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Development of AR Experiment on Electric-Thermal Effect by Open Framework with Simulation-Based Asset and User-Defined Input

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Abstract: Augmented reality (AR), an advanced information and communication technology, has gained widespread concerns in teaching physics due to its possibility for reducing cost of equipment, enhancing comprehension of abstract concepts, and overcoming tendency of diminishing interests of students. Although the fruitful applications have been created frequently with the aid of AR framework using standard devices, for example, head-mounted display, there is less likely for the image detection-based framework to integrate the virtual assets with the real objects with ability of supporting inputs of the invisible elements and thus makes it difficult to maintain evolutions of the augmented information over the physical quantity such as current in the AR-based physical experiment. In this paper, an open AR framework with simulation-based assets triggered by user-defined inputs is proposed to allow physics teachers to create their own AR teaching materials. Considering the teaching of electric-thermal effects by exploring the thermoelectric cooler-based thermal management of power device, furthermore, the proposed framework is illustrated from the perspective of the three paramount tasks: (1) a simple and accurate generation of assets from the finite element simulation; (2) a low-cost and convenient measurement of physical quantities by the microcomputer unit with Bluetooth connectivity; and (3) a real-time and changeable controlment of simulation-based assets by the measured data using the thread-based Python script. Experimental results show that students are excited in the AR application interacted with the real operation of current, and moreover, physic teachers are easy to design and deploy the simulation-based framework with user-defined inputs to create their own AR learning materials for sparking growing interests of students.

Keywords: augmented reality, learning material, simulation-based asset, thermal management, user-defined input

1. Introduction

Augmented reality (AR), integrating the computer-generated virtual objects with the user-situated real scene in real time, is one of the potential information and communication technology (ICT) for education due to its possibility for promoting personalization, increasing understanding, and improving motivation (Cai et al., 2021). To tackle challenges intrinsic in physical education covering the expensive equipment, difficulty in comprehending abstract concepts, and tendency of diminishing interests of students (Long et al., 2021; Sahin & Yilmaz, 2020), currently, the adoption of AR technology in teaching physics such as Physics Playground (Hedenqvist et al., 2021) has been widely concerned by teachers, scientists, and policy makers, and the AR-based application casts a light on an easy, engaging, and fun alternative for physical education toward a sustainable development (Bogusevschi et al., 2020).

Numerous researches have been carried out to investigate the effectiveness of AR-based physical applications (Bogusevschi et al., 2020; Harun et al., 2020; Hedenqvist et al., 2021). For example, effects of AR application for teaching Fleming's rule in electro-magnetism for students are examined, and the result shows that students can see and manipulate superimposed information such as magnetic field lines, and moreover their educational achievements are increased (Harun et al., 2020). Benefited from these fruitful works, the framework for creating AR applications is becoming mature with the rapid progress of generating the virtual objects and recognizing the real world. Recently, the finite element simulation (FES)-based assets and the camera-based image detection are the well-known components in the framework, which reflects observations with a high degree of precision by utilizing the AR technology to physical experiments, such as teaching of structural mechanics (Huang et al., 2017). However, the development of AR-based physical application requires the specialized ICT skills with involvement of importing standard

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files into game engines such as Unity, maintaining augmented information, and SDK computer programming such as Vuforia (Hedenqvist et al., 2021). Obviously, teachers particularly in the K-12 level education (Aydoğdu & Kelpšiene, 2021; Sahin & Yilmaz, 2020) are less likely to create their own AR learning activities even if they can take account of background, needs, and desires of students.

Besides the professional training of employing the typical framework to make AR applications (Osadchyi et al., 2021), recently, there is a trend to create simple and easy AR authoring tools for diverse teachers. For instance, an UI-based tool VEDILS (Mota et al., 2018) is advised to obtain a low entry threshold for programming skills for all. Unfortunately, it is still a time-consuming and complex task for general teachers to translate abstract physical concepts into AR learning materials partly because of integrations of various tools for building and controlling 3D assets, such as simulation-based assets in Unity from the multiple physical code COMSOL (Long et al., 2021; Shrestha, 2021). More important is that the update of assets is triggered typically by the image-based detection of visible objects such as markers, and meanwhile, as far as the authors know, there is no report about the direct measurement of invisible physical quantity such as current in real experiments. Consequently, the available AR-based physical applications focus on only a limited number of concepts and samples and thus make it still under pending issue to address the accessibility and usability of AR learning experiences for meeting the growing interests of students.

Aiming at the goal of the fast and accurate creation of AR-based physical applications with low-cost implement by teachers, in this paper, a framework with 3D assets automatically imported from FES calculations and updated by user-defined inputs of physical quantity is proposed firstly; secondly, a thermoelectric cooler-based thermal management of power device experiment concerning electrical-thermal effects in physical education is adopted for demonstrating the scripts-based software and microcomputer-based hardware; finally, the simulation-based AR application in the thermal management with the input of operating current is explored by teachers and students to validate the proposed method for creating AR learning materials.

2. Framework with Simulation-Based Asset and User-Defined Input

Observation, measurement, modeling, and predication are the predominant skills of students cultured in the physical education. To satisfy curiosities of diverse students during observations of physical phenomena, teachers are easy to incorporate the AR technology into learning activities taking into account of measuring the external physical quantity, building the mathematical model, and predicating the results at different boundary conditions, and the proposed AR framework is given in Figure 1.

After determining the specific topic such as the temperature or thermal management, teachers construct instructional materials to adapt the background of students including the inquiry-based learning on where, how, and what it happens? For instance, the electrical vehicle is one of the widely concerned objects in the students' daily lives, and its reliability is heavily dependent upon the thermal management of power devices due to microstructure degradations induced by the temperature. To concretize and visualize the physical concepts and laws such as Fourier heat conduction equation, therefore, 3D plots calculated from the finite element simulation (FEM) model are used for the assets in virtual scenes, and the simulation-based assets (Kim et al., 2021) are dynamically updated by the external physical quantity based on the used-defined microcomputer (uPC) unit, and the main procedures of the framework for creating AR-based physical application are stated as follows.

Firstly, simulation-based assets (van der Meer et al., 2020) are created with a high accuracy and a simple operation. Considering couplings of the mechanical, thermal, and electrical in everyday physical phenomena, teachers employ the multi-physical field FEM software COMSOL to model and simulate on the real setup (Lu et al., 2022) and thus obtain accurate 3D plots as supplemental information frequently by only modifying boundary conditions of one of diverse library applications.

Secondly, file formats are transformed with an automatic pipeline. The plots in COMSOL environment are exported as the VTK file format, which is incompatible with the standard file input of free game engine platform such as GLB file format in Unity. It is a tedious and

Figure 1

Flowchart of the open framework for AR-based physical application with the simulation-based asset and user-defined input: (a) from student-demanded topics in exploring everyday objects, taking the thermal management as an example, where, how, and what are listed based on the constructive theory; (b) for teacher-required tools, where the user-defined input is implemented by a low-cost microcomputer (uPC) STM8 and Bluetooth module HC06 hardware, and the thread-based data management software using Python scripts to integrate the external physical quantity in real experiments into the simulation-based assets in virtual scenes
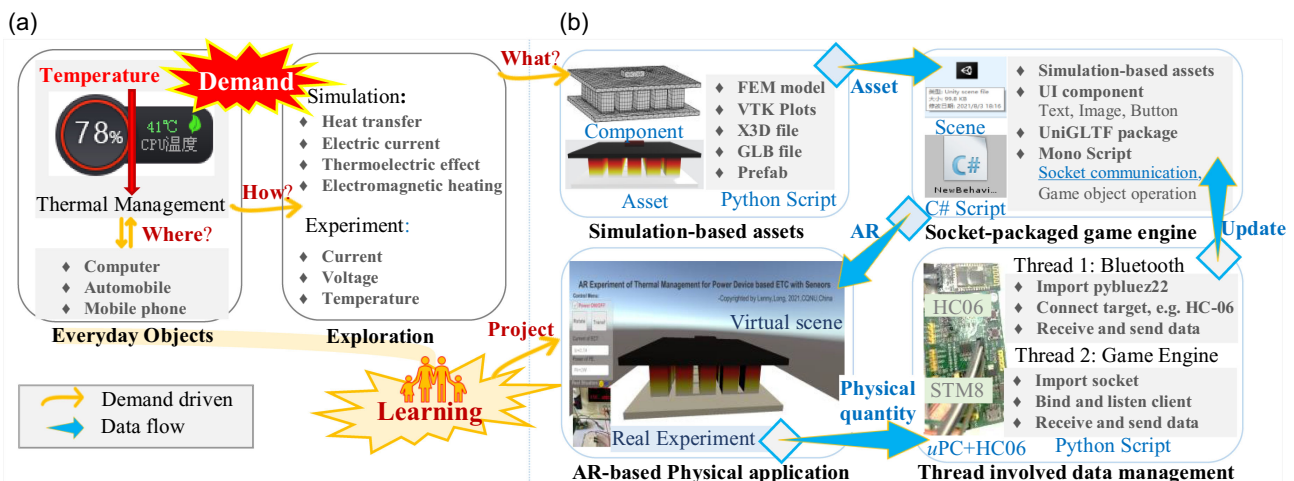
time-consuming task that the transformation of file format from VTK to GLB is processed manually in various open-source 3D visualization tools embracing Paraview and Blender. By the script programmed by Python language, the data flow in file format transformation process is automatically managed to allow teachers to import the VTK plots into the Unity game engine efficiently (Garon et al., 2016; Wheeler et al., 2018).

Thirdly, external physical quantities are collected by a low-cost uPC and Bluetooth module (Cui et al., 2020). The standard hardware such as an expensive head-mounted display for recognizing the real objects provides teachers less possibility for directly measuring the physical quantity such as current in real setup. The uPC STM8 with the analogy-to-digital converter and universal asynchronous receiver/transmitter (UART) is configured to sample the external analogy signal and sent them to the game engine wirelessly by the Bluetooth module HC06. With the aid of the STM8 + HC06 wireless measurement unit (Liu, 2021), the external physical quantity in real world can be mapped onto the assets in virtual scene in real time by the following thread-based Python script.

Fourthly, virtual objects are triggered by the invisible physical quantity during observations of physical phenomena. The simulation-based assets and components of user interface (UI) are managed by the mono script programmed by the C-sharp language in Unity. In the C-sharp script, the measured data from the STM8 + HC06 unit are obtained by the socket communication, and the game objects can be controlled by not only positions and view perspectives but also the external physical quantity. Consequently, the proposed framework allows teachers to create AR-based physical applications with the simulation-based asset and the user-defined input and thus helps students to investigate physical properties, understand formulas, and participate activities.

3. Experimental Setup of Thermoelectric Cooler-Based Thermal Management of Power Device

According to the above-mentioned framework, the implementation of AR experiment on thermoelectric cooler (ETC)-based thermal management of power device (PE) is demonstrated for the teaching of electrical-thermal effects.

3.1. Real experiment and its augmented information

Joule effect and Peltier effect are the two classical electrical-thermal effects during observation of the electrical and the thermal behaviors, particularly in the ETC-based thermal management of PE. The PE works under a large current and high voltage and thus causes an increasement of temperature due to the thermal generation by the loss of electrical energy or Joule effect. To keep the temperature of PE at a favorite range, its heat is absorbed by the ETC operating under an adjustable current. The real experiment is setup in Figure 2(a), where a PE resistance of $5W/2.2\Omega$ is mounted on the cool side of an ETC of 12V/6A with a heat sink on its hot side, and an adjustable direct current power supplier of 36V/3A with a configured output is employed for driving the components. As a result, the relationship between the PE temperature and the ETC operating current, IETC, is traditionally explored without employing the invisible physical quantity such as 3D temperature distribution.

Based on the real experiment, the two predominant components, user-defined input unit and simulation-based assets in the proposed AR framework, are implemented. On one hand, the user-defined input unit is constructed by the STM8 + HC06 configuration according to the typical schematic of uPC system with UART communication and programmed by C language, uPC.c, and furthermore the uPC program mainly deals with functions of sending and receiving data through the UART-related HC06 to collect IETC in real time. Therefore, the customer-built wireless measurement unit with a bill of materials of less than $5 provides the usability of putting the invisible physical quantity in the real world into the virtual environment. On the other hand, the simulation-based assets are generated from the 3D plots of the FEM model, which is built by following a library application in COMSOL, thermoelectric_cooler.mph (COMSOL Inc., 2020), due to its successful configuration of electrical-thermal modules and components, and thus allows teachers to make some simple operations such as modifying parameters of geometry and materials to match the real setup, as shown in Figure 2(b).

After obtaining two inputs of data streams from the real experiment, VTK plots and IETC, three scripts are employed to pipe the data into the Unity game engine for importing and controlling

Figure 2

Generation and controlment of assets in the experiment concerning thermoelectric cooler (ETC)-based thermal management of power devices (PE): (a) real setup; (b) components for measurement and simulation, consisting of the schematic of microcomputer (uPC) with Bluetooth (BT) module and COMSOL model of the setup; (c) scripts for automatic data pipeline of the current and the augmented information, where a two-thread Python-based script, *Linkdt.py*, for linking data from the BT communication in C file, uPC.c, and the Unity virtual objects in C sharp script, main.cs; (d) illustration of simulation-based assets at IETC of 0.1A, 0.4A, and 0.7A, respectively
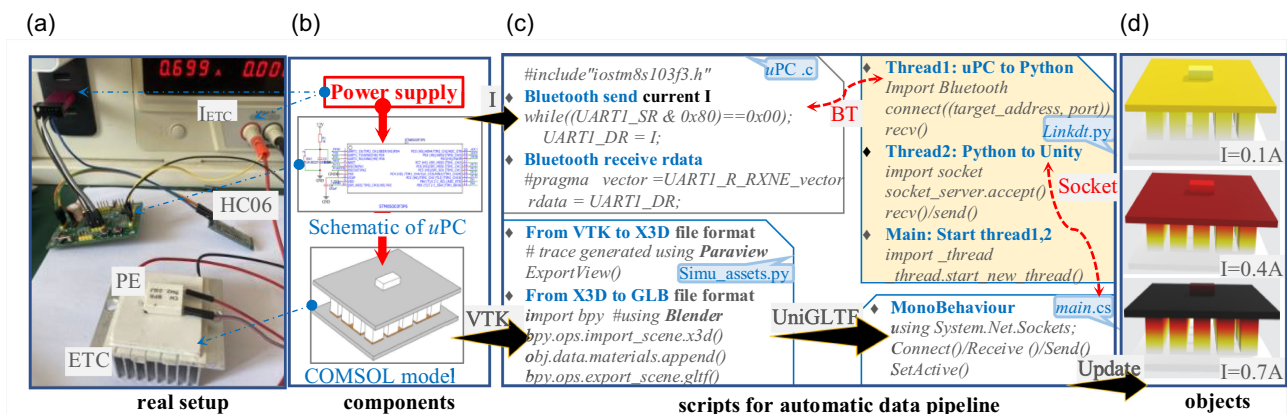
assets in the AR application, as shown in Figure 2(c). The first script programmed by Python language, Simu_assets.py, consists of two main parts: one is the code generated by the trace function in Paraview and another is from importing bpy module in Blender to transform the file format unstructured VTK to X3D, and to GLB, respectively, and furthermore, the 3D plots of COMSOL model are imported into Unity with the help of module UniGLTF through the file format GLB while maintaining their surface colors related to temperature distributions. The second Python-based script, Linkdt.py, has two threads for linking data of IETC with variables in Unity in real time, where one is in charge of the wireless uPC unit by importing Bluetooth module pybluez and the other fulfills the function of exchanging the data with Unity through the socket communication. By the dedicated script for managing uPC unit, the user-defined input is well packaged by the standard communication and the low-skilled programming. The third script, main.cs, is a typical C-sharp file for the MonoBehaviour in Unity to position, hide, and enlarge the assets according to the detection devices including the user-defined input unit. In this way, the externally measured IETC is allowed to control the simulation-based assets toward a large expansion for more applications involved in the other physical quantities.

Benefited from the implement of four steps proposed in the AR framework, the 3D plots in COMSOL at different boundary conditions are automatically imported into Unity as the augmented information of the real experiment. For instance, Figure 2(d) demonstrates the simulation-based assets at IETC of 0.1A, 0.4A, and 0.7A, where the surface colors of the objects denote the temperature distribution. In addition, the simulation-based assets are updated when the current of ETC is changed. Therefore, the accurate assets are rapidly produced from the validated FEM model and dynamically triggered by the used-defined physical quantities according to the real setup, which improves the efficiency and affordance of building augmented information on daily physical phenomena.

3.2. AR application and its calibration

Besides the simulation-based asset, the UI is another graphical element for creating AR application in the ETC-based thermal management of PE. The title, control menu, and real situation are constructed by directly adding the basic components including texts, menus, and buttons in the Unity virtual scene. In the menu, the power of the setup can be set ON or OFF, and the real-time physical quantities such as current of ETC and power of PE are displayed. The AR application with the UI and the simulation-based assets is shown in Figure 3(a).

To achieve the accurate learning experience on the relationship between the temperature and the current IETC, the calibration of the AR application has been conducted on the user-defined measurement unit and the simulation-based assets. Firstly, the measurement unit with a BT-based uPC is calibrated by the look-up table method, where the range of current is only from 0 to 2 A to overcome the heat risk for students and the calibration instrument is the standard digital multimeter Agilent 3441A and thus achieves a relative error of less than 0.3% for collecting IETC. Secondly, the temperature at the top of the resistance is recorded using the thermocouple meter SMART AS877 and compared with the simulated results. By the trial and error method for modifying boundary conditions such as the heat coefficient, the simple optimized COMSOL model produces the augmented information on the temperature having a relative error of less than 2%. Thirdly, the offline approximation of the real-time simulation on generating assets is tested following the specification on video continuity, and there are 40 simulation-based assets embracing ETC and PE at IETC ranging 0 to 2 A with a step size of 0.05A to reflect the ideal superimposed information. Unfortunately, the transient behavior of the temperature is not incorporated into the AR application due to the assets generated from steady-state simulations, and obviously this observation can be added by deploying assets from the transient simulation into the proposed AR framework. Consequently, the AR application in the thermal management provides interactive and accurate learning materials on exploring the electric-thermal effect, such as the evolution of temperature distribution over IETC from 0.7 to 0.4 A as shown in Figure 3.

4. Teaching Result

Based on the proposed AR framework with simulation-based assets controlled by the user-defined input of physical quantity and its application in the ETC-based thermal management of PE,

Figure 3

Illustration on the temperature distribution of the power device mounted on ETC in the AR application when the current of ETC, I_{ECT}, is: (a) the scene when is 0.7 A, or $I_{ECT} = 0.7$ A, and (b) compared with that when $I_{ECT} = 0.4$ A
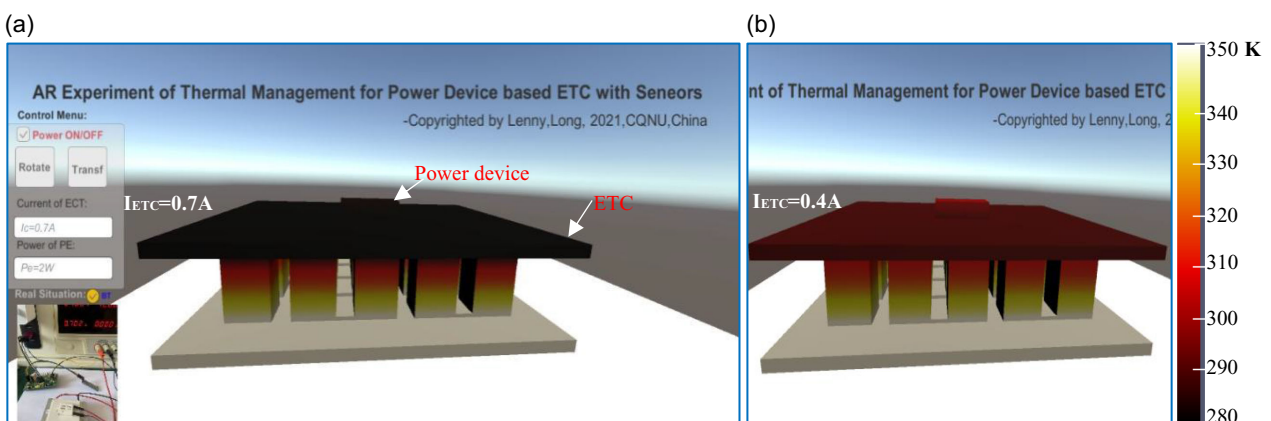
3 physics teachers and 9 secondary students at the Chongqing No.18 middle school are the participants of creating and exploring the AR learning activity during the implementation of Chongqing Baby Eagle Project, China. The questionnaire, interview, and writing essay are used to obtain the instant feedback of their experiences.

For the physics teachers with a little ICT skill, one-hour training is conducted to reproduce the AR-based application in the thermal management, and a topic about the electromagnetic distribution along the wire is given to create their own applications. All of them can grasp the skills of creating simulation-based assets, decorating UI, and programming interactions in the AR framework toward a successful creation of their diverse learning scenarios. Furthermore, the teachers are impressed by both the low-cost (less than 5\$) user-defined input unit and the more efficient (less than 5 minutes) generation codes of the simulation-based assets. In addition, although the teachers are somewhat confused to manually modify the boundary conditions of COMSOL model to match the simulated with the experimental, they insist that the optimization of boundary conditions is more meaningful to culture core skills of students by the manual than the automatic method in the AR application.

Benefited from the interactive and accurate visualization of intrinsic physical quantities in the AR experiment, the students are excited in observing evolutions of the temperature distribution of PE over the current of ETC and prefer to maintain the augmented information with the real operations on the operating current instead of the CCD-based 2D marker. Additionally, all students concreate their understandings of the energy conservation law to explain the fact that the increasing current of ETC causes the decreasing temperature of PE, meanwhile the temperature at the hot side of ETC is increased. Moreover, they are astonished by the capability of separating temperature along the small vertical distance in ETC, which is hardly observed by kids in the traditional experiments.

In summary, this study offers an open AR framework with the simulation-based asset and the user-defined input and illustrates its application in creating the teaching material of electrical-thermal effects for middle school students and teachers. On one hand, the proposed AR framework could be ready for being used by physic teachers since a low entrance to program the Python scripts and an affordable cost to implement the uPC unit. On the other hand, the curiosity of students is cultured with the aid of accurate assets and real operations during observations of everyday physical phenomena, where mathematical models, effects of certain inputs, and simulated results can be dedicatedly designed by teachers. In future, more AR applications with the simulation-based assets triggered by physical quantities will be developed by more participants to support personalization processes of students in AR-based physics education.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

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