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ABSTRACT

Scattering muon radiography was proposed recently as a technique of detection and 3-d imaging for dense high-Z objects. High-energy cosmic ray muons are deflected in matter in the process of multiple Coulomb scattering. By measuring the deflection angles we are able to reconstruct the configuration of high-Z material in the object. We discuss the methods for information extraction from muon radiography data. Tomographic methods widely used in medical images have been applied to a specific muon radiography information source. Alternative simple technique based on the counting of high-scattered muons in the voxels seems to be efficient in many simulated scenes. SVM-based classifiers and clustering algorithms may allow detection of compact high-Z object without full image reconstruction. The efficiency of muon radiography can be increased using additional informational sources, such as momentum estimation, stopping power measurement, and detection of muonic atom emission.

Keywords: Muon Radiography, Multiple Scattering, Tomographic Methods, Image Reconstruction, Classification, and Object Detection

INTRODUCTION

Scattering muon radiography is a novel technique of detecting and 3-d imaging for dense high-Z objects. Muons are unstable elementary particles that are produced when cosmic rays strike air molecules in the upper atmosphere. Each minute, about 10000 muons rain down on every square meter of the Earth. Muons are more strongly deflected, or scattered, by nuclear (uranium, plutonium) or gamma ray shielding (lead) materials than they are by common materials such as plastic, glass and steel. The materials that most strongly deflect muons have high atomic numbers (Z) and high number densities. By tracking the scattering angles of individual incoming and outgoing muons using a set of two high-resolution position-sensitive detectors, we were able to develop a new type of radiography for the object placed in between two sets of detectors [1].

Scattering muon radiography creates an interesting image reconstruction problem. Muon radiography data is an unusual information source, distinctly different from other types of radiography. Conventional radiography uses the absorption of man-made, penetrating radiation to provide image contrast. The direction and spectrum of the radiation can be controlled, and the signal measured is the number of photons or other particles stopped by the object. In contrast, cosmic-ray muon radiography relies on the production of muons by cosmic rays, without any human intervention. The directions of incoming muons have a wide distribution around vertical. The average spectrum of muons is known, but the momentum of any particular particle is difficult to measure. Cosmic ray muons are deflected in matter in the process of multiple Coulomb scattering, with quasi-Gaussian distribution. The center of the distribution is the same (corresponding to zero deflection) for all materials, and its width depends on both parameters of the object and muon energy.

In this paper we discuss the methods for information extraction from muon radiography data and additional sources of information enabling more efficient muon radiography.

GENERAL PRINCIPLE OF MUON RADIOGRAPHY

A new form of cosmic ray muon radiography is based on the multiple Coulomb scattering experienced by the particles as they pass through material. The cosmic ray muon spectrum varies with altitude, geophysical location, and other factors, but the mean muon momentum is about 3-4 Gev. The angular distribution goes approximately as $\cos^2(\theta)$, where θ is plane angle from vertical. The overall muon rate is about 1 $cm^{-2}\cdot min^{-1}$ for horizontal detectors [2].

A muon passing through material is deflected by many small angle scatterings off the nuclei of the material. The particle traverses the material in a stochastic path due to these multiple scatters. The muon emerges from the material at an aggregate scattered angle θ_{scat} (see Fig.1). The angular scattering distribution is approximately Gaussian, with zero mean and a standard deviation for scattering in the plane given by [2]:

$$\sigma_\theta = \frac{13.6\,\mathrm{Mev}}{\beta cp}\sqrt{\frac{L}{L_0}}\left[1+0.038\ln\left(\frac{L}{L_0}\right)\right] \quad (1)$$

where p is the momentum, and βc the velocity of the incident particle ($\beta c \cong 1$ for ultra-relativistic cosmic ray muons). L is the depth of the material, and L_0 is the radiation length of the material.

Radiation length is a characteristic amount of matter for scattering and other nuclear interactions and decreases with increasing material Z number, hence mean scattering increases. The net angular deflection of the trajectory is very sensitive to the atomic number Z. This sensitivity, coupled with the long range of muons, makes muon scattering of particular interest as an information source for the detection of high-Z material in low-Z surroundings.

The experimental apparatus for muon radiography consists of four horizontal positional-sensitive detectors that measure X and Y locations for each muon in four planes (Fig.1). The top two detectors measure the incident muon track, while the bottom two measure the track after scattering.

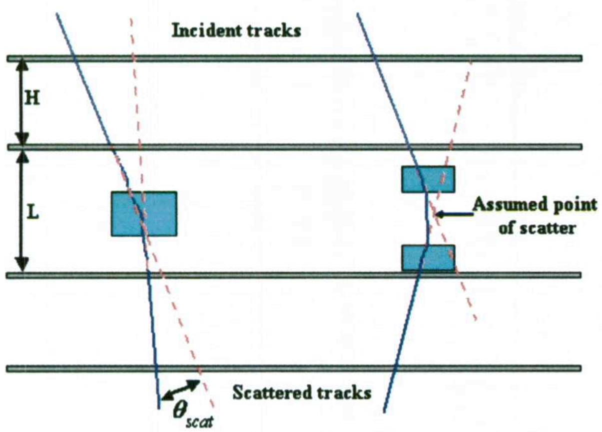

Fig.1. Cosmic ray muon radiography concept. Two pairs of positional-sensitive detectors measure incident and scattered tracks for each muon (solid blue lines). Image reconstruction based on single-scattering approximation (red dashed lines) works satisfactorily in simple cases (left track), but fails for more complicated geometry of the scattering (right track) .The magnitude of scattering is exaggerated for illustrative purposes.

The path of a charged particle through the test material is stochastic and can only be approximately reconstructed. In our initial reconstructions we approximated multiply-scattered tracks as having only a single scattering event, and located the point of scatter by extrapolating the incident and scattered rays to their point of closest approach (Fig.1). The outgoing trajectory of the scattered muon does not need to cross its incident trajectory in three-dimensional space. We may use, however, a point of closest approach for these two tracks as a designated scattering point. Each muon is assigned to a voxel of a three-dimensional image, which contains the point of closest approach for this muon. The average of the squared measured scattering angles gives us an estimate for the material radiation length. We may now create a three-dimensional image with signal in each voxel inversely proportional to the measured radiation length. This simple algorithm allows us to reconstruct test objects in three dimensions [3, 4]. The algorithm works well when a single-scattering approximation is valid, i.e. in the absence of significant amount of a distributed scattering material. However, in practical situations a distributed scatterer is often present. Point of closest approach in these situations may be significantly shifted away from the object of interest.

IMAGE RECONSTRUCTION TECHNIQUES

More elaborate image reconstruction techniques are needed for muon radiography to be effective. The muon radiography problem can be formulated in terms that allow the use of tomographic reconstruction techniques widely used in medical imaging and other applications. Tomography usually refers to the reconstruction of an object from projections taken from multiple directions. In our case we do not have set directions and projections, but we can use similar techniques using our measurements of incoming and outgoing tracks for individual muons. The object is modeled as a set of voxels filled each uniformly by the material of chosen radiation length. The size of the voxel is restricted by the required accuracy of reconstruction, the amount of available data and computational considerations. For meters-sized objects 10x10x10 cm^3 voxels seem to be a reasonable compromise. For each muon we find the voxels which it penetrates, calculate total radiation length from the model of an object, and define the probability of the scattering at the measured angle. The likelihood of the whole data ensemble can then be calculated and used for the model evaluation. Then we change the model of the object and repeat the procedure until the most likely configuration of the object given the data is found. A tomographic reconstruction algorithm for cosmic ray muon multiple scattering radiography was developed by marrying the algebraic framework with a statistical model of the information source and applying maximum likelihood methods [5]. We were able to perform full three-dimensional reconstruction of simulated sea container using maximum likelihood method (see Fig.2). Such reconstructions of complex objects remain computationally intensive, and real-time data reconstruction required in important applications has not yet been demonstrated.

In parallel we continue to consider simpler techniques allowing real-time detection of compact high-Z objects in many realistic environments. Even though single-scattering approximation does not work in some cases, the angles of muon deflection are still so small that we know quite accurately what voxel each muon intersects. The broad angular distribution of the muons allows us to find the voxels with larger number of highly scattered muons. These are the voxels where compact high-Z objects may be located. It appears that the detection algorithm based on the number of highly scattering muons in a voxel is able to provide a reliable detection and three-dimensional localization of high-Z objects in many simulated scenes (Fig.2, see also [6]).

In practical applications, like nuclear contraband detection, we often do not need full three-dimensional reconstruction of the image, but rather a simple yes/no detection of a threat object. We have experimented with support vector machines (SVM, [7]) based classifiers for this task. Raw muon radiography data are not suitable for SVM, their pre-processing being of crucial importance. We have success with cubes of 3x3x3 voxels represented by mean scattering angle in a voxel. With appropriate training, a SVM was able to classify properly cubes containing high-Z objects in the central voxel from other cubes. To make classification of larger objects we need to be able to identify the cubes with objects of potential interest in the center. Pre-processing of voxels based on the amount of scattering may provide us with a list of potential candidates for SVM classification.

Efficiency of all of the methods discussed above is affected by voxelization of the object. It is an attractive idea to define positions of the objects of interest from original data. We are experimenting with k-means clustering of highly scattered muons [8]. Initial results are promising. Depending on their efficiency and reliability clustering results may be used as a pre-processing for SVM-based classification or as a separate method of high-Z object detection based on the compactness of the corresponding cluster.

ADDITIONAL INFORMATIONAL SOURCES

Efficiency of muon radiography is important and it can be increased if additional information is obtained in muon radiography experiments. One example of such information is the experimental measurement of muon energy. As is seen from Eq.(1) the scattering angle depends on both radiation length of the material and muon momentum. Radiation length can be measured more accurately if both scattering angle and energy of each muon is measured in the experiment. Unfortunately, precise measurement of the muon energy is complicated and expensive. Relatively inexpensive way to estimate the energy is discussed in [4]. The idea is to place a sandwich of detectors and plates of known material and thickness below the object measurement area. By measuring particle scattering through these plates we may infer particle momentum.

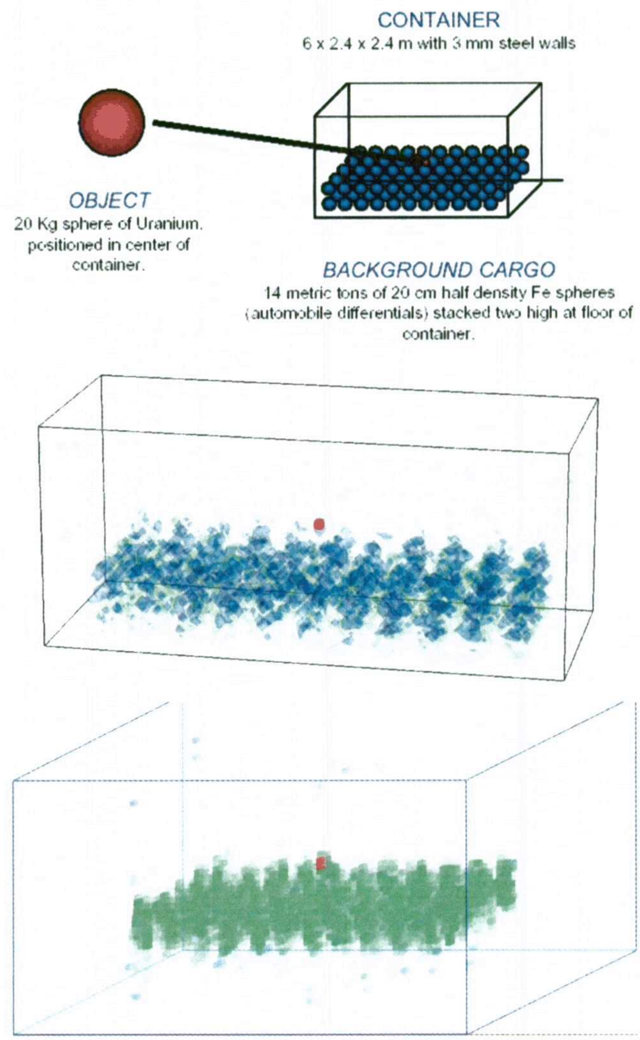

Fig.2. Top: simulated scene with a small (8cm sphere, 20kg) high-Z object in a shipping container with a lot (14 tons) of medium-Z background. Middle: reconstruction of the 1-minute simulation of the scene above by the maximum likelihood method. The object in the middle marked as a high-Z (red), while iron spheres are recognized as medium-Z (blue). Low-Z background is painted green. Bottom: reconstruction of the same scene (2 min simulation) with muon crossing algorithm. Red highlights compact high-Z object, while regions of higher scattering are shown in green.

Another approach is to measure the energy by ranging out lower energy particles consequently by the layers of material with increasing thickness. Cost versus efficiency considerations will define the energy measurement scheme for particular applications.

One may also collect the information from the muons that got absorbed in the object. Energy loss for ionization is defined by the Bethe-Bloch formula [2]. Energy loss depends on atomic number and atomic mass of the material:

$$-\frac{dE}{dx} \propto \frac{Z}{A\beta^2} \qquad (2)$$

When energy loss exceeds initial energy of the muon, it stops in the material. These muons can be detected in the muon radiography experiment presented schematically in Fig.1. Angular scattering and stopping rate depend differently on atomic number of the materials (see Fig.3). Angular scattering depends on radiation length as shown by Eq.(1). Radiation length is in turn a function of atomic mass A and atomic number Z of the scattering material (in g/cm^2) [8]:

$$L_0 \cong \frac{716.4A}{Z(Z+1)\ln\left(287/\sqrt{Z}\right)} \qquad (3)$$

One can discriminate between different materials by measuring both L_0 (from multiple scattering angle) and dE/dx (from stopping rate for known spectrum of muons). Furthermore, some stopped muons enter an orbit around one of the atomic nuclei forming a muonic atom and generating characteristic gamma-emission. This emission, if detected, can also be used for materials discrimination.

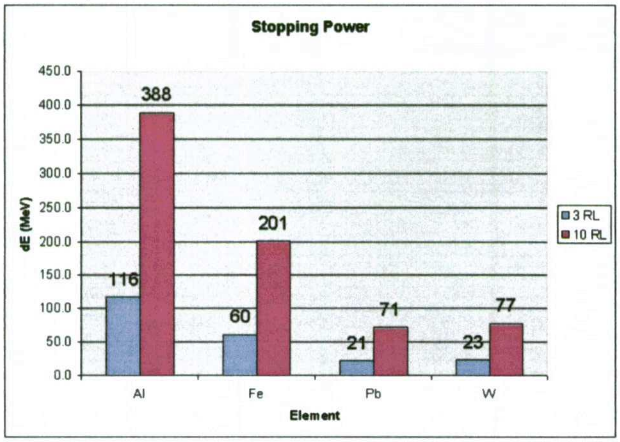

Fig.3. Objects with the same radiation length differs in their stopping power depending on the material. Numbers on a histogram show energy losses for 3 and 10 radiation lengths of aluminum, iron, lead and tungsten.

CONCLUSIONS

Information extraction from muon radiography is an interesting task, which can be approached by different methods. We discuss several such methods and their relative merits. Choice of the most efficient method will be defined by the requirements of particular application (processing time versus accuracy of reconstruction, image reconstruction versus object detection etc.) We also discuss several additional sources of information, which may increase the efficiency of muon radiography. Use of these sources will depend on a trade off between more efficient versus more economical methods.

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