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Muography for structural inspection and assessment

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Muography for structural inspection and assessment

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Foreword

In 2023, the International Committee for Non-Destructive Testing (ICNDT) established a Specialist International Group (SIG) for Non-Destructive Testing (NDT) in Civil Engineering. Three subgroups have been established: SG01: Standards, SG02: Applications and SG03: Emerging Technologies.

SG03, the Emerging Technologies Subgroup, intends to promote knowledge exchange between specialists on emerging NDT in civil engineering (NDT-CE) technologies, to foster international collaboration for improvement towards practical application and to provide objective information about potential and limitations to the NDT community and potential users. SG03 issues documents such as this one to inform the NDT community about recent developments and emerging technologies.

Muography for structural inspection and assessment

Motivation

Inspection and monitoring of the interior of concrete structures is crucial to ensure their safety, reliability and durability. Current standards and inspection mandates rely mainly on visual inspection and tap tests. Only if damage of unknown cause or extent is observed, or any other suspicion about the structural condition of the structure exists, is a more detailed investigation required, which may be based on both sampling/invasive and chemical analysis or by employing NDT methods.

Since the 1980s, X-ray imaging and tomography have been used quite often for the inspection and assessment of engineered structures such as bridges, still providing the best level of detail of all available NDT imaging methods compared to, for example, radar or ultrasonics. However, safety regulations have meanwhile been stringently tightened, posing serious practical limitations (cost and radiation safety) for practical application.

This motivates the demand for a method that is at least comparable to X-ray imaging in terms of resolution, depth of penetration and applicability, but less harmful to the environment and easier to operate. Increasingly, publications and scientific as well as commercial presentations on muography, an imaging technique based on naturally occurring cosmic radiation, claim that this methodology is able to address this challenge, together with evidential proof. The objective of this document is to discuss the current level of development and the road to the future for this technique.

Description

Muography, a purely passive technique using natural cosmic background radiation as a source, has the potential to overcome some of the limitations of radiation-based imaging techniques. Showers of high-energy particles, including muons, are constantly produced by collisions between cosmic rays and the upper atmosphere (see Figure 1). The muons from these showers are highly penetrative and can pass through tens and hundreds of metres of rock before coming to rest and decaying[1]. As cosmic rays are a naturally occurring radiation, there is no cost or energy required to produce them and, as no additional radiation is produced, there are no related safety concerns. It is a passive imaging system. As only a limited number of muons make it to the Earth's surface, imaging might take hours to weeks, depending on the applications.

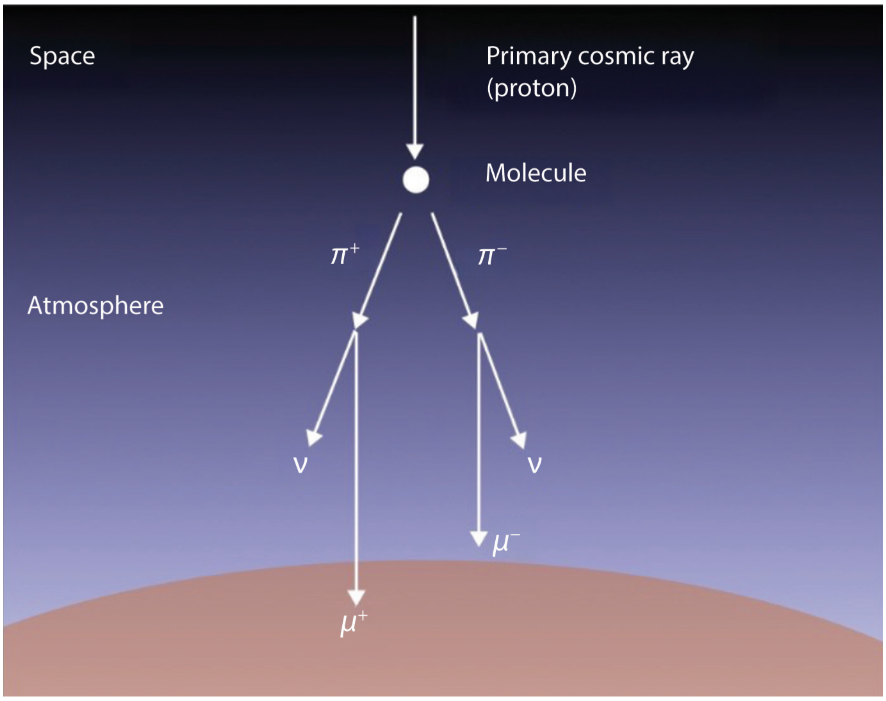

Figure 1. Simplified diagram of cosmic rays interacting with the atmosphere and producing secondary particles (pions π and neutrinos ν), including muons (μ). Other mechanisms exist and other particles are also generated

There are two types of muon imaging technique. The first is muon absorption imaging (or muon radiography) and the second is muon multiple scattering imaging (or muon tomography). While muon radiography (see Figure 2 (left)) uses one detector (or one set of detectors on the same plane) to detect muons after they have passed the object of interest, muon tomography uses two detectors (or two sets of detectors on different planes) to detect muons before and after they have passed the object of interest[2] (see Figure 2 (right)). The latter allows volumetric reconstruction of the scattering properties of the object, resulting in high-resolution 3D images. Since the 1950s, there have been proposals for experiments and actual applications, the most prominent recent one detecting voids in one of the large Egyptian pyramids[3].

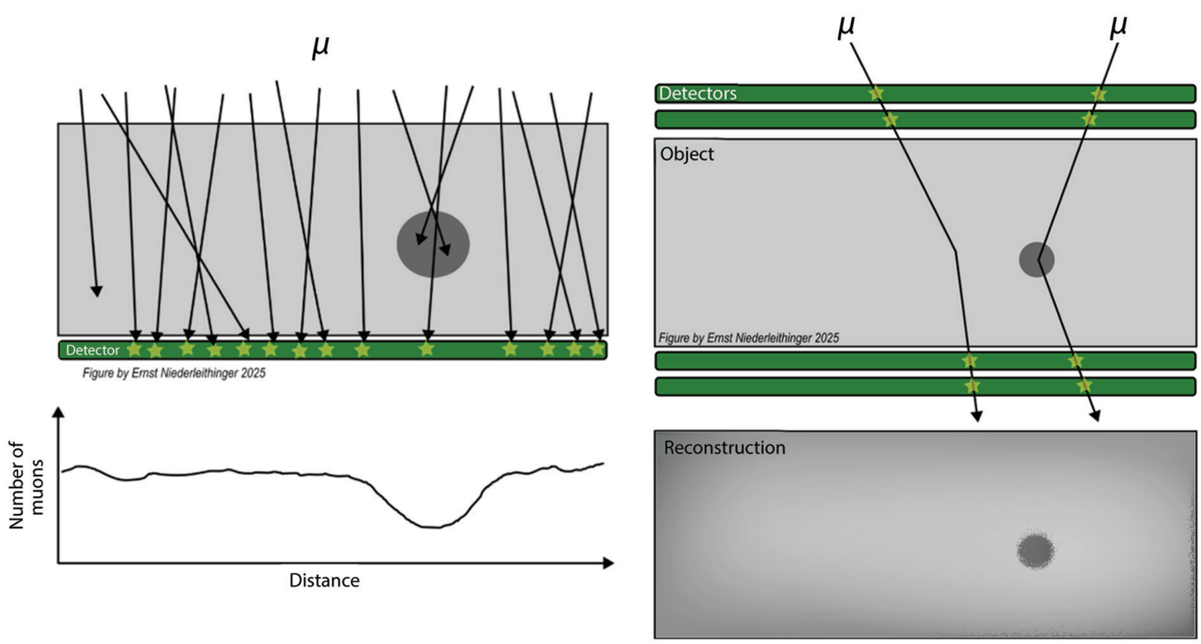

Figure 2. Principles of muon absorption imaging (left) and muon scattering tomography (right). The top images show the data acquisition principles, while the bottom images represent the potential results after data processing, requiring tens of thousands to millions of muons to be detected and tracked

The application of muon tomography on reinforced concrete structures was simulated[4] and, more recently, validated[5]. It is commonly agreed that only muon tomography (not just imaging) would provide the required resolution and accuracy (mm range) for actual applications.

State-of-the-art

To perform muon tomography, several items are required:

- A set of muon detectors (hardware) to capture the flight path of single muons entering and leaving the object of interest. This includes software that detects the muon-related events in the detector signals, identifies events in the various detectors that belong to one specific muon and determines incoming and outgoing paths (and thus the scattering angle); and
- An imaging method and software that reconstruct the density distribution inside the object of interest (or a specific part of it) based on the flight path/scattering angle of tens of thousands to millions of muons.

Laboratory or controlled environment detector set-ups, primarily for nuclear and security applications, have been available for more than a decade, although most are not commercially available (see Figure 3). One such set-up has been used to validate the technology using a reference reinforced concrete element[5]. Meanwhile, several research groups and start-up companies are working on robust mobile detection systems or have presented ready-to-use solutions. Most of them are using scintillating fibre optics as the means of detection. A potential alternative using gas chambers is under development. However, all of them are currently either too small to capture a significant volume of the objects of interest or too bulky to fit through access holes/doors in a box girder bridge, for example.

Figure 3. Examples of muon tomography detecting systems: a laboratory set-up of Lynkeos Ltd (left); and a mobile system by GScan Ltd (right)

Several imaging methods for scattering tomography have been published and used recently[2]. The oldest and most popular ones are known as point of closest approach (POCA) and maximum likelihood expectation maximisation (MLEM)[6]. The latter was used in a validation experiment demonstrating the potential of the technology[5] (see Figure 4). All relevant internal features were detected in this experiment with a subcentimetre resolution in the horizontal direction but limited resolution in the vertical direction. However, other improved, mostly proprietary, imaging and image processing methods are under development at several institutions. For example, GScan Ltd and Lynkeos Ltd[7] are separately exploring machine learning (ML) and artificial intelligence (AI)-supported approaches.

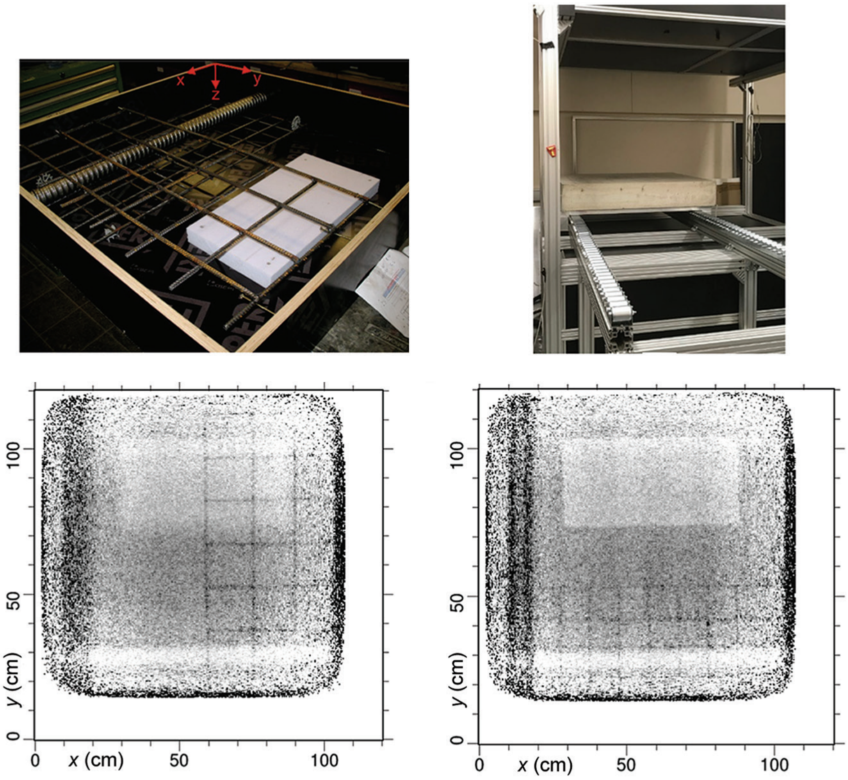

Figure 4. Results of a laboratory validation experiment for muon tomography[5]. Upper left: interior of reference specimen (reinforcement at several levels, Styrofoam block, tendon duct). Upper right: reference block in test specimen. Lower left: muon tomography result, horizontal section in upper half of specimen, showing upper reinforcement, tendon duct and (low-amplitude) Styrofoam block. Lower right: muon tomography result, horizontal section in lower half of specimen, showing lower reinforcement, tendon duct and Styrofoam block

A similar experiment, but using mobile detectors of GScan Ltd, was performed in early 2025 at the BAM laboratories using a reference concrete specimen. Figure 5 shows the results, displaying cross-sections of the imaged data and an ML-based automated interpretation discriminating rebar, tendon duct and voids.

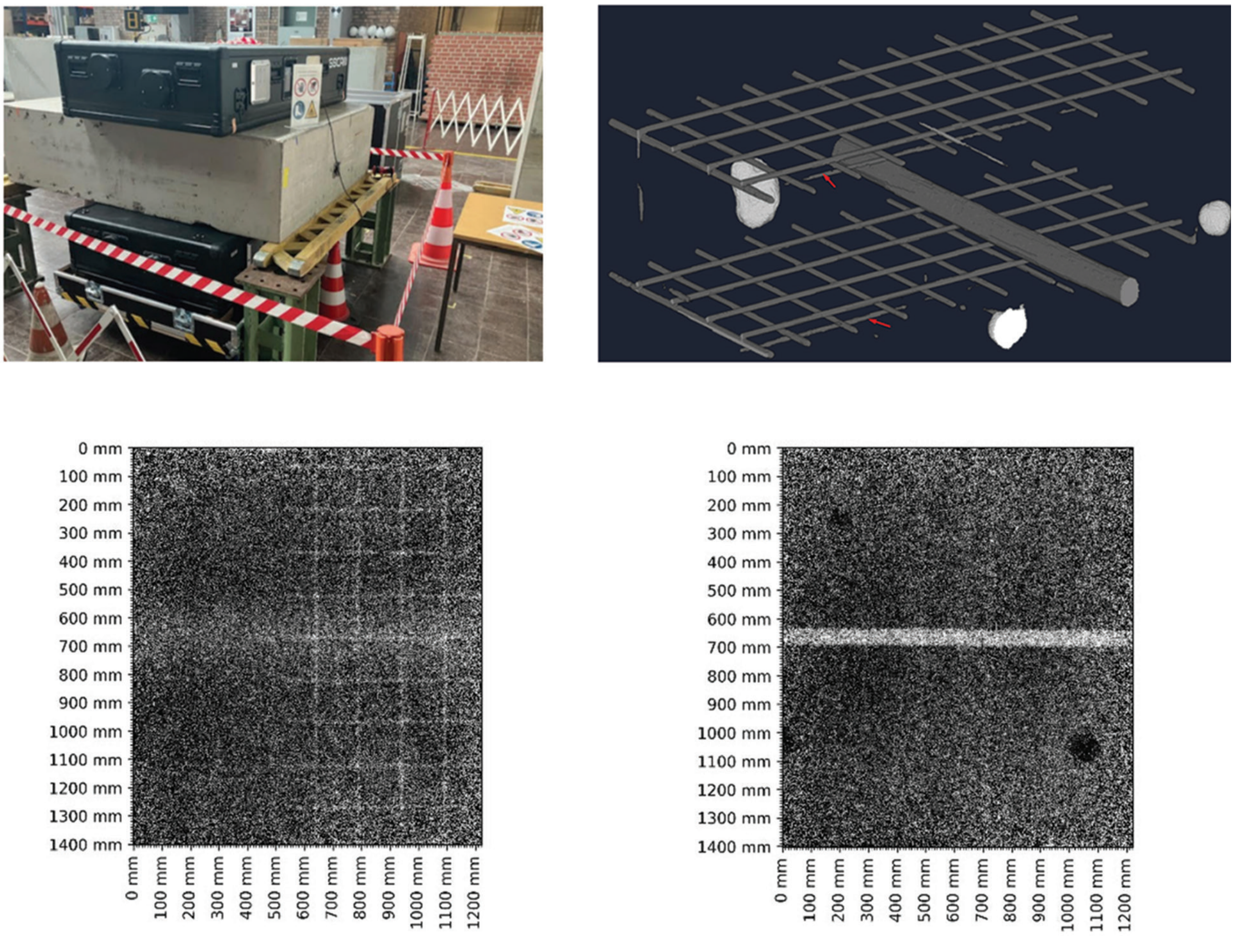

Figure 5. Results of a validation experiment using a mobile muon tomography system from GScan Ltd (two times 120 h measurement time). Upper left: precast test specimen prepared by BAM (rebars, voids and tendon duct). Upper right: ML-enhanced 3D image from the muon tomographic scan having the automatically classified rebars and ducts. Lower left and right: horizontal cross-sections through the image volume, source data for the ML enhancement

Potential benefits and limitations

Recent laboratory and field experiments have shown that muon tomography may be able to replace X-ray tomography in certain application scenarios within the next few years. The resolution of muon imaging is not too far from what is provided by X-ray tomography. However, the images are currently much noisier (potentially leading to a lower probability of detection) and the acquisition time is much longer (days to weeks). In addition, as most muons have an incident angle of ±30° relative to the vertical axis, resolution in the horizontal direction is fully sufficient (better than 1 cm) while the vertical resolution is not yet comparable (in the centimetre range). This limitation in image quality might be compensated for by not having to deal with radiation safety requirements. Compared to other imaging modalities, such as ultrasonic and radar methods, there are several application scenarios where muon tomography could be effective, while the others offer only limited capability, if any. For example, muon tomography shows promise in imaging the interior of tendon ducts.

Road to the future

Muography has shown its potential and feasibility in laboratory tests and is currently being evaluated in a few initial field trials. It is believed that it can play a valuable, if not crucial, role in NDT in the inspection and assessment of infrastructure in the future. To foster practical application, the following steps are deemed necessary:

- Development and full validation of robust, mobile and modular detection systems.
- Development of accessible and well-documented simulation and imaging software, including tools for data preprocessing and image post-processing to reduce exposure time, potentially through machine learning techniques.
- A sufficiently large set of fully documented demonstration and validation experiments on both reference objects and actual structures, complemented by simulations of relevant application scenarios.
- Objective studies on accuracy, reliability and probability of detection (POD).
- Development of commonly accepted guidance/standardisation documents.

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