Real Time Muography Simulator for ScanPyramids mission

Extended Abstract

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ABSTRACT

In October 2015, the ScanPyramids (SP) [1] mission started looking for unknown structures inside Egyptian pyramids with non-invasive technologies. Possibly the most successful imaging technology was muography which is similar to X-ray radiography but with muons. Muons are naturally occurring weakly interacting elementary particles that travel freely through space, attenuated by dense matter. In 2017, ScanPyramids reported their findings of a large void in the pyramid of Khufu located above the grand gallery. The work, first published in the scientific journal Nature [Morishima et al. 2017], entailed the collaboration of three scientific teams using three separate muography techniques. Sensors from each team acquired muons detection data over several months inside and outside the pyramid before analysis revealed the above-mentioned large void. Interpretation of muography analysis results can be ambiguous. It is therefore common practice to assist the interpretation with a numerical simulation of the muons interaction with matter inside the expected object-of-interest. For this purpose, muography experts traditionally rely on GEANT4 [Agostinelli et al. 2003], a Monte-Carlo simulator. This simulator is verified to be accurate; It is however not capable of delivering live simulations due to computational complexity nor optimized for handling complex 3D geometry.

In response to this limitation, the author has designed and developed a Real-Time Muography Simulator (RTMS) for the purpose of the ScanPyramids mission. Thanks to leveraging already existing 3D rendering engines, the new bespoke simulator presents significantly reduced computational loads, hence enabling live simulation on a conventional laptop. Live simulation in RTMS permits to: understand raw detector outputs in context, assist the analysis of results, make live interactive hypothesis during meetings and facilitate the process of deciding optimal detector positioning.

In this talk, the author will present muography results, deliver the basic of muons physics with a parallel approach to photons, explain how classical 3D render engines inspired RTMS design and describe the simulator approach.

[1]International mission co-designed and co-directed by Heritage Innovation Preservation (HIP) Institute and Cairo University. www.ScanPyramids.org

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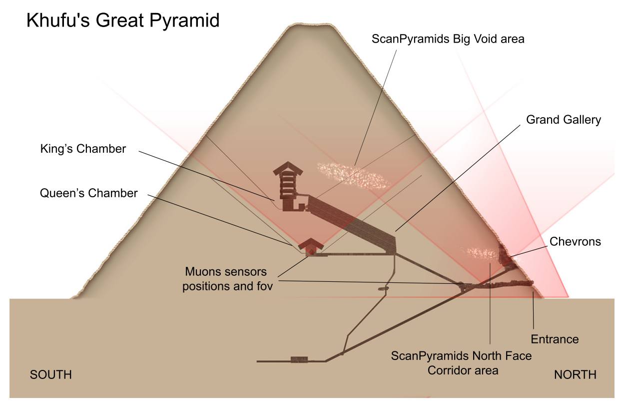

Figure 1: Khufu great pyramid North/South slice with muons sensors and ScanPyramids discoveries.

CCS CONCEPTS

• **Computing methodologies → Interactive simulation**;

KEYWORDS

Real-time, Interactive, 3D, Simulation, Muography, Pyramid

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1 INTRODUCTION TO MUOGRAPHY

Muography is an imaging technique that produces a projectional image of a target volume by recording elementary particles, called muons. It is similar in principle to radiography. Muons are charged particles, almost like electrons but 200 times heavier. They appear naturally on earth when cosmic rays hit the atmosphere. They have different energy levels and come from different angles (highest rate in zenith, nearly none horizontally). They travel mostly in straight lines, scattering effect occurs with dense materials. The muons flux is approximately 10 000 /m^2/min at sea level. Muons loose little energy while going through matter. The energy loss is proportional to the amount of matter they pass. This is proportional to the density (g/cm^3) times the path length (cm). Due to their heavy energy, some of them can cross up to 500m. Muography is the only nondestructive method able to look through matter with such depth. While Nagoya University, KEK and CEA sensors use different physical detection approach (respectively based on AgBr emulsion film, photoscintillator plastic, gas ionization) they all records muons tracks : they count muons according to their incoming direction.

Results are usually displayed as pictures with tan (θ)/ tan (ϕ) axis. (θ, ϕ: horizontal, vertical angles relative to the sensor center)

2 THE NEED FOR SIMULATION

Muography results can be difficult to understand, even for experts, as they represent a flatten view of the residual muon flux crossing a volumetric structure. Furthermore, as muon rate is very low, compared to photon flux, results are still "noisy" even with weeks of exposure time.

Making simulation has two main advantages : reading results by enabling visual correlation with the volumetric structure, analyzing results by finding local differences with simulation (i.e.: if more muons are observed, it means less rock absorption, either due to lower density material or a cavity). Particle experts traditionally rely on GEANT4, a versatile Monte Carlo based simulator that simulates the passage of particles through matter. Whereas GEANT4 simulations are very accurate, they required hours of computational time and are not optimized for highly detailed geometry, and were thus not suitable for live interactive analysis during meetings.

3 RTMS GENESIS

3.1 GEANT4 approach

In our case, GEANT4 Monte Carlo simulations consist on emitting virtual muons outside the pyramid, making them interact with the rocks step by step and checking if they cross a sensor. A vast majority of emitted and simulated muons will not reach the sensors thus will not be part of the result. Computing the simulation, even with low poly 3D models, could take hours depending on the expected confidence interval.

3.2 RTMS approach

The basic idea behind RTMS is to think from sensor view not muon emitter. The principles of 3D engines were an inspiration for many reasons:

- Results can be represented as a picture.
- Sensor projection model perfectly fit with standard 3D camera projection model.
- Photons and muons goes mostly straight. (Photons can bounce and scatter, Muons only scatter).

RTMS has been developed with Unity and improved all along the mission. The global simulation workflow can be described as follow:

Place a camera at sensor position with same projection matrix, then, for each pixel:

- Render geometry with specific shader to estimate *opacity* (Σ length * density)
- Calculate the minimal energy *Emin* to cross this *opacity*
- Use Miyake formula [Miyake 1973] to compute the number of incoming muons that have a greater energy than *Emin*
- Optionally: add statistical variation to simulate a given exposure.

The result is a number of muons / str /cm^2/day. RTMS and GEANT4 simulations match, but unlike GEANT4, RTMS does not rely on a brute-force approach and excludes scattered muons trajectories. Thus GEANT4 simulations and results are blurry due to scattering while RTMS results are sharp.

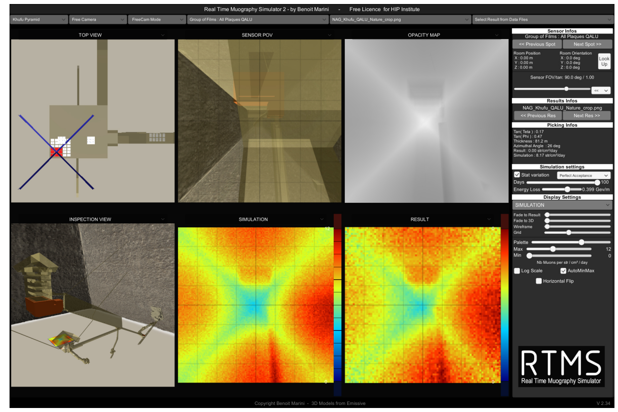

Figure 2: RTMS software

Additional tools were developed:

- Live modular 3D shape to try interactive hypothesis (which might be then accurately simulated in GEANT4 if relevant).
- Fade between 3D view and simulation/ wireframe overlay to instantly understand structure.
- Picking tools to read and compare values.

3.3 3D models

To make a realistic simulation, the author needed an accurate 3D model of the pyramid as input. SP used photogrammetry and lidar to acquire them. For the internal unknown structures, the author assumed that limestone is used.

4 RTMS BENEFITS

RTMS has been used during SP team meetings and contributed to the discovery of SP Big Void and SP North Corridor. Thanks to its real time approach (6 order of magnitude in speed compared to GEANT4 in this case), the 3D visualization, the ability to handle high-resolution input meshes and the interactive tools, RTMS enable:

- to understand raw detector outputs in context
- to assist the analysis of muography results
- to make live interactive hypothesis during meetings
- to facilitate the process of deciding optimal detector positioning

The next release will include real-time scattering to be as accurate as GEANT4.

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