



Original Article

Automation of Sample Handling for ORTEC's Lead-Shielded High-Purity Germanium Gamma-Ray Detector

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Abstract: Gamma spectroscopy is a non-destructive technique for identifying and quantifying radionuclides in environmental samples. High-purity germanium (HPGe) detectors are commonly used for these analyses. To minimize background radiation from sources other than the sample, the detector is housed in a lead shield. ORTEC's low-background shield, weighing approximately 1180 kg, poses challenges for automation, making such systems rare and commercially expensive. Additionally, HPGe detectors require cooling to cryogenic temperatures, typically achieved using liquid nitrogen (LN₂). The drawbacks of LN₂ include its high cost and the limited duration of a 30 L LN₂ charge (around 14 days), regardless of detector operation. An autosampler, an automated sample-handling system, optimizes LN₂ usage by enabling sample changes during idle periods. In this work, we developed a cost-effective and efficient autosampler incorporating a “pick and place” robot and a pneumatic circuit for sample manipulation, linear actuators for automated door operation, and an electronic system integrated with “Maestro” (ORTEC's spectroscopy software) via a custom-developed Python interface. This system integrates mechanical design, electronics, and programming to enhance efficiency, optimize LN₂ usage and reduce downtime, thereby improving overall operational performance.

Keywords: Autosampler, HPGe detector, Linear actuators, Arduino, Programming.



Automatización del manejo de muestras para el detector de rayos gamma de germanio de alta pureza blindado con plomo de ORTEC

Resumen: La espectroscopía gamma de alta resolución es una técnica no destructiva que permite la cuantificación de radionucleidos presentes en muestras ambientales. Los detectores más comúnmente utilizados para estos análisis son los detectores de germanio de alta pureza (HPGe). Para minimizar la radiación de fondo proveniente de fuentes distintas a la muestra es esencial blindar al detector colocándolo dentro de un blindaje de plomo. El blindaje de bajo fondo de ORTEC, que pesa aproximadamente 1180 kg, plantea desafíos para la automatización, por lo que estos sistemas rara vez se automatizan y son comercialmente costosos. Además, los detectores HPGe requieren enfriamiento a temperaturas criogénicas, típicamente logrado mediante nitrógeno líquido (LN₂). Las desventajas del LN₂ incluyen su alto costo y la duración limitada de una carga de 30 L de LN₂ (aproximadamente 14 días), independientemente de la operación del detector. Un automuestreador, sistema automatizado de manejo de muestras, optimiza el uso de LN₂ al permitir cambios de muestras durante períodos de inactividad. En este trabajo, desarrollamos un automuestreador rentable y eficiente que incorpora un robot de "pick and place" y un circuito neumático para la manipulación de muestras, actuadores lineales para la operación automatizada de puertas, y un sistema electrónico conectado con el software Maestro de ORTEC utilizando Python. Este sistema integra diseño mecánico, electrónica y programación para mejorar la eficiencia, optimizar el uso de LN₂ y reducir el tiempo de inactividad, mejorando así el rendimiento operativo general.

Palabras claves: Automuestreador, Detector HPGe, Actuadores lineales, Arduino, Programación.

1. INTRODUCTION

High-resolution gamma-ray spectroscopy using high-purity germanium detectors (HPGe) represents a non-destructive analytical methodology for the identification and quantification of radionuclides within environmental matrices, allowing for accurate isotopic analysis without compromising sample integrity [1, 2]. Given the low specific activity inherent in environmental samples, encapsulating the detector in specialized shielding is essential to attenuate external background radiation, thereby improving signal-to-noise ratios and detection limits [3, 4]. Lead is the main shielding material due to its high atomic number ($Z = 82$) and density (11.34 g/cm^3), resulting in a system with a large mass (approximately 2600 pounds), which consequently makes it difficult to develop automated configurations for HPGe systems by imposing significant mechanical and structural challenges [5, 6]. Although commercially available automated sample changers exist for HPGe detectors, their acquisition cost frequently exceeds that of the detector itself due to factors such as custom engineering for seamless integration with huge lead-shielded enclosures, precision robotic mechanisms to ensure reproducible sample positioning within tight tolerances (typically $<1 \text{ mm}$ for optimal geometric efficiency), compliance with strict radiological safety protocols, and low-volume manufacturing scales that raise per-unit costs [6 - 8]. These prohibitive prices thus restrict accessibility and adoption in various research centers, particularly in academic or government laboratories with limited capital budgets, while also restricting widespread implementation in resource-scarce environments, such as developing countries, where high-throughput radionuclide analysis could improve environmental monitoring or response capabilities to radiological emergencies.

Additionally, HPGe detectors require cryogenic operating temperatures to minimize thermal noise and achieve optimal energy resolution, which are conventionally maintained by liquid nitrogen (LN_2) cryostats. However, this approach involves high costs, logistical

complexities in handling, and a limited lifetime for a standard 30 L dewar (around 14 days, regardless of the detector's operating status) [5]. Emerging alternatives to LN₂ cooling, such as electromechanical systems, have been explored to mitigate these limitations by providing maintenance-free operation for extended periods and potentially facilitating greater automation; however, in developing countries or academic laboratories, the acquisition of such electromechanical cooling equipment remains more expensive compared to conventional LN₂ setups, hindering their widespread adoption despite their advantages [9]. In conventional systems, manual sample exchange prolongs instrument downtime, particularly during non-operational intervals, leading to inefficient depletion of the liquid nitrogen tank and reduced overall throughput. Therefore, incorporating an autosampler is especially effective in facilitating smooth sample transitions during periods of low activity, increasing cryogen usage efficiency, minimizing human intervention, and optimizing laboratory productivity [6]. Furthermore, thanks to advances in auxiliary automation, such as environmental monitoring stations equipped with temperature, humidity and other parameter sensors, it is possible to maintain optimal detector performance in automated workflows [10].

This work presents an automated sample handling system that combines computer-aided design (CAD), mechanical engineering, electronic circuits, and custom software modules for the automation of sample exchange processes for a high-resolution, low-background, front-access, lead-encapsulated HPGe detector manufactured by ORTEC, AMETEK, USA. The mechanical assembly incorporates precision linear actuators for automated shielding enclosure door operation, leveraging established robotic control principles [11]. This design simplifies assembly via off-the-shelf modular components, maintains unobstructed frontal access for seamless manual intervention, and enhances visual and structural aesthetics through streamlined integration (Figure 1). For sample manipulation, an angular robotic arm with multi-joint articulation provides superior kinematic versatility in constrained spaces, along with a compact footprint, simplified architecture, and reduced dimensions (Figure 2 A). The pneumatic circuit for sample gripping

and transfer supports higher load capacities and offers greater efficiency and reliability via rapid response and consistent force (Figure 2 B). The programming includes an intuitive graphical user interface for direct input of parameters such as file name, number of samples, sampling time or radioactive counts required for all samples, a brief description, etc., in addition to advanced capabilities such as real-time email notifications for remote monitoring of progress, errors or completion. This control system uses interconnected Python scripts for logic/data handling, Arduino for hardware interfacing, and protocols like serial communication, imports, and WebSockets, improving reliability, scalability, and usability across research settings. Overall, these elements deliver marked gains in simplicity, versatility, and functionality over prior systems like Auto-HPGe [6] (Figure 3 A and 3 B).

Figure 1: Complete view of the Autosampler



Figure 2: (A) View of the robotic arm placing a sample and (B) View of the placement of a sample using the pneumatic circuit.

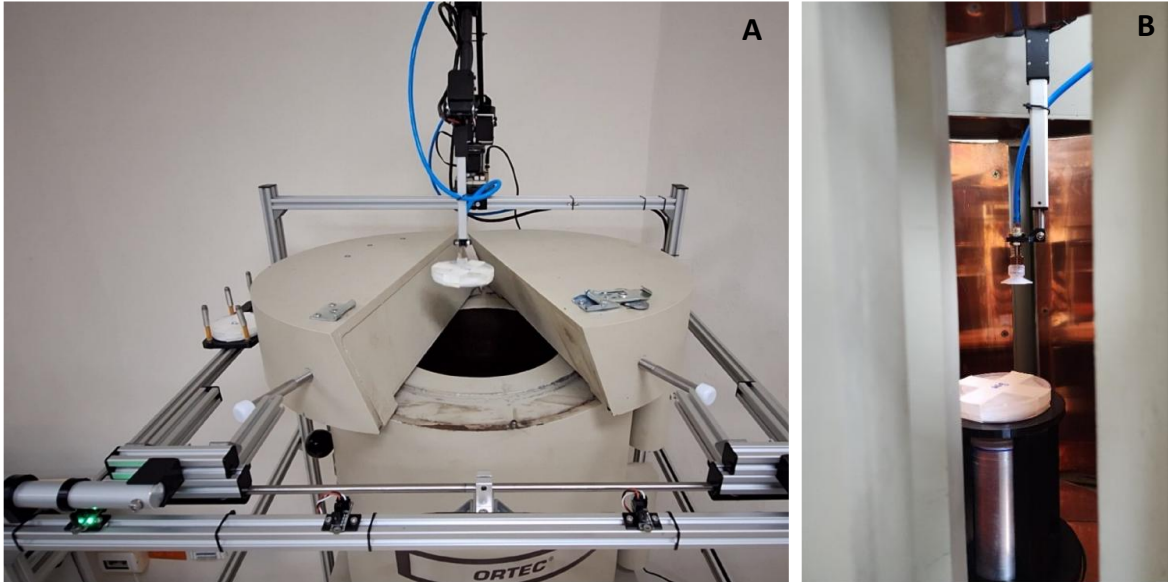
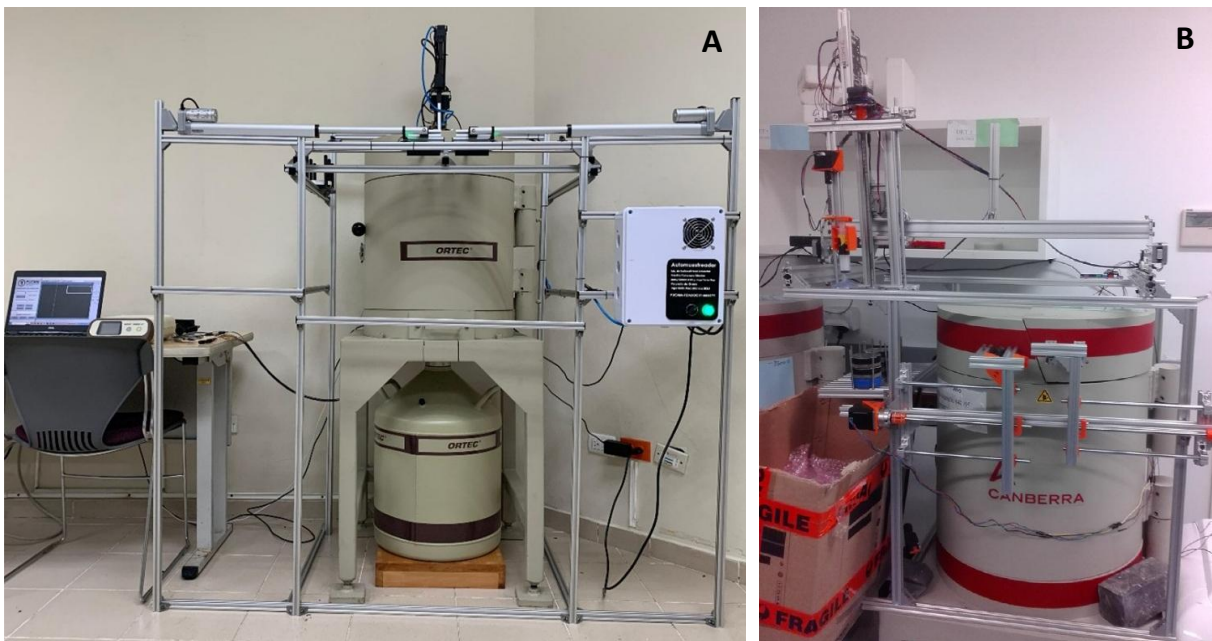


Figure 3: (A) Complete view of our Autosampler and (B) Complete view of the Auto-HPGe [6].



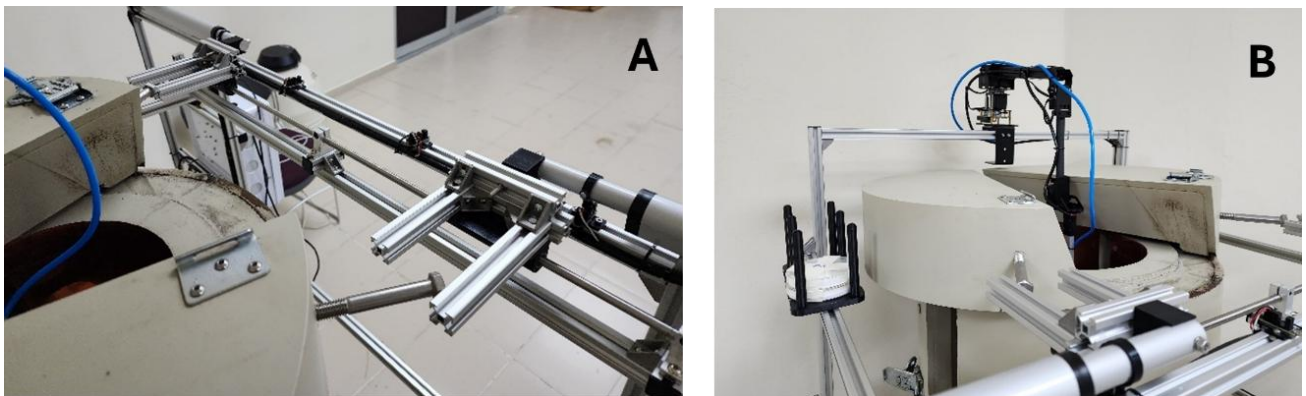
Therefore, the objective of this work is to develop a more economical, efficient, versatile, robust, and customizable autosampler that will increase the number of samples analyzed compared to manual operation for the same period; increase the utilization of each LN₂ charge; and protect operating personnel from accidents due to the handling of heavy lead doors.

2. MATERIALS AND METHODS

2.1. Design and Mechanics

The autosampler consists of two subsystems: one that manages the opening and closing of the upper doors (Figure 4 A) and another for transferring samples between the Petri dish rack and the HPGe detector (Figure 4 B).

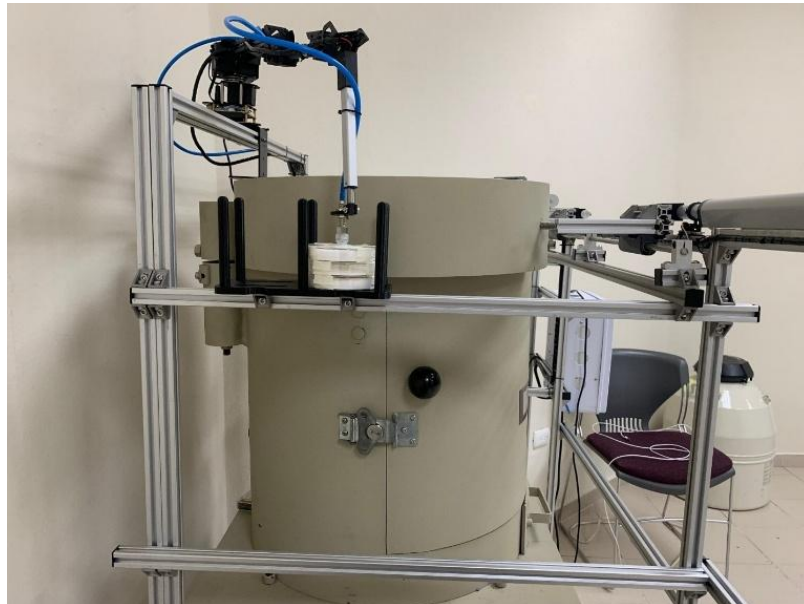
Figure 4: (A) Detailed view of the door management system and (B) Detailed view of the sample transfer system



The first subsystem (Figure 4A) consists of a structure made from 2020 aluminum profiles that support two linear actuators, whose movement is guided by a rail placed in front of the lead shield. This rail helps the actuators follow the linear motion required to open and close the doors. Additionally, the profiles also support the infrared optical sensors used to provide feedback on the actuators' current position.

The second subsystem (Figure 4 B) that handles sample transfer consists of an angled robotic arm with a pneumatic suction cup connected to a mini linear actuator as its end effector. It uses a pneumatic system to pick up and place the samples between the rack on the right (where the sample containers with the sample not yet measured are placed by the operator), the platform inside the shield that surrounds the detector, and the rack on the left (where the samples already measured are placed), always in that order (Figure 5).

Figure 5: Side view of the autosampler, showing the robotic arm retrieving one of the samples from the right rack, next to the empty finished sample rack (left)



Additional aluminum profiles were added with the purpose of increasing structural integrity and countering the movement's vibrations. These create a cage that encapsulates the detector, while keeping virtually the entire frontal area accessible. The system is designed to fit around the detector in a specific way, avoiding the need to lock in the detector from behind. Therefore, the operator can slide off the autosampler to remove it and access the entire detector, and, when desired, replace it.

Corner brackets for aluminum extrusions were used for the connections between the profiles, which require hammer nuts and 10mm M5 bolts. All components are bolted in.

The linear actuators are connected at the ends of their shafts to handles made of U-shaped aluminum profiles to push the detector doors in the required direction of movement. A rail was added to limit the handles' movement to a single plane. The linear actuator is connected to its respective handle using a 3D printed part with linear bearings that slides along the rail (Figure 6).

Figure 6: Detailed view of the door rail and handle assembly



A 3D printer and PLA+ filament were used for the parts with very specific characteristics required for construction. Components such as the sample rack, the sample platform, and the connection between the robotic arm and the mini linear actuator were designed and printed for our system.

Before assembly, the entire autosampler system, including the ORTEC lead shield, detector and nitrogen tank were modeled using the CAD software “SolidWorks” (Figure 7). Even the distribution of the electrical panel, and all 3D printed pieces. This allowed us to have a clear vision of the prototype and to first present any necessary adjustments to the designed model, before applying them to the real one.

Figure 7: (A) Isometric view of the CAD design of the autosampler and its surroundings. (B) Detailed view of the CAD design of the interior of the electrical panel. (C) Detailed view of the CAD design of the door control subsystem. (D) Isometric view of the CAD design of both subsystems and the sample container rack.



2.2. Electronics

The individual mechanical and electronic aspects are intertwined through programming, using one microcontroller in the robotic arm (ESP32-WROOM-32) and another to control the other electronic components (Arduino Mega2560).

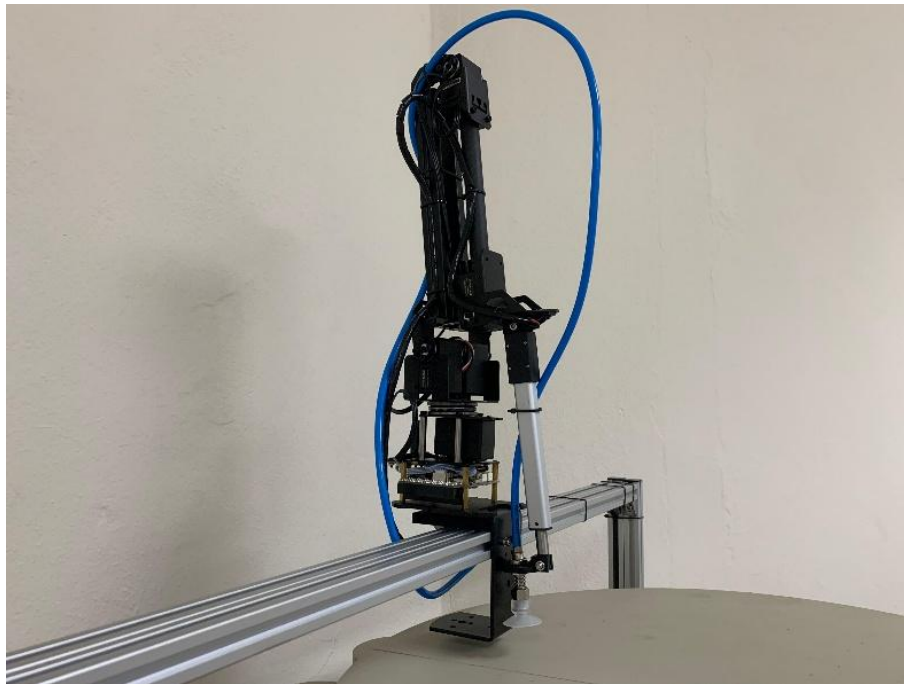
The linear actuators used in the automatic subsystem for the upper doors where 12 V, 150 kg with a 30 cm shaft. These actuators are controlled using an l298n driver with an optocoupler (Figure 8). There are four infrared optical sensors, two for each linear actuator, to receive movement feedback. These indicate the "open" and "closed" positions of each actuator. All these electronics are connected to the Arduino Mega, which is responsible for controlling the movement of the actuators and sending and receiving messages to the Python program via serial communication.

Figure 8: Exterior (cover) and interior of the autosampler's electrical panel



On the other hand, the sample transport subsystem can be divided into the angular robotic arm and the pneumatic circuit (Figure 9). In more detail, the robotic arm manufactured by Waveshare is essentially made up of five servo motors and an ESP-32 microcontroller. This robot draws its power from its own 12 V power supply. The advantage of using servo motors is that they provide continuous feedback on their positions, so we can know exactly where the robotic arm is at any given time. The robot's end effector is a 12 V 10.16 cm stroke mini linear actuator with a pneumatic suction cup at its end. Using another 1298n driver, the actuator's movement is controlled to increase the robotic arm's range so it can pick up and place samples on a broader working volume.

Figure 9: Detailed view of the robotic arm



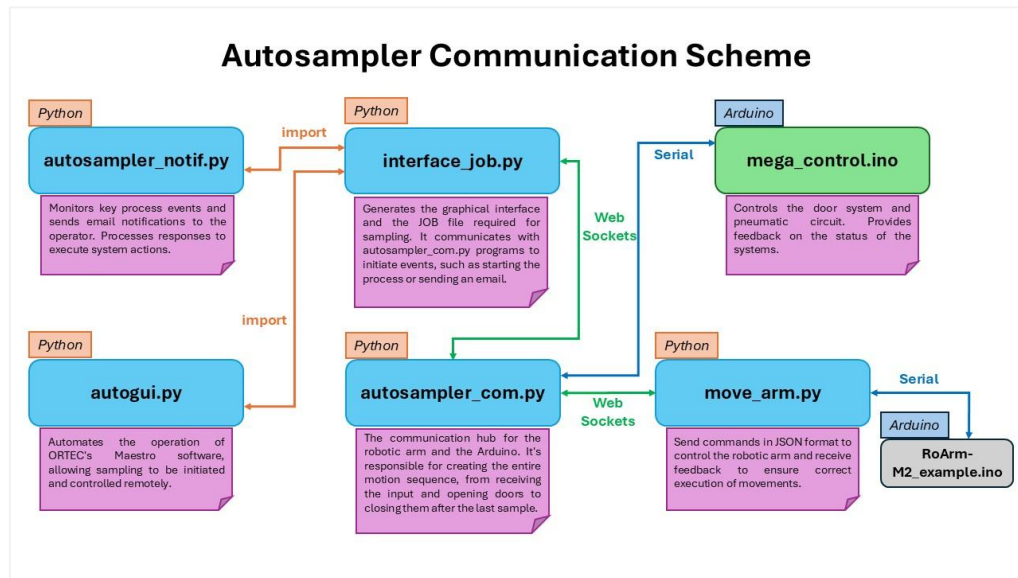
The pneumatic circuit consists of an air pump connected to a solenoid valve, a relay, and a pressure sensor. The powering of the valve is controlled by the relay, which is digitally controlled through the Arduino Mega. The air pump is directly controlled by a l298n drive. Turning the relay on connects the valve and allows the air pump to suction and turning it off cuts the air flow. This is equivalent to the act of "holding" and "releasing" the sample. The pressure sensor provides feedback to the circuit, allowing it to know whether the suction cup is holding a sample or not. For this, the sensor can send three values to the microcontroller: a pressure of about 275.79 kPa (40 PSI) means the air pump is off; 310.26 kPa (45 PSI) means the pump is on, but nothing the suction cup is not holding anything; and 661.90 kPa (96 PSI) means the suction was activated and an object is being held.

2.3. Programming

The autosampler consists of multiple programs running simultaneously and communicating with each other to achieve the desired step-by-step sequence (Figure 10); from entering the sampling data into the graphical interface to closing the detector after removing the last sample and placing it in the sample rack. Part of this complexity is due to

the robustness that has been given to the processes, preparing continuous feedback, error and cancellation sequences, scheduled real-time emails, and more.

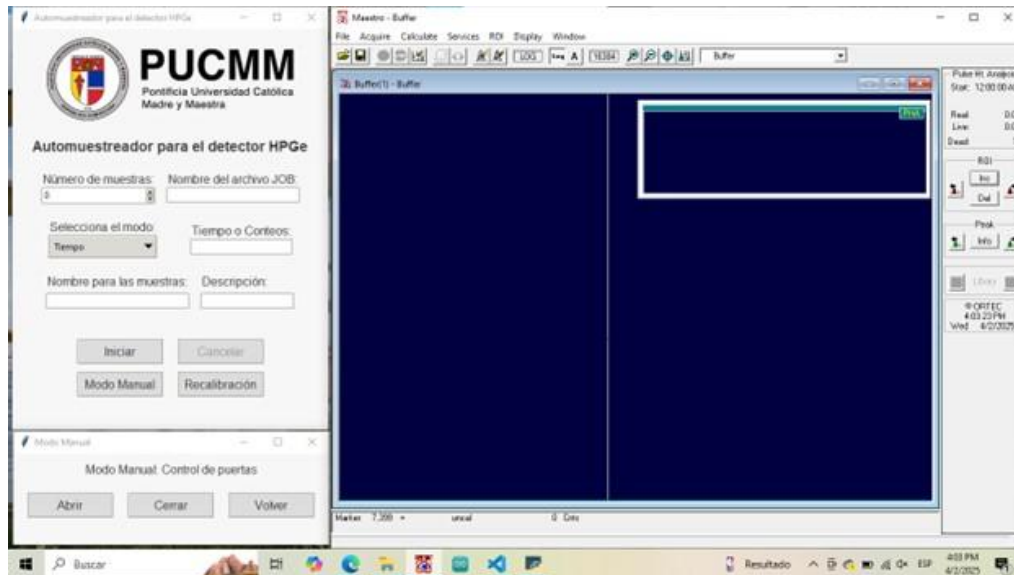
Figure 10: Interconnection diagram between programs



2.3.1. Interface_job.py

This program creates and manages the graphical interface where the user enters sampling data (Figure 11), such as the file name, number of samples, the amount of sampling time or radioactive counts required for all samples, a brief description, etc. When the user clicks "Start," the program uses all this information to create the JOB file that the Maestro software recognizes to automate the use of its user interface (UI). This script also communicates with `autosampler_com.py` via communications protocol to start or end a process. If an anomaly occurs with any of the sensors' readings, an error sequence will start, and the program will notify the operator remotely via email detailing the event. It also has a Manual Mode, allowing the operator to open and close the detector doors with the autosampler in place without needing to initiate the automatic process. And if a problem occurs with the linear actuator's movement, where it's stuck between positions and the system does not know where they are, there is a recalibration button on the interface to reposition the actuators.

Figure 11: Screen capture of how the autosampler is used, with the graphical interface (left) and the Maestro software (right) open side by side



2.3.2. Autosampler_com.py

This script handles communication with `move_arm.py` (which controls the robotic arm) and `control_all.ino` (which controls the Arduino Mega). It defines the entire sequence of movements, including opening the doors, locating the sample, placing it on the detector, and closing the doors, both to start and end the sampling process. It achieves this through WebSocket communication with `move_arm.py` and `interface_job.py`, and serial communication with `control_all.ino`. It is also capable of receiving and analyzing feedback from these programs, so the process only continues when the respective component has confirmed the successful completion of its task. This prevents user error and alerts any potential situation. An example would be if the operator forgot to place the sample before starting the process from the interface. By using the pressure sensor reading the system will know that nothing has been detected, so `control_all.ino` communicates this to `autosampler_com.py` and it is able to stop the entire process and send a message to `interface_job.py` to alert the operator, avoiding wasting time and resources.

2.3.3. Move_arm.py

Waveshare's robotic arm features a built-in program that processes specific commands from messages formatted in JSON (JavaScript Object Notation), a lightweight and human-readable standard for organizing structured data. Therefore, the `move_arm.py` program is responsible for sending the sequence of movements to the robotic arm's microcontroller when authorized by `autosampler_com.py`. The servo motors can provide feedback to `move_arm.py` with the current position of the movement, so this information is used to confirm that the movement sequences have been correctly completed before continuing with the process.

2.3.4. Autogui.py

`Autogui.py` automates the use of the Maestro software using a Python library called `pyautogui`, that allows the program to control the computer's mouse and keyboard. Thanks to the JOB file created in the `interface_job.py` program, the need for software management is greatly reduced, but to upload the file, know when a sample measurement is done or stop the sampling process at any time, it is necessary to directly manage the Maestro UI. Using the images provided for recognition, the program can view the buttons and click them, type, select, and more. These tools are used when the sequence of movements to place a sample in the detector has been completed, and the next step is to upload the JOB file created from `interface_job.py` to the Maestro software.

In addition, this program is responsible for waiting for the appearance of the “Save Spectrum File” dialog box, which serves as a signal that the system requires to confirm the completion of the sampling process, allowing the sample to be removed from the detector.

2.3.5. Autosampler_notif.py

`Autosampler_notif.py` program is responsible for keeping the operator informed of the sampling process remotely. When combined with an internet-accessible security camera, the program sends emails to the operator in real time whenever a critical stage of the process occurs or is about to occur, so that the operator can watch it live from the security camera.

This can be when a sample is about to be inserted or removed from the detector, or at the end of the pre-established sampling process. If an error occurs, `autosampler_notif.py` also sends notifications specifying the exact problem to the operator. Additionally, the program accepts a cancellation email if the user wishes to stop the sampling remotely at any time and for any reason.

2.3.6. Control_all.ino

This is the program that controls all the components connected to the Arduino Mega. It is divided into two parts: door control and pneumatic circuit control. The microcontroller receives and sends commands via serial communication. Upon receiving a command, the program executes the corresponding action and, upon completion, sends a confirmation message to `autosampler_com.py` so that the program can continue with the next step. If a problem occurs, it sends a message detailing the problem to stop the process and sends an email to the operator with information about what happened.

3. RESULTS AND DISCUSSIONS

After the development of the autosampler for the gamma ray detector with lead shielding, a series of experimental tests were conducted to evaluate its performance.

Reliability testing of the sample transfer subsystem demonstrated that the robotic arm, pneumatic suction cup, and their associated control routines consistently executed the sample container collection, transport, and replacement process without failure.

A maximum separation of 3 mm was observed between the two doors in the final closing position of the lead shield. This slight variation is attributed to manufacturing tolerances in the shield doors rather than to a malfunction in the control system. Notably, even with manual operation, the lead doors did not achieve perfect closure. Importantly, this spacing was shown to have no measurable effect on the detector's performance.

The maximum idle time, defined as the interval between the completion of one sampling cycle and the initiation of the next, was approximately 3 minutes and 42 seconds. This short downtime highlights a key advantage of the autosampler: while the detector is idle, liquid nitrogen in the tank continues to be consumed. By automating sample changes, the system minimizes wasted nitrogen, whereas manual changes outside of working hours would result in substantially longer idle periods.

Finally, during positioning tests, the robotic arm successfully reached 59 out of 60 target positions within the permitted error margin of the workspace, yielding a 98% success rate. This outcome demonstrates both the high reliability and precision of the autosampler in executing programmed movements, reinforcing its suitability for continuous operation.

4. CONCLUSIONS

The developed autosampler successfully performed sample changes independently of manual intervention, enabling continuous operation of the gamma ray detector. By drastically reducing downtime, the system allows for more efficient use of the detector, even during nights, weekends, holidays, or outside normal working hours, thereby increasing productivity and improving equipment utilization.

A major advantage of this design is its cost: the total expense of approximately US\$986 is a fraction of the price of commercially available autosamplers, which typically exceed US\$200,000. This affordability makes advanced automation accessible to laboratories and facilities that would otherwise be unable to implement such technology.

While the system is optimized for sample containers with a maximum combined weight (sample plus container) of 350 g and 90 mm diameter vessels, this focused design ensures precise and reliable performance in standard applications. Furthermore, it is customized for ORTEC's high-performance, low-background, front-loading lead shield (model HPLBS1F) for HPGe detectors, leveraging the shield's specifications and Maestro

control software for seamless integration. This specialization facilitates efficient operation, and the modular nature allows for straightforward adaptations to alternative detector configurations through targeted enhancements.

Overall, this work demonstrates that low-cost robotic automation can be successfully integrated into high-precision radiation detection systems, reducing operational downtime while maintaining measurement reliability.

Future work may focus on extending the currently implemented design, which has been optimized for standard Petri dishes, to accommodate a broader range of sample geometries commonly used with HPGe detectors, such as Marinelli beakers (for larger-volume liquid or solid samples), cylindrical beakers, small vials, and planar discs. Additional enhancements, including increased load capacity and compatibility with diverse detector configurations, would significantly broaden the system's applicability in nuclear research, environmental monitoring, and radiological analysis.

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Writing – review and editing: CSC, GAJ, GTGD, AJR, GGB, BEV, TDJ

CONFLICT OF INTEREST

All authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The authors declare that the data supporting the results of this study are available in the article. Derived data supporting the conclusions of this study are available upon request from the corresponding author.

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