Computer Physics
Communications

Recent advances in BazookaSPECT: Real-time data processing and the development of a gamma-ray microscope

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Abstract

Recent advances have been made with the BazookaSPECT detector, a high-resolution CCD-based gamma camera which utilizes an MCP-based image intensifier for upfront optical gain. Operating the gamma camera at high frame rates leads to a massive amount of data throughput, thereby inducing the need for real-time processing. We have developed and implemented a list-mode algorithm which allows for real-time data acquisition and processing at high frame rates. This is accomplished with a graphics processing unit (GPU), which provides processing capabilities in addition to the CPU. We have also developed a gamma-ray microscope based on the BazookaSPECT detector and micro-coded apertures. Experimental phantom images show the gamma-ray microscope having an estimated reconstruction resolution of ~30 µm, an unprecedented resolution in gamma-ray imaging.

Keyworks: CCD-based gamma camera; coded apertures; GPGPU; near-field imaging; gamma-ray microscope

1. Introduction

Recent advances have been made with the BazookaSPECT detector, a low-cost, high-resolution gamma camera for small-animal SPECT and molecular-imaging applications [1]. Shown in Figure 1, the BazookaSPECT detector comprises an image intensifier, a columnar scintillator (or scintillator screen such as gadolinium oxysulfide), an optical-coupling system, and a high-resolution CCD. The scintillator is directly coupled to an image intensifier via a fiber-optic window. With the detector operating in photon-counting mode, as shown in Figure 2, a gamma-ray interaction is seen as a cluster of signal spread over multiple pixels. Significant improvement in spatial resolution is

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Fig. 1. BazookaSPECT gamma camera in an 8:1 imaging configuration.

obtained by estimating the interaction position through a centroid calculation of the cluster. 2-D position estimation can also be obtained through the use of maximum-likelihood (ML) techniques but with added depth and energy estimation, thereby allowing for the correction of depth-of-interaction (DOI) effects in scintillators. Because scintillation light is amplified (via the image intensifier) prior to the imaging chain, the system is no longer limited by light loss from the optical path. This allows for the use of a low-cost, high-speed CCD. It also allows for the use of a low-cost optical system which couples the output screen of the image intensifier to the CCD. The optical coupling system of BazookaSPECT consists of lenses in a macro-photography configuration [1]. Experimental results show that BazookaSPECT currently has an intrinsic resolution of approximately 70 µm when operating in a 1:1 imaging configuration.

2. Real-time data processing

The CCD used in the BazookaSPECT detector is capable of operating at high-frame rates, a critical feature to avoid pileup when operating the detector at high-counting rates. A large number of low-cost, high-frame-rate CCDs are currently available with sensors ranging from 5 MPs (megapixels) capable of operating at 15 fps to sensors with 0.3 MPs capable of operating at 200 fps. These CCDs output an enormous amount of data, which can become problematic for storage of images during long acquisitions. For example, a five-minute acquisition using a 640 × 480 CCD operating at 30 fps with 16-bit images requires 5.15 gigabytes of storage. Storing this amount of data to disk adds latency to the data acquisition.

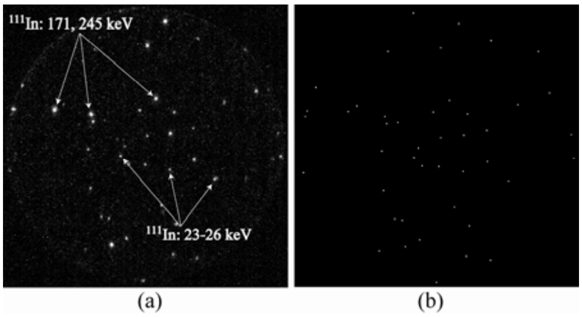

Fig. 2. (a) A frame of data from the BazookaSPECT detector illuminated with ^{111}In chloride. Higher- and lower- energy gamma rays can be identified using energy discrimination. (b) Image showing centroid estimates of the gamma-ray interactions. Centroid and maximum-likelihood position estimates allow for a significant improvement in spatial resolution with BazookaSPECT detectors.

We have developed a list-mode acquisition method for the BazookaSPECT detector that allows for real-time processing of image data and also reduces the amount of required storage. In photon-counting mode, only a minority of frame data consists of regions with clusters from gamma-ray interactions. By extracting the clusters and saving them to disk in a list-mode fashion, all useful information from the clusters is preserved, which can be used if post-processing is desired.

Real-time processing is accomplished with the assistance of a Graphics Processing Unit (GPU), a recent technique known as General-Purpose Computing on Graphics Processing Units (GPGPU). GPGPU entails assigning some of the processing tasks to the GPU, taking advantage of its inherently parallel design to achieve a significant improvement in processing speed.

As previously mentioned, a gamma-ray interaction is seen as a cluster of signal spread over multiple pixels. If the detector were to be operated in an integrating mode, signal spread across pixels would result in a degradation of spatial resolution. We obtain significant improvement in spatial resolution by estimating the interaction position through a centroid calculation of the cluster or via maximum-likelihood techniques. We have demonstrated real-time processing with the centroid method, and we are currently investigating implementation of real-time maximum-likelihood estimation algorithms (including depth and energy estimation) [2]. The real-time acquisition and processing algorithm works as follows:

1. An image from the frame grabber is acquired and smoothed with a median filter to remove hot pixels.
2. The smoothed image is thresholded above the noise, and individual clusters are identified via a fast connected-components labeling algorithm [3].
3. A centroid calculation is then performed on individual clusters, and if desired, an estimate of the energy can be obtained by summing pixel values from the cluster.
4. The centroid location of the gamma-ray interaction, as well as the cluster (e.g. 11 × 11 region), are written to disk.

The centroid algorithm was tested on a BazookaSPECT detector having a Flea2® model CCD from Point Grey Research. The sensor was a 0.3 MegaPixel CCD having a maximum frame rate of 30 fps. An NVIDIA 7900 model GPU was used with RapidMind®, a software package which interfaces with the GPU and provides a C++ like interface. With the use of the GPU, the BazookaSPECT detector is able to acquire and process data real time at 30 fps compared to ~12 fps with just the CPU. The processing speed and capability of GPUs are continually increasing, making them an attractive, low-cost solution for high-speed processing with BazookaSPECT detectors.

3. Gamma-ray microscope

In addition to small-animal SPECT imaging with the BazookaSPECT detector, we are currently developing methods and applications which take advantage of the detector's superb intrinsic resolution. One such device that we have recently developed is a gamma-ray microscope based on micro-coded apertures [4] in conjunction with BazookaSPECT.

In pinhole imaging, ultimately the limiting factor in system resolution is the pinhole diameter. A smaller pinhole will result in higher resolution but at the expense of collection efficiency. A vast amount of literature exists on coded aperture imaging [4-11], and it has been shown that near-field coded aperture imaging, with applications in small-animal SPECT, can be used to provide high-spatial resolution imaging with high collection efficiency.

Fig. 3. An exploded view of the prototype gamma-ray microscope.

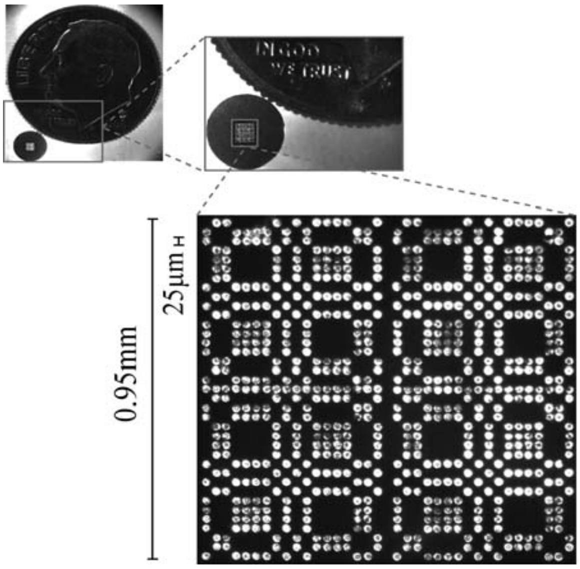

Fig. 4. Micro-coded aperture based on a 38 × 38 MURA with 684 laser-drilled pinholes (25-µm diameter) in a 25-µm thick platinum disk.

We have implemented near-field coded aperture techniques [8-11], scaled to utilize the resolution of BazookaSPECT, which provide planar reconstructions having resolutions in the tens of microns. Our prototype gamma-ray microscope, shown in Figure 3 is arranged in an 8:1 imaging configuration having an intrinsic detector resolution of ~150 µm FWHM. A 40 µm thick gadolinium oxysulfide screen, courtesy of Radiation Monitoring Devices, Inc. (RMD, Inc.), is used as the scintillator. The micro-coded aperture, shown in Figure 4, was fabricated from a 4-mm diameter, 25-µm thick platinum disk. The disk has 684 laser-drilled pinholes each having a diameter of 25 µm. The coded-aperture pattern is based on a 38 × 38 MURA pattern [7] with dimensions 0.95 × 0.95 mm^2 having an open fraction of ~37% .

Having a thickness of only 25 µm, the micro-coded aperture is suited for low-energy imaging (~20-35 keV); however, we have demonstrated that isotopes which emit both high- and low-energy gamma rays can be used with the microscope. For example, in nuclear medicine, ^{111}In is typically used as a higher-energy isotope with 171 and 245 keV gamma rays. At these energies, the 25-µm thick platinum disk and the scintillator are essentially transparent to the gamma rays; however, ^{111}In produces a large fraction of X rays with energies ~24-26 keV. At these energies, the platinum foil and scintillator work very well for imaging. Additionally, although a small fraction of the higher-energy gamma rays interact with the scintillator, the BazookaSPECT detector has energy discrimination capabilities which can be used to identify and reject the 171 and 245 keV gamma rays.

To test the resolution of the gamma-ray microscope, we created a phantom using cation exchange resin beads. Each bead was approximately 50 µm in diameter and had absorbed ~200 nCi of ^{111}In chloride. The resolution phantom is shown in Figure 5a. In coded-aperture imaging, each bead produces a shifted copy of the coded-aperture pattern which results in a multiplexed projection image as shown in Figure 5b. To reconstruct the bead phantom, we used traditional coded-aperture decoding techniques [5-7]. The planar reconstructed image of the phantom, shown in Figure 5c, has an estimated resolution of ~30 µm.

4. Conclusion

We have successfully developed and implemented an algorithm for operating the BazookaSPECT gamma camera in real time with the use of a graphics processing unit (GPU). The use of GPUs to perform computations instead of the CPU is an attractive, low-cost solution for handling massive amounts of data from high-speed, high-resolution CCDs. We currently perform a real-time 2D position estimation of gamma-ray interactions using centroid estimation, and work is underway to utilize GPUs for real-time maximum-likelihood 3D position and energy estimation.

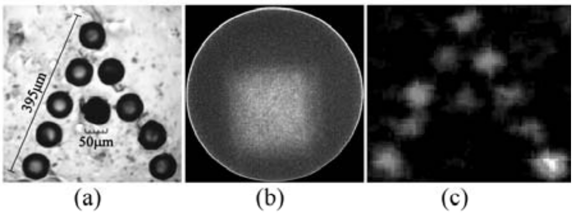

Fig. 5. Micro-coded aperture resolution test: (a) coded-aperture resolution phantom created with cation exchange resin beads which had absorbed ^{111}In chloride (~200 nCi/bead), (b) coded-aperture projection image of bead phantom, and (c) reconstructed planar image having an estimated reconstruction resolution of ~30 µm.

We have successfully developed a gamma-ray microscope based on the BazookaSPECT detector and micro-coded apertures. Experimental results show an estimated reconstruction resolution of ~30 µm for planar imaging. Future work entails the development of even higher resolution apertures as well as the investigation of medical/biomedical applications which can utilize this unprecedented resolution in gamma-ray imaging.

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