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Innovative Applications of Environmental Monitoring using Medical Physics-Based Radiation Sensors

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Annotation: An increase in human sources of radioactivity in the environment may lead to a significantly higher background of natural or artificial ionizing radiation. Even if levels are not generally hazardous, the uncertainties for cancer and hereditary risks in moderate and high doses are not yet quantifiable. In addition, a lot of intentional or unintentional accidents involving a source of ionizing radiation lead to local contamination or a terrestrial contamination plume. Immediately after the event, the authorities working on a tragedy have to deal with many problems, including the radiological characterization of the region, the mapping of the contamination levels, the classification of the areas in terms of intervention measures for protecting the population, etc. The aim of this work package is to remove these problems and make the identification of contamination as short as possible, in order to avoid panic and chaos.

For this purpose, it is possible to develop a radiation sensor based on the position sensing of scintillation light in a coplanar grid (CPG) detector, where the scintillation process is carried out in a sodium iodide (NaI) crystal scintillator. The secondary ionic scintillation threshold is lower than that from scintillation light. This way, it is possible to have a portable detector, which may be a complement to the present ones, especially those allowing these problems and tasks to be performed silently and in a completely remote way. The high sensitivity of a CPG detector for the electromagnetic radiation produced by the scintillation permits the localization of the scintillation activity and also generates an image that allows a quick overview of the extension of the contaminations, as well as the precise localization of hot spots.

Keywords: Radiation sensors, environmental monitoring, medical physics, ionizing radiation, scintillation detectors, Geiger-Müller counters, semiconductor detectors, air quality monitoring, water contamination, soil pollution.

1. Introduction to Environmental Monitoring

In recent years, the worsening of climate change has become one of the biggest problems affecting the health of the planet. Thus, controlling and monitoring its indicators is essential to take action to reverse the situation. There is already a multitude of devices and ways to monitor various indicators, such as air quality or temperature, at home or on a larger scale. However, many of these sensors are quite expensive, mostly requiring professionals for use and configuration. In addition, it is essential to have a ranging infrastructure for meter provisioning and real-time data management. Thus, although there are many ways to measure and monitor it, the need for lower-cost, open-source, portable devices is needed in many situations. Medical Physics enters into this process by trying to fill this gap, designing and developing home monitoring devices that are affordable and accessible to the public at a reasonable price. Those devices devised by Medical Physics group aim to measure physical indicators affecting health or indirectly related to it: temperature, humidity, particulate matter, and electric field level. Nevertheless, the quality of these devices in terms of accuracy is analyzed and discussed, with a focus on the prototype solution capable of measuring humidity, temperature, and particulate matter in the air. Some experiments and results for the calibration and characterization of these devices are discussed. Thanks to the realization of these devices and the conversion of a laboratory into a measurement station, it is possible to access and measure a wide variety of parameters in real-time easily and automatically [1].

During this presentation, an introduction to the problem of climate change and the importance of the monitoring process are reviewed and discussed alongside the recent contributions of Medical Physics to this problem situating it within a wider context of similar devices. Subsequently, a summary of the current state of the devices being certified is also reviewed. Finally, the next steps towards the road to the deployment of these devices in homes and the future of the project are discussed.

2. Overview of Medical Physics

Medical physics is one of the fields of medical science that focuses on the development and application of technologies that use ionizing radiation or other forms of radiation with a view to optimizing their medical use on the basis of selected criteria. It is the discipline that underpins the performance of scientific systems or practices that cause biological modifications. Safety can be defined as the state or condition in which hazards are controlled or prevented. A hazard can be defined as a source of radiation or for the immediate effect of radiation. Radiation safety can therefore be defined as the control of radiation hazards. The implementations of radiation safety are based on the three basic concepts of radiation protection which are justification, optimization and limitation [1].

In hospitals, the ionizing radiation sources used in practices such as diagnosis and therapy are always the same. On their sites there are also other radiation sources such as radioactive waste storage or devices for sterilizing medical equipment. In addition, there is a range of non-ionizing radiation sources. Three systems are presented, as well as the closest detection of uncertainty measurements adapted to clinical practice which are real time radiotherapy localization monitor sub-system, ionizing radiation measurement solution in a hospital environment and calibration system for diagnostic ultra sound phantoms. The fields of application are the implementation of detection modules and systems for portable monte carlo simulation, development of fluence estimation methods based on analytical solutions, analysis and quantification of the dose-response relationship for low doses in ionization chambers, implementation of risk assessment methods for the accidental leakage of radioactive material and development of portable systems for the measurement and assessment of radiation in both health care and environmental aspects, focusing on precise reconstruction methods and applications of the acoustic emissions of the photoacoustic effect in performing using smart, utilitarian and mobile pixelated scintillator cameras. [2][3][4]

3. Radiation Sensors: Principles and Technologies

The development of the first semiconductor detector, which changed the face of radiation detection after its planes of application, is attributed to Gilbert Perciarli. In the early 1950s, a number of research groups working in various institutions produced results on an exploratory basis. However, the year 1956 is taken as the year of birth of semiconductor detectors, and the first commercially available silicon planar detectors were produced in this year by the Nuclear Electronics Group of Philco Corporation. At that time, it was commonly believed that semiconductor detectors would almost completely supplant the scintillation counters, ionization chambers, and gas-filled counters that were used for ionizing radiation measurement. Various scintillation crystals from CsI:Tl to LiI:3 were used in commercial detectors in medical physics, and the 12 mm by 12 mm NaI:Tl cylinders used in medical settings were produced by a number of prominent companies. As a result, photomultiplier tubes with various designs and sizes were produced; for example, six of the biggest 10 inch PMTs weighing nearly 20 kg each were used along with 12 inch diameters NaI:3 detectors to produce a display of high quality images of the radiopharmaceuticals that invaded the respective organs [5].

In early 1956, more than ten American companies were involved in the manufacture of scintillation counters and materials. However, this number began to diminish rapidly in view of the slow growth of the market and the sustained efforts of those companies which were diversifying into other branch markets. In France, the Philippe Company manufactured single-channel analyzers and a few modifications of analog recorders. Commercially available scintillation counters were either imported from America or handmade items. Very few scintillation crystals were produced from vacuum-sealed ampules. A little research, however, was done on crystals of newer and faster types with a view to improving the time resolution of gamma detection [1].

The Mu-Metal, Magnetically Shielded Electronics Amplifiers, Time-Analog Converters, and

Discriminators were bulky and sensitive to humidity; the modular type was No. 6L6, whereas the non-modular type was No. 8110. The double parametric amplifiers, TM252, were used for pre-amplification, followed by a couple of magnetic shielding boxes using Mu-Metal to shield them from external noise. To convert an analog signal to a digital signal, the high speed were used. A shift register which packs data for the PC side could tag bits up to 7 bits in resolution only because of the slow processing time. In addition, a high-energy delay was necessary to perform coincidence experiments.

4. Types of Radiation Sensors Used in Environmental Monitoring

In the last twenty-five years, the field of dose detection and measurement, especially concerning patient safety has evolved astonishingly. From the bulky systems resembling tables of processing equipment for detection of a few millions of dosh worth-of-chemicals used for radiation detection in nuclear plants, the development of solid-state, lightweight, portable equipment that can measure doses in near-real-time and guide clinicians to put an exact value to load in radiotherapy and CT planning has been developed. This advancement should be recognized as a landmark, since until this innovation equipments and systems for treatment planning and audit were never found. That is why, the importance of this domain is twofold. First, systems dedicated to dose detection have been and will be evolved from sporadic laboratory setup to foldable, battery-operated management systems that can be used for both protection and further experimental purposes. Second, the results expected to come from the application of this kind of equipment may change common perception on the importance of this subject in medical care [1].

The ongoing research projects are undertaking the automation of electronic setup and post-processing, developed contemporary with electron-TLD measurements, the fabrication of portable, wearable second generation personal dosimeters for high dose workplace conditions, and the further development of W-LAN connected/read and interpret devices, the previous generation results of which can provide calculation and macro planning parameters for hospitals. In contrast to the huge development that has been attained in this domain, modern chemistries are needed in the simplest, mostly used dose detection and measurement technology ever [6]. The application of natural alkali TLDs in a new conceptual detector trained on large signal temperature response analysis is being undertaken in current projects. This device is openly accessible and widely used for studies in the field of optics, biophysics and geophysical studies, but the radiation response of this simple equipment that is based ontologically different measurement method than all other commercially available systems have never been tested and either patent or journal view has been ever published. Furthermore, the manufacturing of a solid-state electronic setup for exothermic TL reading is in progress whose goal is to reach similar sensitivity to that of a standard reader, therefore significantly extending the application field of this equipment.

4.1. Ionization Chambers

An ionization chamber is composed of a conductive container filled with a gas that is subjected to a voltage gradient via an electrical field, wherein a charged particle that traverses the sensing volume will cause the release of a secondary charge of opposite sign that is subsequently collected by the electrodes generating an electrical current proportional to the initial energy deposition of the ionizing particle. These components exhibit advantageous characteristics that produce a precise measuring environment for comprehensive monitoring of beta, gamma, and X-ray radiation, including long-term stability and minimal temperature dependency, no need for a water- or oil-equilibrated geometry, high volume-to-weight ratio, indiscriminate isotopic detection, as well as the ability to integrate to produce dual-functional sensors for personnel and workplace monitoring [1]. However, a major roadblock towards the adaptation of candidate devices to 3D printing is the chemical incompatibility issues between the photo-curing polymer resin and the commercial electronic components and circuitry used. Moreover, the gas fueling setup is also prohibitive due to the ultra-high-pressure parameters required to utilize the more suitable gases for personal monitoring.

A low-voltage air-ionization chamber for radon detection was developed, suitable for households. The ion chamber design is inspired by commercial models but fabricated from low-cost homemade components. The principle is based on counting alpha particles from radon daughter isotopes causing ionization currents. The chamber detects these currents and is capable of quantifying air radon activity levels. Ion-chamber prototype measurements were validated using a lab-grade radon monitor [7].

4.2. Geiger-Müller Counters

The Geiger-Müller counter (G-M counter) is one of the most pivotal inventions in the field of modern physics and one of the most widely used radiation detectors today [8]. The G-M counter attracted attention as an effective radiation detector immediately after its invention and has since influenced the development of various applications and inventions, as well as the development of nuclear science and technology. For this reason, the G-M counter is appreciated as a scientific tool and is widely used across various fields in daily life. In particular, applications that use G-M counters for environmental monitoring have been widely announced in recent years. This situation was caused by an accident at the Fukushima Daiichi Nuclear Power Station in Japan on March 11, 2011. Some G-M counters purchased by local residents as a result of this accident have been used for the purpose of self-measurement. Some universities and institutes also point out that G-M counters are cheap and operable even with a low level of expertise. The G-M counters produced in Japan are well-known as Radiation Survey Meters (RSMs), and their performance evaluation was actively reported in a manner that is adaptable in many countries. These basic characteristics of G-M counters are addressed as some applications for environmental monitoring.

For the measurement of radiation in hospital environments, a low-cost Geiger-Muller-based radiation detector has been proposed [1]. The Geiger-Muller detector is used in many radiation laboratories because of its low cost, simplicity, and ease of use. It can measure different types of radiation, including beta, gamma, and X-rays by applying a suitable Geiger-Muller tube. In it, a Geiger-Muller tube powered by 400 volts of power supply has been tested. The Geiger-Muller counter is assembled on a breadboard and connected to a Raspberry Pi. When the Geiger-Muller tube triggers a pulse, a round led will switch on for a 100 ms interval with a beep sound, and this event is returned to the Raspberry Pi. The number of triggered requests is counted in an interval time of 60 s and a radiation dose is displayed on a web browser. A radiation dose in microSieverts per hour is derived from a fixed factor to convert the number of requests to a gamma radiation dose rate. This Geiger-Muller based radiation detector will be helpful in regularly measuring radiation in some hospital areas.

4.3. Scintillation Detectors

Scintillation detectors are widely used in nuclear imaging and environmental and personal dosimetry applications. In recent years, this technology has been further enhanced by coupling these detectors to silicon photomultipliers (SiPMs). A few commercial devices are now available incorporating this technology, but examples of standalone detectors are still rare. Plastic scintillation detectors are also an efficient and cost-effective solution for monitoring gamma radiation fields [9]. They are currently in wide use for monitoring nuclear security, environmental surveys, post-accident assessments of radiological incidents, and for radiation protection purposes, such as the monitoring of spent fuel shipments or radiation therapy sources transport. While only the last case calls for portable systems, it is important for all applications to assess the gamma radiation field in large areas in an efficient manner. In such situations, survey meters with energy-compensating Geiger-Muller tubes and scintillation detectors are widely employed. Currently available naI scintillation detectors typically combine biasing electronic circuits and PMT readout coupled to a big, fragile detector crystal. The result is a heavy and bulky instrument that is not suitable for mobile applications. Moreover, encounter ambient lighting noise and showroom designs are unsuitable for most field measurements. Differently, new solid-state light readout technologies, like SiPMs and their derivatives, are becoming increasingly popular in the last few years [10]. SiPMs are low-voltage photodetectors based on an array of single-photon avalanche diodes employing a Geiger mode of operation. They are compact, very robust with respect to ambient light conditions, and provide fast pulse rise times, typically in the 2–5 nS range. They are expected to robustly measure count rates higher than expected anywhere else. With sensor active areas of several square centimeters and a low operational voltage of ~30 V, SiPMs can detect single-photon signal and provide gains around 106, with a much lower voltage and volume if compared to traditional PMT. This translates into lighter and more compact systems, where photomultiplier biasing can be entirely avoided.

4.4. Semiconductor Detectors

In environmental monitoring applications that demand high temporal and spatial resolution, semiconductor detectors represent a serious alternative, especially in situations with limited experimental set-up access. Nowadays, detection with semiconductor devices is well-established for charged (electrons, protons, α-particles) and uncharged (X-ray, γ-ray, and neutron) radiation. Detectors based on Silicon and Silicon Carbide allow the characterization of ionizing radiation sources partially or totally hidden from direct view, such as laser-generated plasmas, ultraviolet sources, and radioactive sources [11]. Different surface and depth active depletion zones are used to detect low and high energetic particles. Both X-ray emissions can be detected thanks to a near-surface region with a high electric field and a low doping concentration.

General-purpose Semiconductor Strip Detectors with metalized and interdigited contacts fabricated on SiC substrates are suitable for high-rate time-of-flight measurements and event-by-event spectroscopic detection, respectively. Depending on the radiation fluence, silicon surface barrier detectors with 3D interdigited contacts, fast Diamond detectors, and 4H-SiC detectors with planar and Schottky contacts can work in both detection modes [12]. Radiation detection with SiC has gained increasing attention in the last decade for X-ray and charged particle detection applications. This is due to its greater band gap compared to Silicon, making it less sensitive to detrimental radiation damage. In addition, SiC detectors at room temperature are capable of detecting ultraviolet, X-ray, electrons, and ions with excellent charge collection efficiency.

In particular, stealthy γ-ray detection relies on coherent Rayleigh scattering. γ-ray light is detected at a distance with a dedication of time-of-flight energy spectral measurements. Right incident angle and choice of appropriately doped nitride waveguides are important. This paper presents the results of time superficial inspection techniques, measurements in laboratories, and prospects for damping with surface- or bulk-mounted SED, MEMS to be designed.

5. Innovative Applications of Radiation Sensors

Innovative environmental monitoring applications based on commercial sensors for radiation measurement are presented. Three particular devices, in a portable version and applied to outdoor environmental monitoring, are detailed. These are solutions designed to read commercial, affordable, and easy-to-use sensors. The initial focus is on ionizing radiation monitoring solutions based on NaI detectors. Then, a new monitoring solution, adapted to read commercial plastic scintillators, is explained. Finally, a solid-state solution to read natural radioactivity from radon and thoron is presented. The devices stage, manufacture, and testing costs are also commented on. Discussion of their restrictive features is included, which could be turned into strengths with commercial value by their corresponding developments and adjustments [1].

The solid-state sensor is an affordable commercial set that could be adaptive to low-cost environmental monitoring. The Radon, thoron, and temperature readings of the sensor can be saved on an SD card in a simple .csv file format. Temperature values are set in Celsius. The reading time can be adjusted by sending commands to the sensor, depending on the monitoring purposes. These results need to be converted into text-readable temperature values. Each number needs to be treated separately, translated into the integer and decimal parts, and identified by their corresponding digit position. The data written into the SD card need to be processed to show information that can be directly understood. Each reading needs to be separated by periods to collect totals and formatted into .txt values to be understood by the acquisition software. Code was developed to control the different tasks where the sensor was read, and local data were stored. Sensors could be connected, and multiple readings could be done and sent to local hard drives in a time-adjustable way. All information is kept on the computer in case of programming or power issues, making the system robust and reliable. Exact reading times could be controlled or adjusted, which is a feature missed in readout solutions that could be further investigated to increase competitiveness.

5.1. Air Quality Monitoring

Insufficient air quality can result in many health problems, which is why guidelines have grown stricter. Air quality reference stations are the gold standard for measuring the presence and concentration of certain pollutants; however, these devices are expensive and difficult to deploy and maintain extensively. Partly due to that dataset that showed air quality in the world, an increasing number of studies have examined the correlation between the measurements from so-called "affordable" sensors and the reference station readings to provide better frameworks to offset the deviations in measurements. The development of low-cost sensors and consumer electronics, such as Arduino-type sensors, has opened the way to new environmental monitoring opportunities. Backed by low-cost microcontrollers and the Internet of Things paradigm, a myriad number of campaign systems dedicated to air quality, both stationary and mobile, have been deployed in metropolitan areas to accurately monitor and uncover each pollutant's distributions to generate pollution maps and history graph for policy formulation. More recently, there have been attempts to harvest internet-connected sensors to monitor the air quality in a citizen-driven manner.

This provides real-time coverage of air quality where data is shared daily via social networks. There are several reported attempts to measure and monitor the presence of air pollutants, including systems that use an array of low-cost micromachined metal oxide semi-conductor sensors to detect CO, O3, and CH4, deployed in indoor environments. The sensors communicate their data using an array of microprocessors. The measurements are sent to a server, where they can be visualized via an online dashboard in near real-time. In addition to detecting air pollutants, it is possible to deduce the temperature and humidity of the monitored place. Earlier versions of the system contained a single gas sensor and were tested only in Tallinn. With the optimized firmware, the system has been greatly improved to 9 gas sensors and is compatible with wide-area wireless technologies, approved for use in Europe. Its capabilities were demonstrated through deployment in several cities, including Helsinki, Tasikmalaya, and Southampton, with the goal of further testing in a commercial environment with automated quality-checking telemetry to improve reliability and portability.

5.2. Water Safety Assessment

Water safety means the safety of drinking water and the operation of water pipeline networks. Approaches include understanding common hazards that threaten the water safety and monitoring of hazard exposure in terms of quantity and quality. Chemical, as well as biological types of parameters, are the focus of the monitoring. Overall water quality assessment is challenging due to the overwhelming diversity of water quality parameters and technologies for their monitoring.

Water quality sensing has been well established in water safety monitoring. For the safety of drinking water, parameters like temperature, pH, residual free chlorine (RFC), turbidity, and the concentration of hazardous chemical contaminants like bisphenol A (BPA) need to be monitored.

For municipal water pipeline networks, similar water parameters need to be monitored to understand the safety of pipeline operations, such as control of urban flooding and identification of pipe ruptures leading to drinking water contamination. However, in existing smart water networks with water quality monitoring, water quality sensing systems are often costly and bulky. Water quality detection often relies on spectrometry-based or chromatography techniques that require costly instrumentation, skilled personnel, and time-consuming chemical preparation. This creates a pressing need for the development of low-cost and portable devices for rapid and real-time water quality monitoring.

A Multi-Parameter Water Quality Monitoring System (MWQMS), in conjunction with smart data-acquisition algorithms, is developed for the simultaneous measurement of pH, RFC, temperature, and BPA. The MWQMS is composed of multi-channel electrochemical sensors for pH, RFC, and BPA. The sensor outputs are processed using a low-cost and low-power microcontroller. Data are then transmitted wirelessly via Bluetooth to a smart device to be visualized in customized software. An assessment on the sensing performance of the MWQMS is conducted using lab-synthesized buffers and real drinking water samples. This is the first low-cost and compact MWQMS capable of the simultaneous real-time, hand-held, multi-parameter measurement of water quality for small-scale applications. It has great promise in drinking water and swimming pool monitoring and other water quality safety assessment applications [13].

5.3. Soil Contamination Detection

Soil pollution can be caused by natural or anthropogenic activity, including rapid urban development, industrial transformation, land cultivation, or improper solid waste disposal. However, soil is often disregarded and regarded as a passive resource, undergoing extensive modifications made to accommodate human activities and endure uncontrolled disposal of harmful pollutants. Hence, there is rising concern regarding the state of contamination of soil. Investigation of soil contamination must begin with a comprehensive spatial knowledge of the degree of pollution of the site, and gamma-ray spectrometry has already been successfully applied in this field [14].

Artificial intelligence is constantly iterating and developing methods for the analysis of natural and technical systems, which can hence be used for the analysis of the radiation field. Multiple applications can be enumerated, including radiation probe wireless nodes based on scintillating or semiconductor materials, aerial survey services using drones or light manned aircraft, and satellite detection services. These services will be described to give an insight into the state-of-the-art equipment and methodologies for environmental monitoring. In addition, they can serve as an indication of what components can be combined to devise an innovative approach by bridging different technologies already existing in this field. It is expected that the fusion of these technologies will create a vast array of artificial intelligence and creative applications for solving urgent environmental problems requiring continuous monitoring of dynamic motivating events (e.g., soil contamination).

5.4. Radiation Mapping in Urban Areas

It is widely acknowledged that radioactive sources pose potential threats in a variety of situations, including nuclear terrorism and accidents. Therefore, radiation monitoring allows for the detection of malicious objects that could cause severe damage. While many systems are designed and deployed to monitor a predetermined area, there are cases where prior knowledge of the search area is not available. For instance, there are inclinations to use a mobile radiation sensor system on an unmanned aerial vehicle (UAV) for wide area search to mitigate a radiation crisis [15]. A calibration-free method is proposed to reconstruct the spatial distribution of radiation based on a DoA-observable route and an adaptive averaging technique to utilize information from accumulated observations. The systematic errors of the calibrated 2D radiation map are examined. Under the requirement of only a partial site knowledge, an initial and a resolved map are illustrated.

Gamma radiation mapping in urban areas is critical for a range of safety/security applications including: detection and localization of radiological/nuclear material such as lost medical isotopes, smuggled material, orphan sources, nuclear waste, illicit nuclear devices; characterization of large areas for remediation after an incident or natural disaster; monitoring the environment and alerting to changes that may indicate illicit activity. Conventional systems that with limited angular coverage offering a 2D representation of the radiation field require hours to acquire a map. A deployed system including an unmanned aerial vehicle (UAV) or ground robotic vehicle with 360 degree coverage generates a 3D more informative map in less time [16]. Given a trajectory, a 3D map formation can be broken down into a series of 2D frames based on the mapping algorithm framework. However, too coarse a trajectory causes missed detections, jagged expected estimates, and poor accuracy. Too small a step size results in redundancy and wasting processing time. Thus, a trajectory optimization method is proposed to find the best one in terms of maximum coverage of the map and minimum cost of the traversal path. In addition, an appropriate noise level for the mapping system to follow under this trajectory is derived, yielding a requirement based on realistic physical constraints. This new trajectory optimization and noise estimation framework could be transferred into various sensor mapping systems to improve mapping performance.

6. Integration of Sensors into Environmental Monitoring Systems

The educational application system of environmental monitoring leverages various types of sensors to monitor different environmental data. These sensors, which require specific data acquisition circuits, are connected to communication interfaces, namely ZigBee, GPRS, Wi-Fi, and RS485, so the system can connect to the internet and process the data. GPRS is typically integrated into main control circuits, power supply detection, power supply activation control buttons, data analysis circuits, and power amplifier circuits. The main control circuit comprises STM32 chips, and a high-precision temperature and humidity sensor is utilized. Furthermore, the data analysis circuit is embedded with a relay and a duty cycle controller. Power detection is conducted using a linear voltage regulator and voltage divider, while the power supply activation control button is incorporated into the system circuit using N-channel MOSFETs [17].

Using a variety of sensors produces a lot of data, and how to transmit or collect data is another crucial technical aspect. A sensor combines communication modules for communication, enabling communication to be established through microcontroller pin control. Typically, ZigBee technology is used to establish wireless sensor networks, where data is not directly transmitted. Instead, serial communication or short-distance transmission circuits are used to send data to communication modules, and data is transmitted to the software. GPRS is frequently used to upload data to the cloud platform and can thus choose either SIM800 (GPRS) or SIM900 (GSM) modules [6].

Proximity sensors use many types of probe electrode structures, including sawtooth thin film structures, step-bar thin film structures, Holed Ring thin film structures, disk thin film structures, Ring-ring thin film electrode structures, and others. These have been investigated for application in vapor detection with various Analyte agents such as Toluene, Flammable Gas CO, CO2, HCHO, VOCs, and NH3. A commercial version of an FID was fabricated to compare with the constructed sensor’s performance in SMD2320. The performance of various fiber optic temperature sensors and optical micro-structural hydrogen sensors will be presented. Lab-on-chip biosensors made on flexible substrate materials such as PHB/PHV paper, polyimide, and cellulose paper have been developed using fast prototyping techniques such as laser micromachining and molding techniques.

6.1. Data Collection and Analysis

Monitoring the environmental impact of radiation sources is essential in a variety of fields such as security, health, and consumer product safety, where the experience and knowledge of physicists are frequently applied. This section discusses an alternate use of standard hospitalgrade radiation measuring devices, repurposing them for environmental monitoring by the medical physics community. Sensor data are sent to an online dashboard that indicates their location on a map and allows real-time comparison with pre-set thresholds for alarms. Various case studies focus on the radiation background monitoring of hospitals, with short-term examples concerning the demo using sensor data from one hospital's collecting equipment.

The device includes a survey meter and charged particle detectors, interfacing standard lectures with a Raspberry Pi microcomputer running custom software. The measured data are sent to an online dashboard that translates them for easy interpretation by non-specialists. Data are sent in a web server, with a string indicating the sensor serial number, the measurement date, the measured radiation values, and their total filter. Each state on the screen is defined by a minimum and maximum radiation value, with parameters defined in a JSON file. If the radiation measurement is not in that range, the box around the radiation value turns red.

A deployment of an array of devices at the hospital measuring background radiation stands as an example of the technology's application across several sites. Sensor data were provided for a month, with deployed background radiation measurements ranging from 0.03 to 0.18 μSv/h. These values are in line with background counts reported by the [1]. System storage is performed in the morning hours to account for the last minutes of operation at dayclose, with data details and admission ranges over time displayed. Data can be further processed as needed, demonstrating the use of standard data streams in custom solutions.

6.2. Real-Time Monitoring Solutions

Ionizing radiation measurement solutions are necessary in hospitals to ensure worker and patient safety. Continuous control of the ambient conditions is needed due to high fluxes of machine-generated x-rays in both therapeutic and diagnostic treatments. Since ionizing radiation is invisible and travels through air with near-zero attenuation, it must be monitored and controlled with electronic dosimeters. This is critical because the ionization effect that rays produce in tissue can lead to damage at the cell level, mainly the creation of free radicals, which in turn can lead to cell death or sporadic growth mutation that may expand into tumors. For these reasons, the monitoring of ionizing radiation exposure is strictly regulated by European directives, limiting each worker dose depending on the work category [1].

The high-energy machines that produce these high photos must also be controlled. Radiation from energetic beams can reach other rooms and hospital workers who are not directly involved in the procedure, which produces a risk for compliance. Due to the impossibility of shielding all the beams, real-time environmental monitoring is required. Nowadays, measurement is done with either personal dosimeters, such as TLDs or films, which offer the best precision but require laboratory analysis (and therefore do not provide real-time measurements), or area survey meters, which do not deposit the data in a database since they do not have internet connectivity (but are priced lower than 500 euros).

This paper presents a low-cost, open-source radiation measurement solution for both worker and environmental monitoring with real-time measurement and continuous control via smartphone. The measurement system works with a ≈ 50 μSv/h gamma dose rate $[\mu Gy/h]$ Geiger-Muller commercial detector and Arduino Asomb232 module processing and connecting. With these components, input signal plugs are conditioned, and the total count of ionizing events is stored. This value allows the dose calculation with a simple equation that considers the detector calibration factor, and this sampled reading is sent to an open-access firebase database. Layout design of the user application is done to provide necessary conditions for minimum power consumption while allowing real-time access to registered data. The system can operate even without access to the internet and functions with minimal battery ships. The system is certified by a calibration center accredited by the Spanish National Accreditation Body and has been validated within a hospital environment.

7. Case Studies of Successful Implementations

The hybrid personal dosimeter is designed to be accessible and efficient for real-time dose measuring [1]. The system allows for the ionizing radiation measurement in hospitals. IoT system includes a network of sensors deployed in the environment, a server with a database to store data from sensors of the network, a server to manage it, and a smartphone application to receive real-time information from the server. Data is transmitted in real-time from the sensors to the server, where they are processed. That state of the network is visualized on the server, and relevant information is sent to the smartphone application. An extended version of the solution is cheaper than current commercial systems, and it is designed with an open-source philosophy. It can be deployed as a prototype or adapted to personal use, bringing the long-awaited real-time dose vision to the field of health professionals. The system was developed as a first step into an independent formulation of the concerns brought by the lack of awareness of the operation, and the surroundings where users work with ionizing radiation every day.

A hospital dose monitoring system deploys a network of sensors across the environment, consisting of a distributed network of sensor nodes and a cloud server hosted in the institution's intranet, replacing the current manual upload procedure with an automated upload. Each sensor node was designed as a low-cost and compact solution taking advantage of available commercial components and open-source designs. The hospitals deploying each system are configured as servers. Calibration tests were performed on seven sensor boards and three reference detectors. Each sensor board was deployed in two hospitals with a laboratory-grade dosimeter, and seed dose test results were confirmed against calibrated dosimeters.

7.1. Case Study 1: Urban Air Quality

Air quality (AQ) is a well-established factor of urban life. Numerous airborne pollutants are associated with short-term and long-term adverse effects on human health, [18]. Some have been proven to be a risk for asthma and other respiratory conditions, for cardiovascular disease; others have been linked to neurological disorders and even cancers. Even worse, exposure to air pollutants is associated with an increase in premature deaths. The scientific community and Public Health Institutions have made great efforts to understand the effects of air pollution and mitigate its sources. Essentially, regulations have been passed in various countries to force efforts in improving air quality, and in many cities, technological efforts have been made to achieve better AQ in smart city solutions. Despite these efforts, however, AQ still shows strong regional and environmental disparities. Only a comprehensive knowledge of air quality can facilitate intelligent traffic management, and provide citizens with the knowledge to better protect themselves.

To this aim, regulatory stations for air quality monitoring (AQMS) have been deployed worldwide according to strict frameworks. Such devices are based on high-end instruments with very accurate sensors to respect monitoring uncertainties that cannot exceed the regulatory limits. Their cost can span from hundreds of thousands of euros to even millions, thus their number is limited. The high cost, lacking variability, demanding maintenance, and challenging calibration render these references seldom in time and space. Low-cost microsensor devices that can be deployed on the vehicles of citizens for a pervasive understanding of the air quality have appeared on the market. Such instruments can sample and transmit data in real time. They are modular, thus additional sensors can be added to provide greater contextual information. High flexibility and low cost enable the use of large sensor networks that can outperform even the denser fixed monitoring stations in temporality, but also in spatiality.

This technology is still in an unripe state, however; sensors can exhibit unexpectedly large errors sourced by environmental interference, sensor aging, and calibration degradation. The remaining significant differences between portable sensors and regulatory stations have prompted regulatory bodies to create guidelines to assess low-cost microsensors readings validity. Under this context, the H2020 EU Project aims to increase the number of smart cities for air quality monitoring. In particular, it targets mass citizen involvement in the air quality monitoring process through crowdsensed networks of low-cost microsensor nodes capable of accurate and dependable measurements.

7.2. Case Study 2: Contaminated Water Sources

A second case study addresses water contamination from sources such as human or animal feces, fertilizers, or toxic waste runoff. This occurs frequently during flooding or catastrophic events, but can also occur as an unintended result of irrigation, chemicals, or leaky old pipes. Measurement of absorbance at 254 nm as surrogates for both inorganic contaminants and most human enteric pathogens are proposed. This approach can be used to first respond to a water contamination event, and is designed to be inexpensive and flexible in deployment directly where monitoring is most critical [19]. The ability of a series of radiation sensor designs available in a variety of sizes and shapes to provide timely and relevant information about contamination in drinking water sources is also proposed. Low-cost simple bottle-sized detectors for at least 200 measurable hours of background counts include palladium foils to self-collect lead; and for soil samples used by pond workers, basin plates with glass samples in transparent lids. Semi-automated sensors based on low energy spectrometric sensors in tamper-resistant boxes may house radioisotope-adsorbing polymeric materials, serve as sandwich traps around esophagus tubes, or trap filter membranes [20]. Containers such as Brita filters, some water pitchers, and certain flashy bottled water may embedded sensors that may be deployed elsewhere if needed.

A water source contamination event that exceeds regulatory levels of pathogen concentrations is feared. Typical plastic test tubes, petri dishes containing collagen or gelatin gels, roll filter slides, and other devices that are now being manufactured may contain passive sensors of opportunity, particularly those with photo and lunch-box ratings, but others report pathogens. Engaging locations in an effort to reduce uncertainties during extreme events will help bus fountains, school systems, stadiums, restaurants, or military bases by either waterfree utensils, or sampling protocols described above followed by chemical treatment or VMAT pipe screening protocol. Finally, other inspection protocols are described and may help.

7.3. Case Study 3: Agricultural Soil Monitoring

The long-term application of an innovative proximal gamma-ray spectrometry system in a medium-scale cooperative agricultural test site is shown. The test site aimed at monitoring soil water content in a 700×80 m2 area where a corn crop is growing, with the data used for closed-loop automatic irrigation on-demand. The gamma-ray sensor developed with a 35-cm3 NaI(Tl) scintillator and a low-power digital acquisition electronics circuit can acquire both the spectrum and the count rate variations at the 1460-keV energy line of 40K selectively. For the continuous monitoring of a large area, two-dimensional correction of the observational count rate variations was developed for efficient sensor calibration and for correcting the shielding effect of the corn biomass. The water-modified calibration was shown to hold for sugar beet and grape crops in the same soil. In this way, operational monitoring of soil water in agricultural fields was shown to be available within a 1-h observation-time and 5-cm water-content precision, and the monitoring system was proposed to be used as a decision support system for closed-loop automatic irrigation on-demand [14].

Addressing the need for monitoring soil conditions, such as chemical, physical, and biological properties, is essential for food security, climate change, and human health. Soil is the basis of key terrestrial and aquatic ecosystem services, including groundwater recharge and biomass production. However, due to human activities, especially agriculture, soil qualities have been altered, causing a loss of soil biodiversity and disruption of physical properties. Soil is not directly observable with remote sensing or on-site by visual inspection. For better understanding of soil properties, desirable soil conditions, key problems, and questions, soil monitoring should be performed, which needs to deal with the spatial coverage, data resolution, and spatial and temporal requirements. As a promising candidate that involves the last mile of data collection, a heterogeneous sensor network provides a flexible and scalable way of observing soil in field, while traditional soil survey methods are labor-intensive, costly, and only cover a snapshot of soil information [21].

8. Challenges in Environmental Monitoring with Radiation Sensors

Environmental monitoring using radiation sensors is key for environmental protection and the safety of citizens. A variety of sensors able to monitor environmental gamma radiation are commercialized. On the other hand, their application in the environmental field is not yet significantly extended. For example, the city of Tokyo actively monitors air radiation levels using commercial survey meters. Also, some municipal offices, such as Oita City in Japan, monitor levels to assure the safety of citizens but only at just one location due to a lack of widespread arrangements. The situation is the same worldwide. The environmental protection and safety of citizens could be better assured with the more extensive application of radiation sensors. This is especially true in cities where there are many radioactive materials in it as in Tokyo (>100,000), significant amounts of nuclear power plants, fuel factories, and nuclear waste temporary storages are deployed and transported or estimated to be transported [1].

As the first step toward extensive use of radiation sensors to monitor environmental gamma radiation, the development of new methods and simple arrangements for a variety of users and a new type of low-cost sensors is pursued. Various gamma radiation sensors can be arranged as stationary, handheld, and vehicle-mounted systems, which are applied to environmental monitoring. In addition, low-cost Geiger-Müller counters are designed not only for surveying but also for monitoring where it cannot be overlooked [22]. Therefore, new methods to use radiation sensors (including tristate consumption of the data) as survey meters and the adaptation to be used as a monitoring sensor are introduced.

8.1. Calibration and Maintenance Issues

The flow of any environment monitoring system, either for early detection of large ionizing particle impingement or for continuous measurements of natural radioactivity, is similar [1]. These systems take advantage of calibration functions applied to the data on event height or counting per time unit and immediately derive either radiation dose rates or useful energy deposit (pulse height) information. This output information is usually visualized on screens and can be sent to a control and command center. Analyzing the monitoring information allows a decision on the required global action, such as the closure of an area or the opening of a safe passage. All procedures, calibration computations, and possible event analysis, in the classical sense, have been published in previous references. However, detailed care must be taken for the maintenance of the measuring systems, as this is essential for properly operated and useful online environmental monitoring systems. Some suggestions and existing systems are described in this section.

Before acquiring the data, detector operation tests must also be routinely programmed. The standard evolution of the main characteristics of detectors equipped with well-known technicians makes it possible to display their evolution in the past months. This evolution determines the change of quality and the expected value for months ahead. Because the working environment of detectors, networks, and general chambers is very different and not controlled, many configurations have been proposed. For example, portable detectors must also check the correct functioning of general chambers, and station performance must be self-tested daily [23]. Even wireless detectors must afford self-testing controls. During normal operation, detectors must periodically check the validity of their calibrations. Dummy source and test pulses can be used to perform this check together with the general acquisition hardware check. In general, the system must determine the degree of discrepancy and act according to its severity (immediate exclusion, warning flag, or normal operation). To avoid huge lose times, access to the internal calibration routines, which are usually not distributed, should be implemented on all devices in the network.

In addition, procedures for recalibrating out-of-service detectors are described, along with the software and hardware implementations.

8.2. Data Interpretation Challenges

Medical physics is an important area of research and development which has taken on a significant role in health, wellness, and safety. External and environmental monitoring is an emerging area of application to better serve the overall mission of monitoring the environment and ensuring levels of radiation for the overall health, wellness, and safety of the American public. Detectors which have mostly been applied in conventional ways in medical applications and familiar to many medical physicists – nuclear scintillation detectors, ion chambers, and semiconductor detectors – have found innovative uses in external monitoring methods and systems. There are a number of areas of research and development using this technology which can be applied for environmental monitoring of both photon and neutron radiation fields. Various topic areas of focus involve challenges in either detector design, data analysis, or system integration. Detection and measurement of a range of energy photons, including alpha particles, and fast neutrons are areas where significant results have already been achieved and further research into device design improvements and validations on state-of-the-art facilities continue to be of justifiable interest. Real-time data analysis for array systems remains a large area of focus involving various approaches based on machine learning or statistical based methodology feeding an optimization algorithm which is key to large area detectors which need to balance performance with cost. Systems integration of the detectors with decision logic and display systems are large areas of focus especially to comply with government and military standards for deployable monitoring systems. Data analysis and processing of analysis results remain primary challenges for sensor applications in general. This is especially true with any number of sensor types, where the data from each sensor must be recorded, preprocessed, and processed. In particular, this is one of the main challenges of the two-layer fast neutron monitoring detector using scintillation sheets in the energy range of 0.025 to approximately 30 MeV. Each type of layer must be segmented into individual small scintillation sheets, which must have their own acquisition and processing electronics [22].

8.3. Public Perception and Acceptance

The perception and acceptance of radiation-based (including laser-based) sensors and their application for environmental monitoring by lay personnel significantly impacts this innovative technology. Addressing the public perception is essential to develop stable public relations and would help researchers know what issues should be addressed in terms of lay communication. Survey findings revealed that five societal issues about environmental monitoring were frequently mentioned: sensors as replacements for conventional solutions, automated sensors, complex sensors and diverse signals, limited public understanding of sensor technology, and research-based development of sensors. Other issues with specific frequencies include concerns about environmental changes, long-term deployment of instruments, costs, potential misuse, privacy risks, trustworthiness, and sensor placements ("who" and "where"). Because the listed issues reflect lay concerns that can potentially impede public acceptance of radiation sensors, inquiry about them or using a participatory approach by exploring mannerisms or formats of engagement or public communication involving these issues would be a way forward. The abovementioned challenges were divided into four scenarios to be debated in group settings and further in one-on-one interviews reflecting individual positioning. The survey and debates revealed three main points in the sensor-image, development scheme, and potential misuse in terms of how to visualize scientists' intuition without oversimplification.

Public acceptance of green technologies is also a multidimensional issue. The understanding of perceived benefits and risks is paramount, as it drives acceptance. Notably, awareness and knowledge are crucial in shaping perceptions; higher educational levels have long been correlated with higher awareness and knowledge regarding green technologies. The risk of a lack of awareness should be addressed by acknowledging that health concerns could generate inaction or adverse attitude formations. Thus, health monitoring must go hand in hand with a commitment to environmental protection. Furthermore, unlike other issues with uneven levels of interest or understanding among group members, public acceptance of some effects of radiation-based sensors or monitoring appeared to be universally and spontaneously common. The Global South (or developing countries) was viewed as a relevant concern by most participants, reflecting awareness that health effects associated with the intended monitoring are not exclusive to 'the community' or high-income countries [1].

9. Future Trends in Radiation Sensor Technology

Considering the new generation of applications and opportunities created by the various recent technical developments, there will be a natural way toward dispersive usage of radiation sensors thoroughly integrated with other systems, such as data acquisition, remote monitoring, and surveillance. Such systems may be fed by a variety of radiation sensor nodes to coherently monitor the respective environment where the system would operate. Each sensor can be employed in monitoring individual, specific aspects or parameters, and can contain additional sensors for measuring environmental or contextual parameters [12]. For example, gamma radiation sensors might serve to signal the presence of nuclear (waste) material, and also, a character monitoring system can be implemented, so that their energy spectrum is reconstructed in order to allow a preliminary identification of radionuclides present in the material as a function of time.

Nevertheless, this functionality would also enhance the operational safety of the system, as every potential failure or malfunction might cause an alert and preventive measures might set in, e.g., a charged particle or neutron sensor coupled to the gamma one, and additional analysis on data revealing possible case scenarios might be carried out. Particle spectral character might also reveal information on a source bias, locale, or type. Another possible use would be the possibility of cooperation between systems, which might be employed, per shape, in a network. Lower cost sensors, and/or simpler but still functional types, could reside in the field, and connect to governmental or utility monitoring centers (typically more powerful but with larger associated operational costs). Concerning this TCP/IP protocol node reaching shakiness [24], the messaging interface on which average TCP/IP networking is built is already the basis for the significant range of professional analysis packages spanning areas from commercial boundary metrology services, to containment facility operations. Suitable packages would, therefore, be non-essential inventions. This co-design process could begin with more essential, scientific, but already known results that allow many of the nurturing geographies of such systems to start being practical. [25][26]

10. Conclusion

Many of the previously mentioned systems can be tested with further improvements. They are inexpensive alternatives, with self-design software and circuits. Classical sensors can be used, limiting the miniaturization of detectors. Nevertheless, environmental monitoring in places such as schools or hospitals is essential. Medical physics systems can be adapted for this goal, making the already available circuits and software more desirable than designing new equipment.

A novel health radiation monitoring approach is presented for medical physicists' use. Hospital staff is responsible for personal dosimetry assessment, environmental radiation monitoring, and even general population exposure. The system monitors radiation dose equivalents in hospital premises with sensors and medical physics. Both passive and active area monitoring can be carried out, along with personal dosimetry.

Files generated by the devices can be easily used with free desktop software. Mobile and Cloud services distribution is also available. As a result, any institutions can maintain this system at a very low cost. Personal dose equivalent results are presented as minutes averaged dose rates rather than dose equivalent files. As a result, the contribution of single measurement points to the personal dose equivalent can be investigated. Some results for a staff member of a hospital are shown, who uses 124I for her patients. Even at work, the staff member's radiation exposure remained below the recommended action level for annual monitoring.

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