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Robotized inspection and health monitoring in the Gran Sasso National Laboratory

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Abstract. The Gran Sasso National Laboratory (LNGS) is the largest underground research center in the world devoted to neutrino and astroparticle physics. It is located in galleries below about 1400 meters of rock mass. In this environment, inspection and monitoring actions are challenging for the maintenance and the safety of the infrastructures and they require a combined use of different strategies. The paper address issues related to the structural safety of the whole environment by proposing solutions for inspection and monitoring of different areas and elements, such as the gallery vaults, the structures of the experimental prototypes, the plants and the machinery. A generic framework is discussed to evidence the features of each specific solution and the interaction between different systems. Tunnel structural healthy is the most difficult to evaluate because the vaults are coated by not removable panels which waterproof and insulate the environment. Therefore, specific solutions are proposed for the inspection and monitoring of the vaults which are visible only in the interspace realized from such cladding panels. In this respect, different methodologies based on the use of robotic systems are presented and discussed in order to implement a suitable inspection and monitoring program. The complementary requirements to perform a mechatronic survey are defined also as basis of ongoing activities currently performed in LNGS.

Keywords: tunnel survey; underground structures; structural health monitoring; non-destructive testing; robotic systems

1. Introduction

Inspection and monitoring are composed by a series of activities needful to assess the structural integrity and safety conditions of existing buildings. In the last years, different non-invasive techniques and procedures have been developed and applied to obtain as many as possible useful

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information for a correct evaluation of the structural health. In some cases, the monitoring systems may be assisted by robotized tools. Indeed, their key advantages are related to the ability of performing inspections in structural areas not easily approachable or to install sensors in locations opportunely selected but dangerous to reach, see Sakagami *et al*. (2019) and Phillips and Narasimhan (2019). Also, for tunnels and underground environments the use of robotized tools becomes essential because they are often able to acquire images of inaccessible zones. Indeed, the investigation of tunnel lining, in the recent years, have been performed using noncontact techniques combining laser, visual, infrared thermography scanning method, see White *et al*. (2014).

The survey on the most important structural elements of a tunnel requires a dedicated and detailed analysis due to the inherent importance of such structures able to allow deformations induced by the loading exerted by the surrounding soil. Moreover, the latter could be subjected to instability of seismically-induced liquefaction phenomena causing, consequently, damages in the underground structures, Azadi and Hosseini (2010). The tunnels are generally loaded in such a way that three different tension states are recognized: axial tension and compression induced by seismic waves parallel to the longitudinal axis of the tunnel; longitudinal bending due to the seismic waves components transversal to the axis of the tunnel; distortion of the cross section (roundness) produced by normal seismic waves (vertical component). During the years, relevant damages produced by high-intensity earthquake have been found in external and underground structures, see Ceci *et al*. (2013) and Wang *et al*. (2001). One of the most significant examples is related to the case of the Dakai metro in Kobe (Japan) during the Hyogoken-Nambu earthquake in the 1995, Hashash *et al*. (2001). In this context, it results evident that technological enhancement of visual inspections and structural health monitoring system for underground structures plays a fundamental role specially to save lives.

Continuous monitoring systems have been widely used also for underground structures and in this case very small changes in the signature of measured quantities could have an important meaning in the prevention of collapse. The information coming from the data processing aims to detect the starting of tunnel failure mechanism, for which is necessary to depurate the measurements from the influence of different environmental factors like temperature or humidity. For example, in Yun *at al*. (2014) an array of sensors (composed by extensometers and tilt gauge) was used to check the deformations on an existing tunnel due to the excavation operations for the construction of a new nearby tunnel. In this case a data-driven technique based on Principal Component Analysis has been successful for using eigenvalues and the corresponding eigenvectors as indicators of the tunnel structural behavior during the excavation. Other interesting cases are related to the realization of monitoring systems through new technologies implementing distributed fiber optic sensing. Mohamad *et al*. (2012) and Di Murro *et al*. (2019) propone the use of these sensors to follow a continuous strain profile due to external input. The results have been compared with the ones obtained by conventional instrumentation measurements showing a good agreement. Some studies, as in the case of Yu *et al*. (2018), have been development for damage detection of subway tunnel structure using a statistical pattern recognition algorithm. The latter has been validated by an experiment of a full-scale two-ring subway tunnel lining in which the damage has been simulated by loosening the connection bolts of the rings.

In the structural health monitoring of civil engineering structures, fiber optic sensors have been widely used, thanks to their small size and high sensitivity. Moreover, unlike electric sensors, fiber optic sensors are characterized by resistance to corrosion and to electromagnetic interference; they are robust enough to resist harsh environments and they can be multiplexed over several kilometers due to the low light attenuation of optical glass fibers. Therefore, optical fiber makes possible distributed measurements over long distances. Several fiber optic sensors have been developed in this field to measure different physical and chemical parameters, such as strain, formation of cracks, temperature and moisture, Bremer *et al*. (2016). For example, a fiber optic sensor was used for real time applications for bridge decks by Domaneschi *et al*. (2017) to detect an unusual behavior (e.g., damage or deterioration) through long-gauge fiber optic strain sensors measurements and a probabilistic study of the dynamic curvature power spectral density. In particular, fiber optic sensors can be applied to carry out a static monitoring of the main vaults of underground tunnels. Through this system, it is possible to catch both transversal and longitudinal deformation due to the very low strain expectations. In Gue *at al*. (2015) practical guidance are given for the planning and installation of distributed fiber optic sensor and presents a brief case study on the monitoring of London's Royal Mail tunnel during the construction of the large Crossrail platform tunnel, showing the benefits of such systems in complex tunnelling scenarios. A Fiber Bragg Grating (FBG) sensing technique was used also by Zhou *et al*. (2018), in order to provide continuous monitoring of railway tunnel deformation in the long term.

In recent years, various approaches for robotic inspection, monitoring and maintenance have been developed to replace standard visual inspection conducted by humans and to make the related procedures safer and faster (Gucunski *et al*. 2015, Potenza *et al*. 2020). Moreover, these series of activity are strongly required to guarantee high levels of structural performance for tunnels. For fast and reliable surface defect analysis, automatic crack detection is developed, and it can be performed using several Non-Destructive Testing (NDT) techniques such as: infrared and thermal testing, ultrasonic testing, laser testing, radiographic testing, Fujita and Hamamoto (2011). Ultrasonic sensors have been widely used as non-destructive sensors in indoor mobile robot navigation and obstacle avoidance, Yao *et al*. (1999). They are cheap and reliable, but they can only detect the existence of objects without giving any further information about objects. Therefore, the combined use of ultrasonic and visual sensors has been proposed in Yao *et al*. (2003). In this project, 24 ultrasonic range sensors and six video cameras are mounted in a semi-ring settled on an autonomous mobile robot. The purpose of the ultrasonic sensors is to detect shape deformation of the tunnel, 'swell' or 'hollow', while the cameras aim to detect structural or surface changes, 'cracking' and 'water penetration status through the crack' (image-based crack detection). In literature there are different techniques to automatically identify the crack and its depth using image processing techniques. They can be classified according to the type of the image used (camera image, infrared image, ultrasonic image, laser image, time of flight diffraction image, electroluminescence image, unmanned aerial vehicle camera image), the objectives (length of the crack, width of the crack, direction of propagation), the dataset, the accuracy and error level, and the image processing technique (wavelet transform, digital image correlation, randomized Hough transforms, threshold method), see Mohan and Poobal (2018).

The structural performances are strictly connected to the deterioration processes due to different motivation: phenomena induced by dust, humidity, absence of natural life or effects produced by the aging of the material, inadequate or poor maintenance. It is evident that, in this particular scenario, activities of inspection, assessment and maintenance are crucial to guarantee an acceptable security and service level. During the years, a great attention has been paid by the scientific community to improve the management of the inspection. Some interesting scientific work are reported in Yu *et al*. (2007), Victores *et al*. (2011), Montero *et al*. (2015), Merendez *et al*. (2018), Nakamura *et al*. (2019), Protopapadakis *et al*. (2019). In particular, in Merendez *et al*. (2018) the robotic system is composed by a mobile vehicle capable of extending an automated crane and, moreover, it is also equipped with an ultrasonic sensor to measure width and depth of detected cracks. An accurate positioning of the sensor is assured by a robotic arm. A set of cameras (attached also to the crane) with computer vision algorithm are used for detecting the defects and an arm positioning algorithm is used for placing the ultrasonic sensors on detected cracks. The peculiarity of this device is that it is autonomous, and it doesn't need to be teleoperated. The mobile vehicle navigates autonomously at a constant distance and prevents collisions using front and back range laser navigation sensors. The navigation strategy is based on simultaneous localization and mapping with a set of reflective beacons placed inside the tunnel. Furthermore, this system is minimally invasive because it allows ongoing traffic on the other lane. A similar procedure to perform maintenance operation can be found in the project described in Victores *et al*. (2011). In this case a robotic arm is positioned on the tip of a crane, and the whole system is mounted on a vehicle. It allows the inspection and maintenance of concrete surfaces in tunnels replacing the manual procedures for the application of advanced composite materials, such as fiber reinforced polymer and epoxy resins. The tool is composed by two systems: a material application system composed by mechanical subsystems and actuators, and a vision and security system composed by camera, laser distance sensor, and security micro-switches. For superficial preparation, an on-board compressor mounted on the wheeled vehicle provides compressed air.

In the above-mentioned activities, the aim is focused on the inspection of visible defects like cracks, spalling and efflorescence. Different is the case of the LNGS. In particular, the features of the underground galleries are peculiar because in this environment is hosted a research center dedicated to the study of fundamental constituents of matter. Indeed, they are endowed of special facilities that make difficult the visual inspection like, for example, equipped wall systems. Moreover, in order to obtain a comfortable environment, the experimental halls have been waterproofed and insulated by cladding panel. In this context, standard procedures dedicated to the inspection of galleries and tunnels are not immediately applicable. Therefore, the aim of the present work is to analyze possible solutions for the inspection and monitoring of the LNGS, in order to propose a suitable mechatronic survey. Section 2 reports LNGS description highlighting how have been realized the gallery vaults and their main structural components, see also Potenza (2018), Lunardi (1990) and Castellani *et al*. (2012). Section 3 explains what are the main obstacles related to the inspection and monitoring of LNGS in relation with safety and serviceability condition of the environment. Moreover, a discussion about possible robotic systems, able to overcome these impediments, is proposed highlighting their advantages and drawbacks. Section 4 closes the paper with the conclusions and the future developments.

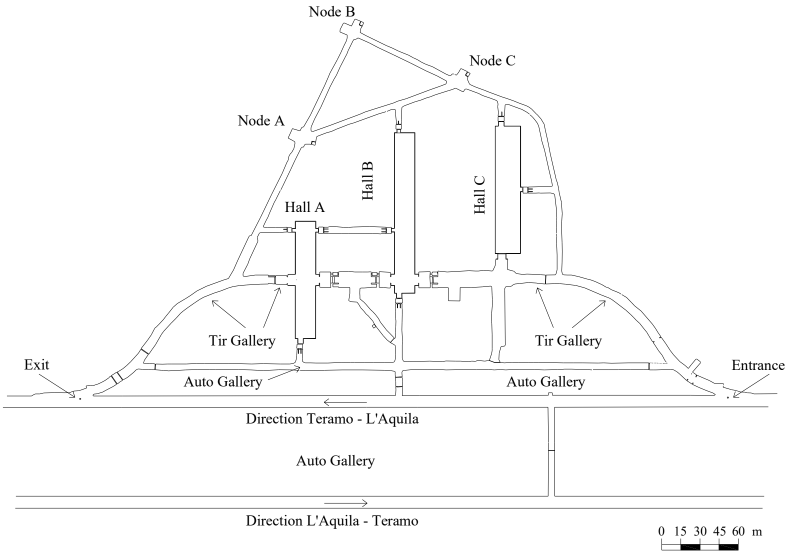
2. Gran Sasso National Laboratory

The Gran Sasso National Laboratory of the National Institute of Nuclear Physics are a very important underground research center, situated in Italy, where almost 1000 researchers working on the study of astroparticle physics. Different customized prototypes are located in the underground Halls (Fig. 1) to study challenging phenomena, such as the birth of the Universe, the nature of subatomic particles and the detection of dark matter particles.

2.1 Description

The underground Halls of LNGS are situated below about 1400 meters of rock mass within the Gran Sasso Mountain, in the center of the Apennine system (Abruzzo region, Italy). The rock

(a) 3D view



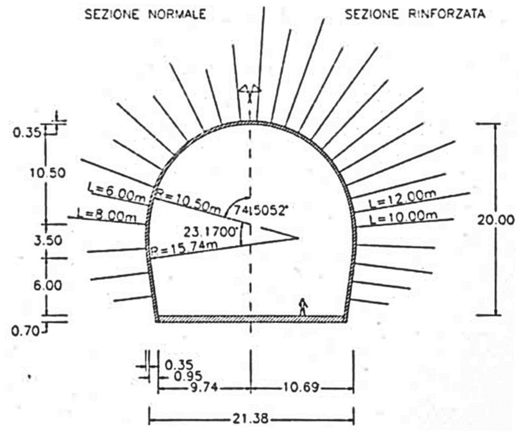
(b) Plan with indication of the main galleries

Fig. 1 Gran Sasso National Laboratory

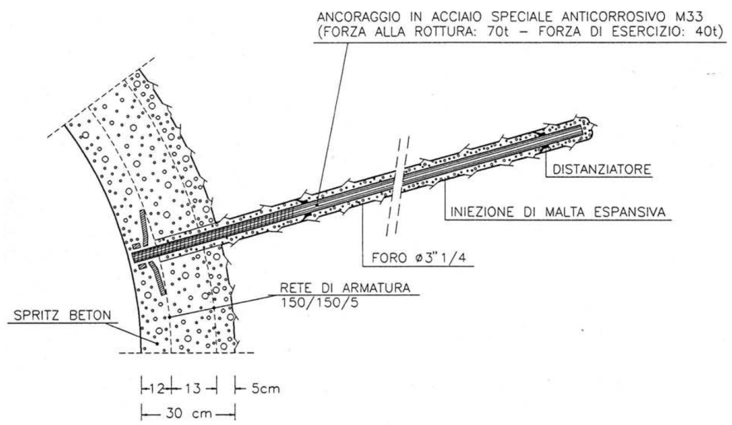
coverage reduces the flux of the cosmic rays and it allows to achieve the so called "*cosmic silence*", expression cited by the famous Italian nuclear physics Antonino Zichichi. He was the creator of the LNGS finding the public funding needed for their realization. It is worth mentioning that the Gran Sasso mountain is crossed by three great important faults: "Valle Fredda", "Fontari" and "Overthrust".

It is possible to entry to the Halls only through the highway tunnel; just outside this highway tunnel (Assergi, Italy) there are the offices dedicated to services of management, protection, administration and also refectory, sheds for storage, conference rooms and small dorms. For the presence of all these facilities, the LNGS is undoubtedly the most ideal place to conduct this specific activity research. The structures of the underground laboratories are showed in Fig. 1. There are three large Halls (Hall A, Hall B and Hall C) and service tunnels (Tir- Gallery and Auto-Gallery), with a total area of about 18000 m^2.

The underground experimental Halls and service tunnels were designed by Lunardi and they were built in 1982, Lunardi (1990). The designer observed, through stabilization calculations, that



(a) Gallery cross-section



(b) Rock bolt details and spritz-beton coating

(c) Rock bolt head

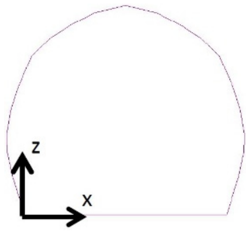
Fig. 2 Consolidation interventions in the galleries designed by Lunardi (1990) and actual condition of a rock bolt head in a picture taken in an accessible point of galleries

the rock mass, due to the excavation, would be stressed over its capacity strength. Moreover, the brittle behavior of the material required the adoption of the stabilization interventions especially to improve the overall cohesion of the rock. For these reasons, Lunardi decided to insert passive anchorages (Fig. 2) to join the discontinuity points and to increase the shear strength of the rock because of the huge coverage and the large dimension of the excavations and above all because of the fragile behavior of the limestone and its overcoming of load-bearing capacity during the excavations. The technical characteristics of the anchorage used are the following: material martensitic stain-less steel (AISI 420), diameter 30.6 mm, length from 6 to 8 m, compressive strength 100 MPa, mesh of 2 meters for side. In the areas, where the rock was more damaged, the length of anchorages is from 10 to 12 m and the mesh is denser (see Fig. 2(a)). Thanks to these consolidation interventions, the coating facilities were designed with very thin thickness (spritz beton layer 30 cm thick showed in Fig. 2(b)) and the use of the cement (source of harmful radiation for experiments) was minimized. Indeed, the rock is became self-bearing and so the crowning in reinforced concrete has no load-bearing function but it is only used to prevent water and stone falling in the tunnel. To obtain optimal air conditioning for the laboratory activities, the experimental halls were waterproofed and insulated using a PVC sheet and polyurethane panels (12 cm thick) supported by an aluminum structure.

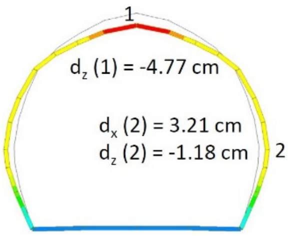
2.2 Static analysis of the vault

Generally, the effects caused by seismic actions on the tunnels showed deformations on both longitudinal and transversal direction. The latter naturally affects the initial shape of the tunnel's cross sections and can depend by the factors as the properties of structure, surrounding rock and soil

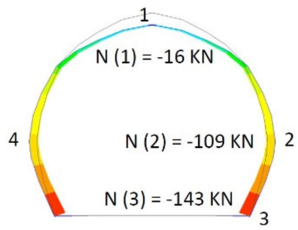
(a) 3D view of the model



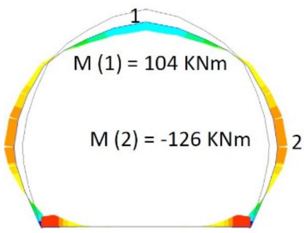
(b) 2D view of the model



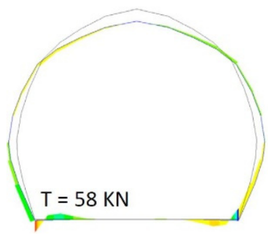
(c) Deformed shape under own weight



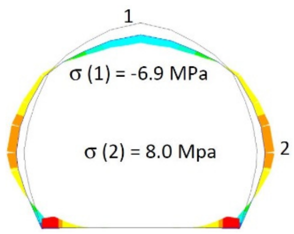
(d) Axial load under own weight



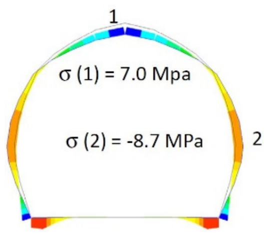
(e) Bending moment under own weight



(f) Shear under own weight



(g) Normal tension due to M and N for external fiber



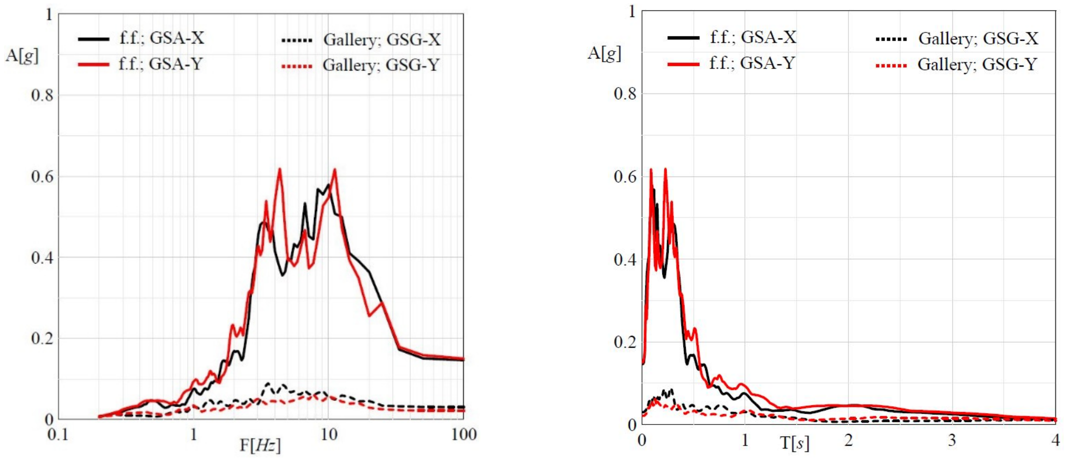
(h) Normal tension due to to M and N for internal fiber

Fig. 3 Numerical modeling of the transversal cross section and ground shaking, Hashash *et al*. (2001). A preliminary static analysis could be performed through the implementation of a one-dimensional finite element model representative of a transversal cross section of the LNGS underground tunnels. Beam elements (based on the Timoshenko theory) are used to describe the curved geometry of the vault; the section of the beam is rectangular (30 cm height and 1 m width). Moreover, it is right to underline that, in some small zones of the concrete ring, the thickness increases up to 40/50 cm. Anyway, the idealization of the structure has brought to a model with a constant thickness of 30 cm. A first simple linear one-dimensional elastic model is shown in Figs. 3(a) and (b). The bottom beam of the model is considered constrained on elastic soil and the coefficient adopted is 10 kg/cm^2 (reasonably value for a rocky soil). As well explained previous, such reinforced concrete coating has no load-bearing function and so the results related to the displacements and stresses are due only to the self-weight. The contribution of the anchorages has not been modeled to simulate an unfavorable limit situation in which all the anchorages lose their functionality (e.g., fracture or loss of friction). The deformations obtained with these models can be considered as limit values which require further observations and experimental tests that aimed to evaluate the conditions of the vaults. Based on above consideration, the results reported in Figs. 3(c)-(f) are related to a load case in which only the self-weight of the elements is taken into account. The main parameters selected to implement the numerical model are reported in the below Table 1. This analysis allows to identify the critical points of the galleries that need to be inspected to assess the actual conditions of the structure (points 1, 2 and 4 in Fig. 3(d)). These locations will correspond to the positioning of the sensors in the subsequent structural monitoring system. It can be observed that the maximum displacement value (-4.77 cm in z-direction) occurs at keystone, while a swelling of the vault (3.21 cm in x-direction) occurs at 5 m height. It is right to observe that, under the self-weight, the horizontal distance between two points, placed at the same quote for each lateral side (points 2 and 4, see Fig. 3(d)), show a spacing. In real conditions, the swelling, even in the case of total interruption of the action of anchorages, is still reasonably constrained by the surrounding rock. The normal stress is only compression (maximum value 143 kN). Due to bending moments at keystone, the fibers stretched are inside the vault, while at 5 m height they are out of the vault (Fig. 3(e)). Moreover, the normal tensions, due to bending moment and axial force, assume a value around 33% of the characteristic strength of the concrete.

Due to its function the main points, on which to collocate the sensors, have been individualized through the evidences of a numerical model representative of a transversal section under self-weight. After that, other loading effects to be considered could be the seismic one. However, the Gran Sasso mountain has a strong attenuation power of the seismic swarm, see De Luca *et al*. (1998). This phenomenon has been also experimentally checked during the L'Aquila 2009 Earthquake. Indeed, the processing of the measurements recorded during such earthquake by two accelerometer stations placed one inside the gallery (named GSA) and the other one external to the mountain (i.e., in free

Table 1 Main features related to the implementation of the finite element model

Section	Rectangular, base = 100 cm, height = 30 cm
Material	Concrete C25/30, cylindrical characteristic strength 25 MPa Specific Weight γ = 2500 kg/m^3 Elastic modulus = 31475 MPa (Lunardi 1990) Poisson coefficient ν = 0.2
External constraints	The base beam has been modelled as a beam on elastic soil for which has been adopted K-Winkler of 10 kg/cm^3



(a) Accelerations related to the frequencies (b) Accelerations related to periods

Fig. 4 Response spectra in terms of accelerations of the measurements recorded during the L'Aquila 2009 Earthquake in the stations GSA (external to the mountain) and GSG (inside the Gallery).f.f.: free field, Gallery: inside the Gallery. X and Y are both horizontal directions orthogonal to each other

field, named GSA), both on the soil, showed a strong attenuation up to a tenth as demonstrated by the spectral accelerations reported in the below Fig. 4. Therefore, the structural monitoring system has been thought, mainly, to follow the degradation of the material. Other information related to the processing of such measurements can be found in Potenza and Gattulli (2011).

3. Towards safety assessment of Gran Sasso National Laboratory

The actions which may help the assessment of safety conditions of the LNGS are inspections, getting information on the structure in a limited time, and monitoring, acquiring data during a continuous time interval. The main structures that have to be inspected and monitored are the vaults of the tunnels that host the laboratories, the experimental prototypes and the plants. Standard procedures can be applied for the experimental prototypes and the plants because they can be easily reached by human operators for visual inspection and sensors installation.

The conditions of the tunnel structures are the most critical ones to evaluate because they are coated by panels and they are not accessible by human operators. Hence, robotic systems are needful to perform both visual inspection and sensors installations. To assess the stability of the vaults of the tunnel it needs: (i) visual inspection on spritz beton layer to investigate on the presence of defects such as cracks, spalling and efflorescence; (ii) monitoring system with fiber optic-sensors (continuous in time and in the space) to evaluate the deformations of the tunnel and to detect possible anomalous structural behaviors; (iii) axial load measurement of the anchorages. All these actions of safety assessment are summarized in Table 2 and they are described in the follow.

Regarding the inspection and to the monitoring of the vaults of the tunnels, current robotic systems described in the introduction are designed to perform survey actions in road tunnels and they are not suitable to LNGS. In this case, the galleries are larger than road tunnels and they are occupied by experimental prototypes and instruments. Therefore, it is impossible to introduce into them a mobile vehicle equipped with an automated crane, as the one used in Merendez *et al*. (2018),

Table 2 Coordinated actions of inspection and monitoring to knowledge enhancement for structural safety assessment of LNGS

		INSPECTION				
		Discrete time				
		Visual inspection by human operators	*Visual inspection by robots*	*Acceleration measurements by accelerometers*	*Strain measurements by fiber optic sensors*	*Load tests*
Tunnel structure	*Spritz beton layer (vault)*		√		√	
	Rock bolts (anchorages)			√		√
Experimental prototype		√	√	√		
Plant	*Pipelines*	√	√	√	√	
	Machinery	√	√	√		
				MONITORING		
				Continuous time		

and the presence of the coating panels with their supporting structures makes inaccessible the vaults of the tunnels.

As shown in Fig. 5, the interspace between the spritz beton/rock layer and the coating panels is variable along the cross-section: it grows from the top to the bottom of the vault; at the base of the vault it is about 20 cm width (picture B in Fig. 5). In this restricted interspace there is also the aluminum structure that supports the coating panels (picture A in Fig. 5).

Therefore, in this case, an appropriate robotic system must be quite small and able to move itself in the delimited interspace between the panels and the spritz beton/rock surface of the gallery by avoiding the obstacles provided by the aluminum structure.

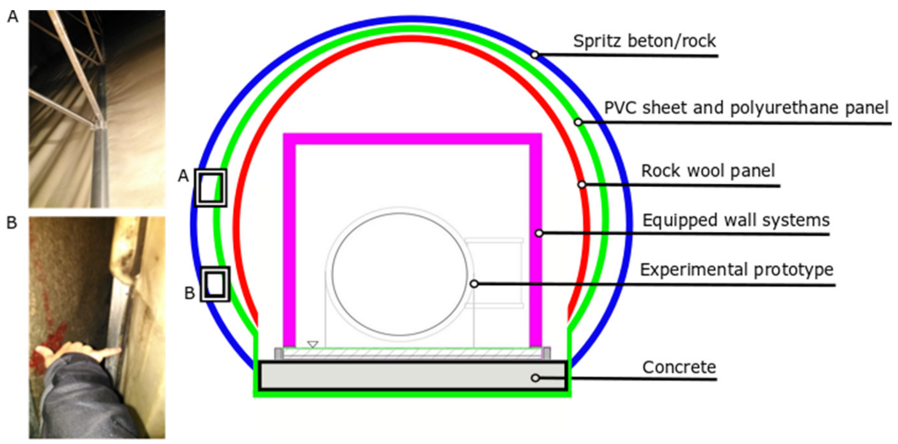
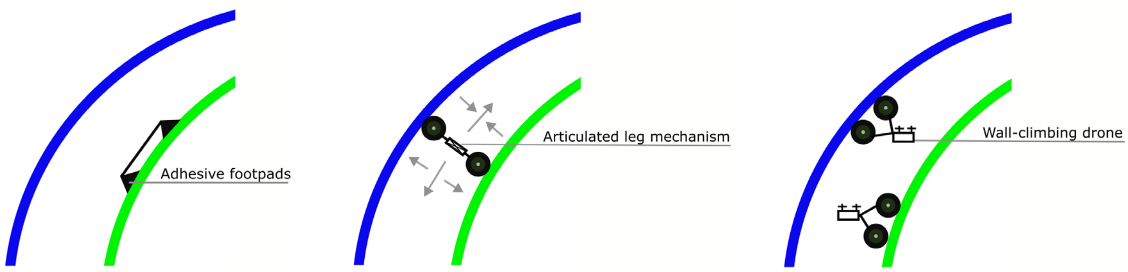


Fig. 5 Sketch of gallery cross section evidencing the interspace between spritz beton/rock layer and polyvinyl chloride (PVC) panels: detail A shows the aluminum structure, detail B the interspace length (≅ 20 cm)

As emphasized in Section 2.2, it is needful to inspect the conditions of the keystone, where the largest displacement occurs. Moreover, in this area the fibers stretched are inside the vault, the cracks may arise from inside of the vault and they may be observed by a robot capable to move in this interspace.

Climbing robots are getting attention for inspections of hard-to-reach environments like the one considered here; robots inspired by climbing animals (such as frogs, geckos) have been designed, using bio-inspired adhesive technology to traverse a wide variety of surfaces, Silva *et al*. (2008). A gecko inspired robot, like the one proposed by Unver *et al*. (2006), equipped with a camera, could be a suitable candidate to be introduced in the interspace between the tunnel and the PVC panels to inspect the tunnel surface conditions (Fig. 6(a)). It is a miniature wall-climbing robot with dry adhesives, steering, peeling, active preloading of the tail and climbing behaviour on inclined surfaces up to 85° at a speed of 1 cm/s. In this case, the gallery shape is approximately considered to be a circle with a variable slope that can have positive as well as negative values. To tackle this issue the gecko-inspired climbing robot could be designed as the StickyBot tested in Santos *et al*. (2008), where its climbing behaviors on vertical and overhanging surfaces have been analyzed. The adhesive and frictional properties of dry adhesive materials can be described by a three-dimensional limit surface in the space of normal and tangential contact forces at the feet. Empirically derived limit surface for directional adhesive pads was used as constraints in a force analysis to prescribe optimal foot orientations and internal forces to apply at the feet of a climbing robot, to maximize its stability on sloped and overhanging surfaces. Of course, it refers to a surface in a good condition (e.g., it could lose the adherence because of the humidity) otherwise other robotic solutions may be adopted, even because this robotic system is lacking in obstacle avoidance and autonomous navigation.

These issues could be solved by adopting an in-pipe inspection robot, such as the prototype developed in Oya and Okada (2005) that is a steerable and wheel-type robot composed of two-wheel frames and an extendable arm which presses the frames against the interior wall of a pipe through a articulated leg mechanism to support the robot. Only one wheel has driven power; one-wheel frame can rotate around the axis of the arm and both of the wheel frames can twist. The ability to twist allows to turn the robot and to avoid obstacles. The height of the robot is adaptable from 140 to 210 mm. A sketch of this robot is reported in Fig. 6(b). The use of articulated/extensible legs will provide the robot to adjust itself to the curvature of the wall, not being affected by humidity or dust, and to fit to the variable interspace. The articulated legs will have wheels to roll over the surface and adjust the height to the space. Additional DoFs (Degrees of Freedom) will be used to

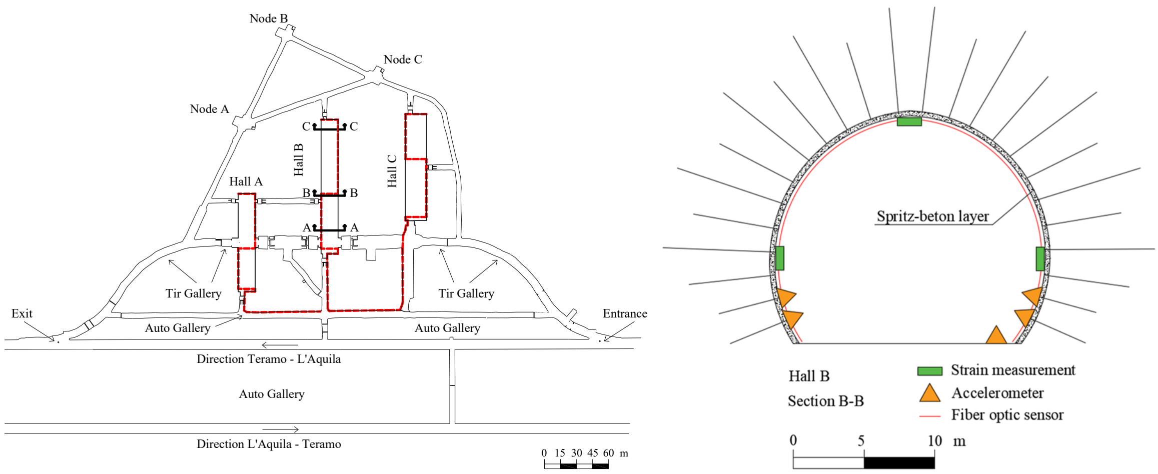


(a) Gecko inspired robot that climbs on the panel (b) In-pipe inspection robot with two-wheel frames and an extendable arm (c) Wall-climbing drone able to fly and to climb

Fig. 6 Sketch of the proposed solutions for the inspection of the rock surface with robots able to move in the interspace between the spritz beton/rock (blue) and the PVC sheet/polyurethane panel (green) circumnavigate or surpass obstacles. Hybrid solutions of mobile robots have been conceived with wheels/tracks and articulated legs for such unstructured environment, as it is described in Ottaviano and Rea (2013), Ottaviano *et al*. (2014) and Rea and Ottaviano (2018).

Another alternative is the wall-climbing drone presented by Romano *et al*. (2019) and based on a multirotor with legs equipped by passive wheels. It can fly like a drone and it can climb on a vertical surface, like a wall-climbing robot (Fig. 6(c)). Then, it results unaffected by the environmental conditions, as well as the wall condition. This drone has four fixed rotors (quadrotor) for flying mode obtained by adding to the initial design two rotors with fixed axes mounted orthogonally with respect to the first four. Additionally, two mechanical limbs with wheels at the end tips are used. The additional two rotors give suitable propulsion to adhere to the vertical wall, the wheels at the leg tips allow to climb with low friction. In addition, it has to point out that when the robot is in contact with the wall (Fig. 5(c)), the generated reaction forces will support a part of the weight, depending by the curvature. On the other hand, the wall-climbing drone described by Romano *et al*. (2019) shows some drawbacks in this case due to its size; the interspace between the rock and the coating panel is less than 20 cm and, therefore, a small drone of the class of Micro Air Vehicles (MAVs) is required. MAVs have length less than 15 cm but their design and development are very hard because they operate in a Reynolds number regime where many complex flow phenomena take place, Pines and Bohorquez (2006). Hence, to make the wall-climbing drone suitable to the confined space between the rock and the panels of LNGS it is needful to face with the issue of scaling the prototype.

The possibility to integrate these robotic systems with some devices able to perform fiber optic installation should be assessed in order to install a monitoring system widespread in all galleries, as shown in Fig. 7(a). The installation of fiber optic sensor on tunnel surface allows to evaluate the deformations of the tunnel and to detect possible anomalous structural behaviors. In this layout have been highlighted the position of the extensometers (Fig. 7(b)) whose collocation has been determined by the evidences of the numerical model (i.e., where the stress and deformations are



(a) Layout in plan for fiber optic sensors

(b) Layout in section for accelerometer, strain and fiber optic sensors

Fig. 7 General layout for a possible structural monitoring system within the LNGS Galleries composed by accelerometer, strain and fiber optic sensors

(a) Load test instrumentation, view 1

(b) Load test instrumentation, view 2

Fig. 8 Non-extraction load tests carried out on the anchorages reachable by human operators: 20-ton hydraulic jacks were connected to the head of the tie rod by means of a supplied sized metal structure to evaluate the existence of an operating load

largest). Moreover, some accelerometers have been introduced at the rock bolts top to measure its structural response due to both environmental noise (sometimes developed by heavy work carried out inside the galleries) or rare events like seismic waves of low intensity (Fig. 7(b)).

Regarding the rock bolts monitoring, as reported in Song *et al*. (2017), it can be performed with different smart sensors which can allow to monitor load, grout quality and defects such as crack, corrosion and delamination. The most used sensors in this field are the piezoelectric and the fiber optic sensors. Among piezoelectric-based NDT methods, the guided ultrasonic waves and accelerometers are more appropriate to monitor rock bolts because of the shape of the bolts, Shi *et al*. (2018). The guided ultrasonic waves are excited in the structure; they are reflected from defects and the arrival time of the reflected waves returns the location of the defects. Moreover, installing a FBG sensor on the anchor plate, it is possible to measure the rock bolts axial load, Ho *et al*. (2017). In this case, the operating load of the anchorages was already verified through non-extraction load tests on the anchorages reachable by human operators, at the base of the vaults under the position of the detail B represented in Fig. 5. On the tie rods n. 10 load tests (max load applied 20 tons) were carried out by using two 20-ton hydraulic jacks connected to the head of the tie rod by means of a metal structure supplied sized (Fig. 8). It is clear that both this kind of load test and the procedures described in Song *et al*. (2017) and Ho *et al*. (2017) are not suitable for the anchorages that are locate above the position of the detail B in Fig. 5, where the interspace between the tunnel surface and the coating panels gets smaller.

4. Conclusions

In this paper, structural safety conditions assessment of the LNGS galleries has been discussed in relation to inspection and monitoring actions. LNGS galleries are large underground tunnels waterproofed and insulated by PVC panels where Nuclear Physics experiments are conducted.

The work has individuated different solutions to perform surveys and measurements in the LNGS underground galleries; in particular, specific issues related to the inspection and monitoring of the vaults of the galleries are presented. The interspace between the spritz-beton/rock layer of the tunnel and the PVC coating panels is inaccessible for human operators (it is large less than 20 cm) and it requires the use of robots to execute visual inspection and sensors installation, evidencing that current automated systems proposed for road tunnel inspection and monitoring are not suitable in this case.

Three robotic systems have been considered for being introduced in this confined space in order to detect cracks and/or other defects on the vault surface (visual inspection). The first one is a gecko inspired robot with adhesive footpads, but the presence of humidity could drastically reduce its adherence ability. For this reason, an in-pipe inspection robot with two-wheel frames and an extendable arm (with an articulated leg mechanism) and a wall-climbing drone are considered more suitable. Moreover, both of them are able to avoid obstacles and this feature is needful because of the presence of the aluminum structure that supports the coating panels. Furthermore, as to the wall-climbing drone, prototype scaling issues have to be considered because normal Unmanned Air Vehicles (UAVs) are too large to enter in the confined interspace between tunnel surface and panels, and a small drone of the class of Micro Air Vehicles (MAVs) is required. Finally, the possibility to integrate these robotic systems with some devices able to install fiber optic sensors, strain and accelerometer sensors is under consideration to obtain a monitoring system of the gallery vaults.

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