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On the Suitability of Augmented Reality for Safe Experiments on Radioactive Materials in Physics Educational Applications

ROSARIO SCHIANO LO MORIELLO[1,2], ANNALISA LICCARDO[3], FRANCESCO BONAVOLONTÁ[3], ENZO CAPUTO[1], ANTONIO GLORIA[4], AND GIORGIO DE ALTERIIS[1], (Graduate Student Member, IEEE)
[1]Dipartimento di Ingegneria Industriale, Universitá degli Studi di Napoli Federico II, 80125 Naples, Italy
[2]Centro Servizi Metrologici e Tecnologici Avanzati, Universitá degli Studi di Napoli Federico II, 80146 Naples, Italy
[3]Dipartimento di Ingegneria Elettrica e delle Tecnologie dell'Informazione, Universitá degli Studi di Napoli Federico II, 80125 Naples, Italy
[4]Institute of Polymers, Composites and Biomaterials, National Research Council of Italy, 80125 Naples, Italy

Corresponding author: Rosario Schiano Lo Moriello (rschiano@unina.it)

ABSTRACT Laboratory experiences have proved to be a key moment of the educational path in most of the so-called Sciences, Technology, Engineering and Mathematics (STEM) subjects. Having the opportunity of practicing on actual experiments about the theoretical knowledge achieved during the classroom lectures is a fundamental step from a didactic point of view. However, lab activities could be forbidden in the presence of tests characterized by safety issues, thus limiting students' cultural growth; this is particularly true for physics experiments involving radioactive materials, sources of dangerous radiations. To face the considered problems, the authors propose hereinafter a mixed-reality solution involving augmented reality (AR) at students-side and actual instrumentation at laboratory-side. It is worth noting that the proposed solution can be applied for any type of experiment involving the remote control of measurement instruments and generic risk conditions (physical, chemical or biological). As for the considered case study on gamma radiation measurements, an ad-hoc AR application along with a microcontroller-based prototype allows students, located in a safe classroom, to (i) control distance and orientation of a remote actual detector with respect to different radioactive sources and (ii) retrieve and display on their smartphones the corresponding energy spectrum. The communication between classroom equipment and remote laboratory is carried out by means of enabling technologies typical of Internet of Things paradigm, thus making it possible a straightforward integration of the measurement results in cloud environment as dashboard, storage or processing.

INDEX TERMS Augmented reality, mixed-reality education, MQTT protocol, physics experiments, radiation measurements, remote laboratory, reverse engineering.

I. INTRODUCTION

One of the key elements of the STEM lab activities are providing students with the aptitude for problem solving. Students use, in fact, STEM lab materials to conduct experiments, explore, and make their own discoveries. With specific regards to physics subjects, carrying out experiments is usually enlightening to understand the physical phenomenon under test [1]. However, some experiments can be characterized by a certain level of risk (as an example, those involving radioactive phenomena) for students, thus requiring the application of personal protective equipment and qualified personnel in order to safely conduct the lab activity. It is worth noting that, while such requests can be met at the university level, their satisfaction is much more difficult to be achieved when high or primary schools are taken into account [2].

Exploiting features and protocols typical of the Internet of Things (IoT) paradigm turns out to be a viable solution to separate the laboratory frequented by students from the environment in which the actual experiment is carried out. In particular, IoT proves to be a valuable learning support since it allows the communication through internet or other networks/protocols among objects located in different locations [3]. IoT can be, in fact, seen as a network of devices of

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various types and sizes (such as industrial systems, medical instruments, smartphones, sensors, etc.) that are interconnected with one an other and share information in order to allow real-time online control and monitoring [4], [5].

In the literature, several notable examples can be found where this technology is applied as support to educational activities; as an example, a mobile application is proposed in [6] to support learning for primary school students. In particular, a network of temperature and humidity sensors is used to monitor the soil data and send them to a mobile application. Another example is given in [7], where a dashboard is implemented on an open source site to monitor the status of thermodynamics law on a physical system.

Besides the things interconnection, other technologies supportive of IoT can be considered, such as Augmented Reality (AR). Ar involves an alteration of reality, thanks to virtual information overlapped on the reality felt by senses. As described in [8], this technology is beginning to increase its exploitation and impact in STEM learning. As an example the authors use AR to support an IoT system [9]; in particular, AR is exploited to display the state of energy decay when the part of interest located on school building plan is framed with mobile camera. It is so possible for students to have the opportunity of understanding as energy decay occurs. Another notable example is shown in [10], where the authors demonstrate that using 3D scans of objects and an appropriate ad hoc application, students can interact with the scanned object and obtain its exploded view to better understand the internal composition.

Thanks to the technologies described above and stemming from their past experiences, the authors propose a mixed-reality solution based on Augmented Reality and IoT communication protocols to safely carry out laboratory activities characterized by possible risk level. The solution feasibility is assessed in the case of radioactive spectrum measurements. In particular, an AR mobile application and a suitable microcontroller-based fake detector allow students in the classroom to move a detector with respect to radioactive source located in an actual remote laboratory. The corresponding gamma-ray energy spectrum is measured by the detector, transmitted according to an IoT protocol, and shown on the students' mobile phone. It is worth noting that the proposed solution proves feasible also for other application fields involving dangerous materials or unsafe environments, such us handling nuclear waste or diagnostic tools based on X rays in the hospitals.

The paper is organized as follows: an overview of the Augmented Reality applications in educational field is first shown in Section II, while the proposed approach for safe AR-based experiments is described in Section III. The feasibility of the proposed approach is then assessed in Section IV by means of a suitable case study involving the measurement of gamma-ray energy spectrum; concluding remarks are finally drawn in Section V.

II. RELATED WORKS

Internet of Things paradigm is increasingly becoming a support tool in the educational field as shown in [11]. An example is presented in [12], where students can monitor the oscillation of a spring-mass system using MEMS (Microelectromechanical system) sensors. The data measured by the sensors are sent through IoT to a remote station where an algorithm implemented in LABView environment allows to carry out some experiments and evaluate how the period of the system evolves with mass, spring constant and amplitude.

Augmented Reality is proving to be one of the best technologies to support teaching in different subjects, making learning more active, effective and meaningful [13]–[19]. An example is reported in [20], where the authors propose an AR application that allows to simulate different physical experiments. In particular, students can build their experiment by combining different shapes and properties of the objects available in the application. In [21], [22], augmented reality is exploited to understand some concepts about electricity or electromagnetism that are hardly visible and understandable starting from studies in standard laboratories. This difficulty was also highlighted in [23], where an interview to some secondary school physics students and teachers highlighted as augmented reality makes it possible the visualization of some difficult-to-understand phenomena such as the magnetic field, greatly improving their understanding.

Another example of augmented reality application in the educational field is shown in [24]. The authors have first scanned the surrounding environment; a 3D object can, then, be introduced in the scene thanks to AR and its shape is deformed according to its interaction with the environment. Moreover, the deformation also depends on the force applied by the user on the object itself through the application. In [25], AR is exploited as support to physics education through the Learning Physics through Play Project (LPP) technique; in particular, it is presented how the capability of students to understand physical phenomena (such as force, net force, friction and two-dimensional motion) has markedly improved thanks to the use of the LPP technique with the support of augmented reality.

There are examples of AR exploitation also in the chemical field. As an example an android application in augmented reality allows high school students to understand the internal structure of the atom once framed target images available on the book by means of phone cameras [26]. Augmented reality is used in [27] to understand the operating principle of Daniell cell by conducting a virtual experiment. Students can conduct the virtual experiment through an android app, selecting the equipment and materials required by a dedicated menu in order to correctly set up the experiment.

In addition, augmented reality is a powerful tool to reduce time during the training phase [28]; as highlighted in [29], an application has been created that helps nursing staff in the training of suture procedures. Augmented reality has been

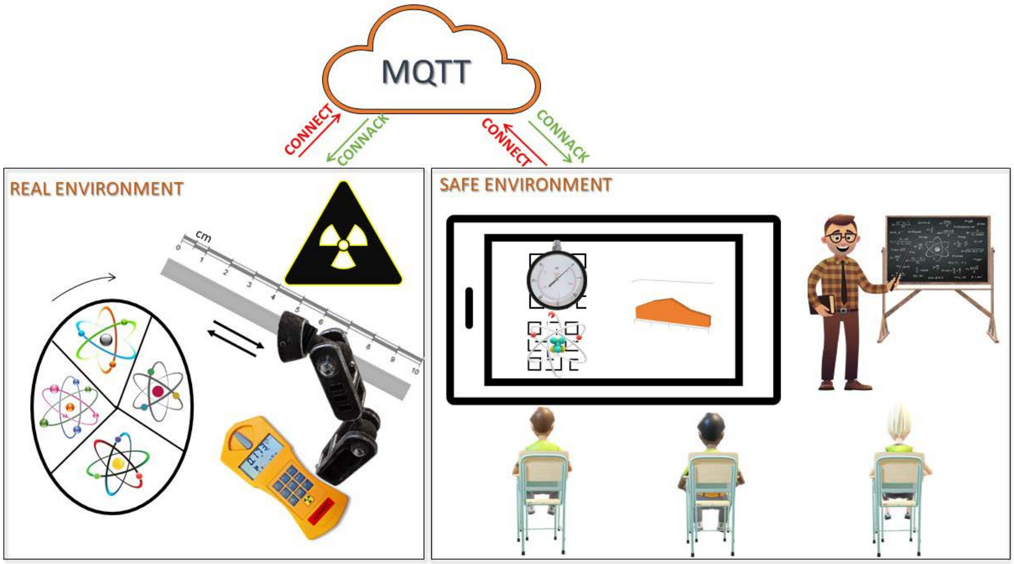


FIGURE 1. **Proposed solution for safe physics experiments: the environment where students can carry out safe AR experiments is specially separated from actual laboratory with hazard condition. Communication between the environments is assured by means of IoT protocols.**

used in [30] to support the training process in higher technical education institutions by increasing learning efficiency, facilitating student training and cognitive activities, improving the quality of knowledge acquisition, generating interest about a topic, and promoting development and expertise in research activities.

At the best of authors' knowledge, no example of AR exploitation allowing students to relive a laboratory experience by directly controlling actual instruments and carrying out real-time and not simulated experiments are available in the literature. A relevant solution of AR application in chemistry teaching is given in [31], where augmented reality gives students the ability to see a molecule from all the possible point of view, visualize how atoms inside the matter and understand more abstract chemical concepts. No interaction with actual chemical substances and compounds as well as with laboratory equipment is allowed. Possible results are gained from approximated models; unfortunately, these are still aspects of actual experiments that cannot be simulated, no matter how accurate the model may be. The most important example of remote controlled instruments and tools can be found in surgery (as an example the Da Vinci robot [32], [33]). The associated technological requirements, however, prevents from their diffusion and implementation for educational purposes.

III. PROPOSED SOLUTION

As stated above, the paper addresses the problem of enabling students to safely carry out experiments in the presence of laboratory activities involving risk conditions. Such experiments (as an example, those with radiation sources) must be conducted under the supervision of qualified personnel and appropriate premises in order to avoid hazards for students. Unfortunately, such requirements may not be always satisfied, especially in non-university school courses, thus depriving students of an important cognitive support. Proposed solution can be tailored to different physics experiments as well as other STEM subjects; nonetheless, the proposed solution will be described in the following with reference to an experiments involving radioactive materials.

To assure safe execution of experiments in this context (Figure 1), the first step consists of separating the environment in which the students are located (in the following referred to as safe environment) from the environment where the experiment is actually carried out by means of measurement instruments, dangerous materials and laboratory equipment (in the following referred to as real environment). The communication between the environments turns out to be fundamental in order to assure the consistency between the operations executed in the safe environment and those occurring in the remote laboratory. It is so possible to make the students relive the laboratory activity as they were in the real environment.

- **Safe environment**: This environment consists of the classroom where students and teacher are located. To safely operate on the actual detectors and sources, all the interaction are mediated by an ad-hoc mobile app based on augmented reality. The app is implemented in such a way as to render a faithful representation of the experiment equipment once fake detector and radioactive source (both realized by means of suitable targets) are framed through the mobile phone camera.

  The detector target contains an appropriate embedded system whose sensors measure its distance and inclination with respect to the fake source. Measured values of distance and inclination are sent to the laboratory to move and arrange the actual source and detector. Within the app, through a dedicated menu, student can request and view the measured values (e.g., the energy spectrum) of the radioactive source.

- **Real environment**: This environment consists of the remote laboratory where actual measurement instrument (the detector), radioactive source and motion system are safely located. The main component is the motion system, mandated to set the position and inclination of the detector with respect to the sources. This system can be implemented with stepper motors, a robotic arm or, in general a system that is able to move the measurement instrument with respect to the radioactive source.

  More specifically, the motion system is controlled by drivers that will implement distances and angles according to the data coming from the safe environment. A further motion system can be considered to change the considered radioactive source; as an example, a rotating flange supporting different radioactive materials selected through a specific angular position according to the framed fake source. In the real environment, the required measurements are carried out, and the obtained results are sent to the safe environment to be shown on the students' mobile phone.
- **Communication**: As stated above, safe and real environments have to be connected in order to exchange configurations and measurement results. To make the considered solution easily scalable, the adoption of protocols typical of Internet of Things paradigm should be advisable. It is so possible its integration in the manifold universe of network devices interacting with one another. Among the available communication protocols the authors focused their attention on Message Queuing Telemetry Transport (MQTT) [34], also known as ISO/IEC 20922:2016 standard.

  MQTT is a lightweight communication protocol based on a *publish-subscribe* model and exploiting Transmission Control Protocol/Internet Protocol (TCP/IP) as the transport level [35]. MQTT is thus particularly tailored for light impact and confined bandwidth situations. Differently from traditional systems based on client-server model (where the server handles clients' requests and is responsible for sending or receiving data), the entity that manages the communication between the several connected devices (clients) in the publish/subscribe model exploited by MQTT is called *broker*. In particular, the broker acts as a dispatcher, forwarding the messages published under a specific argument, referred to as topic, to all the devices that subscribed to the purpose.

IV. CASE STUDY

To assess the feasibility of the proposed approach, the authors realized a prototype implementation of a mixed-reality solution for the safe execution of measurements of gamma-ray energy spectrum. Before presenting the case study, it is necessary to make a premise regarding the type and danger of ionizing radiation. Even inside their school buildings, students are surrounded by numerous sources of the most disparate ionizing radiations (as an example, X-ray, gamma and electron radiation coming from concrete walls, or alpha radiation coming from the radon in the ground and cellars). These radiations are characterized by levels of amplitude such as to make them not dangerous in case of measurement or normal living. It would be very interesting and constructive from the educational point of view to allow students to perform measurements of these levels of radiation, touching with hand both the instruments and the problem. In this case, however, it would be expensive for the school to have all the necessary equipment to perform such operations (as an example, gamma-ray detector similar to that exploited in the case study costs about 3500 €). On the contrary, the total cost of the implemented prototype is about 300 €; the hardware components of the safe environment cost instead only 60 €, a very affordable amount for all schools and that makes convenient rental contracts of the measurement service. In addition, all the sources characterized by harmful levels of radiation would be cut out. Although fortunately not common in everyday life, the risk associated with these harmful sources can generate a greater interest in students, as happens in other areas [36], [37].

Details of hardware and software architectures of both safe and real environments are given in the following, after a brief description of the conducted experiments and exploited detector.

A. GAMMA RAY ENERGY SPECTRUM MEASUREMENTS

Gamma rays are the highest energy part of the electromagnetic spectrum; they are basically similar to all other forms of electromagnetic radiation (e.g. X-rays, visible light, infrared, radio) but have high energy because of their short wavelength. Radioactive nucleus commonly emits gamma rays in the energy range from a few keV to about 10 MeV, corresponding to the typical energy levels of nucleus [38].

The absorption of gamma rays in matter is fundamentally different from that of charged particles such as electrons or alpha particles. The latters give up their energy to the absorbing medium continuously and have well-defined paths in the various substances. On the contrary, gamma rays act discontinuously and their intensity is never reduced to zero even by gradually increasing thicknesses of matter [39]. As a matter of practice, a gamma-ray source can be pernicious if handled without the required care.

Measuring gamma rays is usually accomplished through a detector, essentially an instrumental system capable of determining, in differential form, the energy distribution of gamma photons. The data obtained from a gamma ray detector are normally expressed in two-dimensional form as a pulse frequency versus the energy of the gamma radiation (the so-called gamma spectrum). The interpretation and analysis of a spectrum provides the information necessary for the qualitative and quantitative determination of the gamma-emitting radionuclides [40].

A gamma spectrometer consists of three main parts [41]:

- Detection system comprising the detector and the screen. Any incident photon interacting with the detector gives up part or all of its energy, depending on the type of interaction. The function of the detector is to transform this energy into a proportional electric charge. The purpose of the screen, on the other hand, is to minimize the structural background due to environment gamma radiation. The screen also influences the shape of the spectrum due to the backscattering of the detector photons;
- Pulse analysis system. A gamma ray detector not only records a certain number of pulses, but also classifies them according to the amplitude of their energy levels. To this aim, the electrical pulses leaving the detector must be amplified and sent to an amplitude analyzer. The number of pulses within each energy range is then stored in a special memory unit;
- Data recording and processing system. The data stored in the memory unit are then extracted by means of special recording, printing or display units. The memory unit can also be connected to a computer for data analysis and processing.

The interaction of a monochromatic gamma-ray beam with a detector should theoretically result in an electron distribution characterized by one or more monoenergetic groups and a continuous distribution (''ideal spectrum''). However, the actual spectra differs markedly from its ideal shape due to various factors [42].

One of the most important feature of a gamma spectrometer is the efficiency, whose performance are degraded when distance and orientation with respect to source of the detector change [43]–[45]. This way, making it possible for the student to assess this performance variation should be advisable for educational purposes.

B. HARDWARE ARCHITECTURE

As stated above, the hardware architecture includes an embedded system for distance and inclination measurements in the safe environment, and the detector and the motion system in the real environment. Both architectures are completed by a suitable microcontroller-based board for MQTT communication.

1) SAFE ENVIRONMENT

Hardware components required at students' and teachers' side are mainly focused on both fake detector and sources. In particular, fake detector is needed to measure distance and orientation with respect to the radioactive source. Two commercial electronic boards were chosen to carry out these operations, namely *X NUCLEO 53L0A1* [46] and *X NUCLEO IKS01A2* [47] by STMicroelectronics.

The first board provides distance measurement thanks to the use of a VL53L0X Time of Flight (ToF) sensor [48], a cost-effective ToF laser-ranging module characterized by a measurement accuracy lower than 3% for high accuracy configuration and full scale value as high as 2 m. Moreover, the 940 nm VCSEL emitter of the VL53L0X is capable of covering long distances as well as showing high immunity to ambient light and good robustness to cover glass optical crosstalk [48].

The second board is used to measure inclination with respect to the vertical direction by means of a LSM6DSL tri-axial acceleration sensor [49]. The projections of the gravity acceleration onto to the sensor reference frame are exploited to evaluate the desired angle. LSM6DSL is composed of a 3D digital accelerometer and a 3D digital gyroscope and is characterized by low power dissipation and a high immunity to mechanical shock. The LSM6DSL has full-scale acceleration ranges of $\pm 2/\pm 4/\pm 8/\pm 16$ g and angular rate ranges of $\pm 125/\pm 250/\pm 500/\pm 1000/\pm 2000$ dps [49].

Measurement operations are managed by a NUCLEO L152RE board by STMicroelectronics [50], equipped with a STM32L152RE microcontroller. The board (*i*) communicates with the sensors via Inter-Integrated Circuit (I2C) protocol to receive the measured values of distance and acceleration, (*ii*) processes them to achieve the inclination and (*iii*) sends the obtained results through Universal Synchronous-Asynchronous Receiver/Transmitter (USART) to an ESP32 microcontroller by Espressif Systems [51] mandated to the implementation of MQTT protocol.

This microcontroller is mounted on a ESP32-DevKITC-V4, a typical commercial boards exploited for IoT applications. It is integrated with a Wi-Fi module that allows a direct connection to the Internet through a Wi-Fi router. The microcontroller is characterized by low current dissipation thus making it suitable for battery powered and wearable electronics applications. The Wi-Fi module supports a data rate of up to 150 Mbps, and 20 dBm output power at the antenna to ensure the widest physical range [51]. Figure 2.a shows a block diagram of the hardware architecture of the devices involved in the Safe Environment, while Figure 2.b shows the target for the reproduction of the gamma ray detector with the embedded system inside.

2) REAL ENVIRONMENT

Besides the radiation sources, a gamma-ray detector and a movement system are the main components of the Real Environment. As for the detector, the *i-Spector Digital*, developed and realized by Caen S.p.A., has been chosen [52]; it performs an integrated multi-channel analyzer (MCA) and is characterized by an optional wireless connectivity based on LoRaWAN protocol. This compact unit can be arranged with different silicon photo-multiplier (SiPM) areas (18 × 18, 24 × 24 or 30 × 30 mm^2, as for the exploited instrument). The instrument hosts a preamplifier stage, an integrated power supply for SiPM biasing with temperature feedback loop, a shaper and a full-featured MCA based on 80 MSps, 12-bit ADC, and digital charge integration algorithm. The i-Spector Digital can be controlled through Ethernet and provides as

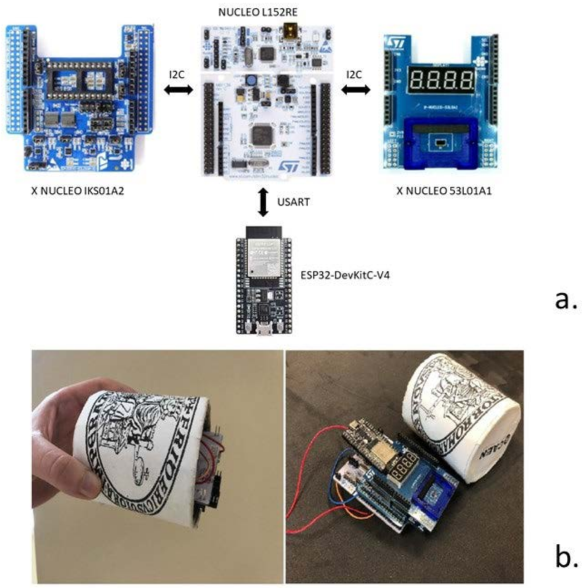


FIGURE 2. **Hardware architecture for the safe environment, composed by a microcontroller, an inertial sensor, a time of flight sensor, a Wi-Fi module (a) and target for AR app (b).**

output an analog amplified signal and the measured 4k channels energy spectrum [52].

The Real environment includes also two motor drivers XNUCLEO IHM01A1 by STMicroelectronics based on L6474 current control and mandated to drive two stepper motors used for angular and linear movement, respectively. These controllers drive the motors by operating the so-called H-bridge. In this circuit, the appropriate activation of two pairs of electronic switches allows to select the direction of the current flowing in the load placed on the output terminals (the topology is called bridged because the load is located between two branches of the circuit) and, consequently, the rotation direction of the motor [53]. Moreover, the switching period and duty cycle allow to modulate the current flowing through the motors thus allowing to select their rotation speed.

The motor used for the inclination movement in the real environment is MotionKing 17HS4401 which has an angular step of 1.8°, nominal current 1.7 A, and a step accuracy of ±5% [54]. As for the linear movement, a $500mm$ linear guide with a $1cm$ step has been chosen and equipped with the same motor mentioned above. The drivers are managed by a NUCLEO L152RE board, connected to the shields for motor control via Serial Peripheral Interface (SPI) protocol. It is worth noting that the IHM01A1 standard configuration provided by the STMicroelectronics does not allow the simultaneous control of several motor drivers from a single microcontroller. This way, an alternative configuration resistors placed on the shields has been adopted, according to [55]. The NUCLEO L152RE board is connected via USART protocol to a further ESP32 microcontroller, which receives distance and angular data sent from the Safe Environment and used to control the motors.

Figure 3 shows a block diagram of the hardware architecture of the devices involved in the Real Environment.

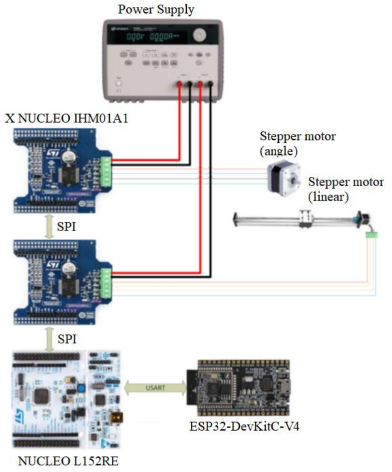


FIGURE 3. **Hardware architecture for the real environment, composed by a power supply, two motor drivers, a microcontroller, Wi-Fi module and two stepper motors, for linear and angular movements, respectively.**

C. SOFTWARE ARCHITECTURE

The firmware implemented on the management boards as well as the main integrated development environments exploited for the realization of the proposed case study are presented and described in the following. As for the Safe environment, the main goal has been the implementation of a mobile app capable of making the students relive the laboratory experience as they were using the actual detector. As for Real Environment, the attention has been focused on the movement of actual detector and the transmission of the measured gamma ray energy spectrum.

1) SAFE ENVIRONMENT

An Android app has been developed in *Unity 3D* environment, to allow students to visualize reproduction of gamma-ray detector and radioactive sources, that are as similar as possible to their real counterparts. To visualize these reproduction is necessary to frame appropriate markers. The developed app allows also to request and see the energy spectrum of the radioactive source, which will be updated every 10 s, through an appropriate menu. Moreover, the available menu allows the user to clear the spectrum samples (and accordingly the graph) as well as quit and close the app. Finally, the app is programmed in such a way as to reset the energy graph whenever a new source (different from the previous one) is framed, thus starting of a new measure.

As for the gamma ray detector, an appropriate 3D scan of the real object has been carried out through a non-contact Laser ScanArm by FARO [56], a measurement system capable of capturing the object and consequently its shape and size. The information obtained in this first phase corresponds to a cloud of points; to convert that cloud to a 3D model format (e.g.,.OBJ,.STL), the Geomagic Wrap software, by 3D Systems, has been adopted. Scan operations have been performed for each internal and external component of the detector. The composition of all scanned components takes place through the use of SolidWorks® 2018 (Dassault Systemes, Paris, France) CAD system. The resulting 3D object is subsequently imported into the Unity environment, where an appropriate algorithm is exploited to obtain an exploded view of the object, thanks to a dedicated button on the display (Figure 4). This operation is fundamental as it allows the student to understand the detector operating principle from its electronic components and to deepen concepts studied in theoretical lectures.

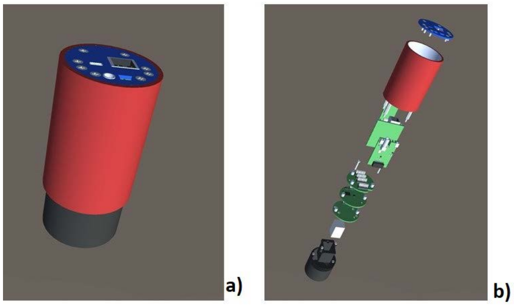


FIGURE 4. Results of the gamma ray detector scan through Laser ScanArm (a) and exploded view allowing students and teacher to visualize the internal components of the detector (b).

To suitably display detector and sources in the app, the corresponding markers have to be defined and recognized; to this aim, an open source tool provided by Vuforia, "*Vuforia Object Scanner*", has been adopted. In particular, the markers have to be framed by different points of view, thus making it possible to train a suitable software component to their recognition. The training quality is graphically represented thanks to a dome whose parts are filled with green colour as the corresponding point of view has successfully been achieved (Figure 5).

Thanks to the operation explained above, it has been possible to have a high level of recognition of the gamma ray detector marker, also by varying the its inclination, that is an operation that the user must be able to perform to evaluate the variation of the spectrum.

As stated above, detector marker has to measure the distance and inclination with respect to the reproduction of radioactive source, i.e. the measured parameters that have to be sent to the Real Environment. To achieve the values of these quantities, the hardware architecture described in section IV-B1 has been exploited. The algorithm for obtaining angle and distance data from the radioactive source has been implemented on the STM32L152RE microcontroller. As shown in Algorithm 1, first operations are mandated to initialize X NUCLEO 53L0A1 and X NUCLEO IKS01A2 boards and set the parameters (such as baudrate and data format) exploited for USART communication. If no errors in the initialization step are experienced, measured data in terms of distance and gravity acceleration components are collected by the sensors. The inclination angle is evaluated from the acceleration data on the three axes through the following equation:

$$\vartheta = tan^{-1}\left(\frac{A_x}{\sqrt[2]{(A_y)^2 + (A_z)^2}}\right) * \frac{180}{\pi} \tag{1}$$

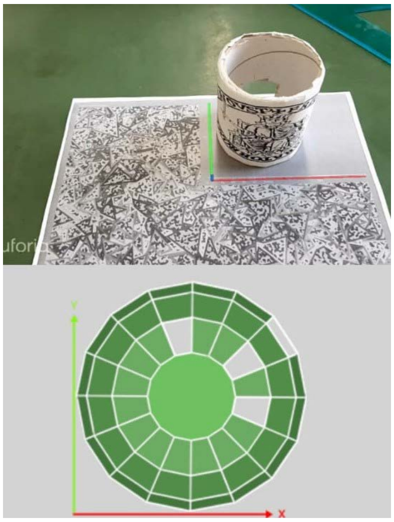


FIGURE 5. Training stage of detector marker recognition by means of Vuforia object scanner: on the top is represented the marker to scan while on the bottom the result of the scanning.

Obtained results are, finally, sent via USART to the ESP32 microcontroller, on which the MQTT communication protocol is implemented to send such data to the Real Environment.

Algorithm 1 Distance and Inclination Measurements in Safe Environment

```
Initialize X NUCLEO 53L0A1 and X NUCLEO IKS01A2 boards;
Setting parameters for USART communication.
LOOP Process
if X NUCLEO 53L0A1 board status and X NUCLEO IKS01A2 is ok? then
    while true do
        Receive distance and accelerometer data from shields;
        Evaluate angle from acceleration projections on the three axes;
        Send data via USART to ESP32 microcontroller
    end while
else
    stop the execution
end if
```

2) REAL ENVIRONMENT

In this environment, the data sent from the Safe Environment should be replicated. Two stepper motors have been used to make the purpose; one motor drives a linear guide to implement the distance from the source, while the other one actuates tilt movements (Figure 6).

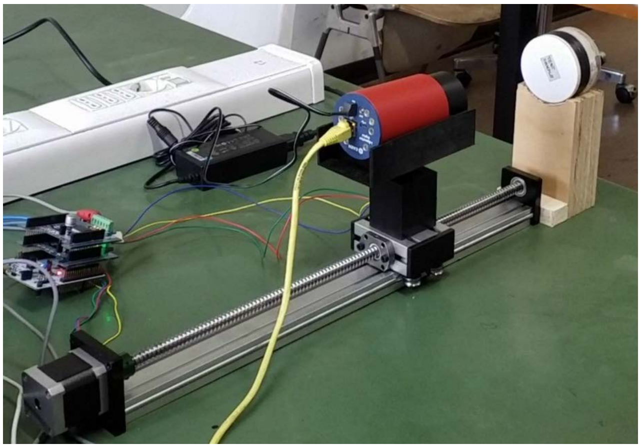


FIGURE 6. Real environment: the gamma ray detector placed on a system of stepper motor remotely controlled by user that allows the movements towards the radiation source.

These two stepper motors are controlled by the two drivers defined in the section IV-B2. The values of the distance and inclination parameters to be implemented are received by the ESP32 microcontroller present in this environment and transferred to the STM32L152RE microcontroller via USART protocol. The microcontroller converts these values into the corresponding motor steps that are sent to the two drivers using the I2C protocol to apply them on the motors. Step values are derived according to the guides' size and the maximum current supported by drivers.

Algorithm 2 Algorithm to Actuate Angle and Distance Sent by Safe Environment

```
Initialize the two X NUCLEO IHM01A1 boards.
LOOP Process
if boards status ok? then
    Read the stored values from EEPROM Memory to take the gamma ray detector to its initial position (minimum distance and inclination respect to the source)
    while true do
        Read data sent by ESP32 microcontroller.
        if Difference between actual and prior value is greater than or equal to 1 cm then
            Actuate received value;
            Save values to EEPROM memory.
        end if
    end while
else
    stop the execution
end if
```

Whenever the system is turned on, the algorithm (Algorithm2) implemented in the firmware of the STM32L152RE microcontroller must be able to return the gamma ray detector to a distance and inclination equal to the starting position. To this aim the last implemented distance and inclination values are written in the microcontroller EEPROM memory to return the two guides to their initial positions. The position and rotation of detector are then controlled by means of values received by ESP32 microcontroller. Moreover, to avoid flickering phenomena due to imperfect marker handling, the movement will be actuated only when the difference between two successive distance values is greater than or equal to 1 cm.

3) REMOTE COMMUNICATION

This section explains how the spectrum data provided by the gamma-ray detector are displayed within the Android app. Since the detector communicates data via HTTP protocol, it was necessary to implement an algorithm that converts those messages to MQTT and then send them to the Safe Environment. This algorithm has been developed in Node-Red environment (Figure 7); for each request of either available every spectrum or reset by students, a relative HTTP command is sent. The flow (i.e. the algorithm implemented in Node-Red) waits for the instruments response; received data will be properly processed by means of a proper function and then sent to the AR application. This function is necessary since the gamma ray detector provides the measured data as shown in Figure 8, so there is a need to drop the alphabetic characters preceding the numerical samples and retain only the numerical array.

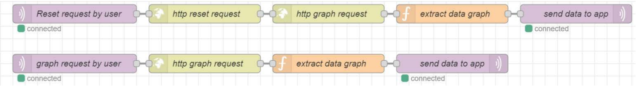
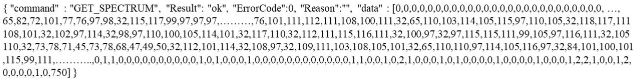


FIGURE 7. The developed node-red flowchart that converts MQTT message in HTTP message to allow communication between the gamma ray detector and AR application.



```
{ "command"  : "GET_SPECTRUM",  "Result": "ok",  "ErrorCode":0,  "Reason":"",  "data"  : [0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, …,
65,82,72,101,77,76,97,98,32,115,117,99,97,97,97,………,76,101,111,112,111,108,100,111,32,65,110,103,114,105,115,97,110,105,32,118,117,111
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110,32,73,78,71,45,73,78,68,47,49,50,32,112,101,114,32,108,97,32,109,111,103,108,105,101,32,65,110,110,97,114,105,116,97,32,84,101,100,101
,115,99,111,………..,0,1,1,0,0,0,0,0,0,0,0,0,0,1,0,1,0,0,0,1,0,0,0,0,0,0,0,0,0,0,0,0,1,1,0,0,1,0,2,1,0,0,0,1,0,1,0,0,0,0,1,0,0,0,0,1,0,0,0,1,2,2,1,0,0,1,2,
0,0,0,0,1,0,750] }
```

FIGURE 8. Example of message provides by gamma ray detector as HTTP answer.

As for the MQTT protocol, a private broker has been exploited. This choice is supported by the fact that such brokers do not suffer from issues related to (*i*) high data traffic, (*ii*) loss of connection, (*iii*) suspension of service. Eclipse Mosquitto Software has been used to run a local broker on a personal computer. Since the measurement instrument communicates via HTTP, sending data directly through that protocol to the Safe environment would be easier. However, the main strength of the MQTT (i.e., the *"one-to-many"* communication capability) would get lost. If all the students subscribe to the proper topic, they will receive the data measured by the instrument at the same time and without any network overhead.

D. EXPERIMENTAL RESULTS

The performance of the proposed solution has been assessed by means of a number of tests conducted on the considered case study. A first set of tests aimed at assessing delay and

TABLE 1. Average and experimental standard deviation among either measured or actuated and nominal distances.

Nominal distance [cm]		10	20	30	40
Safe	Δ	-0.8	-0.4	0.1	0.9
	σ	0.7	1.4	1.5	1.0
Real	Δ	1.2	-1.4	1.6	1.1
	σ	2.0	1.2	2.4	2.4

TABLE 2. Average and experimental standard deviation among either measured or actuated and nominal angles.

Nominal angle [°]		-30	-20	-10	0	10	20	30
Safe	Δ	-0.4	0.2	-0.2	-0.3	0.2	0.3	-0.1
	σ	1.2	1.4	0.9	1.1	1.3	0.8	1.6
Real	Δ	0.9	1.2	-0.7	-0.8	0.6	-1.0	1.4
	σ	1.8	2.2	1.5	1.6	1.8	1.9	1.7

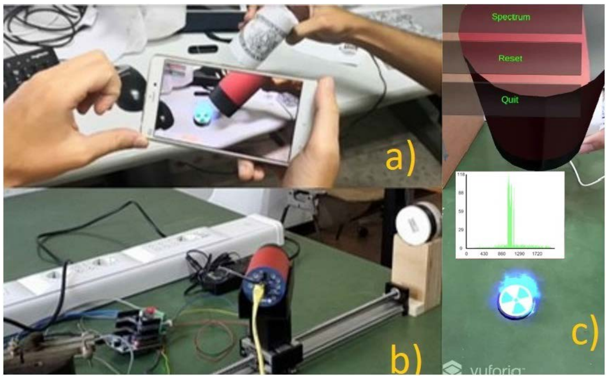

FIGURE 9. The implemented prototype of the proposed solution where in a) it's shown the safe experimental operation, while in b) the real environment that is remotely controlled and finally in c) the interface of the suitable application developed for the measurements of gamma ray energy spectrum.

stability of the communication between Safe and Real Environment by means of the MQTT protocol. Thanks to the use of a private broker that manages messages related only to the considered application, delays never greater than 70 ms have been experienced for messages associated with the distance and inclination control, regardless of load condition of the exploited network connection.

Moreover, the difference between nominal, measured (in Safe environment) and actuated (in Real environment) distances and angles have been evaluated. To this aim, both marker and actual detector have been mounted on ruler and protractor; in particular, nominal distances have covered the range within 10 and 40 cm (corresponding to the stroke of the linear track), while the angle values varied in the interval from $-30°$ up to $30°$. For each value, 30 measures have been carried and the results in terms of average (Δ) and experimental standard deviation (σ) of the differences among either measured or actuated and nominal values are given in Table 1 and Table 2 for distance and inclination respectively. Obtained values are fully compliant with the purposes of the considered application.

Finally, the operation of the proposed case study has been assessed; for the sake of the clarity, a composition of some pictures associates with a typical application example is shown in Figure 9. In particular, the Figure 9.a shows the targets that the user must frame with the smartphone camera to reproduce the detector and radioactive sources in the Safe environment. On the contrary, Figure 9.b shows the corresponding configuration of stepped motors and actual gamma ray detector in the Real environment. As it can be appreciated in Figure 9.c, the interface of the mobile app is equipped with a button menu to allow the user to request the energy spectrum, that is rendered in the same interface. Typical delays between request and representation of the spectrum samples were within 200 ms, which did not affect the user experience.

V. CONCLUSION

A solution exploiting augmented reality allowing students to carry out dangerous laboratory experiences in safe condition has been proposed in the paper. Simulation approaches are based on model that have approximations to the real experiment, so there are phenomena that can be observed only with direct exploitation with instrumentation. On the contrary the proposed solution allows real laboratory experiments to be carried out without losing contact with laboratory instrumentation and in a safe condition. The approach turned out to be particularly tailored for those educational institutes where the expertise in operating with dangerous materials is not well assessed, as an example for secondary schools. The solution has leveraged on the separation of the environment where the classroom was located and the one where the actual experiment was performed.

To this aim, fake laboratory equipment and a suitable application for mobile phone have been implemented for students and/or teacher in the Safe environment to (i) remotely control instruments located in the real laboratory and (ii) show measurement results in terms of gauges and graphs. To make the environments communicating with one another, a communication protocol typical of the IoT paradigm, called MQTT, has been adopted.

Proposed solution has been assessed by means of a prototype for the measurement of gamma-ray energy spectrum. The actual detector is substituted in Safe environment by a marker equipped with microcontroller and sensors capable of measuring the distance and inclination with respect to the source marker. A mobile application has been implemented in such a way as to:

- recognize the markers of both gamma ray detector and radioactive source when they are framed by the phone camera;
- superimpose a representation of the detector as faithful as possible on the marker;
- superimpose a user friendly representation of the source level of danger;
- request the current energy spectrum to the measurement instrument;
- render the corresponding graph on the user display.

Besides the user experience in terms of responsiveness of the app interface, the performance of proposed solution in terms of MQTT messages delay as well as distance and angle measures and actuation has been assessed; obtained results has shown a reliable behavior of the whole system.

The proposed solution has the potential to be exploited into or tailored to different application fields, such as *Massive Open Online Courses* (M.O.O.C) or industrial training in dangerous conditions/environments.

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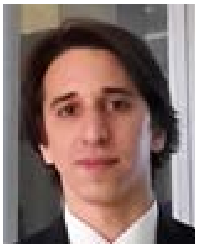
ROSARIO SCHIANO LO MORIELLO received the M.S. degree *(cum laude)* in materials engineering and the Ph.D. degree in electrical engineering from the University of Naples Federico II, Naples, Italy, in 2001 and 2004, respectively. Since 2006, he has been an Assistant Professor of electrical and electronic measurements with the Department of Information Systems, University of Naples Federico II, where he has been an Associate Professor of mechanical and thermal measurements with the Department of Industrial Engineering, since 2020. He is currently the Head of the Laboratory for Industry 4.0 and IoT Measurements, Center for Advanced Metrological and Technological Services, University of Naples Federico II. He has authored or coauthored more than 100 papers published in the most relevant journals or proceedings of international conferences and workshops. His research interest includes electrical, electronic, mechanical, and thermal measurements. In particular, he is dealing with the definition, implementation, and characterization of the Internet of Things-based monitoring and measurement platforms, advanced sampling strategies for embedded measurement systems, and innovative methods based on digital signal processors for compensation of bias and drift of MEMS-based inertial measurement units.

ANNALISA LICCARDO received the M.S. *(cum laude)* and Ph.D. degrees in electrical engineering from the University of Naples Federico II, Naples, Italy, in 2003 and 2006, respectively. From 2013 to 2016, she was a Tenure Track Researcher with the Department of Electrical Engineering and Information Technology, University of Naples Federico II, where she has been an Associate Professor, since 2016. She is currently coordinating research activities with the most relevant Italian companies in the field of electrical energy distribution and transmission, with the aim of realizing support facilities mandated to safely assess the performance of methods based on digital signal processing for network stability measurements in wide-area monitoring systems, defining and implementing a suitable method for uncertainty evaluation in the estimation of technical and commercial losses in the electrical distribution networks, and defining and implementing the Internet of Things (IoT)-based monitoring platform for partial electrical discharge identification in underground distribution networks. She has authored or coauthored over 100 papers published in relevant journals and proceedings of international conferences and workshops. Her current research interests include advanced measurements for monitoring and protection of electrical power systems, the IoT sensors for electrical measurements, and distributed measurement systems and augmented reality (AR)-based remote laboratory. She is a member of the Italian Society of Electrical and Electronic Measurements. She has served on the technical committee of several conferences and workshops. She has received several awards for both her articles and research outcomes. She is involved on the editorial boards of different international journals.

FRANCESCO BONAVOLONTÁ received the Ph.D. degree from the Department of Electrical and Information Technologies, University of Naples Federico II, Naples, Italy, in 2015. He is currently a Research Fellow with the Department of Electrical and Information Technologies, University of Naples Federico II. He has received the national license as an Associate Professor of the scientific area 09/E4 measurements. He is also a Lecturer of sensors and smart metering for master’s degree students in electrical engineering at the University of Naples Federico II. His research interests include instrumentation and measurement and can be divided into three main areas: 1) remote control of measurement instruments: in this context, various solutions have been defined, designed, and developed, based on both proprietary and open-source development environments, for the configuration and management of complex measurement stations distributed on geographic network; 2) measurement methods based on compressive sampling: definition, implementation, and development of innovative measurement methods that exploit the recent compressed acquisition paradigm that allows to obtain reliable measurements starting from a small number of samples of the signal of interest; and 3) distributed measurement systems for monitoring and protecting electrical networks: definition, implementation, and development of innovative platforms based on enabling technologies of the Internet of Things for measuring electricity consumption and protecting distribution systems in the presence of fault conditions. More recently, his research activities are focused on the development of innovative measurement sensors based on artificial intelligence algorithms. He is a member of the Technical Committee TC-37 on Measurement and Networking of the IEEE Instrumentation and Measurement Society.

ENZO CAPUTO received the master's degree in electronic engineering from the University of Naples Federico II, Naples, Italy, in 2019, where he is currently pursuing the Ph.D. degree with the Department of Industrial Engineering. He has participated in several research projects aimed at the implementation of a system for gamma radiation spectrum measurement of a radioactive source in safe condition through enabling technologies of the Internet of Things and data analysis for predictive maintenance in railway domain through machine learning/deep learning algorithms. His research interests include two main areas: 1) remote control of measurement instrumentation: in this context, he has been developed a solution to manage remotely a measurement station distributed on geographic network based on the Internet of Things protocol and augmented reality and 2) monitoring of parameters by drones: definition and implementation of a solution to monitor vital parameters to identify people with symptoms attributable to the Covid-19 virus. This solution is based on the photopletismographic technique to measure heartbeat and on thermal camera to measure body temperature.

ANTONIO GLORIA has been a Visiting Professor at the Centre for Rapid and Sustainable Product Development (CDRSP), Polytechnic of Leiria, Leiria, Portugal, and an Associate Member of CDRSP, since 2011. As a member of the Italian Society of Biomechanics in Orthopedics and Traumatology, in October 2013, he was appointed as a Scientific Advisor/a Counselor. He has been a Treasurer, since January 2016. He is currently a Researcher at the Institute of Polymers, Composites and Biomaterials, National Research Council of Italy, Naples, Italy. He is responsible for the Mechanical Properties Laboratory and the Reverse Engineering Laboratory. Over the past years, he has supervised Ph.D. students and M.D. students as a Professor at different universities in Italy. He has involved in several national and international projects. His main research interests include reverse engineering, design for additive manufacturing modeling and simulation, 3-D/4-D printing, bioprinting, biomimetics and bioinspiration, design of experiments, mechanical analysis, materials properties, design methods and manufacturing, augmented reality, biomechanics, dental materials, and design of scaffolds for tissue engineering. He is the author of international papers, book chapters, and communications/contributions in international and national conferences. He is a member of international scientific committees and chaired technical sessions in seminars, conferences, and workshops. He is also a member of the Italian Association of Design Methods and Tools for Industrial Engineering. He has received many national and international awards. He was awarded and appointed as the "Future Leader" in Science and Technology ("Dialogue Between Nobel Laureates and Future Leaders," STS Forum, in October 2015, Kyoto, Japan). He is also a reviewer and an editorial board member of international scientific journals.



GIORGIO DE ALTERIIS (Graduate Student Member, IEEE) received the M.S. degree in electronic engineering from the Department of Industrial Engineering (DII) and the Department of Electrical and Computer Engineering (DIETI), University of Naples Federico II, and the Ph.D. degree in technology, innovation, and management from DII, University of Naples Federico II, and the Department of Management, Information and Production Engineering, University of Bergamo, in 2022. He is currently a Postdoctoral Researcher with DII and the Advanced Metrological and Technological Services Center (CeSMA), University of Naples Federico II. His Ph.D. studies focused on mechanical and thermal measurements and navigation and guidance control using MEMS technology for inertial navigation, both for measurements and data fusion algorithms. He has participated in research projects on the definition, implementation, and realization of redundant inertial sensor systems for the Internet of Things, on the implementation and procedures for the certification of embedded devices for acceleration and vibration measurement in bridges, and on the experimental verification of a redundant sensor for structural applications. His current research interests include innovative methods based on a redundant MEMS IMU configuration for bias and drift compensation, on the research of innovative techniques for accurate attitude measurements of manned and unmanned aircraft, on the realization of microcontroller and sensor-based solutions for IoT-distributed monitoring systems, and on the use of 5G-based technologies for accurate position measurements.

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