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Software Development for Gamma-Ray Tomograph

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1. Introduction

Gamma-ray computed tomography (CT) is a powerful non-destructive testing technique widely utilized for inspecting multiphase flows, evaluating structured packings, and troubleshooting industrial process equipment without disrupting normal operations. The fundamental validation of this technique in complex fluid dynamics, such as gas-liquid flows in bubble columns, has been extensively demonstrated in the literature [1, 2]. Despite its high efficiency and reliability, CT systems often present a barrier to academic research and institutions due to their high costs and sometimes closed-source software architectures, which act as "black boxes" restricting methodological customizations and improvements [3]. To overcome these limitations, the improvement and development of open-source and modular systems have become a crucial demand in the field of nuclear instrumentation. In this context, this work presents the development and computational upgrade for third-generation gamma tomograph software systems in general. The primary objective of this work is to detail the transition from a proprietary closed framework to a fully open-source Python-based architecture, which seamlessly integrates automated hardware safety, pulse height analysis, and reliable image reconstruction techniques. This work was developed in a close partnership between MS&T (Missouri University of Science and Technology) and SETER (Serviços de Tecnologia das Radiações), located in IPEN (Instituto de Pesquisas Energéticas e Nucleares).

2. Methodology

The architecture of a typical 3G tomograph can be seen in Figure 1. In this figure it is possible to see a mechanism that is constructed with three principal movements: table rotation, detectors translation and table elevation. This architecture relies on an Arduino microcontroller to manage stepper motors responsible for the detectors translation, table rotation and table elevation. To mitigate the physical twisting of cables during continuous rotation, the acquisition geometry was programmed to perform a pendulum-like (zig-zag) movement.



(a) *(b)*

Figure 1: Photo of the assembled 3G tomograph in a laboratory on SETER, IPEN (a) and on MS&T (b).

For the signal acquisition system, the legacy interface was entirely replaced by a modern, asynchronous Python framework. Radiation signals are captured by a detector connected via a serial port, generating raw 768-byte data arrays that are converted into 24-bit energy channels. The processing of the energy spectrum is performed using a Pulse Height Analyzer (PHA) algorithm. A Hann filter is applied via Fast Fourier Transform (FFT) to suppress high-frequency noise and mitigate Compton scattering effects [4]. The filter implementation in the discrete domain is characterized by the Hann window function w(n):

$$w(n) = 0.5\left[1 - cos\left(\frac{2\pi n}{N-1}\right)\right] \quad (1)$$

where N represents the total number of samples and n is the discrete channel index ($0 \leq n \leq N-1$). Subsequently, trapezoidal integration is employed to calculate the useful photon counts strictly within the photopeak region. The total area A under the photopeak, bounded by the integration limits a and b, is computed as:

$$A = \sum_{i=a}^{b-1} \frac{C(i)+C(i+1)}{2} \quad (2)$$

where C(i) represents the registered radiation counts at the ith energy channel. This numerical integration ensures that only the unscattered transmitted photons are accounted for in the subsequent attenuation reconstruction steps. The developed graphical user interface (GUI) for the acquisition system is shown in Figure 2.

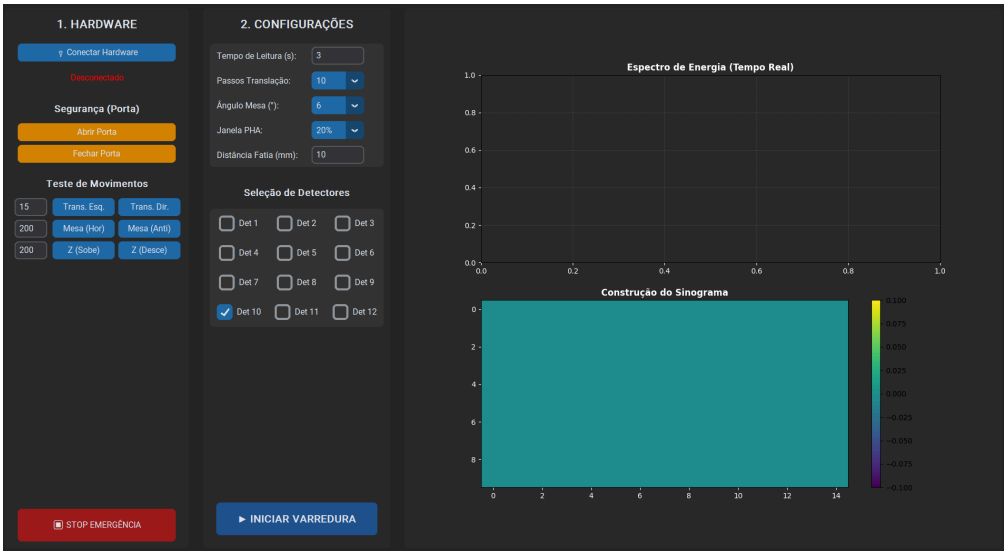


Figure 2: Graphical User Interface (GUI) of the developed Python control software

To align the software with the physical principles of radiation attenuation, an automated safety and calibration routine was implemented. Prior to the scanning loop, a motorized lead shielding door automatically opens to measure the free-beam intensity I_0 without the sample. This procedure is theoretically grounded in the Beer-Lambert law, which governs the attenuation of a monoenergetic gamma-ray beam passing through a medium, expressed as [5]:

$$I = I_0 e^{-\mu x} \quad (3)$$

where I is the transmitted intensity measured by the detector, μ is the linear attenuation coefficient of the material, and x is the thickness of the traversed object. By automatically acquiring I_0 in real time, the software accurately computes the linear attenuation projection P by rearranging the aforementioned principle into Equation 4 [4, 6]:

$$P = ln\left(\frac{I_0}{I}\right) \quad (4)$$

Where P represents the linear attenuation projection used by the reconstruction algorithm. Finally, the collected sinogram data is formatted to be processed using the Filtered Back Projection (FBP) algorithm, accurately reconstructing the two-dimensional cross-sectional density map of the specimen.

3. Results and Discussion

The migration to a multi-threaded Python environment resulted in a responsive, commercial-grade graphical user interface (GUI) that centralizes hardware control and safety mechanisms without freezing during data acquisition. The software now provides dual real-time visualization: the dynamic energy spectrum plot updating the photopeak per scanning step, and the live construction of the sinogram matrix.

Regarding the mechanical and reconstructive aspects, the integration of the automated I_0 calibration significantly improved the mathematical accuracy of the tomograms, transitioning the output from raw photon counts to true material density variations. Furthermore, as will be described in detail in the final version of the paper, several enhancements were made concerning the electromechanical stabilization and the correction of virtual misalignments related to the center of rotation (COR), which drastically reduced artifacts in the final reconstructed images.

4. Conclusions

The 3G project successfully demonstrates the viability of integrating low-cost hardware with advanced open-source software to successfully operate an industrial-grade gamma-ray tomograph. The implementation of automated safety protocols, real-time PHA filtering, and the Beer-Lambert attenuation correction provides a robust framework that matches the reliability of commercial counterparts. By decoupling the acquisition system and relying on Python, the equipment offers high adaptability for future academic and industrial research in non-destructive testing.

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