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HISTORICAL BUILDING STABILITY MONITORING BY MEANS OF A COSMIC RAY TRACKING SYSTEM

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The ubiquitous and steady presence at the Earth's surface and the high penetration capability of cosmic rays, have motivated their use in different fields beyond particle physics. Recently, a new application of cosmic ray detection techniques in the field of civil engineering has been proposed. The aim is the stability monitoring of large structures, in particular the static monitoring of historical buildings, where conservation constraints are more severe and the time evolution of the deformation phenomena under study may be of the order of months or years. As a significant case study, the monitoring of the wooden vaulted roof of the "Palazzo della Loggia" in the town of Brescia, in Italy, has been considered. The feasibility as well as the performance of a monitoring system based on cosmic ray tracking have been studied by Monte Carlo simulation. Possible improvements both in the detector system and in the statistical analysis of the collected data are discussed.

Keywords: Cosmic ray; stability monitoring; historical building.

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1. Introduction

When primary cosmic rays, mainly composed of high energy protons coming from the sun and from the outer Galaxy, strike the Earth's atmosphere, a cascade of many types of subatomic particles is created[1]. Hadronic particles produced in the shower either interact or decay, and electrons and photons lose energy rapidly through pair production and Bremsstrahlung, so that, by the time the charged component of this particle shower reaches the Earth surface, it comprises primarily positive and negative muons. The flux reaching the surface of the Earth is about 10,000 μ/ (min m^2) and the mean muon energy is 3 to 4 GeV. Since muons are heavy particles and do not undergo nuclear interactions, they are highly penetrating in matter and their average energy is sufficient to penetrate tens of meters of rock.

The ubiquitous presence at the Earth surface and the high penetration capability have motivated their use in fields beyond particle physics. Since the mid-twentieth century, attenuation of cosmic ray muons has been used to produce radiographies of large and inaccessible structures[2,3] and in the study of the inner structure of volcanoes[4,5].

In 2003 a new method was proposed[6,7], the muon tomography, in which the angular scattering that every muon undergoes when crossing matter is exploited to inspect unknown objects hidden inside large containers. This technique has been adopted for applications in the civil security domain[8]. It has also been proposed for the detection of radioactive "orphan" sources hidden in scrap metal containers[9,10], to inspect the interior of blast furnaces[11] or legacy nuclear waste containers[12]. The method has also been proposed to perform a diagnosis of the damaged cores of the Fukushima reactors[13] and, recently, the fuel melt at Daiichi 1 has been assessed by muon data[14].

In 2007, cosmic ray muon detection techniques were assessed[15] for application in civil and industrial engineering for the monitoring of alignment and stability of large civil and mechanical structures. A Monte Carlo analysis was developed concerning the case of monitoring of the mechanical alignment of parts of an industrial press.

In the present paper, the same general idea of exploiting the cosmic ray natural source of radiation for the monitoring of the alignment and stability of large structure is applied, with an improved detector scheme, to the case of historical buildings, whose cultural and artistic value often puts severe constraints of non-invasiveness to the monitoring techniques that may be employed.

The features and expected performances of the proposed measurement system were studied with a Monte Carlo technique and were applied to a realistic situation, the exemplary case of the "Palazzo della Loggia", seat of the Mayor, in the town of Brescia, Italy[16,17]. Starting in 1990, the Palace was subjected to a campaign of investigation by the University of Brescia[18,19]. In particular, a mechanical monitoring system was implemented to monitor the stability of its wooden vaulted roof.

In Section 2 the design of the proposed muon stability monitoring system is presented. In Section 3 the mechanical monitoring system used at the "Palazzo della Loggia" is described. In Section 4 the application of the method of muon stability monitoring to the "Palazzo della Loggia" is analyzed and its expected performance is discussed. In Section 5 conclusions are drawn.

2. The Muon stability monitoring system

The main component of the proposed monitoring system is the "muon telescope". It is constituted of a set of three muon detector modules supported by an appropriate mechanical structure and axially aligned at a distance of 50 cm one from the other. Each module is composed of two orthogonal layers of 120 scintillating optical fibers with 3 mm x 3 mm square cross section and 400 mm length. The scintillating fibers are read at the ends by silicon photomultipliers SiPM with 3.0 mm x 3.0 mm sensitive surface.

The two layers of orthogonal scintillating fibers provide the measurement of the crossing position of an incident muon in the *x* and *y* coordinates on the module plane, with a pitch of 3 mm. Considering a flat detection efficiency over the entire surface of the scintillating fiber, the expected spatial resolution on the hit coordinate is about 0.9 mm. The angular resolution of the “muon telescope” is about 2.6 mrad.

The “muon telescope” is mechanically fixed to a structural element of the building, which constitutes the reference system, with its axis aligned in the direction corresponding to the part of the building structure whose displacements should be monitored. Here, a fourth muon detector module, with the same geometry and structure of the previous ones, is positioned as “muon target”.

Thanks to their high penetration capability, cosmic ray muons are able to cross the system of four detectors as well as the interposed building structures and make it possible to continuously monitor the horizontal displacements of the “muon target” relative to the “muon telescope”.

Indeed, the trajectory of a cosmic ray muon crossing the system of four detectors can be extrapolated from the “muon telescope” to the plane of the “muon target” detector, in the hypothesis that it is a perfect straight line. So, the difference between the effective muon crossing point on the ”muon target” and the extrapolated one from the ”muon telescope” allows the position of the ”muon target” relative to the ”muon telescope” to be measured. Possible displacements of the position of the ”muon target” relative to a reference position previously determined can be monitored.

It’s worth mentioning here that the hypothesis of linear extrapolation of the muon trajectory is often only a rough approximation of the actual muon track behaviour. Indeed, in crossing the interposed materials, the trajectories of cosmic ray muons are deflected from the direction of incidence by multiple Coulomb scattering. In the presence of layers of concentrated materials (building structures as floors and walls) the muon trajectories are better approximated by broken lines.

In Section 4.2 it is shown that, depending on the particular case study, the position measurement uncertainty of the monitoring system can be improved by exploiting the information on the geometry and material composition of the building structures interposed between the “muon target” and the “muon telescope”. In this sense, the proposed technique may be seen as the reverse problem of muon tomography[20].

3. Mechanical monitoring of static anomalies in the “Palazzo della Loggia”

The “Palazzo della Loggia” was built in 1574 by the Venetian Government of the town of Brescia. Since its completion, the Palace has cumulated a long sequence of injuries, transformations, repairing interventions, some of which have generated considerable problems of structural stability of the building.

The grandiose wooden vaulted roof was completely reconstructed in 1914, with the same architectural shape and construction techniques of the original one, destroyed by a fire one year after the completion of the building. The shape of the dome is like an upside down ship which reaches in elevation a maximum of 16 m, having the planar rectangular sides of about 25 and 50 m respectively.

Immediately after the complete reconstruction performed in 1914, the structure of the present wooden vaulted roof, which is a characteristic feature of the historical building, exhibited a progressive deformation of the longitudinal top beam and of the key points of the connected arches. The progressive deflection of the top beam was measured to be 190 mm in 1923, 520 mm in 1945, 800 mm in 1980. Starting from 1990, a systematic campaign of investigation and monitoring of the different stability problems of the Palace was committed by the Brescia municipality to the University of Brescia[18,19]. In particular, the progressive deformations of the principal arches of the wooden vault were studied with a specifically designed mechanical measurement system.

On four out of the seven principal truss wooden arches, three couples of wires of 2 mm in diameter, one made of ordinary steel and the other made of invar, were stretched between symmetric points at three different levels, as seen in Fig. 1: A1-B1, at the point of connection of the arches with the building structure, A2-B2 and A3-B3 on the arch reins. The wire tension was maintained by means of a system of pulleys and balance weights.

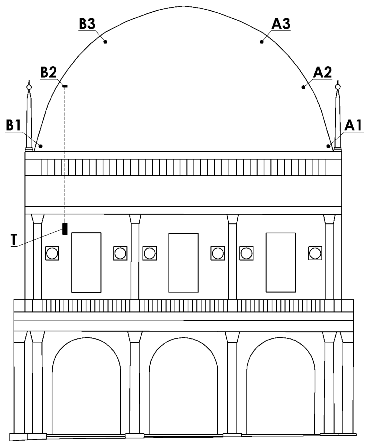

Fig. 1. Schematic cross section of the “Palazzo della Loggia” with the indication of the symmetric points A1-B1, A2-B2, A3-B3, in the wooden vaulted roof, where the couples of iron and invar wires were stretched. The possible positions of the “muon telescope” (T), linked to a structural element of the building (the fixed reference system), and the “muon target”, connected on a point of the roof to be monitored, are shown.

The relative displacements of the symmetric points were continuously monitored by the differential elongation of the two wires; the different thermal dilatation coefficients of the two materials made possible to depurate the deformation of the monitoring system itself, subject to the considerable daily and seasonal thermal variations under the roof covered by lead plates. The elongation of the two wires was measured by a mechanical measurement system based on a vernier with a sensitivity of 1/10 mm.

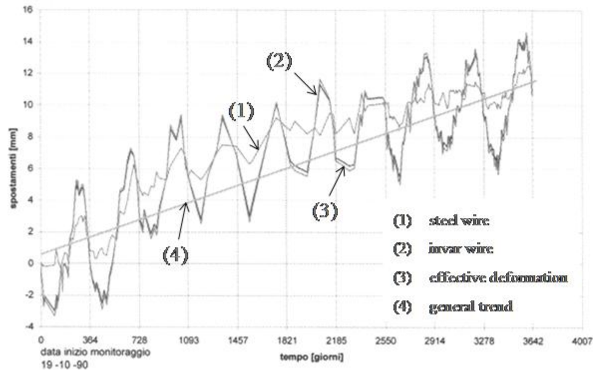

Fig. 2. Elongation of the wires stretched between the points A2 - B2 of the truss wooden arch as a function of time in days. Ordinary steel wire (1), invar wire (2), effective deformation of the structure after accounting for the thermal elongation of the wires (3), general trend of deformation (4). (Courtesy of the authors of Ref. 19)

In Fig. 2, the elongation of the ordinary steel wire, of the invar wire and the effective deformation of the structure are shown as a function of the monitoring time in days, for the couple of wires connecting the arch reins at middle height (points A2-B2). The effective deformation is practically coincident with the elongation of the invar wire. The general trend shows a progressive collapse of the wooden structure of the arch of about 1 mm per year.

4. Simulation of the muon stability monitoring ystem for the “Palazzo della Loggia”

The study of the application of the muon stability monitoring method to “Palazzo della Loggia” was performed by Monte Carlo simulations using the GEANT4 package[21].

A cosmic ray muon generator based on experimental data was implemented in the code in order to simulate as realistically as possible the momentum, the angular distribution and the charge composition of the cosmic ray radiation at the sea level[22]. The structure and composing materials of the “muon telescope” and “muon target” were modeled as well as the relevant structures of the “Palazzo della Loggia” building.

Three configurations were considered as shown in Fig. 1: the first with the “muon target” in position B1 on the wooden arches of the roof, located 0.50 m above the wooden ceiling of the “Salone Vanvitelliano”, at the first floor of the Palace; the second with the “muon target” in position B2, the third with the “muon target” in position B3, located respectively 5.8 m and 10.0 m above the wooden ceiling. In the tree different conditions the “muon telescope” was located on the vertical of the corresponding “muon target”, 3.0 m below the wooden ceiling. The ceiling of the large “Salone Vanvitelliano” was modeled as a bulky 15.0 cm thick wooden layer.

4.1. *Determination of the position measurement uncertainty*

Populations of cosmic ray muons crossing the measurement system were simulated for the three configurations described above. Statistical distributions of the differences Δ*x* and Δ*y* between the muon crossing point coordinates measured by the "muon target" and the crossing point coordinates extrapolated from the "muon telescope" in the "muon target" plane with a straight line model were calculated. Due to the symmetry of the system, Δ*x* and Δ*y* are statistically identical and only Δ*x* distributions will be considered in the following.

In Fig. 3 the distribution of the statistical variable Δ*x* is shown in the worse condition in which the "muon target" is located in position B3, for an elapsed data taking time of 15 days.

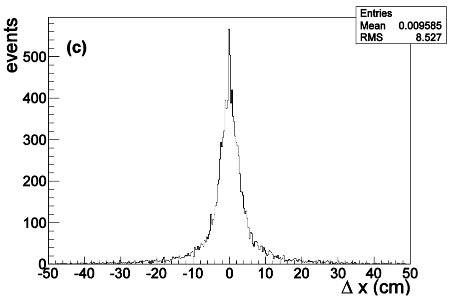

Fig. 3. Distributions of the difference Δ*x* between the crossing point coordinates measured on the "muon target" in position B3, and the crossing point coordinates of the linear extrapolation of the muon trajectory measured by the "muon telescope", with 15.0 cm thick wooden floor interposed. Simulated data taking time is 15 days.

As the "muon target" and the "muon telescope" are exactly coaxial in the simulation, the Δ*x* distribution is symmetric and centered at zero. The shape of the distribution exhibits a central narrow peak with very long tails on both sides. This shape is due both to the intrinsic uncertainty of the "muon telescope" in measuring the direction of the cosmic ray muon and to multiple scattering angular deviations of the muon trajectories traversing the interposed materials. The latter effect dominates for large distances of the "muon target" from the "muon telescope". The long tails of the distribution are mostly due to low momentum muons, suffering larger deviations.

The mean value of the sample distributions represents an unbiased estimator of the position of the "muon target" relative to the "muon telescope" axis. The root mean square of the sample distribution represents the uncertainty in the measurement of the position of the "muon target" relative to the "muon telescope". The uncertainty on the mean value of the sample distribution is given by the well known statistical relation $\sigma_{mean} = \sigma_{distr} / \sqrt{N_{ev}}$, where N_{ev} is the number of events in the distribution.

In the same geometrical conditions, the number of events in the distribution is proportional to the data taking time. Therefore, the measurement standard uncertainty depends on the inverse of the square root of the data taking time. In the three geometrical conditions the expected acquisition rates of cosmic ray muons crossing the full system are respectively: 7.1 μ/min in position B1, 1.2 μ/min in position B2 and 0.55 μ/min in position B3.

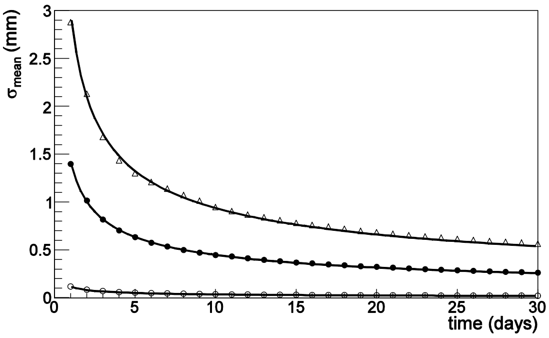

Fig. 4. Standard uncertainty on the mean value of the Δx sample distributions versus data taking time, for the "muon target" in position B1 (open circles), B2 (full squares) and B3 (open triangles). Fitting curves are given by the general relation $\sigma_{mean} = C/\sqrt{t}$; C is a constant and t is the data taking time.

In Fig. 4 the relation of the position measurement standard uncertainty versus the data taking time for the three examined conditions is plotted up to a data taking time of one month. The plots are fitted with the general relation $\sigma_{mean} = C/\sqrt{t}$, where C is a constant depending on the geometry and interposed materials and t is the data taking time. As time increases, the measurement standard uncertainty decreases. As an example, in one month of data taking in position B3, where "muon target" and "muon telescope" are positioned 13.0 m far apart, a measurement standard uncertainty of the order of 0.5 mm may be achieved. The same standard uncertainty may be achieved in a week of data taking in position B2, whereas a 0.1 mm uncertainty may be measured in just one day in the position B1.

The previous results demonstrate that the expected performance of the measurement system is compatible with the requested precisions and with the time scale characteristics of the deformation phenomenon that, in the considered case and, in general, for historical buildings, may span over several years.

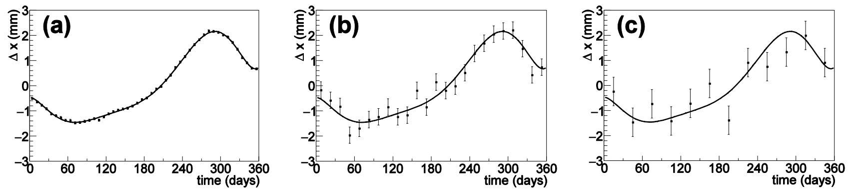

Fig. 5. The same seasonal deformation corresponding to the first year of data taking in Fig. 2, with superimposed the result of the simulated measurements of the position of the "muon target", displaced following the assumed structure deformation. Sampling rate is one week for position B1 (a), two weeks for position B2 (b) and one month for position B3 (c).

To better illustrate the possibility of the proposed monitoring system to follow slow deformation phenomena, in Fig. 5 an example of seasonal deformation reported in Fig. 2 is simulated in points B1, B2 and B3 and the results of the cosmic rays monitoring system are calculated. It is evident how the system can follow seasonal deformations and, even more so, systematic trends.

4.2. *Possible improvements of the performance of the muon stability monitoring system*

The uncertainty of the proposed monitoring system could be significantly improved both by modifying some geometrical parameters of the system and improving the data analysis.

Concerning the design of the measurement system, let us first remark that an increment of 50% of the single module size can improve by a factor 5 the number of accepted cosmic rays, corresponding to a reduction of a factor 2.2 of the data collection time needed to obtain the same standard uncertainty on the position measurement. Moreover, low momentum muons, which suffer the largest multiple scattering, can be discarded by the data sample by means of a muon absorber in the form of a thick iron plate positioned below the muon telescope and followed by a further plane scintillation counter in coincidence. By eliminating the low momentum muons, the long tails of the Δx and Δy distribution can be reduced, thus reducing the root mean square σ_{distr} of the distributions. Finally, the experimental information on the muon trajectory may be improved by designing the muon target as a couple of particle detector modules assembled to form a telescope, allowing both the crossing position and the direction of the incident cosmic ray muon to be measured at the “muon target” point.

The performance of the data analysis can be improved in different ways by exploiting the knowledge of the building geometry and material composition. As previously mentioned, in some sense, this corresponds to consider the muon stability monitoring technique as the “reverse problem” in respect to the muon tomography. Indeed, in the latter case, the position of the detectors is perfectly known and the geometry and composition of the inspected structure can be inferred, in the former case, the geometry and composition of the inspected structure is known and this can help in determining the relative position of the upstream and downstream detectors.

As a first example, in[15,17] it was demonstrated that a more efficient unbiased estimator of the possible displacement of the muon target detector can be obtained by fitting the sample distributions Δx and Δy by an appropriate analytical function representing the parent population of the two statistical variables. In this way, the standard uncertainty on the “muon target” position is expected to improve by a factor of 2 to 3. Indeed, the shape of the parent population can be obtained either with a unrealistically long data taking or, better, by a Monte Carlo simulation of the tracking of a population of cosmic rays through the muon detectors and building structure. This adds to the analysis full information on the building structure and material composition as well as on the muon momentum and direction distributions.

If both crossing point and direction of the cosmic ray are measured also at the "muon target" and it is known, from the building geometry, that the muon deviation is concentrated in few main layers of dense material (floors), more realistic models for the muon trajectory, based on a set of straight lines connected at the dense layers, can be used instead of the simple straight line extrapolation from the "muon telescope".

In the hypothesis of a single concrete floor 30 cm thick, with the "muon target" in position B3, it has been shown, by Monte Carlo simulation, that the resolution of the measurement of the position of the "muon target" can be considerably increased only by the knowledge of the position of the floor. In Fig. 6(a) and (b) the distributions of the statistical variable Δx for the position B3 are shown, for an elapsed data taking time of 7 days, in the case of straight and broken line models respectively. In the latter case, the value of σ_{mean} improves by a factor of 5, which means a factor 25 in data taking time.

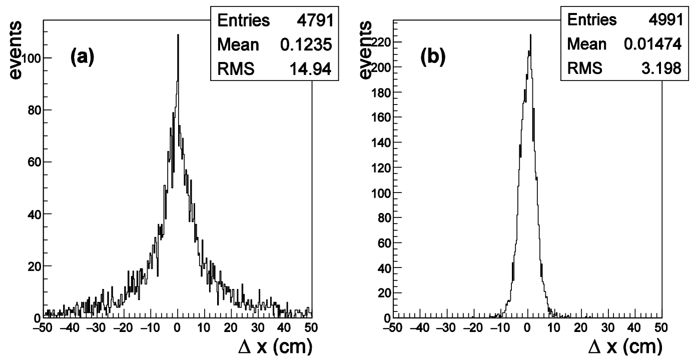

Fig. 6. Distributions of the statistical variable Δx for the position B3, with one 30.0 cm thick concrete floor interposed and data taking time of 7 days, in the case of straight (a) and broken (b) line models.

In the case of two thick and dense layers (floors) interposed between the "muon target" and the "muon telescope", with known position and composition, a model for the cosmic ray trajectory constituted by a line broken in correspondence to the two dense layers may be adopted. By simple geometrical arguments, the values of the two scattering angles θ_1 and θ_2 on the two floors can be expressed as a function of the unknown position x_0 of the "muon target". By the knowledge of geometry and composition of the two floors, the probability distributions $P_1(\theta_1)$ and $P_2(\theta_2)$ of the two scattering angles θ_1 and θ_2 can be calculated by Monte Carlo for the average muon momentum. Therefore, for each muon trajectory, a likelihood function can be constructed:

$$L(x_0) = P_1(\theta_1(x_0)) \cdot P_2(\theta_2(x_0)). \tag{1}$$

By maximizing the likelihood for each muon separately, or collectively for a sample of muons, the most probable value of the position x_0 of the "muon target" can be inferred. Using this analysis technique on a sample of simulated cosmic ray muons, with the "muon target" in position B3 and the presence of two concrete floors 30 cm thick and

4 meters away one from the other, an improvement by a factor of 4 in the "muon target" position resolution, compared to simple straight line extrapolation, can be obtained.

5. Conclusions

In conclusion, cosmic ray muon detection techniques have been investigated for measurement applications in the field of civil engineering and have been demonstrated to be particularly suitable for static monitoring of historical buildings, where the evolution of the deformation phenomena is of the order of months or years. Appealing features of the proposed monitoring system are: (i) the use of a natural and ubiquitous source of radiation, avoiding any problem of radiation protection; (ii) its 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 ease of installation of the monitoring system devices; (iv) the possibility to design a global monitoring system, where the position of different points of the building may be simultaneously monitored relative to the same reference system; (v) the use of well-known physical principles and established technologies in the field of nuclear and particle physics to build up the cosmic ray muon detectors featuring the characteristics suitable to satisfy the requirements of any specific application.

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