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A new approach using simulation of physical models with augmented reality to teach electrical engineering: a case study using electromagnetism

Uma nova abordagem usando simulação de modelos físicos com realidade aumentada para o ensino em engenharia elétrica: um estudo de caso usando eletromagnetismo

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Abstract: This study evaluates a new educational approach using augmented reality to simulate physical models,aiming to enhance perceived learning in electrical engineering. A literature review on augmented reality in education, particularly for electrical engineering, is conducted. An electromagnetism lecture on Coulomb's Law, Electric Fields, and Electric Forces was delivered using this method to a class of 39 students. A pre/post-exposure questionnaire gauged changes in student perception, and the System Usability Score measures the mobile app's usability. Results show improved student perception of learning outcomes. The study also offers future research directions and suggestionsto improvement the proposed method.

Keywords: Electrical Engineering Education, Physical Model Simulation, Augmented Reality, Electromagnetism.

Resumo: Este estudo avalia uma nova abordagem educacional utilizando realidade aumentada para simular modelos físicos, visando aprimorar a aprendizagem percebida em engenharia elétrica. É realizada uma revisão da literatura sobre realidade aumentada na educação, particularmente para engenharia elétrica. Uma aula em eletromagnetismo sobre Lei de Coulomb, Campos Elétricos e Forças Elétricas foi ministrada usando este método para uma turma de 39 alunos. Um questionário pré/pós-exposição mediu as mudanças na percepção do aluno, e a Pontuação de Usabilidade do Sistema mede a usabilidade do aplicativo móvel. Os resultados mostram uma melhor percepção dos alunos sobre os resultados da aprendizagem. O estudo também oferece direções de pesquisas futuras e sugestões para melhorar o método proposto.

Palavras-chave: Educação Engenharia Elétrica, Simulação Modelo Físico, Realidade Aumentada, Eletromagnetismo

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1 Introduction

Various pedagogical approaches have been developed to cater to different learning objectives in science, technology, engineering, and mathematics (STEM) education, ranging from acquiring knowledge through structured lessons to engaging in experimental activities. Technological advancements have also introduced digital tools with the objective of improving the educational experience. In particular, learning tools based on Augmented Reality (AR) have been proposed to improve the student's ability to understand complex topics taught in class (Vergara; Rubio; Lorenzo, 2017; Martín-Gutiérrez *et al.*, 2015).

The adoption of AR technology in domains such as engineering has become increasingly prevalent in the past decade (Alvarez-Marin; Velazquez-Iturbide, 2021). AR bridges the gap between the physical and virtual worlds, allowing the perception of physicality of digital elements in a real environment (Kumar; Mantri; Dutta, 2021; Chu, 2022). However, integrating AR into the classroom requires careful consideration of various factors, such as the requirements described by Alvarez-Marin and Velazquez-Iturbide (2021), including aesthetics, facilitation conditions, information quality, interaction, motivation, perceived enjoyment, perceived usefulness, satisfaction, system quality, technology acceptance, and usability.

This paper explores the impact of AR on STEM education, focusing on its application in electrical engineering.

2 Literature review

Engineering, as a field of knowledge, is dedicated to problem solving through the application of scientific knowledge and the use of mathematical laws that describe the behavior of systems (Bazzo; Pereira, 2006, p. 70–74). In the context of electrical engineering education, several issues related to the topics taught can arise, as discussed by Rosenbaum *et al.* (1990). These issues include a lack of engagement with knowledge, insufficient tools to support various types of learning, and a deficiency in means to communicate knowledge effectively. Despite their origins in 1990, these challenges endure today and are particularly pronounced for topics requiring a conceptual correlation between mathematical understanding and physical models, such as those covered in electromagnetism (Massa *et al.*, 2020; Rahman, 2014).

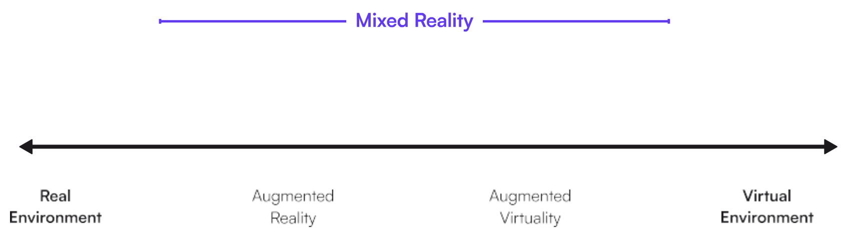
The role of an engineering student is to acquire knowledge that can be generalized to address technical problems. As required by the Brazilian Ministry of Education, engineering students are expected to: model phenomena and physical systems, using mathematical, statistical, computational, and simulation tools, among others; predict system outcomes using models; design experiments that produce real results for the behavior of studied phenomena and systems; and verify and validate models using appropriate techniques (Brasil, 2019). Therefore, the use of established educational approaches, such as pen and paper, text books, videos, slide projections, and images, accompanied by a professor who guides a classroom through recitations and memorization (Faridi *et al.*, 2021), may not suffice for all topics covered in a classroom.

The use of AR in STEM, particularly in electrical engineering education, has gained attention in numerous studies that examine its introduction, development, and adoption in academic settings. A significant body of research has highlighted the factors that influence student acceptance of AR, such as peer influence, accessibility, and perceived impact on learning outcomes (Álvarez-Marín; Velázquez-Iturbide; Castillo-Vergara, 2021a,b; Tirado-Morueta *et al.*, 2018). Considerable effort has been made to develop AR applications tailored for use in electrical engineering classrooms. For example, an image processing system for real-time evaluation of integrated circuits (aviles-Cruz; Villegas-Cortez, 2019) and a deep learning-based AR application for classifying equipment (Estrada *et al.*, 2022).

AR is a technology that, by using specialized software, enables the construction of dynamic interactions, using virtual objects generated by computers to enhance the real-world environment (Yener; Halil, 2020; Alvarez-Marin; Velazquez-Iturbide, 2021). Its ability to superimpose real-word information with digital information makes it suitable for various educational settings, as it allows students to better understand both simple and complex concepts with greater ease (Aviles-Cruz; Villegas-Cortez, 2019).

The term AR became widely known with the proposal of Milgram and Kishino (1994) to disseminate a standard nomenclature for devices that fall under a "virtuality continuum". Their proposal constructed a spectrum that ranged from a real environment to a virtual environment, as shown by Figure 1. According to the description of the authors, one end of this spectrum comprises real-world environments that consists only of physical objects, while the other end includes only synthetically generated digital objects. Between these extremes, one finds what is called mixed reality (MR), which combines features of both real and digital environments to varying degrees.

Figure 1 – Representation of virtuality continuum



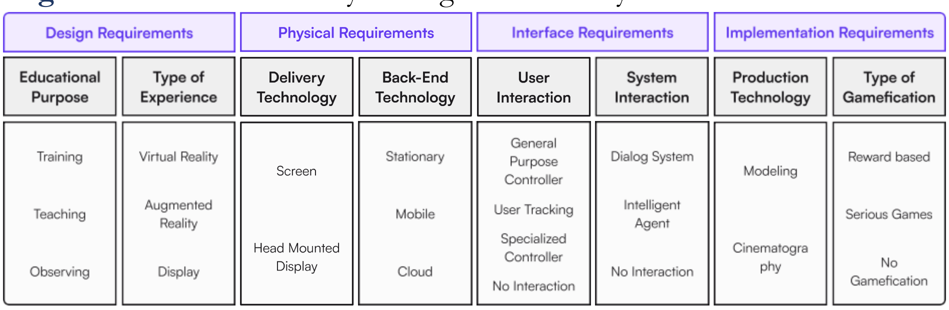
Source: Adapted from Milgram and Kishino (1994).

To mitigate potential confusion and terminology inaccuracies when discussing AR, Motejlek and Alpay

(2021) introduced a novel taxonomy. This taxonomy departs from the description of AR as a spectrum between real-world and virtual environment, and instead categorizes it into four different classes based on the prerequisites to develop an AR application. These categories encompass "Design requirements", "Physical requirements", "Interface requirements", and "Implementation requirements".

Adopting the taxonomy proposed by Motejlek and Alpay (2021) for AR offers a more robust delineationof requirements that align closely with educational objectives, in contrast to the taxonomy proposed by Milgram and Kishino (1994). In particular, the formulation of this taxonomy is drawn from Bloom's taxonomy (Bloom *et al.*, 1956; Anderson *et al.*, 2001), allowing the generation and classification of educational objectives for ARapplications. This association with Bloom's taxonomy establishes a strong and recognized educational approach asits foundation. In addition, it facilitates the exploration of additional dimensions beyond educational outcomes, as it encompasses various other aspects. Figure 2 shows these categories and facets.

Figure 2 – Novel taxonomy for augmented reality



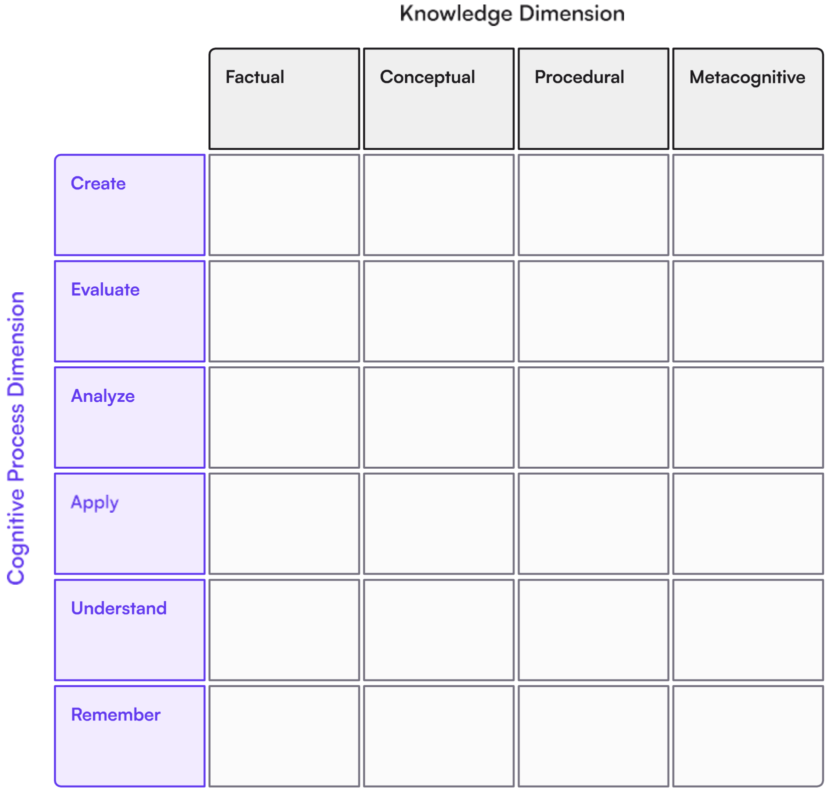
Source: Adapted from Motejlek and Alpay (2021).

Bloom's taxonomy, introduced by Bloom *et al.* (1956), offers a framework for classifying educational objectives. The taxonomy presents a hierarchical arrangement of cognitive skills that are organized into six levels that denote varying degrees of complexity. In the early 2000s, a revision of the taxonomy was undertaken to enhance its relevance to modern educational practices. The updated taxonomy retains the original hierarchical structure and introduces a dimension of knowledge (Anderson *et al.*, 2001), as shown in Figure 3.

The effectiveness of Bloom's taxonomy stems from its generality, since it is agnostic to the means and tools employed in a lecture. Instead, it focuses on delineating the steps necessary to achieve a specific learning outcome. Professors, for instance, can devise a learning plan using the diagram shown in Figure 3 through various mediums such as books, in-class activities, practical laboratories, or any other method with which the professor is most familiar and comfortable applying.

Due to the recent rise of personal computers and the increase in computing power, a transformation in the teaching approach has been facilitated (Nogueira; Alves; Marques, 2019), with a growing emphasis on the incorporation of innovative technologies into established educational approaches (Martín-Gutiérrez *et al.*, 2015). However, established educational approaches, along with their theoretical foundations, persist in their importance and find regular application within the educational community, such as Bloom's taxonomy (Martín-Gutiérrez *et al.*, 2015; Sandoval *et al.*, 2022).

Figure 3 – Revised bloom's taxonomy



Source: Adapted from Anderson *et al.* (2001, p. 28).

Incorporating established educational theories into AR applications provides several benefits, particularly in facilitating integration into existing curricula and offering familiarity to educators. As Martín-Gutiérrez *et al.* (2015) notes, traditional teaching approaches continue to be valid and effective even as new technologies like AR emerge. AR has the potential to enhance student participation and interaction, but its implementation must be carefully managed. This includes ensuring that faculty and educational staff are well prepared to support AR integration (Yener; Halil, 2020).

Although AR improves visualization of complex concepts, the representation of theoretical knowledge such as electrical interactions within circuits remains difficult in traditional laboratory settings (Kaur; Mantri;Horan, 2022). Furthermore, the quality and availability of sensors are factors in the adoption of AR for STEM,which are responsible for detecting environmental data to display to students (Kapp *et al.*, 2022). The effectiveness of AR applications often depends on the functionality of the sensor, which varies depending on educational goals and technical needs.

3 Methodology

As explained by Anderson *et al.* (2001, p. 3), teaching is an intentional act in which professors instruct with a specific purpose, centered on fostering student learning. Professors play a crucial role in guiding students through the material that they, as subject matter experts, consider essential to understand and comprehend.

Hence, as a fundamental step in formulating this method, professors bear the responsibility of planning and constructing the lecture they intend to deliver to their students. Furthermore, the professor is required to determine the optimal learning format that aligns with their teaching approach and, in doing so, achieving the educational objectives established by the Brazilian Ministry of Education (Brasil, 2019). In particular, to organize an educational plan, professors should use Bloom's taxonomy (Anderson *et al.*, 2001).

For the topics considered relevant by the professor for the incorporation of AR, possible interactions should be organized and planned accordingly. For example, if a professor intends for students to acquire conceptual knowledge for a laboratory, such as the proposal of Altmeyer *et al.* (2020), considerations should be taken to the layout of practical experiments, accessibility of the AR application, disposition of information, variations to exercises, and clarification of the expected outcome for students.

As the educational plan takes shape, it is the professor's responsibility to define technical requirements for the development of the AR application, as its final use will be closely tied to how the professor envisions their students using it. These requirements can be chosen from the taxonomy presented by Motejlek and Alpay (2021). In addition to establishing technical requirements, the professor is responsible for communicating with an external actor capable of building the application. This external actor may be an individual, a group, or an enterprise. Regardless of the size of this external actor, the professor must communicate and align the development of the AR application with the envisioned educational plan. Upon completion of the development of the AR application, adjustments to the educational plan may be necessary if the implementation of a particular interaction is not feasible. However, these adjustments should be minimal given the active participation of the professor in the development process of the application.

Having completed the adjustments to the educational plan, the professor is now equipped to deliver the lecture as planned, incorporating the AR application to simulate physical models. At this stage, the professor has the flexibility to conduct their classes according to what is considered suitable for them and their students. However, to prevent the rejection of technology by students, the professor can articulate the reasons and highlight the benefits for students using the AR application (Álvarez-Marín; Velázquez-Iturbide; Castillo-Vergara, 2021a,b).

Optionally, after the lecture has ended, the professor may seek student feedback to enhance both the lecture and the AR application. Novel interactions can be included incrementally, while existing interactions can be updated, adjusted, or removed based on received feedback. If the professor opts to collect student feedback, they should analyze and share the information with the external actor for appropriate action. Similarly, the educational plan canbe updated accordingly.

3.1 Experimental Mechanism

The experimental mechanism is divided into two, with the intention of assessing the perceived educational outcomes of students when the proposed method is implemented in a classroom setting, to understand the potentialchanges in their perception. Students will receive a pre-exposure questionnaire consisting of 5 questions, shown in Figure 4. The questionnaire uses a Likert scale ranging from "Strongly disagree" to "Strongly agree". These questions are designed to establish a baseline for students' perceived knowledge of the topic to be taught, their familiarity with AR, and their perceptions of its potential as a learning tool. After the students have been exposed to the proposed method and have used the AR application developed for the experiment, a post-exposure questionnaire consisting of 10 questions will be administered. Similarly to the pre-exposition questionnaire, it uses a Likert scaleranging from "Strongly disagree" to "Strongly agree".

Figure 4 – Qualitative pre-exposure questions for students

Author	Orginal Question	Adapted Question (Free Translation)
Yener and Halil (2020)	1. I know what augmented reality technology is.	1. Eu estou familiarizado com realidade aumen- tada.
	2. Augmented reality is amusing.	2. Eu acho realidade aumentada interessante.
	3. Using augmented reality is attractive for learn- ing new technical subjects in the engineering field.	3. Acredito que o uso da realidade aumentada como fonte de aprendizado para assuntos técnicos na área de engenharia elétrica é relevante.
Martín-Gutiérrez *et al.* (2015)	4. I believe that the application helps mental visu- alization of abstract concepts.	4. Acredito que a realidade aumentada ajuda a entender e permite a visualização de conceitos abstratos.
Elaborated by the author	N/A	5. Estou familiarizado com a Lei de Coulomb, campos elétricos e forças elétricas.

Source: Elaborated by the author.

In addition, the system usability scale (SUS) is used to assess the perceived usability of the application, consisting of 10 questions, as demonstrated in Figure 5. Each element is associated with a statement on the usabilityof the system being evaluated, and users must rate their agreement with each statement on a five-point Likert scale,ranging from "Strongly disagree" to "Strongly agree" (Brooke, 1995).

Figure 5 – System usability scale

Question Number	Original Question	Adapted Question (Free Translation)
Q1	I think that I would like to use this system fre-quently.	Eu gostaria de usar este aplicativo com frequência.
Q2	I found the system unnecessarily complex.	Eu achei o aplicativo desnecessariamente com-plexo.
Q3	I thought the system was easy to use.	Eu achei o aplicativo fácil de usar.
Q4	I think that I would need the support of a technicalperson to be able to use this system.	Eu acho que precisaria do apoio de uma pessoatécnica para poder usar este aplicativo.
Q5	I found the various functions in this system werewell integrated.	Eu achei que as várias funções do aplicativo esta-vam bem integradas.
Q6	I thought there was too much inconsistency in thissystem.	Eu acho que haviam muitas inconsistências noaplicativo.
Q7	I would imagine that most people would learn touse this system very quickly.	Eu imagino que a maioria das pessoas aprenderiaa usar este aplicativo rapidamente.
Q8	I found the system very cumbersome to use.	Eu achei o aplicativo muito complicado de usar.
Q9	I felt very confident using the system.	Eu me senti muito confiante usando o aplicativo.
Q10	I needed to learn a lot of things before I could getgoing with this system.	Eu precisei aprender muitas coisas antes de come-çar a usar este aplicativo.

Source: Adapted from Brooke (1995).

The SUS is typically administered after users have interacted with the evaluated system but before any debriefing or discussion occurs. Participants are encouraged to share their initial reactions to each item quickly, and discouraged to take prolonged reflection on the system. Respondents are advised to address all items and, if they have difficulty responding to a specific item, they are instructed to mark the midpoint of the scale (Brooke, 1995). The SUS is represented as a single numerical score, which offers a measure of the general usability of the evaluatedsystem. It is crucial to note that individual scores for specific items lack a significant interpretative value on their own (Brooke, 1995). Calculating the SUS involves the following steps.

For each question, responses range from 0 (Strongly Disagree) to 4 (Strongly Agree). To calculate the score, first sum the odd-numbered responses and subtract 5, then sum the even-numbered responses and subtract this sum from 25. Add both sums together and multiply by 2.5 to obtain a percentage between 0% and 100% for each respondent. Finally, compute the average percentage across all respondents to obtain the overall System Usability Scale (SUS) score. It uses a seven-point adjective-anchored Likert scale to classify the system, as demonstrated in Figure 6.

Figure 6 – System usability adjective rating scale

Adjective of the System	Mean SUS
Worst Imaginable	12.5 %
Awful	20.3 %
Poor	35.7 %
Ok	50.9 %
Good	71.4 %
Excellent	85.8 %
Best Imaginable	90.9 %

Source: Adapted from Bangor, Kortum, and Miller (2009).

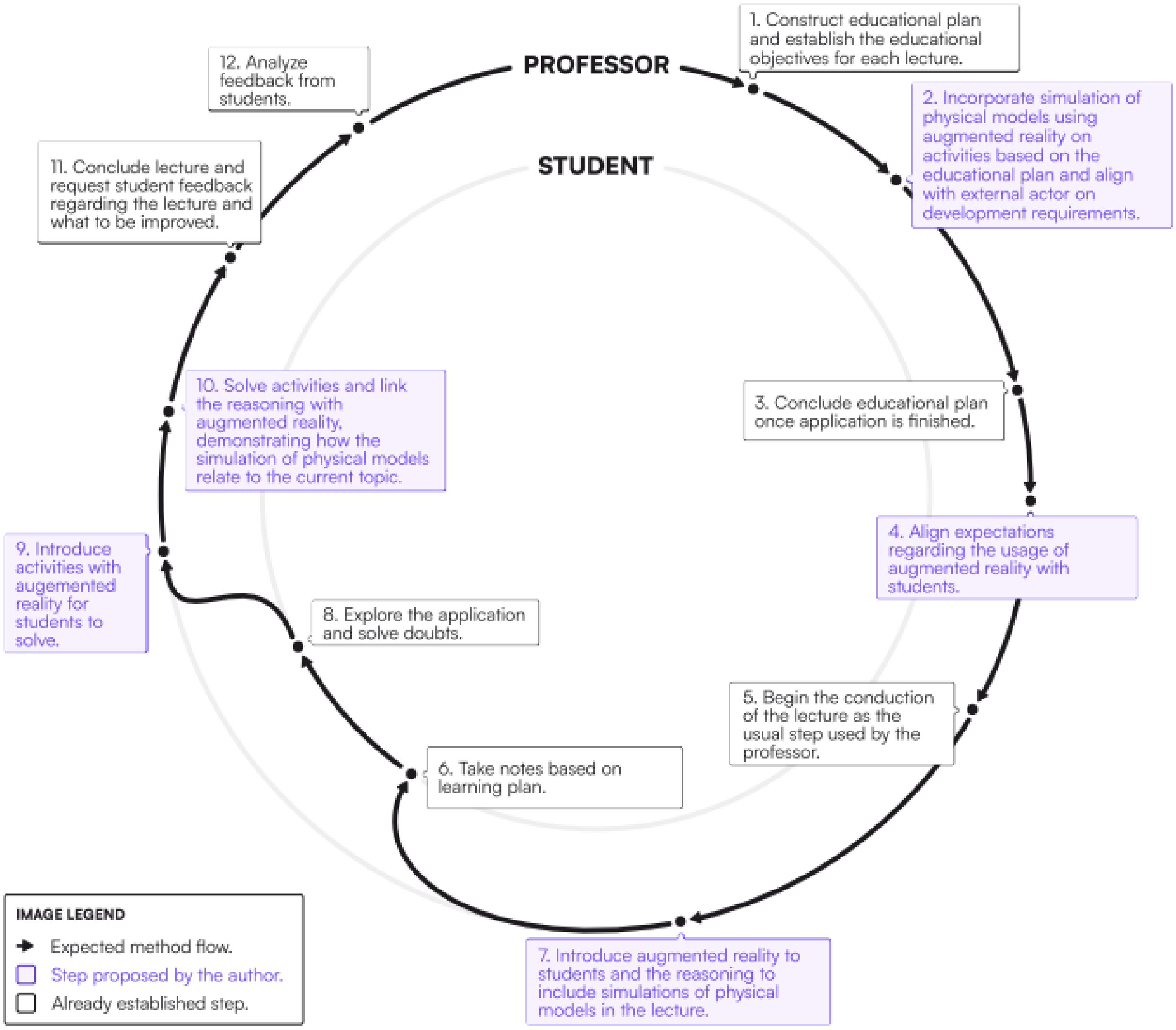
Upon calculation of the SUS, it is possible to assign an adjective rating scale to SUS, incorporating an additional set of descriptive terms to further qualify or explain the participant's ratings (Bangor; Kortum; Miller, 2009).

4 Results and Analysis

4.1 Theoretical Results

Although the primary focus of this paper is on the course of electromagnetism for electrical engineering students, most of the proposed method can be generalized to any educational field that would benefit from the visualization of physical models. For example, chemistry courses could implement the proposed method, enabling the visualization of particles and their interactions. Similarly, other areas such as biomedicine, medicine, physics, and mathematics could implement the proposed method with little or no adjustments. Furthermore, the implementation of this method can be generalized to other educational levels beyond the undergraduate level (Figure 7).

Figure 7 – Proposed method to incorporate simulation of physical models using augmented reality in electrical engineeringclasses



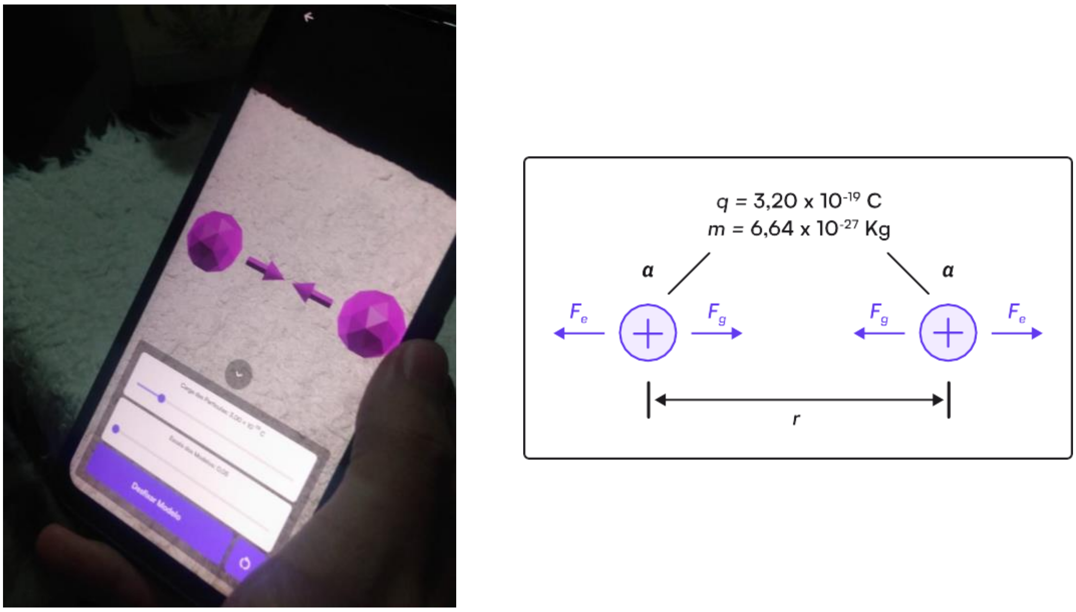
Source: Elaborated by the author.

The proposed method also provides professors with the flexibility to use it according to their specific needs or as new features are implemented into the application, allowing for a gradual incorporation of their usual educational approach. This can occur as additional interactions are integrated into the AR application or in responseto feedback from students about lectures where the method was employed.

When considering the use of the taxonomy proposed by Motejlek and Alpay (2021), the proposed methodcan be adapted for various applications beyond AR. For example, given a certain educational objective that a professor needs, they could establish technical requirements for implementing an application using Virtual Reality (VR) in conjunction with gamefication on a platform different from a cellphone. Since the planning and organizationof the educational plan does not enforce specific means to achieve an educational objective, as it uses Bloom's taxonomy (Anderson *et al.*, 2001), the method can be generalized to various applications.

Figure8 shows the interaction between the AR application and the first activity. This activity involves twopoint-like particles with specific charge and mass. The AR representation illustrates the interaction between these particles, offering students the ability to adjust the size and charge of the particles.

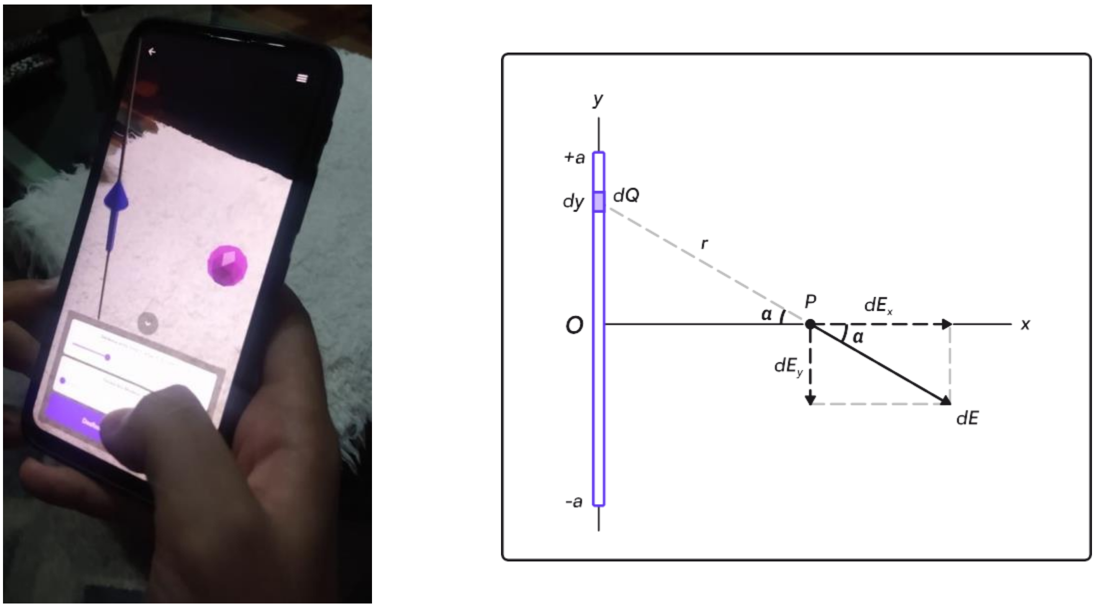
Figure 8 – Interaction between augmented reality application and first activity



Source: Elaborated by the author.

On a similar note, Figure 9 shows the interaction for the AR application and the second activity. In contrastto the first activity, animated 3D models are employed in this scenario. The objective of this activity is to determinethe electric field along the y-axis given a specified line. Students are able to shift the distance between the particleand the line in the AR application, as well as changing the scale of the models.

Figure 9 – Interaction between augmented reality application and second activity



Source: Elaborated by the author.

5 Experimental results

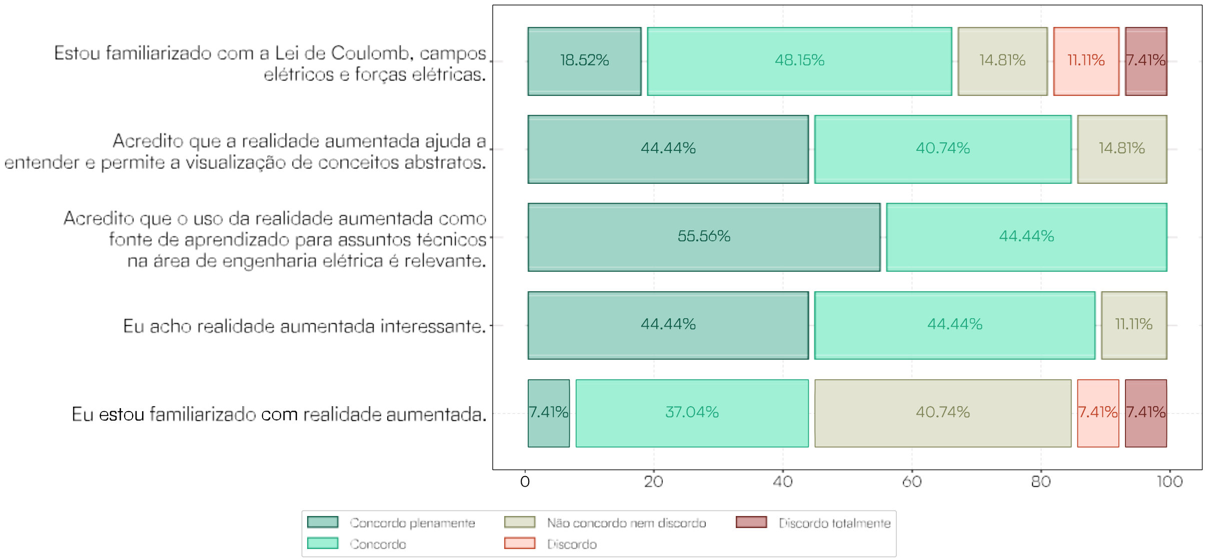
The experimental evaluation involved electrical engineering students from the fourth to the ninth semester.As the experiment took place in a regular classroom during the morning period, 27 students responded to the pre-exposition questionnaire in the first 30 minutes. Throughout the morning, additional students arrived, totaling39 participants who responded to the post-exposition and system usability questionnaires.

To account for variations in responses across the pre-exposition, post-exposition, and system usability questionnaires, the results are evaluated based on the overall responses of students who participated for at least twoand a half hours of a three hours experiment.

Before introducing the proposed method to electrical engineering students, a brief contextualization of the experiment was presented, outlining the covered topics and the methodology to be employed. Subsequently, the pre-exposition questionnaire was distributed to the students, who were allotted 15 minutes for completion. Following the completion of the pre-exposition questionnaire, a 15 minutes introduction to the topics of Coulomb'slaw, electric fields, and electric forces was provided based on the learning plan constructed using the proposed method. Students were given 1 hour and 30 minutes to solve two exercises related to the explained topics, using the AR application developed for the experiment.

At the end of the allotted time, the students responded to the post-exposition questionnaire and the SUS questionnaire. Finally, the students received a document containing explanations and solutions for the aforementioned exercises. Figure 10 shows the average distribution of responses for the pre-exposition questionnaire.

Figure 10 – Average unfiltered response for pre-exposition questionnaire



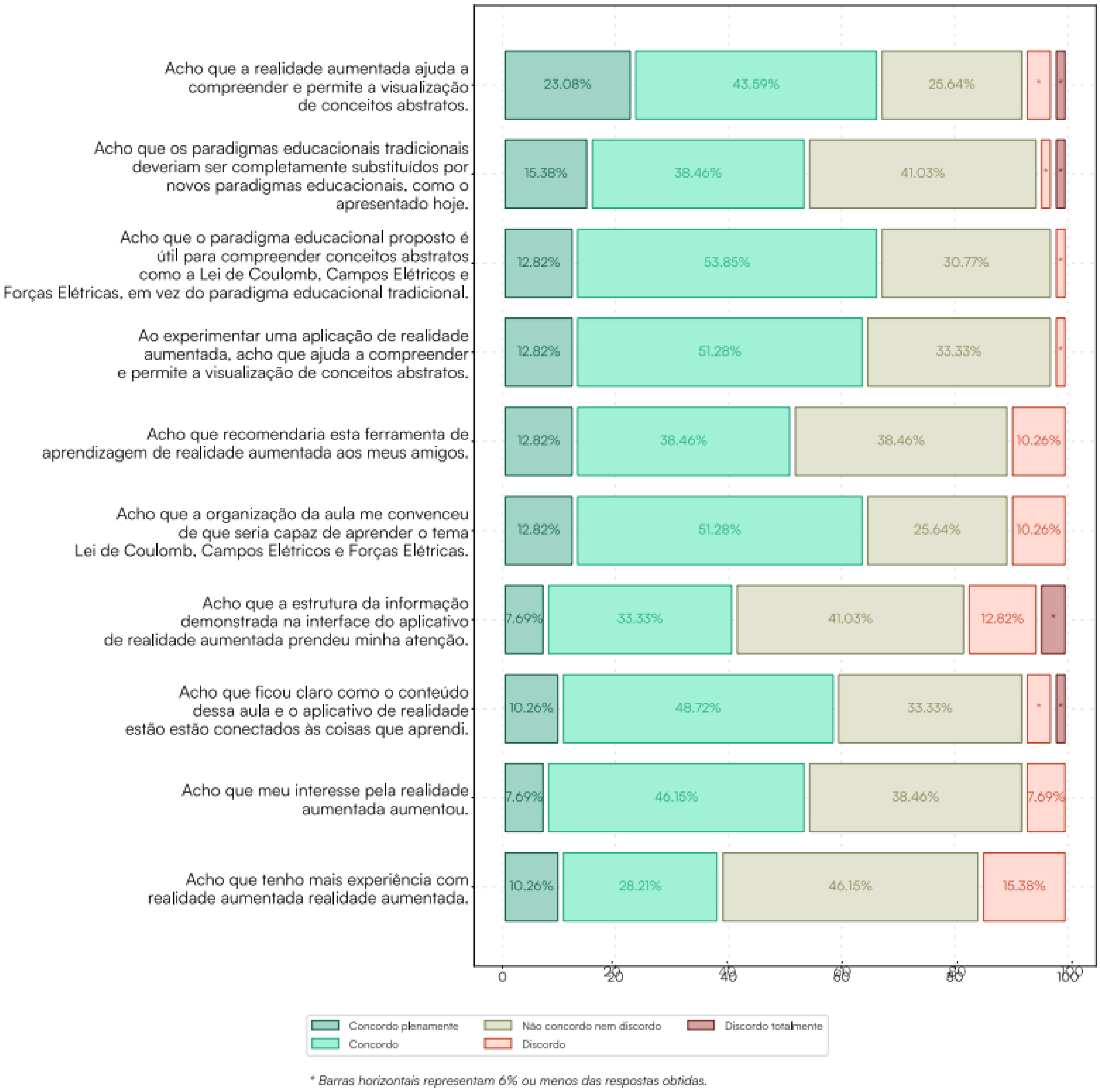
Source: Elaborated by the author.

Before the exposition, most of the students (85.18%) expressed the perception that AR helps to understand and visualize concepts that describe physical models. Furthermore, all respondents recognized the relevance of AR as a tool forlearning technical subjects, particularly those within the domain of electrical engineering. Finally, although somestudents are unfamiliar with AR, the prevailing perception is that it is an interesting technology.

Overall, students' responses to the post-exposition are predominantly positive, with a majority expressingincreased interest in AR, understanding the correlation between experiment content and information in the AR application, and perceiving the proposed application as beneficial for visualizing physical models.

A minority of students (38.47%) believe that they have gained increased experience with AR. This couldbe attributed to pre-existing perceptions of familiarity among students, leading to a sustained sense of familiarity post-exposition. Conversely, 15.38% of students reported a reduced experience with AR, possibly attributed to technical problems encountered during the experiment. Some students faced difficulties using AR on their cellphones due to a lack of the necessary sensors for the application to function properly. Figure 11 shows the average distribution of responses for the post-exposition questionnaire in more detail.

Figure 11 – Average Unfiltered Response for Post-exposition Questionnaire



Source: Elaborated by the author.

The SUS is expressed as a single numerical score that serves as a comprehensive measure of the usabilityof the evaluated system. As previously noted, individual scores for specific items lack substantial interpretative value in isolation (Brooke, 1995).

In the unfiltered dataset, the sus is 55%, indicating that the AR application is considered an "ok" systemfor use. For the filtered dataset, the SUS is 52%, indicating a similar outcome to the unfiltered dataset. However, as Bangor, Kortum, and Miller (2009) noted, this may imply different interpretations. For instance, it could suggest that the application's usage is, on average, neutral. Alternatively, it could indicate that the application is usable without needing further improvements.

It is important to note that both the numerical result and the adjective assigned to the application must beevaluated simultaneously (Bangor; Kortum; Miller, 2009). During the evaluation of the proposed method, some students faced problems using the AR application. These issues included being unable to access it due to theirmobile devices lacking adequate sensors, not having powerful enough hardware to render the 3D models or findingit difficult to understand the interface components of the application.

Many of these problems were resolved through interaction with colleagues in their groups, allowing students to complete the entire evaluation in class. However, these issues may have influenced the results of the SUS.

6 Discussion and conclusions

Traditional educational paradigms retain their importance within diverse educational environments. Thissignificance becomes particularly evident when factors such as the availability of resources and the necessity to engage with students who may be fatigued are taken into account. These aspects are often overlooked in research, which normally focuses on validating novel technological methodologies.

However, it is essential to acknowledge the merits of employing innovative technological methodologies, particularly in scenarios involving the description of abstract topics within electrical engineering classes. As elaborated on within this paper, the construction of a method grounded in established principles of traditional educational paradigms can facilitate the seamless integration of novel technologies, provided that meticulous planning and development are undertaken.

Although the practical implementation of the suggested approach in an actual classroom setting remains pending, during the interview-based validation mechanism, the professor expressed a keen interest in the potentialadvantages of adopting this method in a teaching environment. The professor’s raised concerns, specifically pertaining to the varying levels of technology acceptance among students from diverse social backgrounds, represent a pertinent area for further investigation. In particular, previous studies by scholars such as Álvarez-Marín, Velázquez- Iturbide, and Castillo-Vergara (2021a,b) have already laid the groundwork in the domain of technology acceptance, particularly with respect to AR applications, which could serve as valuable references for further exploration in thisspecific context.

Furthermore, incorporation of AR as part of the educational process of electrical engineering students, canlead to increased motivation, a point underscored by the professor and supported by the literature. This motivation is especially pronounced when students gain access to AR tools, enabling them to visualize complex subjects (Kapp*et al.*, 2022).

Despite the fact that the method presented in this paper is still in an evolving state, it is appears that thereexist potential advantages that can be harnessed and applied within the specific context of courses addressing abstract concepts within the field of electrical engineering.

References

ALTMEYER, K. et al. The use of augmented reality to foster conceptual knowledge acquisition in STEM laboratory courses – Theoretical background and empirical results. *British Journal of Educational Technology*,v. 51, n. 3, p. 611–628, 2020. DOI: https://doi.org/10.1111/bjet.12900. Disponível em: https://bera-journals.onlinelibrary.wiley.com/doi/epdf/10.1111/bjet.12900. Acesso em: 10 nov. 2023.

ALVAREZ-MARIN, A.; VELAZQUEZ-ITURBIDE, J. A. Augmented Reality and Engineering Education: ASystematic Review. *IEEE Transactions On Learning Technologies*, v. 14, n. 6, p. 817–831, 2021. DOI: https://doi.org/10.1109/tlt. 2022.3144356.

ÁLVAREZ-MARÍN, A.; VELÁZQUEZ-ITURBIDE, J. A.; CASTILLO-VERGARA, M. Technology Acceptance of an Interactive Augmented Reality App on Resistive Circuits for Engineering Students. *Electronics*, v. 10,n. 11, 2021a. DOI: 10.3390/electronics10111286. Disponível em: https://www.mdpi.com/2079-9292/10/11/1286. Acesso em: 7 fev. 2023.

ÁLVAREZ-MARÍN, A.; VELÁZQUEZ-ITURBIDE, J. A.; CASTILLO-VERGARA, M. The acceptance of augmented reality in engineering education: the role of technology optimism and technology innovativeness. *Interactive Learning Environments*, p. 1–13, 2021b. DOI: https://doi.org/10.1080/10494820.2021. 1928710. Disponível em: https://www.tandfonline.com/doi/pdf/10.1080/10494820.2021.1928710?casa_token=VGW_NpQnmIQAAAAA:Jnle2u9v3DbupoHn6pTaYNbuL7Ns4xXuTmQeym8AJgmUAgYzgnL2Qr51pcGWiS52MApiKpGKUSHrzras0g. Acesso em: 4 abr. 2023

ANDERSON, L.W. et al. *A Taxonomy for Learning, Teaching and Assessing*: A Revision of Bloom's Taxonomy of Educational Objectives. [S.l.]: New York: Longman, 2001.

AVILES-CRUZ, C.; VILLEGAS-CORTEZ, J. A smartphone-based augmented reality system for university students for learning digital electronics. *Computer Applications In Engineering Education*, v. 27, n. 3, p. 615–630, 2019. DOI: https://doi.org/10.1002/cae.22102.

BANGOR, A.; KORTUM, P.; MILLER, J. *Determining What Individual SUS Scores Mean:* Adding an Adjective Rating Scale. J. Usability Studies, Usability Professionals' Association, Bloomingdale, IL, v. 4, n. 3, p. 114–123, May 2009.

BAZZO, W. A.; PEREIRA, L. T. V. *Introdução à Engenharia:* conceitos, ferramentas e comportamentos. Ed. daUFSC, 2006. [S.l.]: Editora da UFSC, 2006.

BLOOM, B. S. et al. *Taxonomy of Educational Objectives*: The Classification of Educational Goals. [S.l.]: New York: David McKay Company, 1956.

BRASIL. *Resolução nº 2, de 24 de abril de 2019*. Institui as Diretrizes Curriculares Nacionais do Curso de Graduação em Engenharia. Brasília, DF: Ministério da Educação- Conselho Nacional de Educação. Disponível em: https://normativasconselhos.mec.gov.br/normativa/view/CNE_RES_CNECESN22019.pdf. Acesso em: 20 out. 2024.

BROOKE, J. SUS: A quick and dirty usability scale. *Usability Eval. Ind.*, v. 189, Nov. 1995.
CHU, Y. B. A mobile augmented reality system to conduct electrical machines laboratory for undergraduate engineering students during the COVID pandemic. *Education and Information Technologies*, 2022. DOI: https://doi.org/10.1007/s10639-022-10987-9.

ESTRADA, J. et al. Deep-Learning-Incorporated Augmented Reality Application for Engineering Lab Training. *Applied Sciences*, v. 12, n. 10, 2022. DOI: https://doi.org/10.3390/app12105159.

FARIDI, H. et al. A framework utilizing augmented reality to improve critical thinking ability and learninggain of the students in Physics. *Computer Applications in Engineering Education*, v. 29, n. 1, p. 258–273, 2021.DOI: https://doi.org/10.1002/cae.22342.

KAPP, S. et al. Smart Sensors for Augmented Electrical Experiments. *Sensors*, v. 22, n. 1, 2022. DOI: https://doi.org/10.3390/s22010256. Cit. on pp. 4, 13.

KAUR, D. P.; MANTRI, A.; HORAN, B. Design implications for adaptive augmented reality based interactive learning environment for improved concept comprehension in engineering paradigms. *Interactive LearningEnvironments*, v. 30, n. 4, p. 589–607, 2022. DOI: https://doi.org/10.1080/10494820.2019.1674885.

KUMAR, A.; MANTRI, A.; DUTTA, R. Development of an augmented reality-based scaffold to improve thelearning experience of engineering students in embedded system course. *Computer Applications in Engineering Education*, v. 29, n. 1, p. 244–257, 2021. DOI: https://doi.org/10.1002/cae.22245.

MARTÍN-GUTIÉRREZ, J. et al. Augmented reality to promote collaborative and autonomous learning in higher education. *Computers in Human Behavior*, v. 51, p. 752–761, 2015. DOI: https://doi.org/10.1016/j.chb.2014.11.093.

MASSA, A. et al. Teaching Electromagnetics to Next-Generation Engineers—The ELEDIA Recipe: The ELEDIA teaching style. *IEEE Antennas and Propagation Magazine*, v. 62, n. 2, p. 50–61, 2020. DOI: https://doi.org/10.1109/ MAP.2020.2970307.

MILGRAM, P.; KISHINO, F. A Taxonomy of Mixed Reality Visual Displays. *IEICE Transaction on Information and Systems*, vol. E77-D, no. 12, p. 1321–1329, 1994.

MOTEJLEK, J.; ALPAY, E. Taxonomy of Virtual and Augmented Reality Applications in Education. *IEEE Transactions on Learning Technologies*, v. 14, n. 3, p. 415–429, 2021. DOI: https://doi.org/10.1109/tlt.2021.3092964.

NOGUEIRA, J. Robert; ALVES, Ricardo; MARQUES, P. Carmona. Computational Programming as a Tool inthe Teaching of Electromagnetism in Engineering Courses: Improving the Notion of Field. *Education Sciences*,v. 9, 2019. DOI: https://doi.org/10.3390/educsci9010064. Disponível em: https://www.mdpi.com/2227-7102/9/1/64. Acesso em: 10 nov. 2023.

RAHMAN, H. Pedagogical Approach to Teaching a First Course in Engineering Electromagnetics. Interna-tional *Journal for Innovation Education and Research*, v. 2, p. 25–29, Mar. 2014. DOI: https://doi.org/10.31686/ijier.vol2.iss3.153.

ROSENBAUM, F.J. et al. Teaching electromagnetics around the world: a survey. *IEEE Transactions on Education*, v. 33, n. 1, p. 22–34, 1990. DOI: https://doi.org/10.1109/13.53624.

SANDOVAL, S. P. et al. On the Use of Augmented Reality to Reinforce the Learning of Power Electronics for Beginners. *Electronics*, v. 11, n. 3, 2022. DOI: https://doi.org/510.3390/electronics11030302. Disponível em: https://www.mdpi.com/2079-9292/11/3/302. Acesso em: 10 jun. 2023.

TIRADO-MORUETA, R. et al. Exploratory study of the acceptance of two individual practical classes with remote labs. *European Journal of Engineering Education*, v. 43, n. 2, p. 278–295, 2018. DOI: https://doi.org/10.1080/03043797. 2017.1363719.

VERGARA, D.; RUBIO, M. P.; LORENZO, M. On the Design of Virtual Reality Learning Environments in Engineering. *Multimodal Technologies and Interaction*, v. 1, n. 2, 2017. DOI: https://doi.org/10.3390/mti1020011.

YENER, Y.; HALIL, Y. Augmented reality application in engineering education: N-Type

MOSFET. *The International Journal of Electrical Engineering & Education*, p. 1–13, 2020. DOI: https://doi.org/10.1177/0020720920954150.