SAND2024-11763C

Leveraging Afterglow in Scintillation Detectors for Multi-Frame High-Speed Radiography

Nhi Y. Le and Edward S. Jimenez
Non-Destructive Environments and Diagnostics
Sandia National Laboratories
Albuquerque, NM 87123

***Abstract*—This work presents an innovative approach to multi-frame high-speed flash radiography that utilizes slow decay, high-efficiency scintillators paired with flash X-ray sources to enhance image quality for capturing high-speed events. By leveraging the afterglow of the scintillator to maximize signal, this work redefines a traditonally direct imaging system as an indirect imaging system resulting in radiographs that exhibit significant ghosting across each frame. To extract the useful signal, this work presents a novel time-encoded approach and statistical estimators for image processing. Simulation studies presented in this work indicate promise and potential for significant advancements in high-speed imaging applications. This approach not only challenges conventional imaging techniques but also sets a foundation for further research into optimized data collection methods for dynamic events.**

I. Introduction

High-speed multi-frame radiography (HSMF-R) is useful for capturing high-fidelity information of energetic events and other rapidly evolving phonomena. Present data collection techiques for HSMF-R emulate collection techniques similar to high-speed video acquisition [1]; and although the challenges that face high-speed video can also apply to HSMF-R, there are additional challenges in the x-ray imaging pipeline that impose severe limitations. The largest difference between these two imaging systems is the presence of a photon conversion step which typically involves a scintillation layer which converts x-ray photons into visible light photons which then propogate to a high-speed camera. Unfortunately, this step is largely responsible for the degradation of image quality and ultimately constrains the framerate of the imaging system due to the afterglow of the scintillator which is defined as the fraction of radiance of light remaining for a given amount of time after x-ray excitation ceases [2]. Furthermore, high-efficiency scintillation materials such as Cesium Iodide exhibit prohibitively extensive afterglow, resulting in a latent image if the frame rate of the camera is markedly shorter than the decay time. To avoid latent images, users will typically leverage fast-decay scintillators such as Gadolinium Aluminum Gallium Garnet (GAGG) which can have a significantly shorter decay time, but at the cost of severely reduced signal thus creating images that exhibit low signal-to-noise [3].

This work proposes an innovative HSMF-R system designed to address these limitations. By integrating flash X-ray sources with slow decay, high efficiency scintillators, the system is capable of acquiring multiple frames in quick succession, each containing multiple exposures. These multi-exposed frames are processed using a spacetime-based reconstruction technique, producing a sequence of snapshots that visualize the field-of-view across the measured time period. This approach not only enhances the image quality dramatically compared to traditional systems but also offers unprecedented fidelity in capturing dynamic events, crucial for advancing our understanding of phenomena on short timescales.

This study aims to tackle the challenges imposed by the slow decay of scintillation materials in high-speed radiography. The hypothesis posits that the afterglow, when used with a tailored statistical estimator, can improve image separation and quality significantly.

II. Methods

A. Monte Carlo Simulations

Monte Carlo simulations were used to emulate the transport and interactions of photons within the scintillation materials, focusing on afterglow effects, using the Particle and Heavy Ion Transport code System (PHITS) [4]. PHITS, a robust Monte Carlo particle transport simulation program, is employed to simulate the transport and interactions of high-energy photons and electrons within scintillator materials such as Cesium Iodide (CsI). This simulation is vital as it incorporates the physical properties and decay characteristics of the scintillator, thus enabling the generation of realistic radiographs that account for the ghosting effect.

B. Statistical Estimators and Mathematical Modeling

The novel application of statistical estimators, specifically Maximum-Likelihood Expectation Maximization (MLEM) for this summary, was utilized to process the simulated radiographic data, allowing for enhanced image deconvolution.

For a given object $\vec{f}$, the vector of pixels that are formed from measuring $\vec{f}$ in the field-of-view is defined as:

$$\vec{g} = H\vec{f} + \vec{n}, \tag{1}$$

where H is a potentially non-linear mathematical operator that maps from a continuous or discrete object space to an image space. Next, for a set of k timesteps, we define:

$$\vec{f_t} = [f^{(1)}, f^{(2)}, ..., f^{(k)}]^T, \tag{2}$$

where each component $f^{(i)}$ is the ideally observed object at the i^{th} timestep. Next, we can define the block lower triangular temporally encoded operator as:

$$H_t = \begin{bmatrix} \beta_1 H & 0 & \cdots & 0 \\ \beta_2 H & \beta_1 H & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \beta_k H & \beta_{k-1} H & \cdots & \beta_1 H \end{bmatrix}, \beta_i \geq 0. \tag{3}$$

Where $\vec{\beta}$ is the afterglow profile sample at the k timesteps that form equation (2). Now, one can define:

$$\vec{g}_t = H_t \vec{f}_t + \vec{n}_t, \tag{4}$$

where $\vec{g}_t$ is the collection of high-speed x-ray frames with ghosting present. With this constructed operator, we can approximate the values in equation (2) using statistical estimators. This summary presents MLEM, however, the full work will demonstrate several statistical estimator candidates.

III. Results

The methodology successfully separated exposures overlaid due to the afterglow effect, as demonstrated by the figures included below. This has shown to improve both the resolution and clarity of the high-speed CT images significantly.

Figure 1 presents a subset of the Monte-Carlo simulated high-speed radiographs with afterglow-induced ghosting, obtained using PHITS. This full set of frames acquired simulated real-world wide-spectrum Bremsstrahlung radiation and photon statistics, but ignored other sources of randomness or noise, and depicts two objects composed of distinct materials (polyethylene and aluminum) traversing the field-of-view over 20 timesteps.

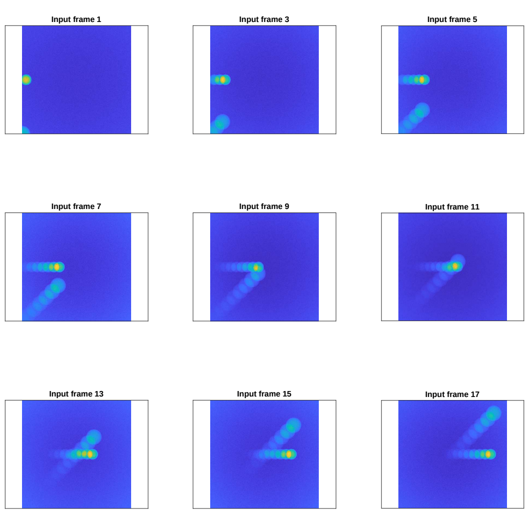

Fig. 1. Simulated high-speed radiographs with afterglow-induced ghosting.

Figure 2 presents the deconvolved images constructed from the developed MLEM estimator. Results exhibit feasibility and promise as the as the estimator based on a temporal encoding and system geometry seems to be sufficient to deconvolve radiographs with multiple exposures present.

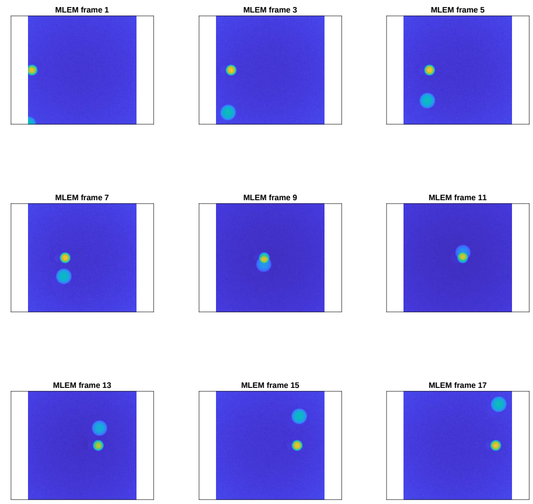

Fig. 2. Deconvolved images using the MLEM estimator.

IV. Discussion

This work presents a substantial shift in multi-frame high-speed imaging by utilizing the afterglow effect to overcome traditional scintillator limitations, leading to clearer imaging sequences suitable for improved quantitative measurements.

V. Conclusion and Future Work

These results have paved the way for advancements in high-speed imaging and hold great promise towards expanding to Multi-volume High-Speed Computed Tomography. Leveraging afterglow characteristics to enhance signal suggests a significant impact on industrial and security-based imaging applications.

Acknowledgment

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

REFERENCES

[1] B. Wilburn, N. Joshi, V. Vaish, M. Levoy, and M. Horowitz, "High-speed videography using a dense camera array," in *Proceedings of the 2004 IEEE Computer Society Conference on Computer Vision and Pattern Recognition, 2004. CVPR 2004.*, vol. 2. IEEE, 2004, pp. II–II.

[2] T. M. Buzug, *Computed Tomography: From Photon Statistics to Modern Cone-Beam CT*. Springer-Verlag, 2008.

[3] A. Yoneyama, R. Baba, and M. Kawamoto, "Quantitative analysis of the physical properties of csi, gagg, luag, cwo, yag, bgo, and gos scintillators using 10-, 20-and 34-kev monochromated synchrotron radiation," *Optical Materials Express*, vol. 11, no. 2, pp. 398–411, 2021.

[4] K. Niita, T. Sato, H. Iwase, H. Nose, H. Nakashima, and L. Sihver, "Phits-a particle and heavy ion transport code system," *Radiation measurements*, vol. 41, no. 9, pp. 1080–1090, 2006.