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A Cosmic Rays Tracking System for the Stability Monitoring of Historical Buildings

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Cosmic ray radiation, thanks to its high penetration capability and relative abundance, has been successfully used in scientific research and civil applications for a long time. For example, techniques based on the attenuation of cosmic ray muons or on their angular scattering have been used to study the inner structure of volcanoes, to search for hidden chambers in Egyptian pyramids, to inspect nuclear waste containers and to monitor blast furnaces. In addition to these imaging techniques, cosmic ray muons have also been used for the detector alignment in large experiments in nuclear and elementary particle physics. In this context, a cosmic muon detection system for the stability monitoring of historical buildings will be here presented. The employment of cosmic rays is envisaged where the time scale of deformations is typically very long, and where conservation constraints could prevent the use of standard mechanical systems. The stability monitoring of Palazzo della Loggia (Brescia, Italy) has been considered as a case study, and performance and limitations of the technique have been evaluated using Monte Carlo (MC) simulations. A muon detection system based on two telescopes with three sensitive layers of scintillating fibers coupled to silicon photomultipliers has been studied. Results from MC studies, taking into account systematic uncertainties, are here presented. Finally, the main features and performance of a small-size detector prototype, developed as a proof of principle and consisting of three layers of 3x3 mm^2 scintillating fibers, as those used in the simulations, are also described.

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1. Introduction

Cosmic ray muons [1] that reach the Earth surface at a rate of about 10,000 μ/(min m^2) have been used since decades to align detectors in nuclear and particle physics. Since the mid-twentieth century, attenuation of cosmic ray muons has also been used to produce radiographies of large and inaccessible structures in the fields of geology, archeology, speleology [2]-[9], imaging of the inner structure of volcanoes and in the prediction of volcanic eruptions [10]-[15]. Recently, in a spectacular application Morishima and collaborators announced the discovery of a large "void" in the Cheope pyramid [16]. Radiographic images of the interior of large objects such as large vessels [17], radioactive waste containers [18] and in industrial applications [19, 20] have also been explored.

In 2003 a new method was proposed [21, 22] in which the Coulomb multiple scattering that every muon undergoes when crossing matter is exploited to inspect unknown objects hidden inside large volumes. This technique, known as muon tomography, has been rapidly adopted for applications in the civil security domain [23]-[25]. It has also been proposed for the detection of radioactive "orphan" sources hidden in scrap metal containers [26]-[28], to inspect the interior of blast furnaces [29] or legacy nuclear waste containers [30]. The method has also been proposed to perform a diagnosis of the damaged cores of the Fukushima reactors [31] and, recently, the fuel melt at Daiichi 1 has been assessed by muon data [32].

In this paper we present another use of comic rays in an alignment system based on muon detection. Such system can be applied to the monitoring of vertical structures [33] and in particular to historical buildings. More details about this application can be found in [34, 38]. In the following a possible design for the monitoring system will be presented.

2. The monitoring system

The proposed stability monitoring system consists of muon detector planes assembled to form a so called "muon telescope" as depicted in Fig. 1. Assuming to use scintillator fibers read by silicon photomultipliers SiPM [39, 40], a set of three square muon detection planes, of about (400x400) mm^2 area and about 6.0 mm thickness, are positioned horizontally on an appropriate mechanical structure at a distance of 500 mm from each other. The number of modules has been chosen to allow for a minimal level of redundancy on the tracking information of the crossing muon.

A possible design, per module, can consists of two orthogonal layers of about 400 mm wide and 400 mm long, composed of 128 scintillating fibers with a (3.0 $\times$ 3.0) mm^2 cross section, to provide the measurement of the crossing position of an incident muon in the x and y coordinates with a pitch of 3.0 mm. With this granularity on the crossing point and the described geometrical dimensions, the angular resolution of the telescopes in measuring the muon direction is expected to be about 3 mrad.

The proposed monitoring system is composed by two identical telescopes, positioned one above the other, at a given distance, inside a historical building. The two telescopes (upper and lower) are mechanically anchored to the building structure. Their initial horizontality is measured with standard instrumentation such as mechanical inclinometers. Floors or furniture may be inter-

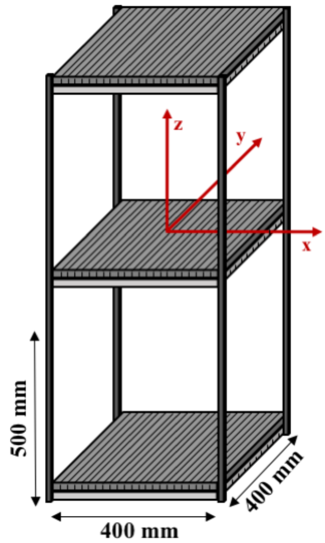


Figure 1: Structure of the muon telescope formed of three muon detection modules axially aligned at a distance of about 500 mm each other.

posed between them. The muon crossing point in x and y coordinates is defined as the position of the axis of the crossed scintillating fiber, on the corresponding layer, in the coordinate system shown in Fig. 1. For the cosmic ray muons, the three measured points on the three layers, for each coordinate, are fitted with a straight line in both telescopes. Tracks are reconstructed in the $x-z$ and $y-z$ views independently. Details about the reconstruction technique can be found in [38]. In the following only the projection of the reconstructed tracks in the $x-z$ plane is considered.

From the reconstruction of a sample of cosmic muons, the relative position x_D and the relative inclination θ_D between the two reference frames integral with the two telescopes are estimated. Having measured (x_D^o, θ_D^o) at a given time, that we can define as "reference", each successive measurement of the same quantities provides a control of the stability of the relative position/inclination of the two telescopes. Since the detectors are anchored to the building, the detection of a relative movement would imply a deformation of the structure.

To study the performances of such a system, we simulated its use inside the historical building of the City of Brescia known as the *Palazzo della Loggia* [41]. The stability of the roof of such palace has been indeed monitored for ten years through a mechanical system.

3. The Palazzo della Loggia in Brescia: a study case

The *Palazzo della Loggia*, built in 1574, is the most famous building of the town of Brescia, Italy. As many other historical palaces it underwent modifications and renovations. In particular the roof was completely reconstructed in 1914: its maximum elevation is 16 m, and its shape is that of an upside-down ship, with planar rectangular sides of about 25 m and 50 m respectively. Immediately after its reconstruction, the roof structure started to deform. In particular, the progressive deflection of the top beam was measured to be 190 mm in 1923, 520 mm in 1945, 800 mm in 1980.

A systematic campaign of investigation using mechanical measurement systems has been performed for more than ten years, from 1990 to 2001 [42]. Four, out of seven, principal arches were monitored with three couples of wires at different heights as represented in Fig. 2 .

Fig. 2 shows the mutual displacements of the points A2 - B2 as a function of the monitoring time, expressed in years. Cyclic seasonal deformations of the structure of the order of few millimeters have been highlighted superimposed to a clear collapsing of the wooden structure of the arch. The deformation trend amounts to about 1 mm per year.

This case study was reproduced with a dedicated Monte Carlo package based on GEANT4 [43]. In the simulation a system of two telescopes, as described above, has been used. The geometry and the relevant structural parts of the *Palazzo della Loggia* building as well as the structure and composing materials of the two telescopes were modeled. A cosmic ray muon generator based on experimental data [44], already used in other nuclear physics experiments, have been used to simulate the momentum and the angular distribution of the cosmic ray radiation at the sea level.

4. Results

With the setup described above, cosmic ray muons were simulated through the measurement system in the three configurations previously defined.

As previously reported, a sample of cosmic rays can provide the relative position x_D and inclination θ_D of the two telescopes (see [38] for details). For a given number of muons, we repeated the estimation many times and calculated the standard deviation of the obtained distribution. Fig. 3 shows the distributions of the statistical variable x_D for the three configurations, for a sample of 500 tracked muons.

To collect the same statistics of tracked muons, due to geometrical acceptance and to the angular distribution of the cosmic muons, the three configurations need different time intervals: the closer the two telescopes, the shorter the time. For the Δz(350cm) configuration, for example, 500 muons correspond to about 1.5 hours of data taking, 7.5 hours for the Δz(880cm) configuration and 16 hours for the Δz(1300cm) configuration, assuming a 100% muon detection efficiency for the scintillating fibers. The standard deviation of the distributions can be considered as the resolution

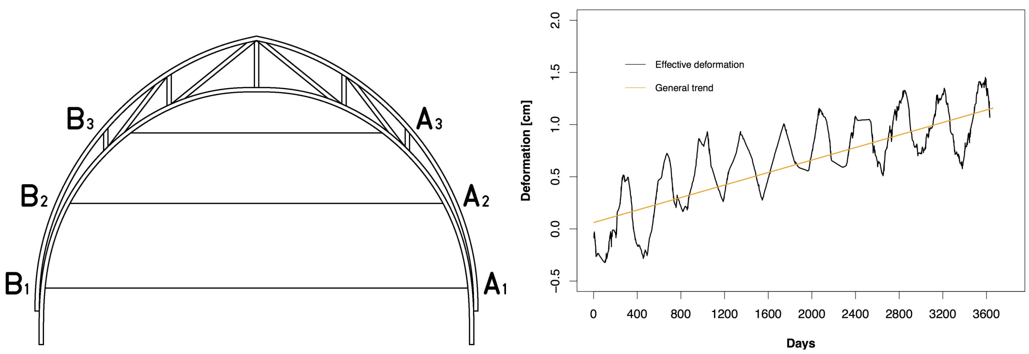


Figure 2: (left) Schematic view of the position of the mechanical measurement systems in the wooden vaulted roof. (right) Elongation of the metal wires stretched between the points A2 - B2 of Fig. 2 of the truss wooden arches as a function of time in days, as reported in [42].

with which the relative position x_D and inclination θ_D can be measured. As it is evident from Fig. 3 the closer the two telescopes, the better the accuracy.

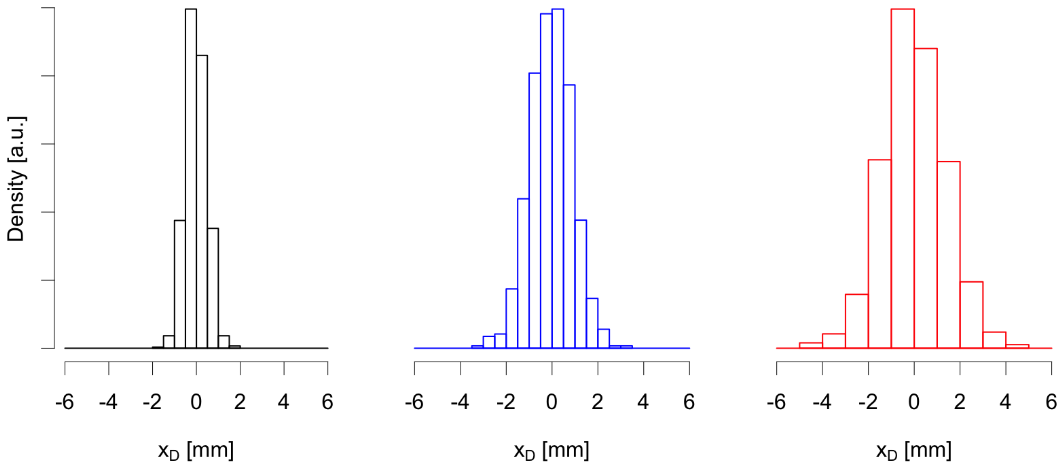


Figure 3: Distributions of the x_D for samples of 500 tracked muons for the three different configurations: Δz(350cm) left, Δz(880cm) center, Δz(1300cm) right.

As the lower telescope and the upper telescope are perfectly aligned in the simulation, the x_D and θ_D distributions are symmetric and centered at zero. The width of the distributions is due both to the resolution of the telescopes and to the multiple scattering suffered by the muon trajectories.

For a given configuration, the resolution clearly depends on data taking time. Supposing to wait an infinite time, one can expect to have a perfect measurement. This is obviously false, since also systematic effect must be taken into account. For example the position and inclination of the two telescope and of the modules inside the telescope can be know only with the accuracy given by the commercial instrumentation (optical systems, inclinometers, magnetometers, etc.). Assuming standard resolutions of $\sim$100 μm for positioning, 2 minutes of degree for horizontality and 0.10-0.15 degrees for rotations around the vertical axis, many specific simulations have been performed. In each of them the three detection planes of the two telescopes could be positioned, with respect to the "nominal" position and orientation, extracting a Gaussian distributed random number having as standard deviation the values reported previously. On top of that also the relative position and orientation of the two telescopes, relatively one with respect to the other, was also set in the same way extracting random values from Gaussian distributions with the specified standard deviations.

An efficiency to detect a crossing muon per single fiber of 80% has been assumed. Since the muons need to cross all the six layers of the two telescopes, this means an overall detection efficiency of about 30% per muon.

A differential calculation has been performed assuming that any relative movement of the monitoring system, that is of the two telescopes, can be attributed to the building structure they are anchored to. Following the procedure described above, extracting randomly the position and angular parameters of the detectors, 100 different geometries, for each of the Δz(350cm), Δz(880cm) and Δz(1300cm) configurations, a specific Monte Carlo production has been produced. In the reconstruction, on the other hand, the nominal geometry, where all the components of the monitoring system are perfectly aligned, has been used. The values of x_D and θ_D have been calculated twice, for two different samples containing the same number of muons. One has to be considered as the "time zero" reference measurement (x^o_D, θ^o_D) while the other the control/monitor measurement (x^t_D, θ^t_D). The standard deviation of the distributions of the difference of such values (x^t_D - x^o_D) and (θ^t_D - θ^o_D), have been used to estimate the resolution of our system. The procedure has been repeated for different data taking times. The results are summarized in Fig.4. In a day of data taking the system is capable, in the three configurations respectively, to detect displacements of $\sim$ 0.3 mm, $\sim$ 1.3 mm and $\sim$ 3 mm and misalignments of $\sim$ 0.3 mrad, $\sim$ 0.6 mrad and $\sim$ 0.8 mrad.

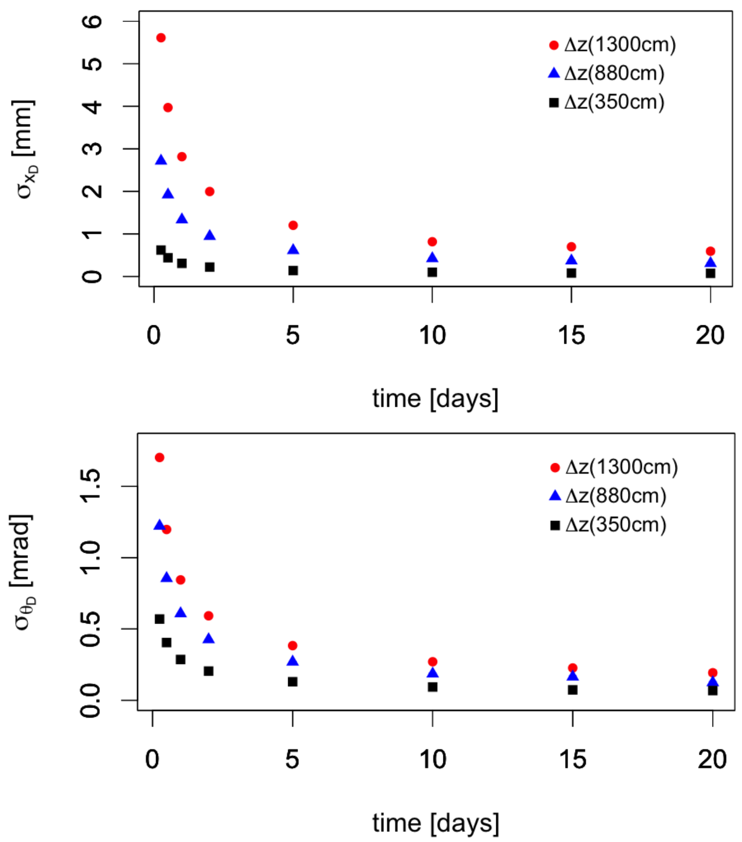


Figure 4: Resolution on the relative position x_D (top) and inclination θ_D (bottom) of the two telescopes *vs* data taking time taking into account the geometrical sources of systematics and an overall detection efficiency of 30%.

It is worthwhile noting that rhe resolution shown in Fig. 4 is clearly specific to the case study of *Palazzo della Loggia*. For other situations, a dedicated Monte Carlo simulation would be required.

4.1 A small scale prototype

A small scale prototype with reduced potentiality and features have been built and operated to validate the Monte Carlo package. As shown in Fig. 5, the system consisted of a muon telescope, composed of three layers, a single layer. Each layer contained 8 (200x3x3 mm^3) fibers . Two blocks of aluminum were placed in between to induce multiple scattering in the cosmic ray muons. The position of the upper layer with respect to the lower telescope, displaced by 3.8 mm, was measured tracking the muons crossing all the apparatus. The system proved to be capable to detect a relative displacement and the Monte Carlo to be reliable in estimating the resolution of the system.

5. Conclusions

A design of a monitoring system based on the tracking of cosmic ray muons for the stability of historical buildings have been presented. A Monte Carlo study proved that such system can be competitive in respect to the ones of monitoring systems today widely employed and generally referred to as Structural Health Monitoring (SHM) methods. Some examples are given in [45, 48] and references therein.

Given the fixed rate of cosmic ray muons and the performances of the system, the method proposed is clearly indicated for static monitoring and in this sense it is complementary to most of the SHM techinques. The main advantage of using cosmic rays is clearly that this technique allow to monitor internal parts of buildings with high resolution even if such parts are not visible one to another.

As an example, in the case study presented in this work, as summarized in Fig. 4, the system is capable to detect a displacement of about 1 mm at at distance of 13 meters in just few days.

Other appealing features of the proposed monitoring system are: (i) the use of a natural and ubiquitous source of radiation; (ii) the applicability also in presence of horizontal and/or vertical building structures interposed between the reference system and the parts to be monitored; (iii) the limited invasiveness, and the flexibility and easiness of installation of the monitoring system devices; (iv) the use of established technologies in the field of nuclear and particle physics.

The goal of our research group, in the near future, is to build and test a demonstrator, of the dimensions reported in Fig. 1, to prove and define the capabilities of the system in a measurement

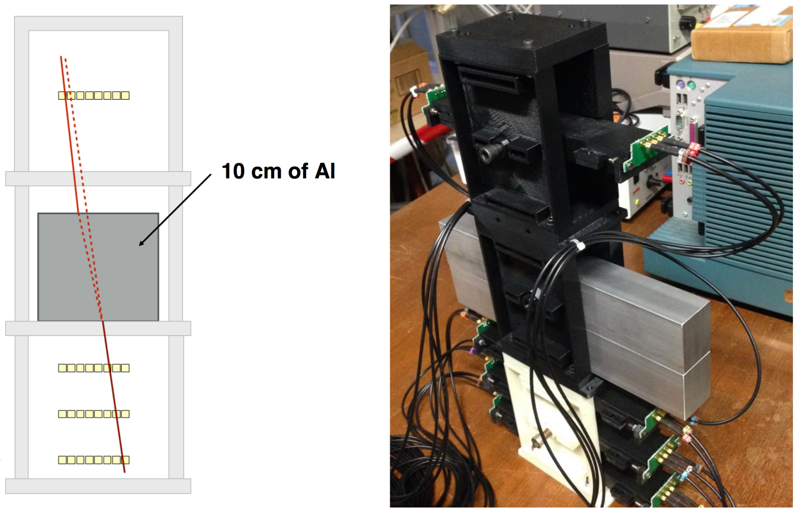
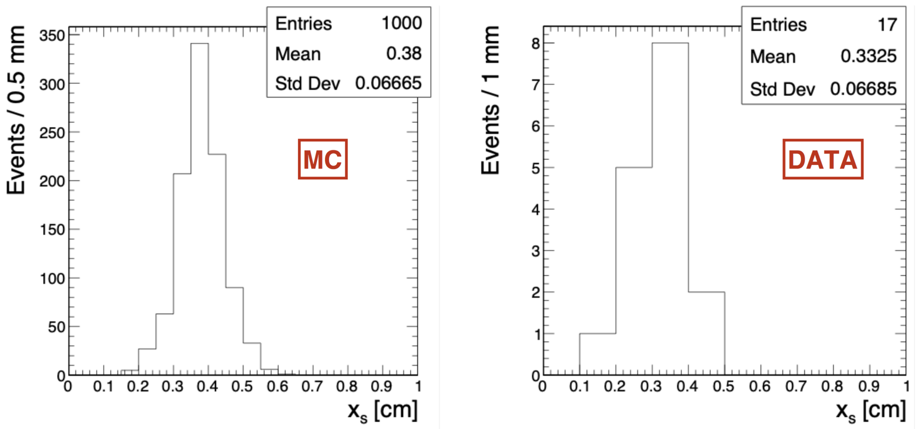


Figure 5: A photo and a schematic overview of the small scale prototype.



1000 samples of 100 events each (~2 days)

17 samples of 100 events each (~2 days)

Figure 6: Distribution of the displacement measured with 17 samples of 100 muons (data) compared with 1000 samples of 100 muons generated with the Monte Carlo.

campaign inside a historical building.

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