Resource Constrained Electronics and Signal Processing for UAV Radiation Sensors

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Abstract—This paper details the development of an inexpensive, power-efficient, and lightweight radiation detection system specifically designed for deployment on Unmanned Aerial Vehicles (UAVs). The system addresses the need for swift, remote radiation detection capabilities during radiological and nuclear emergencies, a demand emphasized by events such as the Fukushima accident in 2011. The design is based on readily accessible components, which lessens reliance on costly, specialized hardware like Field-Programmable Gate Arrays (FPGAs) and Application-Specific Integrated Circuits (ASICs). The proposed system comprises two types of detectors: inorganic scintillators, specifically CsI:TI and GAGG:Ce, paired with Silicon Photomultipliers (SiPMs) for gamma-ray detection, and solid-state detectors provided with a 4Li converter for thermal neutron detection. These detectors operate independently, increasing redundancy and system reliability. The system’s performance, evaluated through extensive testing, has shown significant improvements in linearity and noise characteristics over previous iterations. Beyond its primary function in emergency response, the system could find applicability in diverse fields such as environmental radiation monitoring, geological surveys, industrial inspections, and scientific research.

Keywords—UAVs, Gamma and Neutron Detectors, Mobile Radiation Detection System, Emergency Response.

I. INTRODUCTION

Following high-profile events such as the Fukushima Daiichi nuclear power plant accident in 2011 [1, 2, 3], radiation monitoring has grown in importance as a component of worldwide risk mitigation efforts; additionally, such incidents have highlighted the importance of fast, accurate, and accessible detection systems to quickly identify and locate radioactive contaminants during and after emergencies. As such, easily deployable radiation monitoring systems may result essential not only for immediate disaster response, but they may also play an important role during standard operations or over the course of recovery and decommissioning phases following the shutdown of a nuclear power plant [4, 5]. Indeed, radiation contamination data is an essential information for decision-making, especially regarding the safe reoccupation of interested areas and the extent of environmental remediation which could be required; moreover, in the context of ongoing radioactive monitoring, these systems may provide valuable data that help to understand long-term impacts on the environment and form potential future prevention strategies [6].

In response to these needs, robotics advancements and the downsizing of sensor technologies have increased the employment of Unmanned Aerial Vehicles (UAVs) as a critical instrument in dealing with Chemical, Biological, Radiological, and Nuclear (CBRN) threats [7, 8, 9]; in fact, these units provide an efficient way of investigating and assessing potentially hazardous environments, while at the same time greatly reducing the risk of personnel exposure to harmful agents than traditional methods.

By focusing on radiological and nuclear (RN) threats, the role of UAVs in countering emergencies has become increasingly significant [10, 11]; indeed, they easily allow to limit the exposure of first responders and military personnel to dangerous areas which may otherwise be impossible to reach. Moreover, the capability to swiftly approach the locations of interest enhances their detection efficiency while minimizing potential signal attenuation caused by shielding materials. Thanks to great flexibility and adaptability, UAVs equipped with specific detection systems are currently employed in several sectors, such as homeland security, nuclear safety and security, environmental recovery, and military operations [12, 13].

However, the development of UAV-based remote sensing systems faces challenges related to cost, size, power consumption, and system complexity [14]. In addition to these difficulties, many existing radiation detection systems are based on expensive hardware such as Field-Programmable Gate Arrays (FPGA) and Application-Specific Integrated Circuits (ASICs), posing barriers to widespread diffusion [15].

In response to these challenges, we propose an inexpensive and lightweight radiation detection system that can be mounted on UAVs; the architecture of the unit is based on commonly available components, an aspect which reduces the requirements of expensive and very specialized hardware and thus making the system easier to deploy at large scale. In addition, in the event of contamination, the system can be easily discarded thanks to its inexpensive nature, further reducing the risks associated with decontamination processes. Finally, our system aims to not only support first responders during emergencies but also contribute to the advancements in easily accessible radiation monitoring technologies.
II. ANALOG FRONT-END AND MULTI-CHANNEL ANALYZER

Designing an efficient and mobile radiation detection system when faced with limited computational and memory resources requires a meticulous optimization of several aspects. These include a strategic selection and integration of hardware components, the application of efficient signal acquisition and processing techniques, and fine-tuning of the overall design methodology. This section details our methodology for tackling these challenges, ultimately leading to a radiation detection system designed for integration with low take-off weight category UAVs.

Our design includes two types of detectors, specifically inorganic scintillators attached to Silicon Photomultipliers (SiPM) for gamma-ray detection, and off-the-shelf and solid-state detectors for thermal neutron detection; those units are acquired by means of two completely independent channels to improve the reliability and robustness of our system.

Signals are digitized by a Multi-Channel Analyzer (MCA) board built around a Microcontroller Unit (MCU), specifically, the AVR128DB48 model from Microchip. While this MCU comes with inherent computational limitations, such as an 8-bit architecture and a 32 MHz clock speed, it offers a range of integrated peripherals that make up for these aspects by facilitating robust and effective data acquisition and processing.

Once collected, data is transmitted to a ground station through a 2.4 GHz radio module, ensuring reliable medium to long-range communication. Additionally, the inclusion of a GPS unit in the system facilitates the geo-localization of the detectors.

A. Radiation Detectors

The inorganic scintillators utilized in our system, namely CsI:tl and GAGG:ce, were procured from Epic Crystal company (Fig. 1). Their selection was determined by the advantageous properties they offered for our specific application requirements. CsI:tl is recognized for its high light yield of 60,000 photons per MeV, peaking at 550 nm, and it offers a good energy resolution, ranging from 5.5% to 7% at 662 keV. Its high density of 4.5 g/cm³ and effective atomic number (Z_{eff}) approximating 50 contribute to robust stopping power in a small volume. Although slightly hygroscopic, CsI:tl is well-suited for UAV use due to its compact size, low weight, and ruggedness [16]. The CsI:tl crystal was wrapped in BC-642 PTFE Reflector Tape from Saint-Gobain for optimal light reflection.

Similarly, GAGG:ce presents itself as another promising candidate for UAV applications. It features a high light yield of 50,000 photons per MeV, peaking at 520 nm, with an average energy resolution of 6% to 8.5% at 662 keV. GAGG:ce boasts an even higher density of 6.6 g/cm³, leading to very high stopping power with a Z_{eff} close to 50. Benefiting from a relatively rapid decay time of 88 ns, it offers an advantage over CsI:tl, which exhibits a slower decay time of approximately 1 μs [17]. Although GAGG:ce comes at a higher cost, its superior stopping power and faster decay time make it very valuable in high counting rate situations. For optimal light reflection, the GAGG:ce crystal was coated with 0.2 mm BaSO₄ and wrapped in 0.03 mm aluminum foil.

![Inorganic scintillators, SiPM, and 3D-printed holders used to assemble the scintillation detectors.](image)

Both CsI:tl and GAGG:ce scintillators were individually optically coupled to their own 6 mm × 6 mm S13360-6050 SiPM from Hamamatsu, using BC-630 silicon optical grease. This SiPM exhibits good photon detection efficiency at both emission wavelengths, making it an excellent match for the scintillators. The crystals’ size was chosen based on a trade-off between cost, weight, and stopping power, resulting in dimensions of 40 mm × 40 mm × 10 mm.

While gamma-ray detection is crucial for identifying many radioactive and nuclear materials—especially considering that gamma-ray sources are widespread—the ability to detect thermal neutrons can be particularly useful in homeland security applications and in certain emergencies involving nuclear accidents or uncontrolled nuclear chain reactions [18].

Thus, incorporating thermal neutron detection capabilities in our system allows for a more comprehensive and nuanced understanding of a radiation environment, enhancing its utility in various emergency response scenarios. For this purpose, we selected thermal neutron detectors sourced by Radiation Detection Technologies company, which employ a Microstructured Semiconductor Neutron Detector (MSND) technology with a ⁶Li converter and 2 cm × 2 cm active area. In terms of performance, they offer up to 30% thermal neutron detection efficiency and can respond to thermal neutrons with energies up to 1 eV. Being radiation-hardened, these detectors can withstand high radiation levels without performance degradation. Importantly, they are gamma insensitive, allowing for specific neutron detection while reducing background noise from gamma rays. Thus, the incorporation of these detectors greatly enhances our system’s ability to detect nuclear threats in complex and challenging radiation environments.

B. Analog Front-end for SiPM

The design and realization of the analog front-end (Fig. 2) for the SiPM were carried out in our laboratory. This electronics architecture incorporates a charge preamplifier to process the
SiPM current, tailored with an approximate decay constant of 100 µs. Following the preamplifier, a single inverting stage serves as a CR-RC shaper provided with pole-zero cancellation and with a 5 µs time constant. Such a time constant assures the full integration of slower scintillating pulses from the CsI:Tl detector, optimizing energy resolution. However, the system may accommodate a lower time constant when employing the faster GAGG:Ce detector in high counting rate scenarios.

To avoid distortion in the signal amplitude and high counting rate complications, we used DC coupling both at the input stage between the SiPM and the preamplifier and at the output of the shaper to the MCA.

Moreover, the gain across both stages was distributed to limit an excessive reduction in bandwidth and slew rate, with the total gain empirically determined based on prior testing. This strategy balances the need for signal amplification without compromising system stability or performance.

As operational amplifiers (op-amps), we selected the OPA354 from Texas Instruments. These single-supply op amps provide very high speed, with a gain bandwidth product of 250 MHz and a slew rate of 150 V/µs, while delivering an output current of up to 100 mA, all operating on a single 3.3 V power supply; therefore, they are well suited for the role of preamplifier, shaper, buffer, and other functions. Once provided with the scintillation detectors, the circuits were housed in aluminum enclosures (Fig. 3) to further mitigate the effects of environmental light and electromagnetic interference.

C. Multi-channel analyzer board

At the heart of our design is a custom-made MCA board. This board houses a variety of components, including two Adjustable Gain Amplifiers (AGAs), two Peak Detectors (PKDs), an MCU evaluation board, a temperature sensor, a temperature-compensated bias generator for the SiPMs, a radio communication module, a GPS module, and an SD card (Fig. 4).

The AGAs are op-amp-based, using the same op-amp type as in the front end, with their gain adjustable using multi-turn trimmers. Following the amplification stage, signals are directed to the PKDs. These PKDs, also op amp-based, utilize the same high slew rate and current output to drive the load of the hold capacitor without inducing instability issues (Fig. 5).

As will be demonstrated later, PKDs respond linearly and without distortion to input signals ranging from 60 mV (baseline) to 2.5 V (the full-scale range of the MCU internal 12-bit ADC), even with rise times down to approximately 1 µs.

Each PKD is equipped with two Single-Pole Single-Throw (SPST) switches, controlled by the MCU: when an input signal surpasses a predetermined threshold, one of the MCU internal analog comparators initiates a process to store and convert the peak value. During this conversion, a switch at the PKD input is opened to prevent subsequent pulses from interfering with the conversion process, ensuring a non-paralyzable behavior. Upon completion of the conversion, the hold capacitor is reset. Each conversion takes about 25 µs (the same duration as an incoming
pulse) allowing the system to easily manage up to several thousand pulses per second. Alternatively, the MCU internal 16-bit, 32 MHz timer/counters peripherals can measure the pulse width of an incoming signal. This allows us to create a histogram of pulse widths, which can be linked to the signal's amplitude using a non-linear relationship typical of Time over Threshold (ToT) conversion.

The MCU's internal Real-Time Counter (RTC) schedules several critical functions: it orchestrates the transmission of the 1024-channel spectra through the radio module (ML01DP5, Ebyte), activates sampling of the temperature sensor (BME280, Bosch) and associated bias compensation process, and it updates data from the GPS module (MTK3339, MediaTek).

Additionally, our system incorporates a bias generator, which is designed around a MAX5026 boost converter (Analog Devices), followed by a voltage doubling circuit. The output voltage, ranging from 20 to 70 V, can be controlled by the MCU through an MCP4725 Digital-to-Analog Converter (DAC) (Microchip Technology), in conjunction with a resistor network.

At the ground station, users can monitor and download data in real time through a dedicated user interface. This interface provides access to all relevant information and allows modification of various parameters, including the operating voltage of the SiPMs.

Furthermore, once the GPS module achieves a satellite fix, the system records radiation and geolocation data in GeoJSON format, a geospatial data format based on JavaScript Object Notation (JSON), which encodes various geographic data structures, including coordinates, shapes, and other features. GeoJSON is largely compatible with different GIS (Geographical Information System) software like QGIS, ArcGIS, or simple web-based platforms such as Google Maps, Mapbox, and OpenStreetMap, and it easily allows users to visualize and analyze the geospatial radiation data.

Finally, the MCA board is compact and lightweight with dimensions of 10 cm × 10 cm × 5 cm and a weight of less than 200 grams, and it is optimally suited for portable applications. Moreover, the average current draw remains below 50 mA, an aspect that further emphasizes the efficiency of our system and its suitability for long-term, battery-powered operations.

### III. RESULTS AND DISCUSSION

In the following subsections, the results obtained from the tests conducted on our radiation detection system are described. The initial evaluation focused on the electronic subsystems to get insights into the system's noise performance and linearity.

Subsequently, we exposed the scintillation detectors to gamma-ray sources to assess the quality of the detectors' response and calculate the energy calibration factors. These evaluations, comprising both electronic characterization and gamma radioactive source exposure, took place at the Laboratory of Nuclear Measurements, University of Pisa, Italy. Further evaluation was conducted at the Polytechnic University of Milan, Italy, where the response of thermal neutron detectors was investigated. Finally, an operational field test was carried out at the French Alternative Energies and Atomic Energy Commission (CEA) in Saclay, France. For this, the detection system was installed onto a UAV and tested under real-world conditions.

#### A. Noise and Linearity Analysis

To thoroughly assess the linearity of the response along with the noise levels imparted by the acquisition chain, a trapezoidal waveform characterized by a 10 ms period, a 20 ns rise time, and a 5 ms fall time was generated using a LeCroy Wavesurfer 3104z oscilloscope. This waveform served to inject a variable charge - ranging from 50 pC to 1.85 nC - into the preamplifier's input via a 1 nF coupling capacitor (Fig. 6).

![Fig. 6. Setup used to investigate the potential non-linearity and noise level introduced by the electronic acquisition.](image)

The output pulses originating from the front end were subsequently digitized using the PKD and the ADC integrated within the MCU (as depicted in Fig.7(a)). AGAs were set to unitary gain.

In examining the system’s response, we found a notable linearity relative to the injected charge, with a percentage non-linearity measuring less than 0.6% (refer to Figs. 7(c), (d)). Additionally, the noise attributed to the entire acquisition chain - expressed as charge resolution- was established to be less than 1% and approached 0.1% across the full dynamic range (see Fig. 7(b)). Given the typical energy resolution observed in scintillator materials, the noise levels reported here are notably negligible.

In comparison to our prior system iterations [19, 20], the current setup showcases an improvement of an order of magnitude in both linearity and noise performance. This substantial advancement is the result of several adjustments to the electronic subsystem, including meticulous component selection and thoughtful circuit re-design strategies.

#### B. Scintillation Detectors response

Upon verifying the linearity of the analog-to-digital conversion process, our investigation then focused on assessing the linear response of the system to various gamma-ray energies. Simultaneously, we evaluated the spectral features of the gamma spectra, alongside parameters such as energy resolution and non-linearity, to thoroughly evaluate the system's performance.
The obtained data (Table I) returned a clear representation of the detectors’ response and performance, as reflected in the gamma spectra (Fig. 9) and the linear response to different gamma-ray energies (Fig. 10). A noteworthy observation from these tests was that the ratio of gamma photopeak to Compton scattering was higher for GAGG due to its superior stopping power.

The measurements indicated that the detectors’ responses' energy resolution and non-linearity values fall within a suitable range considering the system's intended use. Specifically, this system was engineered for deployment on UAVs and is designed to cater to emergency response scenarios. Instead, the primary requirement is that it can operate effectively under real-world conditions, which is a benchmark it successfully meets according to our testing outcomes.

Following the initial characterization of the scintillation detectors, we proceeded to estimate the minimum distance required to detect a gamma-ray radioactive source in a potential real-world scenario. This experiment was performed at the NBC Defence School in Rieti, Italy, which provided a concealed 500 MBq $^{137}$Cs source situated inside a hangar. The system, equipped with two CsI:tl crystals, was mounted on a DJI Matrice 200 UAV.

From earlier testing, the detectors were known to exhibit a sensitivity of approximately 7000 cpm per $\mu$Sv/h for a $^{137}$Cs source. For our experiment, the detection limit was calculated as the average value of the background count rate plus three times its standard deviation. Using a counting time of 1 second, the count rate yielded a detection limit of roughly 0.28 $\mu$Sv/h. This sensitivity allowed the system to detect the presence of the source from approximately 11 meters.
Commission have recommended that the activity level for many radionuclides considered to be hazardous materials is within the range 37 - 370 GBq. While these activity levels may appear significant, it's important to note that radionuclides such as $^{137}$Cs and $^{60}$Co have specific activities on the order of TBq per gram. This means that only milligrams of these materials are needed to pose a threat [21].

C. Thermal Neutron Detectors response

To further evaluate our system's capabilities, we conducted a series of tests focusing on the response of our detectors to thermal neutrons at the Polytechnic University of Milan. For this purpose, the detectors were exposed to a polyethylene moderated Am-Be neutron source ($2.14 \times 10^6$ s$^{-1}$) yielding a thermal neutron fluence rate (with energies up to 5 eV) equal to $437 \pm 14$ cm$^{-2}$s$^{-1}$ (Fig. 11).

![Fig. 9. Gamma spectra obtained from CsI:tl and GAGG:ce crystals when exposed to $^{137}$Cs (a), $^{60}$Co (b), and $^{241}$Am (c).]

The average detection efficiencies for the two detectors were measured to be $0.132 \pm 0.012$ and $0.131 \pm 0.011$ respectively. These results align closely with the data provided by the manufacturer, thus further confirming our detectors' performance and suitability as UAV radiation sensors.

D. Field tests

The culmination of our tests occurred during an in-field evaluation, which was conducted as part of a simulated radiological and nuclear scenario under the aegis of the Horizon 2020 INCLUDING Project at CEA, Saclay, France. This exercise aimed to simulate the identification, recovery, and decontamination of orphan sources of $^{137}$Cs and $^{99m}$Tc. Within this scenario, the $^{137}$Cs was provided as a sealed source with very low activity, whereas $^{99m}$Tc was presented in a liquid form (Fig. 12).

Despite the challenging nature of this real-world test due to the low activities of the employed sources, our UAV-mounted detection system successfully identified the presence of both radioactive sources in a matter of minutes. After only a three-minute hovering phase at approximately 4 meters from the sources, the user interface displayed a distinct photopeak for each radioactive source, demonstrating the system's ability to identify different types of radioactive materials quickly and accurately in a real-world operational environment (Fig. 13).
IV. CONCLUSIONS

This work focused on the design and implementation of a lightweight and resource-constrained radiation detection system tailored specifically for small-category UAVs. The development and deployment of effective radiation detection systems for UAVs are becoming increasingly important in managing radiological and nuclear emergencies; additionally, such systems are essential for immediate response to catastrophic events and play a crucial role in subsequent recovery and long-term monitoring. The proposed system is different from conventional solutions, utilizing off-the-shelf components and avoiding costly, specialized hardware like FPGAs or ASICs. This design choice enhances accessibility, facilitates deployment on a large scale, and allows for easy replacement if contamination occurs.

A dual-detector configuration has been integrated into the design to extend the radiation detection capabilities of the unit. It employs inorganic scintillators (CsI:tl and GAGG:ce) with SiPMs for gamma-ray detection, and solid-state detectors equipped with a Li converter for thermal neutron detection. The separate acquisition channels introduce redundancy, enhancing system robustness and reliability. The core of the acquisition system is an AVR128DB48 MCU, which, while limited in terms of computational power, also offers multiple integrated peripherals which are well-suited for data acquisition and basic processing. Finally, the collected data are transmitted automatically to a ground station via a 2.4 GHz radio module, while a GPS unit tracks detectors’ geolocation allowing the reconstruction of radiation contamination data.

Through extensive testing, we have confirmed the system’s robustness and efficiency: performance parameters, such as linearity, noise, and detection of gamma and thermal neutrons, meet the acceptable ranges for their intended purpose as an easily deployable or disposable tool for first responders. Field tests have further validated the system’s capability to detect sources from considerable distances, demonstrating its readiness for various radiation detection applications.

Beyond emergency response, the system could find use in environmental radiation monitoring, geological surveys, industrial inspections, and scientific research. By advancing drone-mounted radiation detection, we can enhance safety, improve response times to radiological incidents, and provide a practical, cost-effective solution that will influence the future of radiation detection technology.

REFERENCES


