

Date of publication xxxx 00, 0000, date of current version xxxx 00, 0000.

Digital Object Identifier 10.1109/ACCESS.2017.DOI

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

ROSARIO SCHIANO LO MORIELLO^{1,2,5}, ANNALISA LICCARDO^{3,5}, FRANCESCO BONAVALONTÀ^{3,5}, ENZO CAPUTO^{1,5}, ANTONIO GLORIA^{4,5}, and GIORGIO de ALTERIIS^{1,5}

¹Università degli Studi di Napoli Federico II, Dipartimento di Ingegneria Industriale, Piazzale Tecchio, Naples, CO 80125 ITALY

²Università degli Studi di Napoli Federico II, Centro Servizi Metrologici e Tecnologici Avanzati, Corso Nicolangelo Protopisani, Naples, CO 80146 ITALY

³Università degli Studi di Napoli Federico II, Dipartimento di Ingegneria Elettrica e delle Tecnologie dell'Informazione, Via Claudio, 21, Naples, CO 80125 ITALY

⁴Institute of Polymers, Composites and Biomaterials - National Research Council of Italy, Via Campi Flegrei, 34, Naples, CO 80125 ITALY

⁵These authors contributed equally to this work

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

ABSTRACT Laboratory experiences proved to be a key moment of the educational path in most of the so-called STEM (Sciences, Technology, Engineering and Mathematics) 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

STEM (Sciences, Technology, Engineering and Mathematics) labs offer students the chance to carry out the experiment about the set of science, technology, engineering, and math skills. One of the key elements of the lab activity is providing students with the aptitude for problem solving. In fact students use STEM lab materials to conduct experiments, explore, and make their own discoveries. Especially in physics subjects, carrying out experiments is crucial order to understand the physical phenomenon under test [1]. However, some experiments can be characterized by a certain level

of risk (as an example, for experiments related to radioactive phenomena) for students so it is required 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 as it allows the communication through internet or other networks/protocols among objects located in different locations [3]. In fact, IoT can be seen as a network of devices of various types and sizes (such as industrial systems, medical instruments, smartphones, sensors, etc.) that are interconnected with each other and share information in order to allow real-time online control and monitoring [4]- [5].

In the literature, several notable examples applying this technology as a support to educational activities are presented, as in [6], where a mobile application is proposed 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 the 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), which corresponds to an alteration of reality, in which virtual information is 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, in [9] the authors use AR to support an IoT system; 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, thus giving to the students 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.

On the basis of 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 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 as handling nuclear waste or diagnostic tools based on X ray 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

In [11] it is shown how IoT is increasingly becoming a support tool in the educational field. An example is presented in [12] where students can monitor the oscillation of a spring-mass system using MEMS (Micro-electromechanical system) sensors. The data measured by the sensors are sent through IoT to a remote station where an algorithm implemented in the 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]. There are several works showing the effectiveness of this technology; an example is reported in [20], where the authors propose an application in AR 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 used as support to understand certain concepts such as 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 ability 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 augmented reality applications also in the chemical field such as in [26], where an android application in augmented reality allows high school students to understand the internal structure of the atom once framed by means of phone cameras the target images available on the book. 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.

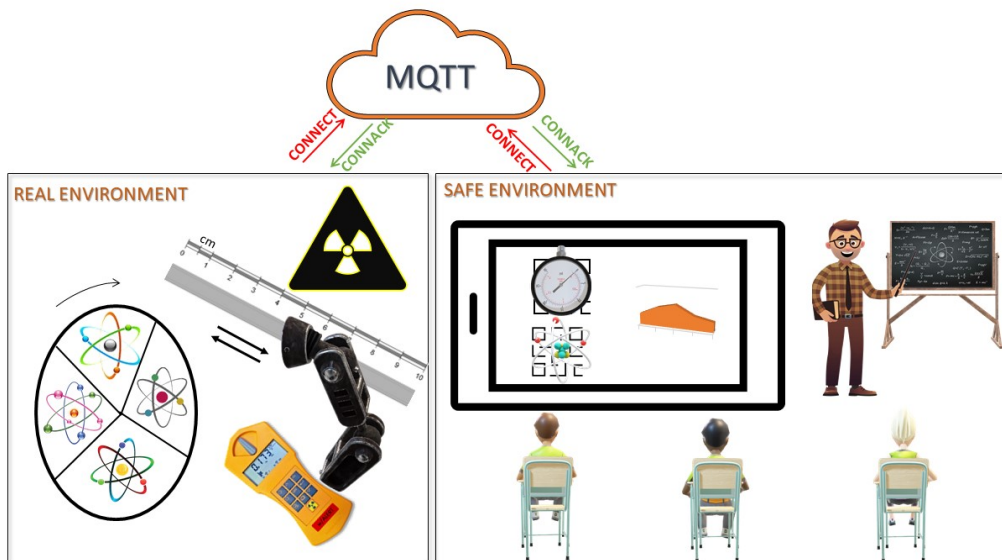


Figure 1. Proposed solution for safe physics experiments.

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 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 its angles, visualize how atoms are arranged in an element, to understand more abstract chemical concepts. No interaction with actual chemical substances and compounds as well as with laboratory equipment is however allowed. 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 conditions may not be guaranteed, especially in non-university school courses, thus depriving students of an important cognitive background. Proposed solution can be tailored to different physics experiments as well as other STEM subjects; nonetheless, radioactive materials will be taken into account in the following.

To assure safe execution of experiments in this context, 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 (i) measurement instruments, dangerous materials and laboratory equipment are located (in the following referred to as real environment), and (ii) the experiment is actually carried out (Figure 1). Finally, 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 detects 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 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 towards 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. 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, thus allowing its integration in the manifold universe of network devices interacting with one another. The authors focused their attention on Message Queuing Telemetry Transport (MQTT) [34], also known as ISO/IEC 20922:2016 standard, among the available communication protocols.

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), 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 latter give up their energy to the absorbing medium continuously and have well-defined paths in the various substances, whereas 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 in function of 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 that gave rise to the spectrum [40].

A gamma spectrometer can be considered to consist 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 ambient 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 information provided by a gamma ray detector is normally expressed in terms of pulse frequency as a function of the energy of the gamma photons. 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”). In reality, however, the spectra obtained experimentally differ markedly from the ideal spectra 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 of the detector with respect to source 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 triaxial acceleration sensor [49]; in particular, the components of the gravity acceleration with respect 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, STMicroelectronics [50], equipped with a STM32L152RE microcontroller. The board communicates with the sensors via Inter-Integrated Circuit (I2C) protocol to receive the measured values of distance and acceleration, processes them to achieve the inclination and 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, and 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]. Figura 2.a shows a block diagram of the hardware architecture of the devices involved in the Safe Environment, while Figura 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; 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 mm², as for the exploited instrument) and 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

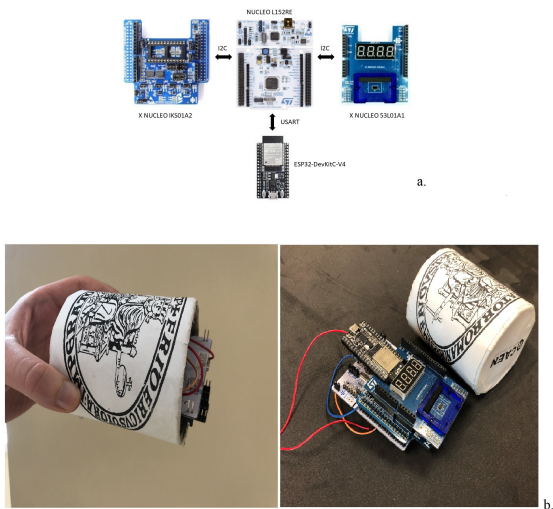


Figure 2. Block diagram of the hardware architecture for the Safe Environment (a) and Target for AR app with hardware architecture (b)

digital charge integration algorithm. The i-Spector Digital can be controlled through Ethernet and provides as output an analog amplified signal and a 4k channels energy spectrum calculated onboard [52].

The Real environment includes then two motor drivers XNUCLEO IHM01A1 by STMicroelectronics based on L6474 current control and mandated to control 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.

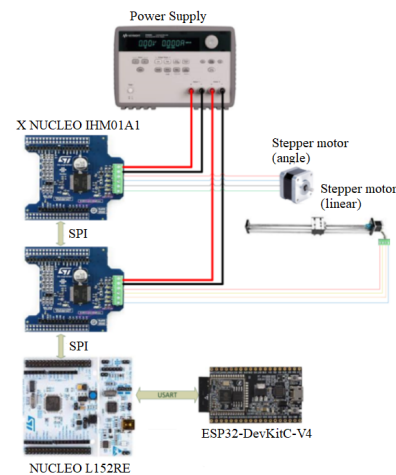


Figure 3. Block diagram of the hardware architecture for the Real Environment

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

In order to allow students to view the radioactive source and the gamma ray detector, an Android app has been developed. The app, developed in *Unity 3D* environment, allows student to visualize reproduction of the gamma ray detector and the radioactive source, 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 seconds, 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, .

For what concerns 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 (Figura 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.

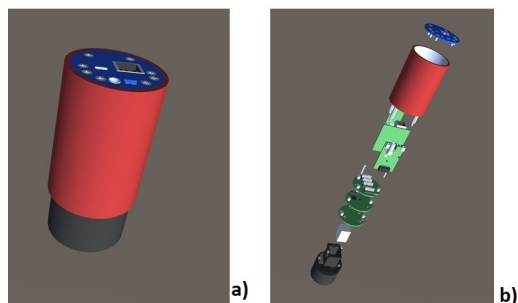


Figure 4. Results of the Gamma ray detector scan through Laser ScanArm (a) and exploded view allowing students and teacher to visualize the internal components of the detector (b).

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 (Figura 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 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 2, 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

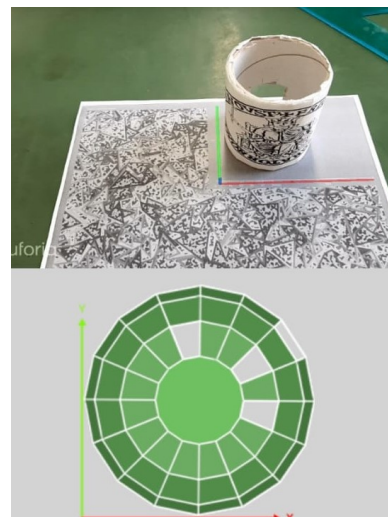


Figure 5. Training stage of detector marker recognition by means of Vuforia Object Scanner.

gravity acceleration components are collected by the sensors. The inclination angle is derived from the acceleration data on the three axes through the following equation:

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

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

Algorithm 1 Distance and angle derived

```

1: Initialize X NUCLEO 53L0A1 and X NUCLEO IKS01A2 boards;
2: Setting parameters for USART communication.
   LOOP Process
3: if X NUCLEO 53L0A1 board status ok? then
4:   while true do
5:     Read distance and accelerometer data from boards;
6:     Derive angle from acceleration on the three axes;
7:     Send data via USART to ESP32 microcontroller
8:   end while
9: else
10:  stop the execution
11: 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 this possible; one motor drives a linear guide to implement the distance from the source, while the other one actuates tilt movements (Figura 6).

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

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 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.

Tabella 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

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

		Nominal angle [$^\circ$]						
		-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

Finally, the operation of the proposed case study has been assessed; for the sake of the clarity, a composition of some pictures associate with a typical application example is shown in Figura 9. In particular, the Figura 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, Figura 9.b shows the corresponding configuration of stepped motors and actual gamma ray detector in the Real environment. As it can be appreciated in Figura 9.c, the interface of the mobile app is equipped with a button menu to allow the user to request the energy, 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.

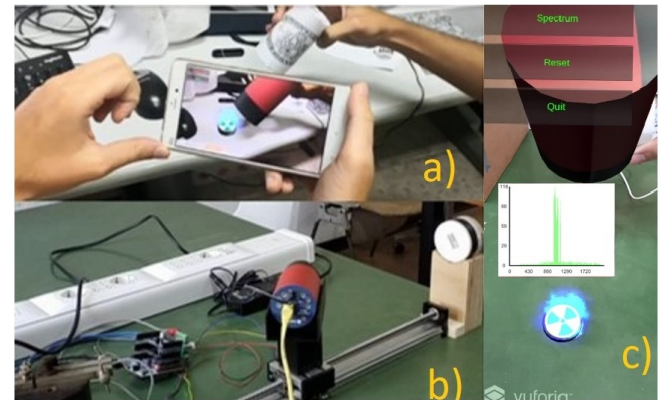


Figura 9. Details of the implemented prototype of the proposed solution; a) Safe environment, b) Real environment and c) interface of the realized app for the measurements of gamma ray energy spectrum.

V. CONCLUSIONS

A solution exploiting augmented reality to allow students to carry out dangerous laboratory experiences in safe condition has been proposed in the paper; proposed 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. Moreover, the adopted communication protocol makes it possible its extension and application within the Industrial IoT paradigm.

VI. ACKNOWLEDGEMENT

The authors want to thank Dr. Alessandro Cortopassi, Dr. Franco Vivaldi and Dr. Cristina Mattone from CAEN S.p.A. for the offered opportunity of testing the proposed AR solution on their gamma ray detector i-Spector.

Moreover, the authors wish to thanks A. Smith, M. D'Angelo and S. Cannavacciuolo from STMMicroelectronics at Arzano (Italy) for both the offered opportunity of testing the proposed solution on their STM32 microcontrollers and the technical support during the execution of the experimental tests.

Finally, the authors wants to thanks Dr. Francesco de Pandi for the techical support.

Riferimenti bibliografici

- [1] Ejiwale, James A. "Facilitating teaching and learning across STEM fields." *Journal of STEM Education: Innovations and Research* 13.3 (2012).
- [2] Bolla, Jennifer, Retha Meier, and Elizabeth Meyr. "The Safety of Physics Science Activities in a High School Physics Classroom." *Open Journal of Social Sciences* 4.08 (2016): 133.
- [3] Ashton, Kevin. "That 'internet of things' thing." *RFID journal* 22.7 (2009): 97-114.
- [4] Vermesan, Ovidiu, and Peter Friess, eds. *Internet of things: converging technologies for smart environments and integrated ecosystems*. River publishers, 2013.
- [5] Vermesan, Ovidiu, and Peter Friess, eds. *Internet of things-from research and innovation to market deployment*. Vol. 29. Aalborg: River publishers, 2014.
- [6] Pruet, Putjorn, et al. "Exploring the Internet of "Educational Things"(IoET) in rural underprivileged areas." *2015 12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*. IEEE, 2015.
- [7] Liana, Yeni Rima, S. Linuwih, and S. Sulhadi. "The Development of Thermodynamics Law Experiment Media Based on IoT: Laboratory Activities Through Science Problem Solving for Gifted Young Scientists." *Jurnal Penelitian & Pengembangan Pendidikan Fisika* 6.1 (2020): 51-64.
- [8] Ibáñez, María-Blanca, and Carlos Delgado-Kloos. "Augmented reality for STEM learning: A systematic review." *Computers & Education* 123 (2018): 109-123.
- [9] Mylonas, Georgios, Christos Triantafyllis, and Dimitrios Amaxilatis. "An augmented reality prototype for supporting IoT-based educational activities for energy-efficient school buildings." *Electronic Notes in Theoretical Computer Science* 343 (2019): 89-101.
- [10] Liarokapis, Fotis, et al. "Web3D and augmented reality to support engineering education." *World transactions on engineering and technology education* 3.1 (2004): 11-14.
- [11] Mathews, Suja P., and R. Raju Gondkar. "Solution integration approach using iot in education system." *International Journal of Computer Trends and Technology (IJCTT)* 45.1 (2017).
- [12] Irwandi, I., et al. "MEMS and IoT applications in ISLE-based STEM physics learning media for mechanics topic with LabVIEW integration." *Journal of Physics: Conference Series*. Vol. 1462. No. 1. IOP Publishing, 2020.
- [13] Saidin, Nor Farhah, N. D. A. Halim, and Noraffandy Yahaya. "A review of research on augmented reality in education: Advantages and applications." *International education studies* 8.13 (2015): 1-8.
- [14] Billingham, Mark. "Augmented reality in education." *New horizons for learning* 12.5 (2002): 1-5.
- [15] Ke, Fengfeng, and Yu-Chang Hsu. "Mobile augmented-reality artifact creation as a component of mobile computer-supported collaborative learning." *The Internet and Higher Education* 26 (2015): 33-41.
- [16] Cho, Young Hoan, Su Yon Yim, and Sunhee Paik. "Physical and social presence in 3D virtual role-play for pre-service teachers." *The Internet and Higher Education* 25 (2015): 70-77.
- [17] Lai, Joel Weijia, and Kang Hao Cheong. "Adoption of Virtual and Augmented Reality for Mathematics Education: A Scoping Review." *IEEE ACCESS* 10 (2022): 13693-13703.
- [18] Jang, Jaehong, et al. "Augmented reality and virtual reality for learning: An examination using an extended technology acceptance model." *IEEE Access* 9 (2021): 6798-6809.
- [19] Rossano, Veronica, et al. "Augmented reality to support geometry learning." *IEEE Access* 8 (2020): 107772-107780.
- [20] Kaufmann, Hannes, and Bernd Meyer. "Simulating educational physical experiments in augmented reality." *ACM SIGGRAPH Asia 2008 Educators Programme*. 2008. 1-8.
- [21] Pittman, Corey, and Joseph J. LaViola. "PhyAR: Determining the Utility of Augmented Reality for Physics Education in the Classroom." *2020 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*. IEEE, 2020.
- [22] Radu, Iulian, and Bertrand Schneider. "What can we learn from augmented reality (AR)? Benefits and drawbacks of AR for inquiry-based learning of physics." *Proceedings of the 2019 CHI conference on human factors in computing systems*. 2019.
- [23] Abdüsselam, Mustafa Serkan. "Teachers' and students' views on using augmented reality environments in physics education: 11th grade magnetism topic example." *Pegem Journal of Education and Instruction* 4.1 (2014): 59-74.
- [24] Sung, Nak-Jun, et al. "Real-time augmented reality physics simulator for education." *Applied Sciences* 9.19 (2019): 4019.
- [25] Enyedy, Noel, et al. "Learning physics through play in an augmented reality environment." *International journal of computer-supported collaborative learning* 7.3 (2012): 347-378.
- [26] Suprpto, Nadi, Wisnu Nandyansah, and Husni Mubarak. "An evaluation of the "PicsAR" research project: An augmented reality in physics learning." *International Journal of Emerging Technologies in Learning (IJET)* 15.10 (2020): 113-125.
- [27] Tarnq, Wernhuar, Yu-Jun Lin, and Kuo-Liang Ou. "A virtual experiment for learning the principle of daniel cell based on augmented reality." *Applied Sciences* 11.2 (2021): 762.
- [28] Lee, Kangdon. "Augmented reality in education and training." *TechTrends* 56.2 (2012): 13-21.
- [29] Rojo, Ana, Laura Raya, and Alberto Sanchez. "A novel mixed reality solution based on learning environment for sutures in minor surgery." *Applied Sciences* 11.5 (2021): 2335.
- [30] Hruntova, Tetiana V., et al. "Augmented reality tools in physics training at higher technical educational institutions." *Proceedings of the 1st International Workshop on Augmented Reality in Education Kryvyi Rih, Ukraine* (2018).
- [31] Chen, Shih-Yeh, and Shiang-Yao Liu. "Using augmented reality to experiment with elements in a chemistry course." *Computers in Human Behavior* 111 (2020): 106418.
- [32] Moran, Michael E. "The da Vinci robot." *Journal of endourology* 20.12 (2006): 986-990.
- [33] Byrn, John C., et al. "Three-dimensional imaging improves surgical performance for both novice and experienced operators using the da Vinci Robot System." *The American Journal of Surgery* 193.4 (2007): 519-522.
- [34] Iso/iec 20922:2016 information technology – message queuing telemetry transport (mqtt) v3.1.1 (06/15/2016).
- [35] Hillar, Gaston C. *MQTT Essentials-A lightweight IoT protocol*. Packt Publishing Ltd, 2017.
- [36] A. Bianco, Why taking risks in the classroom pays off for students—and teachers <https://www.edsurge.com/news/2018-02-14-why-taking-risks-in-the-classroom-pays-off-for-students-and-teachers>(2018).

- [37] S. of Education, The benefits of risk-taking in the classroom <https://soeonline.american.edu/blog/benefits-of-risk-taking> (2020).
- [38] Bagher, Askari Mohammad, Mirzaei Vahid, and Mirhabibi Mohsen. "Introduction to radioactive materials." *J Renew Sust Energ* 3 (2014): 59-67.
- [39] Nelson, G., and Doug Reilly. "Gamma-ray interactions with matter." *Passive nondestructive analysis of nuclear materials* 2 (1991): 27-42.
- [40] Pasternack, Bernard S. "Linear estimation and the analysis of gamma ray pulse-height spectra." *Technometrics* 4.4 (1962): 565-571.
- [41] Kumaran, M. K., and M. Bomberg. *A gamma-spectrometer for determination of density distribution and moisture distribution in building materials*. National Research Council Canada. Division of Building Research, 1985.
- [42] Fleck, K., N. Cavanagh, and G. Sarri. "Conceptual design of a high-flux multi-GeV gamma-ray spectrometer." *Scientific Reports* 10.1 (2020): 1-7.
- [43] Greenberg, Robert R., Peter Bode, and Elisabete A. De Nadai Fernandes. "Neutron activation analysis: a primary method of measurement." *Spectrochimica Acta Part B: Atomic Spectroscopy* 66.3-4 (2011): 193-241.
- [44] Rietjens, LH Th, et al. "Influence of the distance between source and crystal on the detection-efficiency of a gamma-scintillation spectrometer." *Physica* 21.1-5 (1954): 110-116.
- [45] Rydin, R. A. "Resolution, Efficiency and Background Effects in Semiconductor Sandwich Fast Neutron Spectrometers. EUR 2994." (1966).
- [46] X-nucleo-5310a1 ranging and gesture detection sensor expansion board based on v15310x for stm32 nucleo, datasheet (2016).
- [47] Getting started with the x-nucleo-iks01a2 motion mems and environmental sensor expansion board for stm32 nucleo, datasheet (2017).
- [48] World's smallest time-of-flight ranging and gesture detection sensor,datasheet (2018).
- [49] inemo inertial module: always-on 3d accelerometer and 3d gyroscope, datasheet (2017).
- [50] Stm32 nucleo-64 boards (mb1136), datasheet (2020).
- [51] Esp32-wroom-32d & esp32-wroom-32u, datasheet (2021).
- [52] Caen, I-spector digital, <https://www.caen.it/products/i-spector-digital/>.
- [53] Fully integrated microstepping motor driver, datasheet (2015).
- [54] Motion king 17hs stepper motor 42mm 1.8 degree, http://www.motionking.com/Products/Hybrid_Stepper_Motors/17HS_Stepper_Motor_42mm_1.8degree.html (2020).
- [55] Stepper motor driver expansion board based on l6474 for stm32 nucleo, datasheet (2015).
- [56] Faro edge scanarm@laser line scanning with a competitive advantage,datasheet (2011).



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. Since 2020, he has been an Associate Professor of mechanical and thermal measurements with the Department of Industrial Engineering, University of Naples Federico II. He is currently the Head of Laboratory for Industry 4.0 and IoT Measurements at the 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 interests include electrical, electronic, mechanical, and thermal measurements. In particular, he is currently dealing with the definition, implementation, and characterization of the Internet-of-Thing-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. degree (cum laude) in electrical engineering and the Ph.D. degree 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 an 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 involve advanced measurements for monitoring and protection of electrical power systems, IoT sensors for electrical measurements, and distributed measurement systems and augmented reality (AR)-based remote laboratory. Dr. Liccardo is a member of the Italian society of electrical and electronic measurements. She received several awards for both her articles and research outcomes. She is involved in the editorial board of different international journals and served in the technical committee of several conferences and workshops.



FRANCESCO BONAVALONTÀ 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 students of master's degree in electrical engineering at the University of Naples Federico II. His research activity is centered in the area of 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, its research activities are focusing on the development of innovative measurement sensors based on artificial intelligence algorithms. Dr. Bonavolontà is a member of the Technical Committee TC-37 on Measurement and Networking of the IEEE Instrumentation and Measurement Society.



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 National Research Council of Italy (Institute of Polymers, Composites and Biomaterials), Naples, Italy. He is responsible for the Mechanical Properties Laboratory and the Reverse Engineering Laboratory. Over the past years, he supervised Ph.D. students and M.D. students as a Professor at different universities in Italy. He is also a member of the Italian Association of Design Methods and Tools for Industrial Engineering. He was 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, bio-printing, 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 currently the author of international papers, book chapters, and communications/contributions in international and national conferences. Mr. Gloria is also a member of international scientific committees and chaired technical sessions in seminars, conferences, and workshops. He received many national and international awards. He was awarded and appointed as "Future Leader" in Science and Technology ("Dialogue between Nobel Laureates and Future Leaders," STS forum—October 2015, Kyoto, Japan). He is also a reviewer and an editorial board member of international scientific journals.



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 activity can be divided into 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 photoplethysmographic technique to measure heartbeat and on thermal camera to measure body temperature.



GIORGIO de ALTERIIS is a postdoc researcher with the Department of Industrial Engineering (DII) and Advanced Metrological and Technological Services Center (CeSMA) from the University of Naples Federico II. He has reached his M.S. degree in Electrotechnical Engineering from the University of Naples Federico II and the Ph.D. degree in Technology, Innovation, and Management from the University of Naples Federico II and the University of Bergamo. His research interests focus on mechanical and thermal measurements and guidance navigation and control using MEMS technology for inertial navigation, both for measurements and the data fusion algorithm. His research activity is currently oriented on innovative methods based on a redundant MEMS IMU configuration for bias and drift compensation. His scientific interests are also for microcontrollers and sensors for IoT-based distributed monitoring systems.

...