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Muon tomography using cosmic-ray muons

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Abstract. The paper discusses about the R&D of a setup for muon tomography utilizing the scattering suffered by the muons due to electromagnetic interaction with the atomic nuclei while passing through any matter. The design of the setup has been optimized using numerical simulation for material discrimination and for further application in inspection of civil structures. An image processing algorithm based on pattern recognition method has been developed and tested for its performance in distinguishing between light and heavy elements and detecting defects in civil structures. The hardware developmental activities related to the muon tracking detectors and data acquisition system have been discussed.

1. Introduction

The three-dimensional imaging or tomography of an unknown object using the cosmic-ray muons is a non-destructive evaluation technique that has been widely in use since last few decades in various fields, such as homeland security, volcanology, archaeology, civil engineering etc., to name a few. The abundance of minimum ionizing cosmic muons at sea level with a particle flux 1/cm^2/min makes the muon tomography advantageous in many respects. Firstly, it is a natural radiation source available free of cost unlike other sources and can penetrate deep and therefore, useful and cost-effective in evaluation of huge objects, like monuments, volcano, reactors etc. In addition, it does not pose any health related hazard and hence calls for no special safeguard in carrying out the imaging operation. Two techniques of muon tomography are now established based on the interaction modes of muons with matter. One of them is, namely, muon absorption or transmission tomography, where the loss of energy of muons due to ionization of the atoms through inelastic collision within the test object is considered. The other one is called muon scattering tomography where deviation of the muons due to elastic scattering from the atomic nuclei while passing through the test object is studied. In the present paper, an R&D effort on utilization of Muon Scattering Tomography (MST) for discrimination among different materials has been reported which aims towards its implementation in inspecting civil structures for their internal defects.

The muons undergo multiple Coulomb scattering due to their electromagnetic interaction with the atomic nuclei while passing through any material. The distribution of the net scattering angle can be expressed as a Gaussian distribution [1] with its mean at zero and the standard deviation σ as follows.

$$\sigma = \frac{13.6\ [MeV]}{\beta c p}\sqrt{\frac{L}{X_0}}\left(1 + 0.0038 ln\frac{L}{X_0}\right)$$

Here $\beta = v/c$ is the ratio of the muon velocity v to that of light c and p is the momentum of the muon, L is the length traversed by the muon in the material. X_o is the radiation length which can be expressed in terms of a few physical properties of the material, such as its atomic number Z, atomic mass A, and density ρ as follows [2].

$$X_0 = \frac{716.4\ [g/cm^2]}{\rho}\frac{A}{Z(Z+1)ln\left(\frac{287}{\sqrt{Z}}\right)}$$

It is obvious from these mathematical relations that the scattering angle depends on the physical properties of the material and the momentum or energy of the incident muons. Therefore, by measuring the scattering angle, in principle it is possible to discriminate between different materials with different values of Z, A and ρ depending upon the resolution of the measurement procedure when the muon momentum is known.

We have adopted the MST technique for distinguishing between different materials which can be made useful for imaging civil structures and evaluation of their internal condition. We plan to develop a prototype MST setup using position sensitive gaseous detectors for tracking the muon trajectories before and after their passage through the test object. The measurement can be accomplished using multiple position sensitive detectors to collect position information at discrete locations along the incident and scattered trajectories of the muons. The information can be utilized to reconstruct the path following various mathematical models. Eventually, the scattering angle can be determined from the reconstructed incident and scattered trajectories. We have proposed such a setup and studied its performance by producing numerical images based on the scattering of muons in the test objects followed by their analysis using statistical process and an image processing technique based on Pattern Recognition Method (PRM) [3]. Afterwards, the simulation framework has been used to investigate the efficacy of the setup in detecting a few cases of defects commonly found in civil structures [4].

The process of building the MST setup is currently under progress using Resistive Plate Chamber (RPC) as the position sensitive detectors for tracking muons. An initiative has been taken to develop a simple low-cost data acquisition system based on FPGA which has been reported by us in [5]. Further R&D in this direction is in progress and some preliminary test results will be reported here. Several other R&D projects are also underway to explore the possibility of using Gaseous Electron Multiplier (GEM)-based detectors as the muon tracker [6]. In the following, a comprehensive report about the numerical work along with the instrumentation carried out by us for the R&D of the proposed MST setup will be furnished.

2. Numerical simulation

The design of the prototype MST setup has been optimized within the practical feasibility limit to achieve uniform muon flux across the inspection volume. The performance of the setup in distinguishing different materials has been studied by producing images numerically by simulating the Coulomb scattering of the muons in test object and analyzing those using the PRM. The images for a few civil structures have been produced using the same simulation framework and analysed to study the scope of the proposed setup for monitoring the defects. A brief description of the entire numerical work has been provided below.

2.1. Modelling of MST setup

A model of the MST setup consisting of two sets of trackers, each having three position sensitive gaseous detectors, has been built in GEANT4 [7] platform. The detectors have been modeled with 2 mm thick gas volume enclosed between two parallel electrodes. An inspection volume of dimension 30 cm × 30 cm × 30 cm has been considered between the two sets of trackers where the test objects have been housed, as shown in figure 1 where the muon trajectories are shown by red line along the Z-direction. The detector area has been optimized to 50 cm × 50 cm and the vertical separation between them 7 cm for practical purposes. The entire setup has been placed inside a large concrete housing and filled with air.

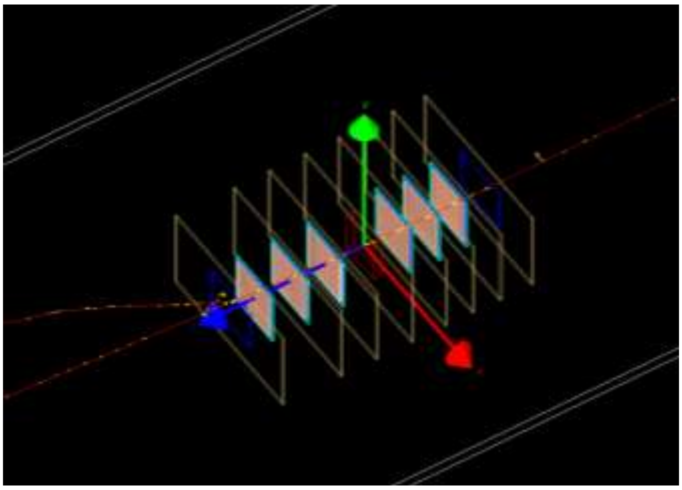

Figure1. Prototype MST setup in Geant4

2.2. Track reconstruction and scattering vertex determination

The MST setup modelled in GEANT4 has been subjected to a muon flux obtained for the latitude and altitude of the laboratory from a generator CRY [8] with an exposure of three and half hours. The physics list in GEANT4 has taken care of all the electromagnetic and weak interactions of the charged particles and gamma radiations and the hits in the sensitive detector volume have been stored. The uncertainty in the hit position due to the detector resolution has been introduced by generating a random value with the actual hit point as its mean and the standard deviation equal to the spatial resolution. For the sake of simplicity, the spatial resolution of all the detectors has been considered same. The following selection criteria have been implemented to extract the valid muon scattering events: i) a track must have hits on all the detectors, ii) the angle between the tracks reconstructed from the pair of hits on the first and the second detectors and that from the pair of the first and the third ones in each set of trackers must be less than 0.5^{o}, iii) the angle between the tracks in upper and lower sets of detectors must not be less than 1.5^{o}.

Two algorithms for determining the scattering vertex have been explored and used. They are namely, Point of Closest Approach (POCA) [9] and Binned Clustering Algorithm (BCA) [10]. Both algorithms assume a single vertex of scattering instead of multiple ones. The POCA is a geometrical algorithm which determines the closest point of approach between two skew lines in a three dimensional inspection volume. When the tracks of incident and scattered muons do not intersect, the mid-point of the line segment connecting the closest points of the tracks has been considered as the scattering vertex. In BCA, a least square fitting function is used to determine the position of the scattering vertex. The same algorithm assesses the clustering of scattering vertices through calculation of a weighted metric distance which is used for material discrimination. It has been found that the BCA algorithm is able to differentiate high and low-Z materials, like air and lead, with half an hour exposure while more exposure (at least one hour) is needed to differentiate between two closely lying high-Z materials, like lead and uranium [3]. Taking the momenta information of the muons into account along with improved spatial resolution and larger area coverage of the detector in the setup, the BCA can be useful in material discrimination in shorter time. However, while studying the civil structures, POCA has been used to determine the scattering vertices for image production in order to reduce the computational load.

2.3. Image production and processing
The ability of the proposed setup in differentiating materials on the basis of scattering of muons has been examined using test blocks made up of different materials and placed in the inspection volume. In the present work, two dimensional images of the test objects have been produced by projecting the scattering vertices on the orthogonal planes i.e. XY, XZ and YZ planes at the centre of the inspection volume. Instead of considering the three dimensional volumetric distribution of the scattering vertices, the projected two dimensional map of the same on the XY plane has been used for further analysis in order to reduce the computational expense. Examples of the projected images of two test blocks (iron and lead) produced with three and half hours muon exposure and three different detector resolutions (ideal, 200 micron, 1 mm) have been shown in figure 2. The performance of the proposed MST setup in segregating different materials has been evaluated by determining statistical significance using t-statistics. It has been noted from the results of the analysis that the data with spatial resolution of 200 and 500 micron are not significantly differentiable from the ideal resolution as the null hypothesis could not be rejected for these two cases [3]. Eventually, the numerical investigation of the civil cases has been carried out with 200 micron resolution.

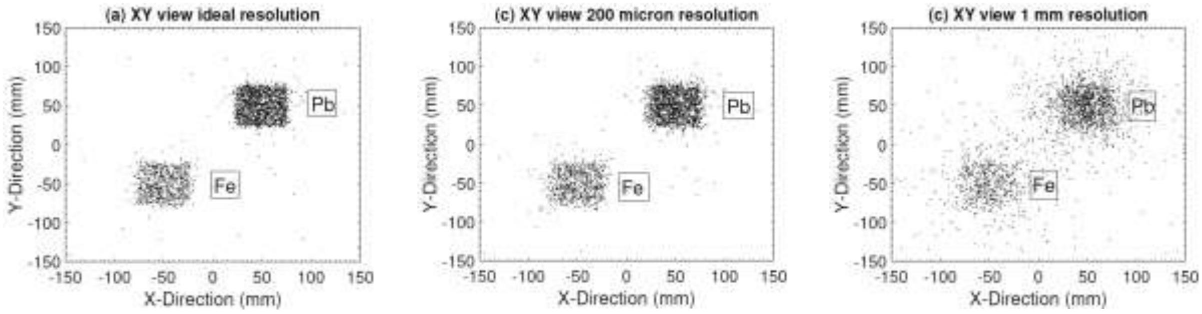

Figure 2. The two dimensional images produced by the projection of scattering vertices on the central XY plane with ideal, 200 micron and 1mm detector resolution

An image processing technique, namely PRM, has been proposed by us to analyse the projected image for material discrimination. In this method, a filter has been designed based on a specific pattern of a reference image and it has been used to scan the images of the test objects to search for the same pattern. The clustering density of scattering vertices inside a given pixel of the reference image has been considered as the search parameter in the filter as it increases with the Z-value of the materials. The images have been segmented into 75 × 75 pixels, each having an area of 4 mm × 4 mm. In the present work, two filters of size 4 × 4 pixels have been designed with clustering densities of the scattering vertices obtained for iron and lead. These two materials have been particularly opted for their low and high Z-values respectively. It can be mentioned here that any other material can be used to design a filter as per the requirement of the application. The size of the pixels and that of the filter matrix have been decided on the basis of computation time, required accuracy in shape identification, amount of data etc. The assumptions of the proposed PRM are the following: i) the muon exposure should be same for the reference and test images, ii) the longitudinal dimension of the reference and test objects should be same, otherwise to be scaled to the size, and iii) the tracking detectors should have same spatial resolution. In figure 3, images of five test objects obtained with three and half hours muon exposure and 200 micron spatial resolution and further processed with iron and lead filters respectively, have been shown. It can be seen that the iron filter has rejected the test material (aluminium) having lower Z-value than itself. Similar discrimination has been observed in case of lead filter where the materials (lead, thorium) having same or higher Z-value than that of the lead have been passed by the filter. It should be noted that the designed filters have been acting like high-pass filters.

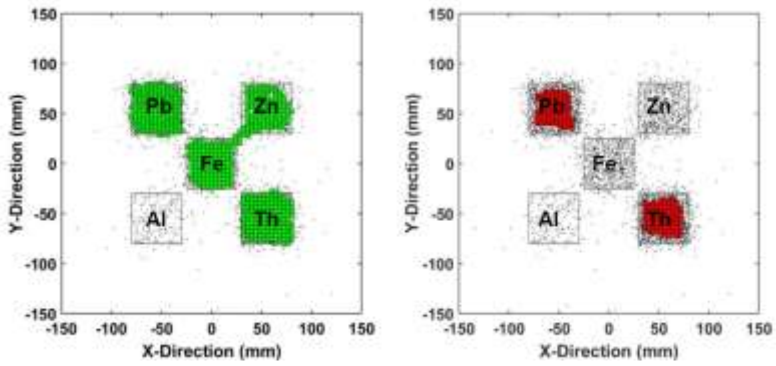

Figure 3. The PRM processed images using iron (left) and lead (right) filters

The PRM has been tested for its performance by comparing it with a cluster finding algorithm, namely, Density-Based Spatial Clustering of Applications with Noise (DBSCAN) [11]. The algorithm identifies a set of test data as an eligible cluster if a specified number of data points is found within a given radius around the test point. The two dimensional image of two test blocks made up of iron and lead produced with the same exposure and detector resolution and processed with DBSCAN and PRM respectively has been shown in figure 5.

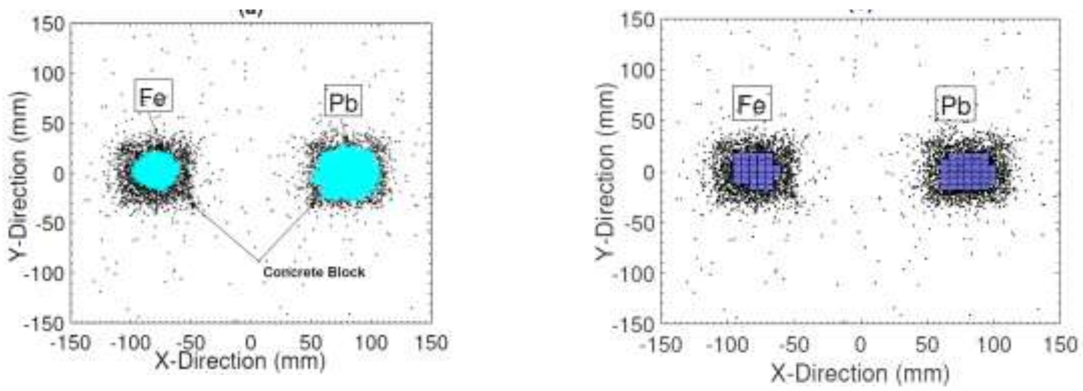

Figure 4. Images processed with DBSCAN (left) and PRM (right)

2.4. Imaging of defects in civil structures

The images of a few defects commonly found in civil structures have been numerically produced using the present MST setup with 200 micron detector resolution. Those have been processed and analysed with the PRM algorithm to study the efficacy of the setup to detect the defects. The following three cases have been considered for investigation: i) rusted rebar in Reinforced Cement Concrete (RCC), ii) Concrete Filled Steel Tube (CFST) and iii) void in concrete deck. The dimension of the defects in these cases along with the exposure has been varied to study the statistical significance of the PRM in detecting the defects. In figure 5, a few examples of the images of the first two test cases (RCC, CFST) and those after processing with the PRM have been shown along with the model of the test cases. The detailed study on this can be found in [4].

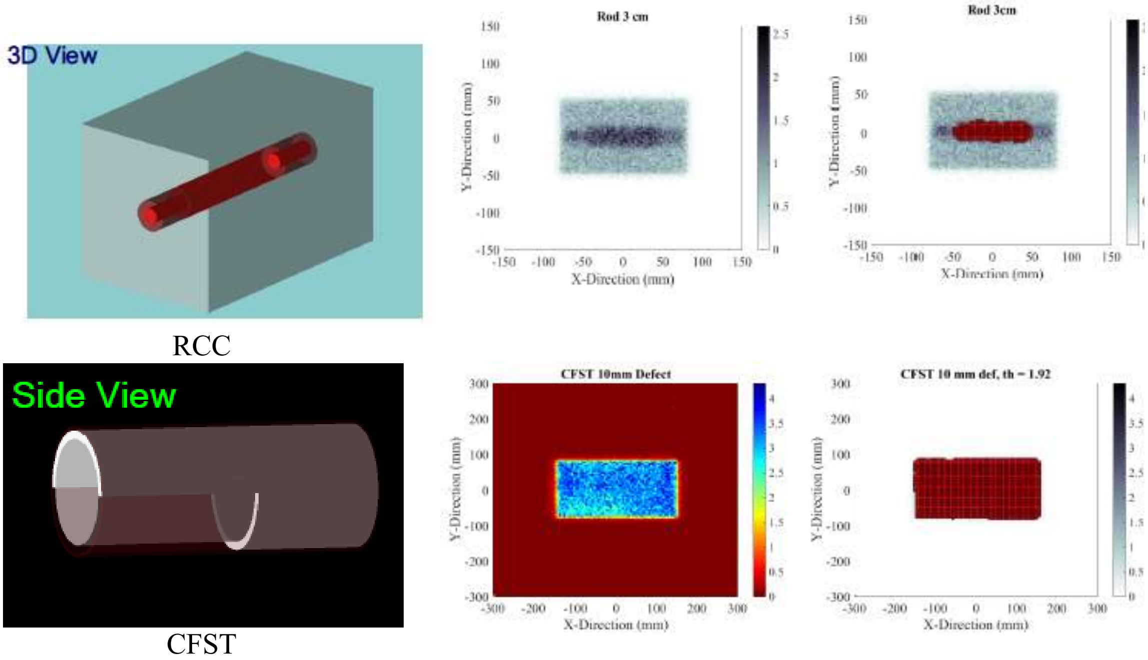

Figure 5. The two test models (left) of the civil structures, RCC and CFST along with their two dimensional projected images based on the scattering vertices (middle) and that after processing with the PRM (right)

3. Experimental measurements

The construction of the MST setup has been initiated with a few developmental activities on the muon detectors, readout electronics and data acquisition, etc. RPC and GEM-based detectors are currently under consideration and their detailed characterization is in progress. A few small RPC prototypes of dimension 30 cm x 30 cm made with Bakelite plates have been fabricated and characterized. Several research activities carried out to study and optimize their design parameters for efficient operation in connection to other experiments [12] have been utilized in the R&D. An effort has been put to explore environment-friendly gas mixture to operate the RPCs which should be relevant for the R&D of the MST setup too [13]. There have been several experimental and numerical activities performed to understand the functioning of GEM-based detectors [6] which are relevant for this R&D activity. Presently, an effort is underway to explore the feasibility of using the thick version of the GEM, namely Thick-GEM (THGEM), available from the local industry.

A simple cost-effective Data AcQuisition system (DAQ) has been proposed [14] for acquiring the position information from the RPC based on FPGA and utilizing the Time-over-Threshold (ToT) property of NINO ASIC [15]. A developer board based on ALTERA MAX-10 FPGA has been used for pulse width measurement and programmed on Intel Quartus Prime platform. A schematic diagram of the DAQ scheme has been depicted in figure 6. Initially, the readout system has been tested by acquiring signal from a single strip triggered by three-fold coincidence of plastic scintillators to trigger only one strip of the RPC has been used to test the proposed readout system. The data from seven strips altogether have been collected by the NINO front-end chip with three strips on either sides of the triggered strip at three different working voltages. The fraction of the ToT obtained from the central strip with respect to the total ToT of the neighbouring six strips has been determined to study the performance of the readout scheme. The details of the study can be found in [14].

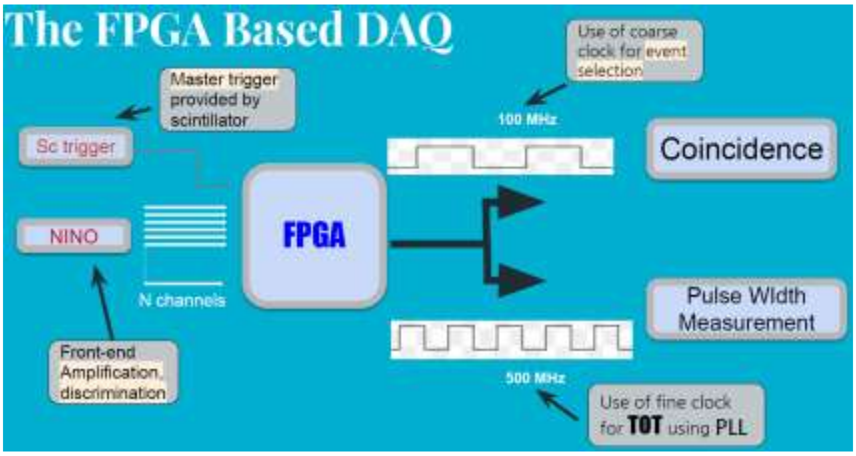

Figure 6. Schematic diagram of the FPGA based DAQ

To progress with the testing of the DAQ, the RPC with 8 × 8 readout strips in X and Y plane has been triggered with two-fold coincidence of scintillators and the muon hit map has been produced using the proposed readout system. The schematic diagram of the experimental setup is shown in figure 7. A lead block has been used to produce its image based on the muon absorption. The images obtained for two locations of the lead block have been shown in figure 8.

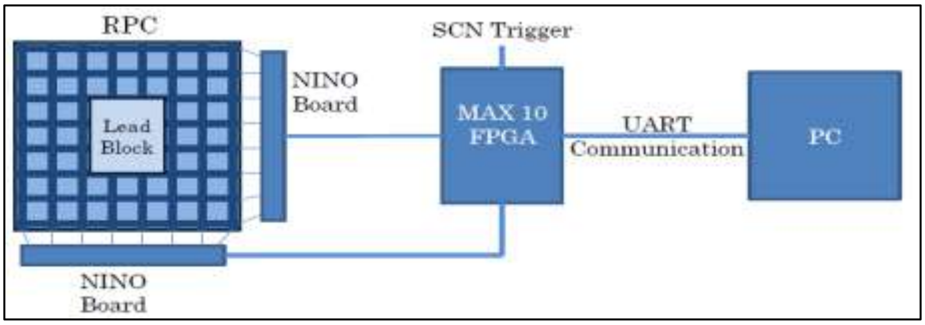

Figure 7. Schematic diagram of the test setup for FPGA based DAQ

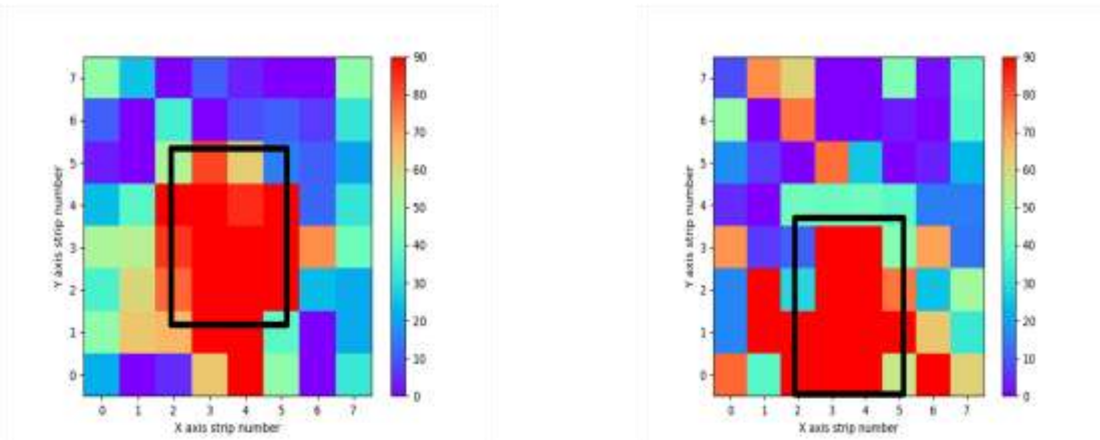

Figure 8. The images of the lead block as produced by the FPGA based DAQ

4. Summary and conclusion

We have proposed a MST setup to be built using position sensitive gaseous ionization detectors as muon trackers for material discrimination which would be upgraded for inspection of civil structures for their defects. The design and performance of the setup has been studied using numerical simulation by producing images of different materials based on the distribution of scattering vertices within the inspection volume. An image processing algorithm has been developed for discriminating high and low-Z materials based on pattern recognition method. It has been compared to standard statistical method and clustering algorithm to evaluate its performance. The present setup having detectors of position resolution of 200 micron combined with the proposed image processing algorithm has been found to be able to identify different materials and critical defects in civil structures with nominal exposure of around seven days. However, for detecting finer defects, more exposure may be required. The construction of the MST setup is currently under progress following the design parameters obtained from the simulation. Several types of detectors are under characterization and qualification stage to be considered as the muon trackers. A readout system has been designed and developed using NINO ASIC and FPGA for acquiring position information. It has undergone some preliminary tests and measurements which have produced promising results. Further activities are underway to improve the image processing algorithm and progress with hardware development related to the detectors and readout electronics.

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