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Development of muon scattering tomography for detection of reinforcement in concrete

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Abstract: Inspection of ageing, reinforced concrete structures is a world-wide challenge. Existing evaluation techniques in civil and structural engineering have limited penetration depth and do not allow to precisely ascertain the configuration of reinforcement within large concrete objects. The big challenge for critical infrastructure (bridges, dams, dry docks, nuclear bioshields etc.) is understanding the internal condition of the concrete and steel, not just the location of the reinforcement. Muon scattering tomography is a non-destructive and non-invasive technique which shows great promise for high-depth 3D concrete imaging. Here a method is presented to locate reinforcement meshes placed in a large-scale concrete object. A reinforcement mesh was simulated as two layers of 2 m long bars, forming a mesh. Two layers of the mesh were placed at several distances from each other inside a large concrete block. Previously, we have shown that using our autocorrelation technique for single meshes inside the concrete and using only one week worth of data taking, bars with a diameter of 7 mm and larger, could easily be detected for a 10 cm mesh spacing. The signal for 6 mm diameter bar exceeds the background and becomes very clear after two weeks of data taking. Here we show that we can detect the vertical positions of two mesh layers inside the concrete. This is a very important result for non-destructive evaluation of civil structures.

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1 Introduction

Old reinforced concrete structures may need to be inspected or replaced. Knowing the location of the steel is the first step towards determining the condition of the reinforcement. The key for assessing and substantiating the structure for life extensions is being able to state the design was built as planned (location and size of reinforcement) to a high quality (no voids from construction) and that the internal condition is satisfying (not degraded — reinforcement corrosion, cracking — beyond a critical value). Muon tomography is a novel, non-destructive imaging technique, which allows for imaging the interior structure of large objects. In [1] a method for the precise estimation of the rebar size based on muon tomography was presented. Using only one week worth of data taking, bars with a diameter of 7 mm and larger, could easily be detected for a 10 cm spacing. The signal for 6 mm diameter bar exceeds the background and becomes very clear after two weeks of data taking. Many structures have more than one layer of rebar mesh. Here we present a technique to detect the depth of a second layer of rebar mesh.

2 Muon scattering tomography

Muon scattering tomography (MST) uses cosmic ray muons as probes. When traversing material, Coulomb interactions take place between the muons and the nuclei of the material. As a result muons exit the material under an angle. The angular distribution of scattering of muons can be described by a Gaussian distribution with a mean of zero and a standard deviation $\sigma_\theta$ described by [2]:

$$\sigma_\theta \approx \frac{13.6 \text{ MeV}}{pc\beta} \sqrt{\frac{T}{X_0}} \left[ 1 + 0.038 \ln \left( \frac{T}{X_0} \right) \right]$$  \hspace{1cm} (2.1)

$$X_0 \approx \frac{716.4\text{A}}{Z(Z + 1) \ln\left( \frac{287}{\sqrt{Z}} \right)} \left( \text{g cm}^{-2} \right)$$  \hspace{1cm} (2.2)
where $p$ is muon’s momentum, $\beta$ is muon’s speed divided by the speed of light $c$, $T$ is the thickness of the material and $X_0$ its radiation length. $A$ is the atomic weight of the medium in g mol$^{-1}$. Hence, the standard deviation depends on the atomic number, $Z$, of the traversed material.

In this work, we use Monte Carlo simulations of an MST system as it is not feasible to obtain the high statistics data sets for many configurations in a reasonable time. A $2 \times 2$ m$^2$ MST system based on the system described in [3] is simulated using GEANT4 [4] to simulate the passage of the muons through detectors and scanned object and the CRY library [5] to generate the muons. A $200 \text{ cm} \times 200 \text{ cm} \times 50 \text{ cm}$ reinforced concrete block was placed as a test volume in the middle of the MST system. Concrete was formed as a material with a density of 2.3 g/cm$^3$ and the rebars were simulated as iron bars with density of 7.87 g/cm$^3$.

3 The autocorrelation method

For details on the method, please see [1]. For each muon that traverses the test volume, the incoming and outgoing tracks are reconstructed. A fit assuming that they meet in a vertex is performed. The scattering angle is reconstructed and the vertex is assigned to a $10 \text{ mm} \times 10 \text{ mm} \times 10 \text{ mm}$ voxel. For each voxel only the $N$ most scattered tracks are used to calculate the weighted metric, $\tilde{m}_{ij}$, for that voxel, where

$$\tilde{m}_{ij} = \frac{\|V_i - V_j\|}{\theta_i \cdot \theta_j}$$

(3.1)

where $V_i$ is the position of the vertex of muon $i$, $\theta_i$ is the corresponding scattering angle. The median of the weighted metric distribution is calculated. The median of that distribution is then used as a discriminator for each voxel [6]. The results are projected on the $XZ$ plane, where $Z$ points in the vertical direction.

To detect the rebar, the periodicity of the mesh is exploited by calculating a variation of the standard autocorrelation, $R_s$, where

$$R_s(\tau) = \int_{y_{\text{min}}}^{y_{\text{max}}} \int_{x_{\text{min}}}^{x_{\text{max}}} f(x', y')f(x' + \tau, y') dx' dy'$$

(3.2)

$R_s(\tau)$ has a periodic structure on top of a triangular background. After background subtraction, $R_s(\tau)$ is Fourier transformed. Figure 1(a) shows an example of the resulting normalised Fourier spectrum. The peak locations are determined by the mesh size. The presence of these peaks proves the presence of the rebar mesh and provide the mesh spacing, rebar diameter and location of the rebars, see [1].

4 Multiple layers

Thick concrete structures often have two layers of rebar mesh. Here two layers of rebar mesh were simulated with different spacing using 1 week equivalent of muon data. The top layer was placed around 7 cm into the concrete. The mesh spacing was 10 cm and the metal bars had a diameter of 8 mm. A second layer was placed directly underneath, 10 cm, 20 cm deeper, 30 cm or 40 cm
deeper. The analysis as presented in section 3 is repeated but the autocorrelation is done in strips using sliding windows to combine 5 rows of voxels into a 5 cm height window. An example for a separation of 20 cm at a depth of around 7 cm is shown in figure 1(a). As can be seen, when the window contains the 10 cm mesh, the autocorrelation yields a peak in the normalised Fourier spectrum at 0.1. The peak at 0.9 is the result of applying FFT on a real signal. Real signals yield symmetrical results due to the nature of the Fourier transform. By scanning the window vertically, the location of the second layer can be found. This is illustrated in figure 1(b), where the spectrum is shown for the 20 cm separation case with the window at various depths.

Figure 2 shows the amplitude of the peak at 0.1 in the normalised Fourier spectrum as a function of depth for various mesh separations. To enhance the signal, the signals of the two bins around 0.1 were added. The double layer, i.e. with 0 cm separation, leads to a much higher signal as expected, see [1], where the signal is shown as a function of the rebar diameter for a single layer. As the incoming angles are small and the resolution of the detectors are finite, the scattering vertices are well defined in the horizontal plane but there is large uncertainty in the vertical direction. This is known as z-blurring. The z-blurring fuses the two mesh layers into one apparent object when the layers are too close. Thus, for two layers of rebars two peaks are encountered as long as the spacing is large enough. When the spacing gets smaller, the two peaks merge. This occurs for the 0 cm and 10 cm separation.

![Figure 1](image1.png)  
**Figure 1.** (a) Normalised Fourier spectrum taken at a depth of around 7 cm for a separation of 20 cm. (b) Peak at 0.1 in the normalised Fourier spectrum measured at various depths for 20 cm separation.

![Figure 2](image2.png)  
**Figure 2.** (a) Amplitude of the peak at 0.1 in the normalised Fourier spectrum as a function of depth for various mesh separations. (b) Zoom of the same plot.
In figure 3 the depth of the second peak was extracted and plotted as a function of the set separation. The graph shows very good correspondence between the two, showing that the method works well. The right most peak location, or the peak location if the two underlying distributions have merged, yields the depth of the second rebar layer. The depth of the second layer can be determined with a few cm precision.

Figure 3. Correspondence between the set depth and the reconstructed depth of the second peak.

5 Conclusions

Inspection of ageing, reinforced concrete structures is a world-wide challenge. Muon scattering tomography is a non-destructive and non-invasive technique which shows great promise for high-depth 3D concrete imaging. Here a method is presented to locate reinforcement rebar meshes placed in a large-scale concrete object. Using the autocorrelation method for thin strips, the depth of a second mesh of rebar in a thick concrete structure can be reconstructed within a few cm, which is more than precise enough for non-destructive evaluation of civil structures. Further work will include the use of different mesh sizes and different diameter rebars and improving the position resolution.

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