The Application of Augmented Reality Technologies in Physics Education

Hunter Chen, Ben Parrott, Zachary Saunders

***Abstract*—The application of mixed reality technology, notably augmented reality, in the realm of physics education may allow for an enhanced learning experience for students. The research circulating in this field is based heavily in presenting detailed implementations of augmented reality with respect to enhancing the way physics-based material is taught. This report presents and provides an analysis of six impactful papers in the field of augmented reality implementations for physics education. The applications detailed in these papers are comprehensive and each implementation provides the possibility to enhance the experience of students in physics education; unfortunately, there is a succinct lack of proof regarding the efficacy of these implementations in comparison to other virtual teaching methods as well as traditional teaching methods. It is essential that further research is done to distinguish the efficacy of augmented reality implementation opposed to more affordable and easy-to-access methods.**

I. Introduction

Our topic is to do with the learning of physics through Augmented Reality, which can be technological implementations at any level from primary school to university. Our analysis will focus on research that covers the use of Augmented Reality in a broad set of physics learning topics. Physics is a fundamental pillar of the sciences and advancements in AR models to teach it more effectively is a respectable goal for research in computer science.

Regarding where our topic sits within the discipline, there are a few layers of crossover to consider. Augmented Reality is the driving element of our topic and is classified as a subtopic of the broader field of computer graphics. Even Augmented Reality is more of an encompassing topic than the more specific and technical components of computer graphics such as ray tracing, vector graphics, 3D modelling, and image processing. Our focus on Augmented Reality is concentrated on applications related to education in the field of physics. The research on our topic is most closely associated with the implementation of VR in different areas of education and, more broadly, the use of digital visual representations to assist in learning at all levels.

There are many subjects taught in school that deal with very complex topics and abstractions that are hard for students to visualise and understand. Physics is a subject that contains many complex topics like electricity, magnetism, forces, and thermodynamics are complex for learners to visualise. Using Augmented Reality technologies can assist with or even become the standard in physics education [1]. Building intuition and a better understanding of abstract physics concepts for learners early on will provide a lifelong advantage in understanding these concepts and inspire more to become interested in the field. Providing students with more choices in learning methods can also broaden their horizons and introduce them to more advanced concepts at a young age, thanks to the use of Augmented Reality.

Physics stands out as a topic that is difficult to grasp because of unquantifiable metrics and abstract moving parts; although this is not a unique problem, similar obstacles are faced by students in molecular chemistry and molecular biology. For example, students in the process of learning rudimentary thermodynamics will have a difficult time visualising the interactions of subatomic particles to generate heat without the assistance of visual aids. Something like this would heavily benefit from the virtual detail provided by advanced augmented reality implementations as mixed reality technology is said to be a more effective tool compared to conventional physics teaching methods [*1*].

II. Look Inside: Understanding Thermal Flux Through Augmented Reality (ZS)

A. Introduction and Previous Work

The paper *Look Inside: Understanding Thermal Flux through Augmented Reality* [2] is motivated by the goal of addressing the complexity involved in conveying complex topics in the realm of physics education. The researchers make it clear that the main problem in teaching physics is the fact that many aspects of the subject are abstract and very difficult to conceptualise without advanced assistance. Many key concepts in physics involve parts that are unquantifiable or difficult to simulate in a standard teaching environment. Something that they claim can be fixed by utilizing the frontier of mixed reality technologies, notably augmented reality solutions [2].

The research into this specific implementation of augmented reality is relatively sparse considering physics is only part of a larger educational sector with all aspects requiring advanced research. Concerning other work done in this area, in 2017 a tablet-based mixed reality game was developed with the goal of enhancing students' perception and understanding of electrical circuits and the flow of subatomic particles like electrons [3]. This paper essentially provides a framework for implementing an augmented reality experiment that may improve students' understanding as well as their engagement. The details of the implementation including the prototype used for the experiment are specific to thermal flux and thermodynamics, so the application of this research is limited. Although the goal of the paper isn't necessarily to prove the efficacy of such a model, the researchers in this instance are more concerned with developing a mixed reality experiment architecture that is seemingly effective given what we know about the inclusion of technology in education [4]. Structurally the paper is split into two key sections, a detailed description of the technical details regarding the model and an analysis of the improvements the model provides over a more rudimentary thermal flux experiment.

B. *Method of Study & Description of Research*

Research carried out in this paper was focused on creating a client-server model that utilizes the advantages of augmented reality to enhance the quality of learning for students. The model created by the researchers made use of the popular commercial Mixed Reality device, Microsoft's HoloLens to facilitate the student's enhanced view of the experiment. The inclusion of the HoloLens in the implementation architecture meant that multiple client-server connections could be established and handled simultaneosly making the experiment suitable for a classroom environment. The rudimentary component of the experiment involved simply heating and cooling a set of metallic rods; the more complex architecture comes from the computer systems that facilitate the monitoring of the state of the metal rod as well handling the live feedback to the client device.

The basis of the experiment model involves having several metallic rods built from various conductive materials (copper, brass, aluminum) propped up on a clamp. Both ends of the support mechanism have equipment in place to simulate the effects of thermal flux. On one side, a cartridge heater is used to raise the temperature of the rods while the other end sports a small CPU fan essential for reducing the temperature of the rods. The intensity of the heat contributed by the cartridge heater is managed by a 12v power adapter connected to one side of the metal beams. The feedback essential to the experiment and the client-server architecture comes from a thermal camera placed centrally to the rods and support setup. This camera ensures that changes in temperature can be captured in real-time over the duration of the experiment.

Image data processing and client-server interaction is handled via an external computer connected to the thermal camera with usb. The ease-of-use of the HoloLens client means that processed temperature data can be stored and transferred from the server to the client via a simple wireless connection on request. There are two key components to the augmented visual data shown to the students in the HoloLens, the temperature of the rod itself is represented in augmented reality using a shifting color gradient that overlays the metal pipes; alongside this a 3D rendered graph is displayed above the experiment and shows the user real-time quantified data from the temperature readings.

The creation of the virtual components of the experiment were seamless and somewhat trivial thanks to the inclusion of the HoloLens (as it has many easy-to-use built-in client capabilities). Graphics renders on the experiment were created using the Vuforia software development kit, a popular tool for creating augmented reality applications [2]. The virtual environment for the experiment was handled using an ID number for the metallic rod and markers on the experiment boundary to mark the edge of the augmented space.

Some minor configurations need to be done to ensure the experiment functions as intended but these operations are trivial enough to be done easily by a teacher or knowledgeable student.

C. *Conclusions of Study & Analysis*

The researchers seemingly achieved their goal of creating an augmented reality model for enhancing the learning experience of the thermal flux experiment, but the true gravity of their research has yet to be directly proven or quantified. The efficacy of their model when it comes to teaching implementations is not proven in this paper but rather, the researchers argue that the vast increase in technical and virtual components makes this model superior to any rudimentary thermal flux experiment. With a relatively straightforward experiment, the advantages provided by their model are evident and further supported by claims made in the paper *When learning about the real world is better done virtually* [4]. The main advantages of their augmented reality based implementation come from the extensive increase in available sensory data given to the user including: real-time temperature feedback, interactive parameters, live data analysis, the possibility for multiple clients and virtual client collaboration. As is said in the paper's analysis of the model, "the proposed system enables students to perceive physical phenomena in a novel and more relatable way." The only evident downside to their model is the increased cost and configuration difficulty, two factors that could feasibly be reduced given further development. The biggest inhibiting factor is the inclusion of the Microsoft HoloLens as the client, considering the HoloLens is a very state-of-the-art device with a steep price tag. With all factors considered, the mixed reality thermal flux experiment presented in this paper does offer a unique and enhanced educational experience when compared with its traditional counterpart.

This paper provided some quality insight into the possible uses of augmented reality technologies in the field of physics education. The experiment architecture constructed and analyzed by the researchers provided a significant number of improvements when compared to its traditional counterpart. The virtual environment facilitated by the augmented reality model seemingly makes for a more relative and feedback driven experience for the user [2]. The paper achieves its original goal of contributing a well thought out augmented reality model for teaching thermal flux but is missing some key elements to definitively prove the superiority of their model over traditional methods. Some inclusion of student feedback and relevant user data during testing of the model would have solidified the effectiveness of their architecture. This is something touched on in the discussion section of the paper [2] and will hopefully be fleshed out in further research.

III. An Augmented Reality Platform Targeted to Promote Learning about Planetary Systems (ZS)

A. *Introduction and Previous Work*

Expanding the accessibility and capability of augmented reality implementations is an important component of the computer graphics research field. *An augmented reality platform targeted to promote learning about Planetary*

Systems is a paper that looks to contribute to this component by developing and testing a comprehensive mobile augmented reality implementation for a formal teaching environment [5]. The model presented in the research is centered around basic astronomy, a unique sub-discipline of physics and a perfect learning topic to excite the intrigue of young students. Unlike other implementations looked at in this topic review, the unique architecture covered in this paper is specific to mobile devices [5]. Given that in 2022 mobile devices are so very common, especially in western nations, it is easy to see how research into this are of augmented reality provides insight into one of the more feasible applications of augmented reality in a formal teaching environment.

Research in the computer graphics field relevant to this type of formal implementation of augmented reality is fairly sparse, especially for education applications that rely on geospatial data to function [5]. The implementation detailed in this paper, 'PlanetarySystemGO', is an evolution of a previous iteration of a similar idea titled 'SolarSystemGO' [6]. A majority of the model's design was handled entirely by computer engineering students in their final year of study under supervision by higher education professionals from the Polytech of Portugal.

B. Method of Study & Description of Research

Contrary to other models, like the HoloLens based client-server architecture detailed in the prior paper review, the PlanetarySystemGO architecture relies on a somewhat extensive web of back-end services in order to make the function of the mobile app simple and easy to use. Each component of the apps architecture serves a direct purpose in abstracting the complicated processes and systems for teachers and students.

The application itself is a good example of gamified learning techniques employed using a geospatial rendering similar to methods used in popular commercial mobile implementations like 'Pokemon GO' (a possible inspiration for the name of the app). Using the devices built-in camera, accelerometer, gyroscope, and GPS systems in conjunction with the provided surrounding natural or artificial environment a virtual landscape is created that can be traversed by the user of the mobile device. This provides a gamified aspect to the model because students are required to search for planets based on their relative location to other celestial bodies on a simulated virtual plane. Live feedback assists the users over the duration of the lesson, changing the color. On location of the virtual objects, users are prompted with a layout of information and possible multimedia regarding the specific virtual object that was located. This provided insight creates a link between the relative virtual object and the newly discovered information creating an effective learning tool for classrooms. An important factor regarding the efficacy of this architecture is its adaptability and ability to facilitate many different types of updated content. These functions are all enabled by the multi-layered backend processes and supporting repositories [5].

Central to the web of backend functionality is the back-office, which controls presentation and processing of data collected over the duration of the application's runtime. This aspect of their model gives direct access of important collected data to the teachers and administrators with access to the application back-office. An example use of the back-office is the teacher using user collected data to assess the student's engagement in the lesson as well as their performance relative to other students. In conjunction with the content repositories and web services, the back-office enables the adaptability of the PlanetarySystemGO architecture allowing for administrators to access, share, modify, and create new pedagogical content for use in formal teaching environments.

The architecture detailed in the paper handles management of application resources and multimedia using multiple repositories each with different intended accessibility parameters. These content repositories are split into three different types, a public repository with unrestricted access, the school/district repository for organized access, and a private repository for teacher and administrators. These multi-layered repositories enable more extensive content collaboration and development making for a more adaptable architecture [5]. Teachers can use this system to adapt publicly available content into their classroom and work with other teachers and schools to further improve the learning experience.

C. Conclusions of Study & Analysis

The objective of this research paper was to present a unique and adaptive mobile augmented reality implementation to teach basic astronomy in an engaging and effective manner. The implementation described in the paper is comprehensive and meets the necessary requirements to be considered a useful model. It has the benefit of accessibility given the reliance on mobile devices and is made easy-to-use through the extensive web of backend capabilities that abstract many of the complex processes for the users and administrators. A key feature of the PlanetarySystemGO's architecture is its newfound adaptability, a stark improvement on the previous iteration of this application. The back-office system alongside the multiple repositories allows for expedient development and collaboration of application parameters and content. It means the system can be tailored to varying levels of complexity and different physics-based concepts; given this fact, the application holds the capability to teach students about celestial bodies from our solar system in the milky way as well as any other observable planets and stars in distant galaxies

Technical literature regarding such mobile augmented reality models is currently very scarce in the field of computer graphics in an educational context, usually AR teaching models use marker based virtual environments as opposed to geospatial ones. This fact highlights this paper as an important contribution to field of literature regarding augmented reality in physics education. Research in this paper is accompanied by an analysis of student engagement and results extracted from the model's back-office following a trial run of the AR system. Feedback on the implementation was generally very positive with no students having a dislike towards the ‘game’ and a majority of the students showing a heavy level of engagement with some minor technical difficulties regarding hardware limitations that are expected with varying device quality. The testing could have been more comprehensive with multiple groups of students involved rather than just a single group. Also, the efficacy of this mixed reality model of teaching could have been solidified with a direct analysis of user data compared to a standard teaching model. Improvements to the implementation could also be made regarding the algorithm that controls data analysis and processing in the back-office; such improvements could have a direct impact on the application’s performance [5]. The quality and ease-of-use of the application interface requires some improvement as well.

IV. Impact of Visuospatial Abilities on Percieved Enjoyment of Students toward an AR-Simulation System in a Physics Course (BP)

A. Introduction and Previous Work

Impact of Visuospatial Abilities on Perceived Enjoyment of Students toward an AR-Simulation System in a Physics Course from María-Blanca Ibáñez, Ángela Di Serio, Diego Villarán and Carlos Delgado-Kloos discusses the impact of an AR-based learning environment designed to help students solve electromagnetism problems [7], especially those with low spatial abilities. The authors identified that visualising complex physics ideas for learners with low spatial abilities, especially electromagnetism, can be challenging. However, with the introduction of AR to help create such models, much can be done to help.

Work has been done in a similar area [8], [9], where they attempted to teach electromagnetism concepts through both virtual and augmented reality. While these papers cover similar topics, no work has been done in specific to see if students with different levels of visuospatial abilities could benefit from using augmented reality to help improve their learning experience.

B. Method of Study & Description of Research

The authors created a physics evaluation task for undergraduate students presently taking the subject. This test was designed to help students see the three-dimensional trajectory that a charged particle takes when it enters a magnetic field at a speed that is not parallel to the field direction. The students were then evaluated on their learning experience and how their spatial abilities affected them.

Students could use the tools to build vectors representing the magnetic field's direction and the particle's velocity within the 3D space. They could also position the charged particle that would enter the magnetic field. The students were then given a task split into two parts, one for the general information they would later use and the other for the questions to be answered. Through the application, they were then able to answer the questions.

The experiment aimed to "evaluate the influence of learners' visuospatial abilities on their perceived enjoyment, attitude and intention to use an AR-based learning environment". So, the authors formed three groups from the 68 students who opted to help aid the study based on the student's visuospatial abilities. The information gathered from each of the groups would later be used to compare each of the groups to see whether or not the students' enjoyment differs when using the AR application.

Students were taught the basic principles of electromagnetism and how to determine the position of points in a 3D space through an AR tutorial application. So they could answer the questions to the best of their ability. They received 25 minutes to solve the required questions during the test using the AR-based application. The results showed that the mean score for the perceived enjoyment in the low visuospatial ability group was significantly higher than in the medium level. These results were calculated using the Post hoc analyses using the “Least Significant Difference (LSD) post hoc criterion for significance”. We can see this through the results where the low visuospatial ability group (M=4.26, SD=0.58) was far higher than the medium visuospatial ability group (M=3.79, SD=0.77). However, there is very little difference when the results of the low visuospatial ability group are compared to the high visuospatial ability group (M=4.2, SD=0.6).

C. Conclusions of Study & Analysis

Through the research presented in the paper, the authors investigated using AR to help students learn electromagnetism and the impact their spatial ability has on their attitude towards it. The study’s results suggested that learners who were classified with low spatial abilities enjoyed using the AR application more than those who were classified with medium spatial abilities. This statistic is interesting because there is a minimal change compared to the high spatial group. It was not precisely what the researchers had hypothesised to happen; it was still encouraging. They showed that AR learning tools might be beneficial, particularly for students who usually struggle with visualising complex physics concepts.

However, the researcher is inconclusive as there is no statistically significant difference between the student’s enjoyment with high spatial abilities and the student’s enjoyment with medium and low spatial abilities. Meaning that there will need to be more work done on whether or not AR learning environments benefit students with low spatial abilities is inclusive. This work may include expanding the research group or trialling a different AR program to see if they get the same or similar results.

A significant benefit to this study is how they could take such a large sample of students and be able to research all of them. As they wanted to have three different groups, one for low spatial abilities, one for medium spatial abilities and one for high spatial abilities, having a sample size of 68 students allowed them to do so. With this amount of students, they could form three different groups and get a good array of data from each.

However, the research paper lacked when it came to describing the application itself. The authors described what the application aimed to do but did not talk about the hardware itself. Leaving this out seems to be a disadvantage to the paper as they do not describe in detail how the program works nor briefly touch on the fact that it was downloaded on the student's devices. Suppose they had provided only a small amount of insight into how the application works. In that case, it may help visualise the idea and perhaps help understand how this may help people with low spatial abilities.

V. PhyAR: Determining the Utility of Augmented Reality for Physics Education in the Classroom (HC)

A. Introduction and Previous Work

The paper *PhyAR: Determining the Utility of Augmented Reality for Physics Education in the Classroom* seeks to explore potential use cases of augmented reality technology in secondary, and post-secondary physics courses, supported by a qualitative analysis of their prototype augmented reality (AR) application, PhyAR. With the recent advent of more affordable, and more powerful augmented reality solutions such as the Microsoft HoloLens, the study argues that it can facilitate distribution of AR solutions in areas where it otherwise could not easily have done [10]. The use of online web-based applications like PhET has been identified to be used widely in classrooms for physics education, and the motivation to develop an AR solution which draws inspiration from PhET was then explained. Previous works in developing AR solutions for physics education were also identified, such as MagicBook, where the developers of PhyAR take the inspiration of anchoring virtual objects to real objects in the real world.

Furthermore, the authors aim to discuss implications of their PhyAR application, as well as, more broadly, the adoption of AR technology in physics classrooms through a qualitative analysis based on a laboratory study with university students in STEM backgrounds. With the promising study results by Dünser et al. as mentioned by the authors of the paper, which showed that AR was potentially beneficial for teaching electro-magnetism concepts [11], the authors have expanded upon the concept, and developed an AR solution for broader physics education applications.

B. Method of Study & Description of Research

PhyAR was developed using Unity3D and the Mixed Reality Toolkit for use with the Microsoft HoloLens. It was able to illustrate many physics concepts in AR, which included Coulomb's Law, Elastic Collision, Parallel Circuits, Volume, Magnetic Field, and the Doppler Effect. Each of these concepts had extensive integration with AR technologies, and showed each concept clearly through diagrams displayed in AR, for educational use in classrooms. They then presented each of these concepts to a group of 15 university students with ages ranging from 21 to 31, with varying degrees of VR and/or AR experience, and recorded their responses through a questionnaire that was conducted post-study. The students were free to explore each concept until they were satisfied that they had experienced all features within each scene. The questionnaire consisted of 5-point Likert scale questions, as well as free response questions regarding possible use cases and preferences. Together this allowed the study to collect extensive information and feedback from these 15 university students.

C. Conclusions of Study & Analysis

In conclusion from the qualitative study between the 15 students, participants were reported to have found the system to be easy to understand, motivating and interesting. The author identifies that these positive reactions were likely due to the exposure of a new application to the participants. Furthermore, the study shows that the participants agreed that they could learn more from PhyAR than traditional teaching methods and wanted to keep using the application after the study. In short, the results from the 5-point Likert scale questions were very positive.

On a less positive note, a majority of the participants have reported discomfort, as well difficulty controlling the hardware. The authors recognized this as a hardware limitation of the Microsoft HoloLens, and expects these problems to dissipate as future iterations of similar AR hardware is released.

This study only involved the participation of 15 students aged between 21 and 31, and severely lacks participation from other demographics, especially the secondary student demographic that the application was supposedly designed for. The overwhelmingly positive reaction to the application shown in the study therefore does not necessarily reflect that of the target audience, as the 15 students all already had a background in STEM, meaning there is a high chance that they are already familiar with the physics concepts shown to them in the application. One of the key factors to consider when developing new teaching mediums is taking learners of all backgrounds into consideration, and this study does not adequately gather feedback from those who perhaps have a more shallow background in physics, or from younger audiences who are still exploring their interests in STEM. It is hard for students who are already familiar with a concept to grasp how difficult it is to learn said concept, therefore it is difficult to draw any useful conclusion from their response saying that the system is easy to understand.

Although it is difficult to tell whether this study shows adequate evidence of whether PhyAR is suitable for classrooms (especially secondary classrooms), the ideas presented through the developed application are promising. The results gathered from the group of 15 university students show promise that the concept can be applied in a classroom setting, and with further iterations and more thorough qualitative studies, it can potentially prove to be the next generation of physics education in classrooms. As the authors have pointed out, the version of PhyAR presented also did not take full advantage of AR technology by not including integration for physical objects into the AR experience. The already positive feedback from their participants shows great promise so far as a proof-of-concept application, and they identify that the next iterations will include improvements in such areas.

Further steps to take in order to assure a well-rounded, and useful conclusion from any further qualitative study would be to include more participants, especially those that are currently in secondary study, as well as those who do not have a background in STEM. In general, the idea of PhyAR that was presented in this paper is a very promising concept with much ground to cover in the physics education sphere. More work in development and feedback gathering is definitely due, although the positive feedback from STEM university students makes a strong case for its use in general physics education and has the potential to revolutionise the industry in the future.

VI. Determining Design Requirements for AR Physics Education Applications (BP)

A. Introduction and Previous Work

The paper, Determining Design Requirements for AR Physics Education Applications, by Corey Pittman and Joseph J. LaViola Jr., presented the idea of using AR applications to aid physics learning in high school classrooms. In the paper, the authors presented the results of several interviews with high school physics teachers about how AR may benefit them in their classrooms and their experiences around AR [12]. A prototype application was also developed using the Microsoft HoloLens and then presented to the teachers so they could experience it firsthand.

While researchers have previously tried using tablets and smartphones for AR-based education applications [13], the exact content that may specifically be delivered through an AR headset varies. PhET Interactive Simulations, developed by Perkins et al. [14], also provide an interactive way for topics such as physics, chemistry, maths, and others to be demonstrated in the classroom. PhET provides practical and hands-on examples for both handheld and desktop devices.

B. Method of Study & Description of Research

The authors started by presenting the methods by which they gathered data, their results, and a discussion. They started with a prototype application they called HoloPhysics, designed for the Microsoft HoloLens to illustrate a variety of physics topics. Some examples that HoloPhysics can present are as simple as a ball rolling down a ramp, while others could be as complex as presenting an illustration of Coulomb's Law. These examples are just a taster for the teachers of what AR could achieve.

The authors chose to conduct six individual semi-structured interviews with physics teachers with a range of experience from 1 to 31 years. Only two teachers interviewed had used AR in their classrooms before, but all six had used the PhET software. Fortunately, each teacher had used the PhET software before and was open to learning new ways of teaching. The interviews found five themes, Exploration, Variable Presentation, Novelty, Reinforcement, and Collaboration, forming four separate recommendations. The four recommendations were: *Augment the Visible*, *Visualise the Invisible*, *Present Both Concepts and Calculations* and *Enable Collaboration and Demonstration*.

The first recommendation, *Augment the Visible*, was that teachers wanted to be able to see more than just the ball and the ramp. Through a free-body diagram, they wanted to see the forces acting upon the ball down the ramp. Doing so would mean they could see why the object moved the way it did and how it would differ if the forces acting upon it were changed.

The following recommendation, *Visualise the Invisible*, formed due to the limitations that computer-based simulations and textbook illustrations can form. The authors believed that presenting complex ideas through AR, which would not typically be easily presentable, would help students immensely, especially during their first exposure to the ideas.

Present Both Concepts and Calculations; the third recommendation was about having software that can be run with and without much input from the user, which means that students can view what happens before investigating its reasoning. Another key feature that may help students at different levels of understanding or learning differences may be the ability to turn features within the application on and off.

The last recommendation, *Enable Collaboration and Demonstration* was to do how they wanted to integrate an option for experiences to be shared among students but still allow each student to go at their own pace. Doing so would mean that students could rerun the experiment at 0.5x speed and observe what happened with the given inputs and why that happened.

C. Conclusions of Study & Analysis

HoloPhysics was developed for the Microsoft HoloLens and presented to 6 physics teachers to gain their input and experiences to help further develop the application. The authors found five recurring themes, which helped them create four further recommendations to improve going forward. These recommendations will lead to further expansion of the application, allowing the software to be trialled with a larger group of students and teachers so they can get a better range of feedback.

Although HoloPhysics was a prototype application, interviewing students and teachers would mean that the data they collected from the interviews would be more diverse. They could compare a teacher's needs and requirements against a student's needs and requirements. By only focusing on six physics teachers but 0 physics students, it seems like a vital aspect of the paper was missed.

VII. Effects of learning physics using Augmented Reality on students' self-efficacy and conceptions of learning (HC)

A. Introduction and Previous Work

This paper, *Effects of learning physics using Augmented Reality on students' self-efficacy and conceptions of learning*, aims to study how AR-assisted learning effects the self-efficacy of students, by conducting a quasi-experimental study with a two group of teenage students using their own AR application [15]. They identify things that are already known about this topic in their Practitioner Notes, notably noting that AR-based learning environments can give learners to naturally interact with the material, and they hope to add to this existing knowledge by showing various capabilities of AR-based learning environments through a quasi-experimental study.

This paper also includes a literature review portion, where the authors dissect and analyse previously published papers on the topic. They recognized many prior works that extensively study the advantages of using AR-based applications in physics study, and through the literature review, identified two questions to focus on in their research. These questions were *"Do students' learning self-efficacy change during the learning process in an AR learning environment? If so, what changed?"*, and *"Do students' conceptions of learning change in their learning process in an AR learning environment? If so, what changed?"*. These questions were chosen in order to examine the impact of AR technology applied in physics education on students' self-efficacy and conceptions of learning, after the authors concluded that in the papers that they reviewed, few explored the mechanisms behind AR technologies.

B. Method of Study & Description of Research

The authors developed AROSE (Augmented Reality Optical Simulation Experiments), an AR application that demonstrates photoelectric effects. This application was developed for mobile devices like the iPad (as shown in the figures), using Vuforia SDK and Unity3D. Within AROSE, they included four different physics experiments, which showed various phenomena of the photoelectric effect. There was also a Flash equivalent consisting of three similar physics experiments for the control group. To conduct the research, a total of 98 students aged between 16 and 18 were chosen in total, and placed into two experimental groups, the experimental group and the control group with 49 students each. The experimental group was provided instructions in AR-assisted learning, where the control group was provided instructions in Flash-assisted learning. This learning environment lasted a total of four weeks, with each student engaging in their environment for 40 minutes per week. Both a pre-questionnaire and a post-questionnaire were given to the students to gather a variety of data that the students were able to input from a scale of one to five. All in all, this allowed the researchers to gather data on the effects of AR on students' self-efficacy and conceptions of learning by comparing data gathered between the two groups, as well as comparing the data gathered before and after the intervention.

C. Conclusions of Study & Analysis

The study concludes that using AR technology can significantly enhance students' self-efficacy in physics learning, especially in terms of conceptual understanding, higher-order cognitive skills, practical work and social communication. It mentions how the AR environment gave students a highly immersive learning environment where the students can place themselves in experiments, which boosted the students' conceptual understanding compared to those in the Flash group. They quoted much feedback received by students comparing the use of AR technology in physics learning to other traditional learning, and it is almost always to do with the fact that they are now able to visualise basic physics concepts. The paper also concluded that integrating AR technology into physics classrooms can promote the generation of high-level conceptions of learning as an answer to their second research question proposed. This is shown in the experimental data, where students in the AR group performed significantly better in high-level conceptions compared to the Flash group. Authors attributed this improvement in performance to the fact that AR is inherently more interactive than Flash, as Flash is all computer-generated virtual screens with no respect to the student's actual environment.

Interestingly, some students reported that they wished for implementation of AR technologies in other fields of study such as Chemistry, as it can help with the visualisation of concepts that are hard to understand through traditional methods.

The authors report that the above findings are in accordance with other previous work, with a few papers in 2014 and 2015 also having similar findings.

Limitations of the applications for this study were also identified, as some students reported hardship with recognizing inputs in the AR application. The authors recognized this as a shortfall of software and says that it can be improved upon in future software iterations. Overall, the authors think AROSE yielded many promising results and next steps and hopes to revolutionise classroom teaching to align better with the evolving world, as researchers work together to overcome challenges.

AROSE certainly yielded very convincing results in comparison to their Flash control group. The paper goes very in-depth about their AROSE implementations but does not mention much about their Flash alternative. It leaves a lot of room for detail on their implementation of the Flash-assisted application, since it would not be a fair comparison if the Flash application was not as well rounded out as the AROSE application. Flash is also a very outdated framework for developing applications on the desktop, and it raises the question of whether other frameworks, such as game engines, could have been used to produce a much more engaging and better alternative to Flash to give to the control group.

The paper used an ANCOVA analysis to analyse the results they yielded from the study, which is an appropriate way to come to a meaningful conclusion with not a large sample size (of 98 students). The findings have strong statistical backing and show a strong improvement in almost every aspect for students using AROSE when compared to the Flash group.

In the diagrams shown in the paper, it was shown that AROSE had been implemented for mobile devices. As there is a much wider range of AR hardware than personal mobile devices, it would've been interesting to see if an implementation of AROSE on a full-fledged head-worn AR device, like the Microsoft HoloLens would've improved the finding further when compared to the Flash group. HoloLens and other head-worn devices already have a lot of mature frameworks for developing AR applications to integrate with the hardware, and with the added layer of immersion in AR technology, it could further improve students' self-efficacy in learning.

As the study was only done with students aged between 16 to 18, it is difficult to draw conclusions for the effectiveness of AR-based learning on students' self-efficacy outside of this age range. Teenagers change rapidly, and this method of learning may only be effective for teenagers around this age range. The paper does not seem to address this concern, and while a sample size of 98 students in this age range can draw a convincing conclusion for AR-based learning in secondary education, it becomes difficult to say the same for primary education, or tertiary education. In further study, experiments could be performed with larger variety in student age, as well as academic background. This improvement combined with possibly implementing AROSE on more robust AR devices (such as the HoloLens) will surely draw a much more convincing answer for the effects of AR-based learning on students' self-efficacy.

VIII. Discussion

The six papers that we chose were mostly built upon the seemingly pre-established fact that augmented reality (AR) applications in physics education are more beneficial for young learners compared to traditional methods of learning and presented their own applications using existing AR frameworks and hardware. This fact is generally accepted, as each of these six papers make references to older papers that did studies to compare AR-based learning methods with other learning methods. With the exception of [15], which conducted an extensive study on how AR applications can affect the self-efficacy of students in the physics classroom, the rest of the papers mainly focused on feedback that their own software had received from students who used them.

Current hardware solutions for AR applications are also very limited, with all of the papers developing their own AR solutions for either the Microsoft HoloLens, or for mobile devices. Even though there are extensive software frameworks to integrate software with these hardwares, it is clear in the papers that there are severe limitations in these hardware for classroom applications. In [10], students reported that the hardware was difficult to control. Similarly, in [7], the study group was reported to have had to have been trained how to use the AR hardware in order to use it with no problems. It's difficult for both students and teachers to transition to different learning methods, and it's important to consider the ease in such a transition, especially to a method like AR. Although there were some hardware limitations concerning the mobile implementations described in the report, they generally provided a more accessible venue to access augmented reality [5]; these mobile models also have the advantage of being easier to operate and configure given their general architecture includes extensive back-end processes.

In [10], the authors mention that with future iteration of AR hardware (as successors of the Microsoft HoloLens), these hardware problems will eventually be eliminated. However, it is also important for the developers of software applications (such as PhyAR) to accommodate a wide variety of hardware, as it's important for schools to have a certain degree of freedom in choosing their adoption method. As it is right now, the most popular device that these papers have chosen to develop for is the Microsoft HoloLens. Being one of the only AR head-worn devices that is commercially available, it is no doubt that it will get the majority of market share upon wider adoption of AR-based applications in classrooms. However, with the price of the Microsoft HoloLens 2 being $3,500 USD, it is difficult for classrooms to justify such an investment in AR-based learning, especially when its benefits over traditional learning are not concrete.

This is a very important consideration in the adoption of AR devices in mainstream education, as the cost in investing in such hardware can be instead spent elsewhere, where there is concrete evidence in improving students' learning. Of course, as AR technology matures and as the commercial scene becomes more competitive, the introductory cost of the hardware will decrease. But it is still a significant investment, and more research of AR-based learning in comparison to traditional learning methods is definitely needed.

With the exception of [15], where it directly compares AR-assisted learning and Flash-assisted learning (and draws a conclusion that AR has positive effects in various aspects of self-efficacy in learning), none of the papers give concrete evidence that AR has significant advantages when compared to traditional learning methods, besides referencing older papers. Further research in proving the advantages of AR-based learning over traditional learning, especially using the software developed by each study will for sure be needed to convince the public to adopt AR learning methods in schools, especially with such a high adoption cost.

Furthermore, we must consider the fact that most of the respondents in the studies conducted by our papers, especially in [5], [12] and [10] are new to the idea of learning through AR applications. A majority of these respondents reported enjoyment, or otherwise positive reactions to AR-based learning methods, where the authors then concluded that AR-based learning was enjoyable and alluded to its applications. In reality, most students who are exposed to new ways of learning, whether it's AR, VR, or even a generic computer-based learning method, are more likely to report that they had enjoyed it over regular methods of learning, simply due to such methods being new and interesting. This issue is slightly touched on in [10], where they mention that the overwhelming positive response is likely due to the novelty of AR methods. In any case, this is a very recognizable issue with the way these papers conducted their studies, especially regarding their analysis of feedback from their respondents in respect to their applications.

Through these papers, an obvious future step to take as outlined earlier would be to put more study in comparing AR-based applications to traditional learning methods. It is also interesting to note that all of these papers developed their own applications, with their own implementations around existing AR frameworks. In the future, work could be done collaboratively between the authors of these papers, and a central engine for AR physics classrooms could be developed to ensure consistency, maintainability and ease of adaptation into different stages of education. As concepts in physics, especially with regards to universally recognized laws and constants will never change, having a centralised database of information to serve will ensure the same universal concepts are taught to students across the world. Lastly, with so much of the field of research focusing on the software, researchers can consider studying into developing appropriate hardware solely for the purpose of education. Without much of the unneeded features for education on devices such as the HoloLens, it will reduce the cost of production, as well as build upon features that are suitable in a classroom environment, such as ease-of-control, extended usage and more. This will clear the obstacle of adoption cost, as well as prominent hardware issues as pointed out by these papers. There is no doubt that AR applications have the potential to transform the physics classroom, and with more future work in areas pointed above, there is a strong chance that physics education can be revolutionised by AR.

IX. Conclusion

The augmented reality implementations detailed throughout this report all provided some unique insight and innovation regarding the methods we use to teach physics. One of the more promising aspects of this field of study identified in our report is the capabilities and potential of mobile augmented reality implementations, which have the potential to circumvent the downsides of more complex and expensive models, such as implementations that rely on marker-based clients like the Microsoft HoloLens for example. Regardless, each paper added a different perspective to the use of mixed reality technology in formal teaching environments; but a central flaw across the research was a lack of proof in terms of efficacy, especially considering the stark lack in comparisons between other physics teaching methods.

Generally, the research analysed in this report did not provide sufficient evidence that augmented reality should be used as the preferred method of teaching in physics; there is currently not a strong enough case to be made regarding whether augmented reality lies in the future of physics education. Given the rise of other technologies applicable to education like virtual reality, the internet, and CGI, as well as the remaining presence of traditional techniques, there is a high bar for evidence to prove superiority in the field of physics education; the analysis provided throughout this report does not meet this bar, but still is a step in the right direction. Of course, this does not mean augmented reality should be disregarded, the future of this field is promising, and provided more research is undertaken, it could become the preferred way to teach physics.

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