academic databases, including:

- Springer
- Elsevier
- IEEE Xplore (Institute of Electrical and Electronics Engineers)
- ScienceDirect JSTOR
- Additionally, Google Scholar was used to identify relevant studies that were not indexed in the primary databases.

Inclusion/Exclusion Criteria: Articles were included based on the following criteria:

- Published in English within the last 10 years (2015—2020): This ensures the inclusion of recent advancements in AR technology and educational practices.
- Peer-reviewed journals or conference proceedings: This ensures the quality and credibility of the research.
- Focus on AR in STEM education: Articles that were solely focused on AR in general education or non-STEM subjects were excluded.

These are the steps described in this study:

3.1 ARTICLE SELECTION

Selection of the most relevant journals and articles was focused in the field of AR and STEM Education. The primary search was conducted in major databases, including Springer, Research Gate, Elsevier, IEEE and others. Selected articles in the field of AR and STEM education were also performed through the web search engine, Google Scholar by using “augmented reality framework” AND (STEM OR science OR technology OR engineering OR mathematics) keywords.

3.2 INCLUSION AND EXCLUSION

The following conditions were fulfilled by journals and articles chosen for the systematic review in Table 1.

Table 1. – Inclusion and Exclusion

Inclusion	Exclusion
Published from 2015 until 2020	Published before 2015
Available in full-text articles	Not available in full-text
Focus on AR articles	Focus on Virtual Reality and Mixed Reality even though in AR term
Articles describe frameworks or application of AR	Not describe the framework
Articles about STEM education	

3.3 DATA EXTRACTION

The extraction step was performed and the following related data were extracted from the included articles:

- Publication year
- Field of study
- AR Framework
- Features and component of framework
- Mobile AR applications

3.4 FRAMEWORK DEVELOPMENT

To analyse the elements and components for the MAR framework, a qualitative content analysis approach was employed. This method systematically involved coding and analysing of textual data from the selected articles [22]. The processes were:

- Data Extraction: Relevant sections from the selected articles that discuss components, features, and design principles for effective educational MAR applications were extracted. This included information on:
    - Types of AR technology used (marker-based or markerless)
    - Multimedia elements employed (text, graphics, audio, video)
    - Pedagogical approaches addressed (inquiry-based learning, problem-based learning)
    - Targeted learning outcomes (knowledge acquisition, skill development)
- Coding: Extracted data were coded based on pre-defined categories related to MAR framework components. These categories emerged from initial readings and may be refined throughout the analysis
- Thematic Analysis: We will identify recurring themes and patterns within the coded data. This will allow us to synthesize the key elements and components for a robust MAR framework specifically designed to promote Inquiry Based Learning in STEM education.

4. RESULTS AND DISCUSSION

In this section, the findings were presented and discussed based on the earlier research questions. In this research, 1,390 AR in STEM education papers were found. The papers were extracted by following the criteria to ensure its relevance to the study purpose. The review included 742 articles published from 2015 to 2020. By reviewing and verifying them based on the focus of current study, the number of articles was reduced to 137 papers. Finally, the total of final papers was decreased to 67 papers.

In addition, this study was categorized into two categories, which were AR framework as well as features and component for designing framework. Table 2 shows total number of studies for the two categories. The first category focused on previous studies that were relevant to AR framework in STEM education. In the other hand, the second category focused on the investigation into components and features for designing an effective framework of AR in STEM education.

Table 2. – Percentage of categories by studies

Categories of studies	Number of studies	Percentage (%)
AR Framework	22	33%
Components and features for designing framework	45	67%

4.1 FRAMEWORK

How many studies of AR frameworks were conducted?

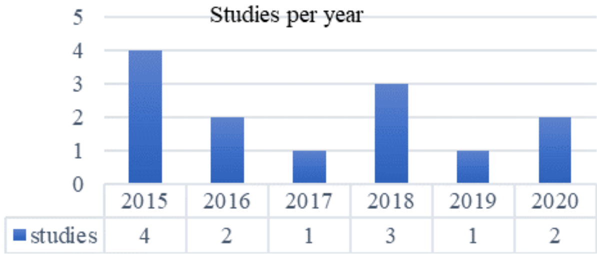

FIGURE 1. - Total studies of AR framework and application per year

There were 22 papers of AR frameworks and applications found. However, out of the 22 articles, only nine mentioned their framework but did not include it in their studies. According to these 13 papers, they were designed for fields, such as safety education, health care education, architecture, creative thinking, while others were designed for STEM education. Therefore, to develop an effective MAR framework more research studies on component or features are needed. Fig 1 shows yearly studies related to AR framework and implementation of in education from 2015 to 2020. Studies were published four in 2015 (18%), two in 2016 (9%), one in 2017 (4.5%), three in 2018 (14%), one in 2019 (4.5%) and two in 2020 (9%).

The existing framework and model are listed in Table 3. A few studies attempted to develop the AR framework but for different settings and purposes, for example, like [12] develop a mobile augmented reality education (MARE) design framework in health education, but the study did not test or validate their developed framework with real implementation. The finding from their study indicated that AR has potential and affordances in health care education. Meanwhile, [13] indicated that the MOIAR application emphasized on identifying location-based outdoor real-life learning objects. Therefore, now they focused on how the AR method improves the mobile learning application and how the MOIAR has affected learners in the mobile learning setting.

Reference [14] stated in a study that the proposed system would be effective in enhancing access to safe information and safe knowledge transfer. However, the significant time required for VR and AR scenario creation still remains an issue in the study. Reference [15] designed the Education Augmented Reality App (EDAR) framework to improve the level of creative thinking amongst preschoolers. In this study, the ADDIE model was applied to the proposed framework. Furthermore, [16] presented Collaborative Mobile Augmented Reality Learning Application (CoMARLA) to increase student learning. CoMARLA focused on the ICT topic. Learning approach and gender were primary effects attributed to the analysis. In fact, male students appeared to make substantial improvements in learning as opposed to female students. However, this study stated that the results might have some consequences for the existing teaching and technology development efforts.

In addition, [17] reported in a study on the emotional influence of incorporating AR technology into learning. and thus, the study did not apply the development system and teaching model yet. Consequently, [18] develop a framework for mobile AR but focused on the networking course offered by universities. Yet, an effective framework for guiding the design and development of MAR, especially in education, still lacks. On the other hand, Reference [19] made a lesson to improve the use of periodic table related to chemical elements and reactions by using AR technology in the work. The students could view a list of chemical reactions and perform simulations of basic chemical reactions. Furthermore, Double-Slit Experiment Augmented Reality (DSIAR) application by [20] was used to simulate the physical experiment and double-slit experiment. In this article, DSIAR offered students the ability to monitor and communicate with a series of 3D laboratory equipment models by markers. Yet, the sample size was not enough.

Moreover, work by [5] that focused on the combination of AR and Machine Learning on a mobile platform, AUREL, was proposed to support STEM education. Reference [21] proposed an AR-based multimedia environment for experimental education. This paper presented the experiment simulation engine that supported physical, chemical and biological simulation.

Table 3. – Existing Framework and Model

YEAR	FRAMEWORKS /MODELS	FIELD OF STUDY	TARGET GROUP
2015	Mobile Augmented Reality Education (MARE)	Health Care Education	Physicians
2015	Multi-Object Identification	Architecture	Students

	Augmented Reality (MOIAR)		
2015	Mobile based VR + AR	Safety Education	Students (higher education)
2015	Education Augmented Reality App (EDAR)	creative thinking	Students (Pre-school)
2016	Collaborative Mobile Augmented Reality Learning Application (CoMARLA)	Science Computer	Students (undergraduate)
2016	Eco-Discovery AR-Based Learning Model (EDALM)	Science (Ecology)	Students (middle school)
2017	Mobile-Augmented Reality (MAR)	Computer Science	Students (Higher Education)
2018	Double-Slit Experiment Augmented Reality (DSIAR)	Science (Physics)	Students (Secondary School)
2018	Multimedia Development Life Cycle (MDLC) model	Science (chemistry)	Students, teachers and public
2018	MechE	Physics	Students
2019	Augmented Reality Learning (AUREL)	STEM education	Students and teachers
2020	AR-based multimedia environment	STEM education (Science)	Students (middle school)
2020	ScholAR	Geometry	Students (Middle School)

4.2 COMPONENTS AND FEATURES IN FRAMEWORK

What are the components or features in developing an effective MAR framework?

In this study, the components and features in developing MAR framework, especially in STEM education, were identified. In order to perform the effective MAR framework, there were five components or features from reviewed literature, which were AR system, multimedia elements, teaching method, learning outcomes and student emotional state in using AR. The study identified 45 articles which were reviewed to investigate the components and features in developing an effective MAR framework in STEM education.

The main type of AR system is marker-based AR and markerless AR, which is also known as image-based and location-based. According to previous studies, most of them stated that markers were used mainly for education application.

In addition, most studies used several types of multimedia elements in their AR application and gained positive impacts on student learning [22]. Teachers could include the learning activities that have used mobile AR learning applications with multimedia contents, such as text, audio, graphics, animation, and video. The students subsequently became more experienced, motivated and interested in the learning process. The use of multimedia elements in the classroom would be more fun, improving student performance and enhancing understanding.

Another important component in developing an effective educational application is to rely on the teaching method. Based on the study, several teaching methods were found in STEM education. However, studies that used different pedagogical approaches and features in developing AR educational apps are still less. A learning outcome is what the students are expected to achieve at the end of the learning process. AR that is designed for teaching and learning can enhance the learning outcomes by improving the interactive elements and engagement.

4.3 TYPE OF AR

What are the types of AR used for STEM Education?

Fig. 2 indicates that most articles (67%) used image-based AR in developing the educational application. Therefore, most studies have applied image-based AR in the applications [2] [24]. In AR technology, there are many types of AR system. According to [7], two main AR types were defined, namely image-based AR and location-based AR. Image-based AR or also known as marker-based AR needs a particular visual object and scan with a camera. The devices must recognize the content from the camera view [23]. Mostly marker-based AR use a printed media, images or QR code to specify the object. Location-based or marker-less AR links the AR material to a specific area by using a GPS or compass to provide user location-based details. With the accessibility of digital devices, it usually generates maps, instructions, information or navigation assist.

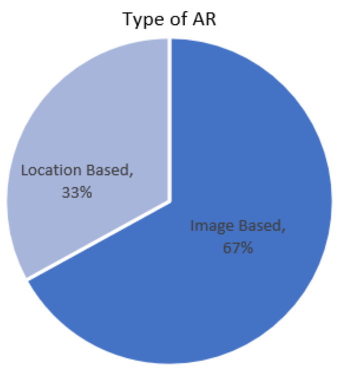

FIGURE 2. - Percentage the type of AR systems

Table 4 presents the analysis of AR system used in previous studies. Reference [2] also revealed that most studies indicated that markers were used mainly for educational applications. Image-based AR can be used to improve students' visualization ability, hands-on skills and conceptual comprehension. Therefore, marker-based AR tends to be more practical for use due to its low cost and ease of implementation [2] [23]. Only four articles (33%) had discussed on the use of location-based AR.

Table 4. – System of AR

AR system	*Author*	*Location*	*Field of study*
Location Based	[13]	House, Alberta Legislature building	Architecture
	[25]	Science center	STEM education (science)
	[26]	Santiago de Chile	STEM
	[27]	Not specified	Architecture
Image Based	[14]	Construction site	Safety Education
	[28]	Science center	Science
	[29]	Museum, home and school	Natural science
	[17]	Botanical garden	Science (Ecology)
	[30]	School	STEM education (Chemistry)
	[31]	School	Science (Physics)
	[19]	School	Science (chemistry)

[32]	Classroom	Mathematic (Calculus)
[33]	Not specified	STEM education (science)
[34]	Not specified	STEM education (Robotic)

4.4 MULTIMEDIA ELEMENTS

What are the multimedia elements used in AR for STEM learning?

Table 5. – Multimedia element used in the studies

Multimedia elements	Number of studies
Text	10
Graphic	8
Audio	4
Video	7
Animation	2
3D model	9

Table 5 summarizes the multimedia elements used in previous studies. Multimedia elements consist of text, graphic, video, audio and animation. Therefore, 3D models were also reported as the major elements of interactive multimedia in AR. Most AR applications contain interactive multimedia elements, such as animate holograms, interactive displays, virtual 3D models and even virtual 4D models. Each element plays an important role in delivering knowledge and information. Due to the enhancement in student learning, [35] found that the presentation of objects in 3D provided the exploration of spatial problems that were difficult to grasp in 2D media. They also reported that most studies that were focused on children with learning disabilities primarily adopted audio, graphic, animation, and video as multimedia elements in their AR application.

The analysis in those findings definitely showed that most AR applications used multimedia elements that consisted of text, graphics, audio, video and animation [19] [36]. Implementing these elements with a variety of colors could help to build interfaces for applications that can trigger the students' senses and have a significant effect on student learning processes, particularly those with low cognitive ability or understanding. It also improves the classroom learning process.

The data showed in the Fig. 3 indicated that most studies used text, 3D models and graphics to present information in AR applications. The adoption of AR technology and multimedia elements in the development of learning and training applications has intensified, signifying the many educational benefits to which learners and educators can gain [22]. Animations may also enhance the comprehension when used in ways that are consistent with the cognitive concept of multimedia teaching [35]. A very interesting study by [7] found that the use of multimedia elements would improve student performance, enhance understanding and spatial ability. Therefore, it enabled the learner to view invisible phenomena or assisted students to imagine 3D models or abstract objects [37].

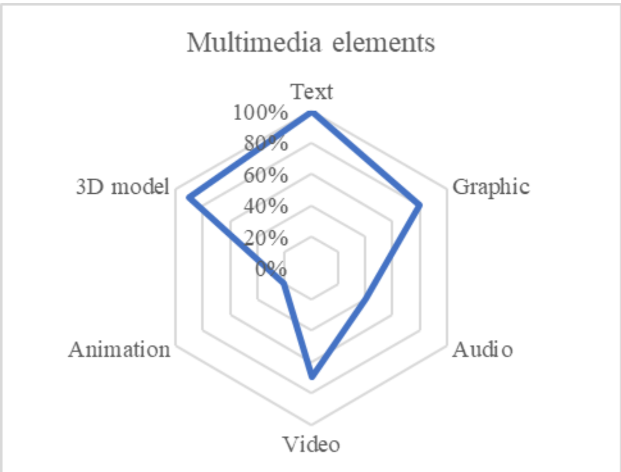

FIGURE 3. - Percentage of multimedia elements used in studies

4.5 TEACHING METHOD

What is the teaching approach used in STEM learning?

Higher order thinking skills (HOTS) was one of the approaches highlighted in the curriculum as recommended teaching pedagogies through the implementation of inquiry-based learning, problem solving and project-based learning [38]. Such theoretical perspectives offer specific cognitive experiences, which will improve the various learning experience features that AR may bring. Additionally, the learning practices proposed by such concepts can be implemented in smartphone AR applications. Through the learning approach it may guide decisions about the learning environment, practices, and how to implement AR [12].

Several studies investigated the teaching method in STEM education. Reference [10] stated that the STEM approach was a teaching and learning technique that was included in the implementation of science, technology, engineering and mathematics in solving problems so as to address the challenges of daily life, society and culture. This method allowed students to investigate and explore the environment through real-world enquiries and problem-solving. Based on the study, several teaching methods were found in the STEM approach, which included inquiry-based teaching, project-based teaching and problem-based teaching. Therefore, inquiry-based teaching provides on thinking skills, scientific process skills, solving skills in real world scenarios, planning, innovating, working collaboratively along with inquiry-based learning approaches, including the 5E (engage, explore, explain, elaborate and evaluate) [10]. This teaching method of encouraging students to raise questions and explore their own thoughts allows them to develop their problem-solving abilities and achieve a better understanding of learning topics, especially in STEM subjects. It may also help to improve leadership skills and the student's capacity to solve problems [39].

Project-based teaching method helps students to learn and build skills through innovative learning environment and lead to real-life problems. In this method of learning, a teacher is seemed more as a mentor than as a provider of knowledge and ideas. A teacher can recommend tasks, but the students themselves are both tried and practiced. In fact, this method is completely successful by giving exposure at the early age as well as develop student learning by improving their visual, cognitive and critical thinking abilities; hence, enhancing collaboration and greater involvement in STEM.

Furthermore, problem-based teaching is the development of critical thinking and creative skills. The students evaluate, generate and define an issue that has arisen. Therefore, problem-based thinking is appropriate in STEM fields as it allows students to build the knowledge and confidence in identifying of issues that are never encountered before. Problem-based learning follows a learning cycle, such as problem posed, identifying learning issues, individual and small group learning, application of learning, and reformulating the problem. In fact, this is an excellent technique to apply pedagogies of engagement in STEM disciplines [40].

4.6 LEARNING OUTCOME

What are the STEM learning outcomes in AR?

A learning outcome is what the students are expected to achieve at the end of the learning process. AR that is designed for teaching and learning can enhance learning outcomes by improving the interactive elements and engagement [2]. Therefore, the impact in the learning outcomes will be explored. Based on the research, several outcomes of learning by using AR in STEM education was analyzed.

Conceptual understanding

Conceptual understanding is knowing more than isolated facts and methods. The successful students understand the ideas, and has ability to transfer their knowledge into new situations and apply it to new contexts.

Practical Skill

Practical skill is necessary for theoretical knowledge of skill-based subjects. Most topics in science need to be done in practical knowledge that include laboratory experiments. Practical skills also include teamwork, problem solving, communication and leaderships.

Inquiry-based

Inquiry-based learning is an educational approach that concentrates on investigation and problem-solving. It focuses on issues that require critical and creative thinking so that students can develop their skills to ask questions, design investigations, interpret evidence, provide explanations and arguments, and communicate findings [41]. Several studies had indicated that AR was beneficial in the classroom environment by enhancing inquiry, collaboration, creating teaching resources and assisting student's self-expression [42].

Spatial ability

Spatial ability or visual-spatial ability is ability to understand, reason, and remember the spatial relations amongst objects or space. Spatial ability is an ability that has correlation with the success in many fields of study, especially in STEM education. Several studies reviewed and claimed that AR helped to enhance spatial ability [37].

Conceptual change

Conceptual change is basically described as learning that transforms an existing concept, such as belief, idea, or mind set. Conceptual change requires more than just learning discrete information and processes. A productive student knows ideas and has potential to adapt and extend his understanding to different circumstances. The study indicated that AR was effective to be integrated into education to facilitate conceptual change.

4.7 STUDENT'S EMOTIONAL STATE

What are the impacts of AR on student emotional state?

Table 6. – The number of studies included student's emotional state by using AR

Emotional States	Number of Studies
Motivation	10
Learning gain	10
Learning performance	9
Understanding	8
Experience	8
Engagement	5
Collaboration	5
Interest	4
Attitude	4
Satisfaction	3
Memory	2
Interaction	2
Exploration	2
Enjoyment	2

Table 6 shows the effective outcomes that occur when using AR in education. Most studies had reviewed the outcomes of using AR in their research. Based on Table 6, most student emotional states that appeared were motivation, learning gain and learning performance from 10 studies. The studies focused on student outcomes and showed that most emotional states were motivation, followed by attitude, enjoyment, engagement, satisfaction and interest. The review also investigated measures of cognitive outcomes. One of the most common outcomes was capability to recall information and understand the content. In addition, it also included developing, integrating, assessing, evaluating and remembering the content [37]. AR research may also increase the student interest and enthusiasm and enhance the learning experience [20] [43].

4.8 COMPARISON WITH EXISTING FRAMEWORKS AND FRAMEWORK NOVELTY

The qualitative content analysis revealed several key components for effective educational MAR applications, aligning with existing frameworks proposed by [44] and [45]. These frameworks emphasized similar elements like: (a) Type of AR System - Choosing marker-based or markerless technology based on learning objectives and context. (b) Multimedia Elements - Utilizing a combination of text, graphics, audio, and video to cater to various learning styles and enhance engagement and (c) learning outcomes- Focusing on both knowledge acquisition and skill development, including critical thinking and problem-solving. However, a crucial distinction lies in the limited emphasis on pedagogical approaches within existing frameworks. Meanwhile, some like [46], acknowledged the potential of AR for inquiry-based learning, a comprehensive framework that was specifically designed to promote Inquiry Based practices within STEM education was absent.

Addressing this gap, the proposed framework offers a novel approach by:

- The framework incorporates core inquiry principles, encouraging students to actively investigate, analyze, and solve problems through interaction with virtual elements.
- The framework prioritizes the design of AR experiences that promote student-driven inquiry. This includes posing questions, investigating phenomena, and analyzing data within the AR environment.
- Recognizing the varying needs of learners, the framework integrates scaffolding strategies within the AR application. This provides support and guidance throughout the inquiry process, gradually decreasing as students develop critical thinking skills.

- The framework emphasizes formative assessment strategies embedded within the AR experience. This allows students to reflect on their learning journey and receive feedback to adjust their inquiry and deepen understanding.

These novel elements distinguish the proposed framework from existing models. While other frameworks offer valuable design principles, they often lack a specific focus on promoting inquiry-based learning practices. This Inquiry based focused framework addresses this critical gap by providing a comprehensive guide for developing AR applications that actively engage students in the scientific inquiry process within STEM education.

5. CONCLUSION

This study investigated the essential elements and components for designing a framework for Educational Mobile Augmented Reality (MAR) applications, specifically for STEM education. Through a qualitative content analysis of existing research, several key components for effective educational MAR applications, including the type of AR system (marker-based or markerless), multimedia elements (text, graphics, audio, video), and learning outcomes (knowledge acquisition and skill development) were identified. These findings aligned with existing frameworks for educational AR applications. However, a critical gap regarding the limited emphasis on pedagogical approaches within these frameworks was identified. The study analysis revealed the lack of frameworks that are specifically designed to promote Inquiry-Based Learning in STEM education. The proposed inquiry based-focused MAR framework offers valuable insights for educators, policymakers, and AR application developers. This framework equips educators with a practical guide for designing and implementing AR experiences that actively engage students in the scientific inquiry process within STEM subjects. By incorporating inquiry principles, educators can foster critical thinking, problem-solving, and independent learning skills. In addition, the framework highlights the potential of AR to enhance STEM education. Policymakers can leverage these findings to support the development and integration of AR resources in educational settings. The framework also provides valuable insights for developers who are creating AR applications specifically for STEM education. By focusing on inquiry-based principles and identified components, developers can design AR experiences that promote deeper learning and scientific inquiry skills. While this study addresses a critical gap in existing frameworks, further research is needed to explore the full potential of inquiry-based-focused MAR applications. Comparative studies can explore the effectiveness of inquiry-based focused MAR applications as compared to traditional teaching methods in STEM education. In addition, building upon the immersive potential of the Metaverse [47], future research can explore how inquiry based focused MAR applications can be integrated into these virtual environments, while simultaneously leveraging advancements in 3D model visualization [48] to allow students to manipulate complex models and conduct collaborative scientific investigations within a blended physical-digital learning space. By pursuing these research avenues, inquiry-based focused MAR frameworks can be further refined and validated, ultimately promoting a more engaging and effective learning experience for STEM education.

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CONFLICTS OF INTEREST

The author declares no conflict of interest.

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