TECNOMUSE: a novel, RPC-based, muon tomography scanner for the control of container terminals

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Abstract. Every year, 700 million twenty-foot (container) equivalent units pass through the container terminals of the harbours all over the world. Only a small percentage (3-4%) are scanned to inspect the presence of radioactive materials. The need for controls is hampered essentially by three factors: the amount of both time and personnel necessary to control each container and the use of scanning methods based on systems potentially harmful to the personnel itself. Muon tomography can become a strategy for fast and reliable inspection of containers without using ionizing radiation. This technology takes advantage of multiple Coulomb scattering of the muons (particle produced by cosmic rays) through media to understand the composition and the geometry of the scanned volume. The TECNOMUSE project has the purpose to realize a muon tomography scanner based on a novel geometry and, for the first time, using Resistive Plate Chambers detectors. In this work, the preliminary results from the TECNOMUSE scanner are evaluated via Monte Carlo simulations. Many different simulations have been made with the aim to assess the detection capabilities of the device, its spatial resolution and the time required to reconstruct and distinguish different materials.

1. Introduction

1.1. Muon tomography

Muon tomography is an imaging technique taking advantage of the muons produced by cosmic-rays interacting with the atmosphere [1, 2]. At sea level, the muon rate is about 10,000 per minute per square meter [2] and their energy distribution is peaked at 3-4 GeV. Since muons reach the sea-level at different incidence angles, it is possible to produce a three-dimensional image of a scanned volume by evaluating the differences in the trajectories of the muons.
muons before and after passing through the media contained in the volume to scan.

1.2. The TECNOMUSE project
The aim of the TECNOMUSE (in English: Muon Technology for Harbour Security) project is the development of an innovative muon tomography scanner, based on Resistive Plate Chambers (RPC) detectors [3, 4]. RPCs are gaseous detectors allowing both high spatial and high time resolution (on the order of few hundred picoseconds). By placing a pair of detection planes above the volume to scan and a pair below it, it is possible to detect the incoming and outgoing trajectory of a muon and, from their deviations, to infer the composition of the scanned volume (see Section 2.1).

Beyond the scanner, another objective of the project is the realization of an integrated infrastructure allowing an user, by means of a user-friendly software interface, to: (a) access the system through an access control system that guarantees the security of the infrastructure; (b) have a comprehensive control of the diagnostics of the scanner; (c) create images of the scanned volume after creating its related registry; (d) start a scan and display images from the tomographic reconstruction in real time; (e) evaluate the contents of the scanned container and act accordingly.

2. Materials and Methods
2.1. Muon tomography reconstruction from Multiple Coulomb Scattering
The physical principle on which relies the scanner developed in the TECNOMUSE project is the multiple Coulomb scattering of muons. An incoming muon that goes through an object is deflected from its original trajectory with a deviation angle that has a Gaussian distribution around zero and a standard deviation depending on the atomic number (via the radiation length) and the thickness of the traversed material. Eq. 1 shows the relationship between these quantities (from [1]):

\[\sigma \approx 13.6 \text{ MeV/c} \sqrt{\frac{x}{X_0}}\]  

(1)

where \(p\) is the particle momentum, \(x\) is the thickness of the traversed object and \(X_0\) is the radiation length of the material composing the object itself, that is related with the atomic number \(Z\).

2.2. Monte Carlo simulations
Monte Carlo simulations have a pivotal role in the preliminary evaluation of detectors and, for this reason, they are widely used both in High Energy Physics and Applied Physics.

In the context of the TECNOMUSE project, simulations have been carried out with the aim of selecting the best detection geometry for the RPC detectors in terms of detectors sizes and placements and testing the goodness and the reliability of the developed reconstruction software. Results from simulations are reported in this work since they have allowed to optimize the performance of the TECNOMUSE tomograph well before its realization.

The simulations have been developed with the GATE toolkit [5] that is based on the Geant4 [6] libraries but it allows a more efficient management of time and geometries. In this work, three different simulations with different purposes are reported (see Fig. 1):

(i) Verify the geometries and materials identification capabilities: an ensemble of cubes, cylinders and words made of Water, Iron, Tungsten and Uranium, see Fig. 1 (a) and (b);
Figure 1. TECNOMUSE scanner design and scanned object for different purposes. (a) Overall design of the TECNOMUSE scanner highlighting the placement of the different RPC detectors, shown with a wireframe appearance. The cyan and yellow RPCs bring information about the X-coordinate, the green RPCs along the Y-coordinate and the red ones along the Z-coordinate. (b) Detail of the objects at the center of image (a) made of water (cyan), iron (green), tungsten (yellow) and uranium (red). (c) Detail of the bar phantom object, made of four quadrant of tungsten slabs with the same area (25×25 cm²) and different (3 cm, 2 cm, 1 cm and 0.5 cm) thickness and spacing pitch. (d) Tungsten (red) and lead (yellow) cubes placed among steel I-beams (in grey).

(ii) Assess the imaging capabilities and select the best voxel size\(^1\): a bar phantom object (a geometry borrowed from medical imaging applications) made of Tungsten, see Fig. 1 (c);

(iii) Evaluate the importance of time resolution: some tungsten and lead cubes placed among many steel I-beams for construction, see Fig. 1 (d).

It is important to stress that the simulated muons reproduce the angular and energetic distributions of real cosmic muons.

2.3. Tomographic reconstruction and analyses

The software for the reconstruction of tomographic images starting from the interaction points of the muons in the detectors has been developed from the algorithm developed by Schultz et al. \cite{7}. The algorithm has been adapted to be geometry-independent and to be suitable to the detectors used in the TECNOMUSE project.

\(^1\) The voxel is the size of the unitary and elementary cubes composing the three-dimensional image. They are the three-dimensional extension of the pixels in two-dimensional images.
Figure 2. (a) Top, (b) Central and (c) Bottom axial (along the vertical axis) images of the setup depicted in Fig. 1 (b). For the generation of these images, having 2 cm voxel size, about 12,000 muon trajectories have been simulated, corresponding to about 30s of data acquisition in the real scenario.

The results and images reported have been obtained from reconstruction and analyses made with MATLAB (version R2017b) before the implementation of the software integrated infrastructure.

3. Results
3.1. Definition of the geometry of the scanner
The Monte Carlo simulations have allowed to select the best placement for the RPC detectors, aimed to improve the counting efficiency of the scanner. Moreover, since each plane of detectors bring information about just one of the planar directions (along the X- or Y-axis, see the cyan and green detectors in Fig. 1 (a), respectively), the simulations have allowed to maximize the area in which both coordinates are available. At the same time, simulations have been useful to define the best size of each detector, constrained by the size of standard containers. A detection area of about 180×180 cm² has been realized in the central section of the detector (i.e. the intersection of cyan and green detectors).

The simulations have also suggested the usefulness of the vertical detectors in the lower part of the scanner (depicted in red and yellow in Fig. 1 (a)), allowing to detect the outgoing muons scattered at large angles.

3.2. Recognition of geometries and materials identification
Muon tomography allows to identify both the shapes and the elemental composition of the objects in the scanned volume. The capabilities of the developed algorithm for tomographic reconstruction have been tested, at first, on simple geometries and, progressively, by combining complex shaped objects made of different elements, as the ensemble depicted in Fig. 1 (b). In the image from the top layer of Fig. 2 (a) it is possible to read the word "ALTO" (i.e. "High" in Italian) and, in the upper half of the image, only the medium- and high-Z cubes are visible. The (b) image shows all the words and letters that are made of tungsten and, for this reason, clearly readable. Only some objects have voxels in red, accordingly to the presence of high-Z materials. In the lower half of the image, only the boxes made of iron and tungsten are visible. In Fig. 2 (c) beyond the word "BASSO" (which means "Low" in Italian) the only cubes visible in the upper half are only those made with medium- and high-Z materials.
Figure 3. Image reconstruction via muon tomography of the bar phantom with voxel size of (a) 5 cm, (b) 2 cm and (c) 1 cm. Both 1 cm and 2 cm voxel sizes allow to properly see 2 cm thick slabs but not the 1 cm thick ones. For the generation of this image, having 2 cm voxel size, about 200,000 muon trajectories have been simulated, corresponding to about 5 minutes and 30 seconds of data acquisition in the real scenario.

The outcomes confirm that the reconstruction software allow to recognize the geometry and the composition of the objects.

3.3. Selecting the best voxel size
Fig. 3 shows the tomographic reconstructions of the bar phantom in Fig. 1 (c) with different voxel sizes: (a) 5 cm, (b) 2 cm and (c) 1 cm, respectively. Each image represent the reconstruction obtained from about 200,000 incoming muons (corresponding, with the scanner layout previously described, at about 5 minutes and 30 seconds of data acquisition in the real scenario).

As expected, the 5 cm voxel size reconstruction does not allow to recognize none of the four sectors since their bigger pitch is 3 cm, while both the 2 cm- and 1 cm- voxel sizes allow to identify the 2 cm-pitch sector. The reconstruction with 1 cm voxel size appears noisier than with 2 cm voxel size, and does not make possible to recognize the sector with 1 cm pitch, though. For an acquisition time compatible with the real scenario (about 5 minutes), 1 cm voxel size does not bring any benefits respect to 2 cm one.

For this reason, in order to have a good balance between spatial resolution and counting statistics in each voxel, the 2 cm voxel size has been chosen has the best trade-off for the reconstruction of the image.

3.4. Importance of time resolution
The innovative and the most engaging aspect in the TECNOMUSE scanner is the use of RPCs as muon detectors, with the aim to take advantage of their superior time resolution. Such time resolution allows to identify the momentum of the incoming muons. The momentum is a key information since, according to Eq. 1, is strictly related with the scattering signal associated with the scattered muon.

Fig. 4 clearly shows the benefits of the temporal information on the image contrast between low-/medium-Z objects and high-Z ones. In the (a) image is quite difficult to identify the tungsten and lead threats (in red) among the steel I-beams (in black), since they appear very noisy. Conversely, thanks to the temporal (i.e. momentum) information, see Fig. 4 (b), the threats are clearly recognizable.
Figure 4. Image showing the importance of time information in the reconstruction of muon tomography images. Respect to the image without taking into account the impulse of incoming muons (a), the tungsten and lead threats (highlighted in red) are more clearly visible in the image with the time information considered (b). For the generation of this image, having 2 cm voxel size, about 120,000 muon trajectories have been simulated, corresponding to about 3 minutes and 20 seconds of data acquisition in the real scenario.

4. Conclusions
The work has presented the first performance evaluation of the novel muon tomography scanner developed in the context of the TECNOMUSE project.

The Monte Carlo simulations allowed to define: the geometry of the scanner, the reliability of the developed reconstruction software, the best trade-off in voxel size of the image (i.e. 2 cm) and the importance of time resolution in the contrast of the images. The measurements with the actual scanner will take advantage of all the information obtained in this preliminary evaluation.

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