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Tunnel convergence monitoring by radar interferometry

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Abstract

The measurement of displacements at the crown and convergence is crucial in tunnelling. In the case of restoration interventions, the need to demolish the existing lining often occurs leading to the requirement of close control and monitoring to guarantee the safety of the workmanship during the operations. During the demolition works contact sensors cannot be easily used as well as targets would need to be continuously removed and replaced. The use of radar interferometry, a completely remote sensing technique that avoids the need to place targets on the monitored scenario, seems to be a good option to overcome the limitations of traditional sensors. This paper will describe the testing of this remote monitoring technique in an existing tunnel in central Italy, detailing the characteristics of the equipment used, the installation process, the monitoring data, and evaluating the results obtained.

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Keywords: Innovation; Tunnel; Monitoring; Convergence.

1. Introduction

Since the 50s, the construction of modern Italian transportation infrastructures such as roads, motorways, and railways has required the excavation of a large number of tunnels to overcome the obstacles generated by a mountainous morphology. Italy is among the countries in the world with the largest number and length of existing

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tunnels. Many of the oldest tunnels are still in operation, but the extensive investigation programme carried out in the last years has revealed defects affecting the concrete lining as the result of ageing and the need for refurbishment (Beyond a tunnel vision, 2021; Agresti et al. 2022; De Feudis et al., 2023). This represents a significant problem for Italy's transportation networks and, as a consequence, a special plan of maintenance and repair works has been launched to guarantee the continuation of tunnel service in safe conditions, functionality, and compliance with updated regulations (Barla et al., 2021). The restoration interventions can encompass a wide variety of approaches mainly based on the severity of the damages identified and the general state of preservation of the tunnel. In many cases, when major rehabilitation works are needed, the complete demolition and the successive reconstruction of the tunnel lining especially along the crown sections, pose important safety issues for the workmanship and the machinery used in the operations. In particular, the sudden collapse of altered concrete blocks during the demolition is difficult to avoid and prevent completely, even by the most experienced operators. Real-time monitoring systems with early warning capabilities can therefore assist the operators during demolition activities by promptly identifying potential unexpected behaviors of the tunnel linings.

Among the different monitoring techniques available nowadays, Ground-Based Radar Interferometry (GB-InSAR) is a highly versatile and efficient tool to detect in real-time the displacements of unstable slopes, glaciers, snowpacks, volcanic edifices (Atzeni et al., 2015, Barla et al., 2010, 2017, Intrieri et al., 2013, Luzi et al., 2007, Schaffhauser et al., 2008) as well as of man-made infrastructures (Huang et al., 2020, Pieraccini et al., 2008). Although radar sensors have been mainly adopted in outdoor environments, in the last years, specific applications have also been tested for tunnelling and underground mining monitoring (Barla & Antolini, 2015).

This paper will present a new underground application of the GB-InSAR technique to monitor the displacement and convergence of an existing tunnel lining subjected to restoration works. After a brief description of the experimental site, the interferometric technique, and the characteristics of the equipment used, a specific chapter will be devoted to the illustration and the discussion of the results obtained so far as well as to the discussion of the potential use of the technique as an early warning tool in an operational environment. Finally, some concluding remarks and the potential future developments of the application will be given.

2. Materials and methods

2.1. Description of the experimental site and objectives of the test

The experimental monitoring activities with the GB-InSAR were carried out inside one tube of a double-tube motorway artificial tunnel located in central Italy. The tunnel was built at the beginning of the '60s and is nowadays characterized by a total length of about 230 m since two further extensions of 70-83 m, respectively at both tunnel entrances, were added later. The tunnel has a maximum depth of about 8 m from the surface and its construction phases involved at first the excavation of a trench followed by the construction of the tunnel's crown, side walls, and the invert.

After more than 60 years of service, the central and older portion of the tunnel's lining was found to be affected by a large number of defects. These included a widespread surface alteration of the concrete and structural joints and a more localized deeper deterioration of the linings, i.e., longitudinal open and persistent cracks running along the tunnel's crown. These latter are particularly dangerous since they can promote the potential formation of unstable blocks. In both cases water infiltration and leakages from the linings were common.

To solve the issues posed by the tunnel's deterioration state, a rehabilitation intervention was designed and realized. This consisted of the demolition and the reconstruction of the more altered concrete lining layers as well as the stitching and sealing of the main cracks along with the installation of suspended steel ribs secured to the concrete lining through chemical anchors. In general, the demolition of an existing tunnel's lining as well as the other aforementioned activities implies the generation of vibrations and a temporary redistribution of the initial state of stress inside the structural elements.

Therefore, any potential undesired effects on the surrounding structures in terms of variation of displacement and deformations needed to be promptly identified.

The above construction site was then considered an opportunity to test the effectiveness of the GB-InSAR technique to monitor the displacement and convergence of the existing tunnel lining. Before the starting of the demolition operations, the monitoring system was installed in the tunnel and activated to test its feasibility as a monitoring and early warning tool in an underground scenario where variations over time in the electromagnetic characteristics of the objects illuminated by the radio signal are continuously caused by the movements of vehicles and equipment in front of the structure to be monitored.

2.2. The radar interferometry technique

The Ground-Based Interferometric Synthetic Aperture Radar (GB-InSAR) is an active radar-based remote sensing system, designed in general terms to monitor the displacements of objects (Rudolf et al. 1999). By using the SAR technique (Curlander & McDonough, 1991) which combines multiple coherent range images of the scenario taken from slightly different positions, the radar systems become able not only to measure the sensor-to-target distances but also to map the monitored scenario in two dimensions. The SAR images are hence two-dimensional complex images where each pixel contains two main information i.e., the amplitude and the phase components of the radar signal. The radiometric amplitude is directly related to the power of the back-scattered signal from all the objects contained in each resolution cell (represented as a pixel in the SAR image) while the phase of each pixel is related to the sensor-target distances and it can be exploited to obtain the accurate position of each target. By using at least two GB-InSAR images of the same object acquired at different times, it is possible to exploit the phase difference to retrieve the variation of the sensor-target distances of each homologous pixel, using the equation (1):

$$\Delta\phi_{10} = \phi_1 - \phi_0 = \frac{4\pi\,(A'B' - AB)}{\lambda} \quad (1)$$

This relation shows that the interferometric phase ϕ of every pixel of the radar image depends on the wavelength of the radar signal (λ) and is directly related to the difference paths of the sensor-to-target distances AB and A'B', e.g., the displacement that occurred between the first observation at time t_0 and the second observation at time t_1 as shown in Fig. 1. The monitoring of the displacement is limited to one dimension, i.e., the Line Of Sight (LOS) of the sensor. Only the projected component of the real displacement vectors along the LOS can be monitored.

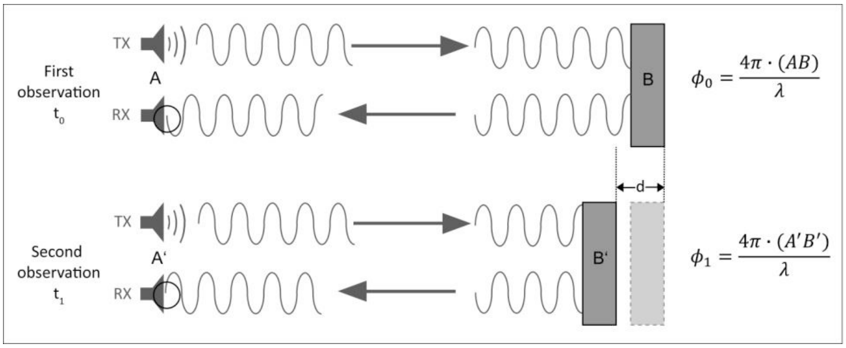

Fig. 1. Relation between the phase difference and the displacement of an object during two consecutive GB-InSAR observations.

Since the accuracy of the displacement measure depends on the target reflectivity, to obtain reliable results the different objects in the scenario must reflect a large amount of the radar signal received. In general, soils, rocks, and all concrete and metallic structures possess favourable radiometric characteristics which allow for a good accuracy in the displacement measure. Moreover, passing objects in front of the radar sensor for a short period does not influence the image acquisition due to the sampling being done in the frequency domain.

Concerning the underground applications of the GB-InSAR technique, most of the surfaces are in principle capable of backscattering the radar signal. In such cases, particular care should be taken to select an adequate radar emission power and an adequate geometry to limit all the potential unwanted reflections that can be generated from objects outside of the monitored scenario.

2.3. Characteristics of the equipment, installation, and data processing

The equipment used for the experimental activities was a specifically designed ground-based radar called HYDRA-U optimized for use in underground applications. The instrument is composed of a radar head equipped with two antennas (one for signal transmission and one for receiving) mounted on a pan/tilt unit capable of rotating the radar unit thus realizing the synthetic aperture. The motion of the radar antenna over a circular trajectory provides finer angular resolution than conventional beam-scanning radars. The circular trajectory used for obtaining the synthetic aperture (often denoted as ArcSAR) permits a more compact design of the radar and a wider-angle coverage compared to the traditional linear SAR. An IR camera and a laser scanner are also coupled with the radar sensor. The instrument is completed by a power supply and control unit. The system was installed along one sidewall of the tunnel using a metallic shelf as shown in Fig. 2a. By tilting the radar head 25° from the horizontal and by using a synthetic aperture equal to 120° it was possible to monitor the tunnel crown and one sidewall up to a distance of about 22 m from the radar installation point (Fig. 2b). The accuracy of the displacement measurement along the LOS depends on the wavelength of the radar signal and is equal to ±0.1 mm.

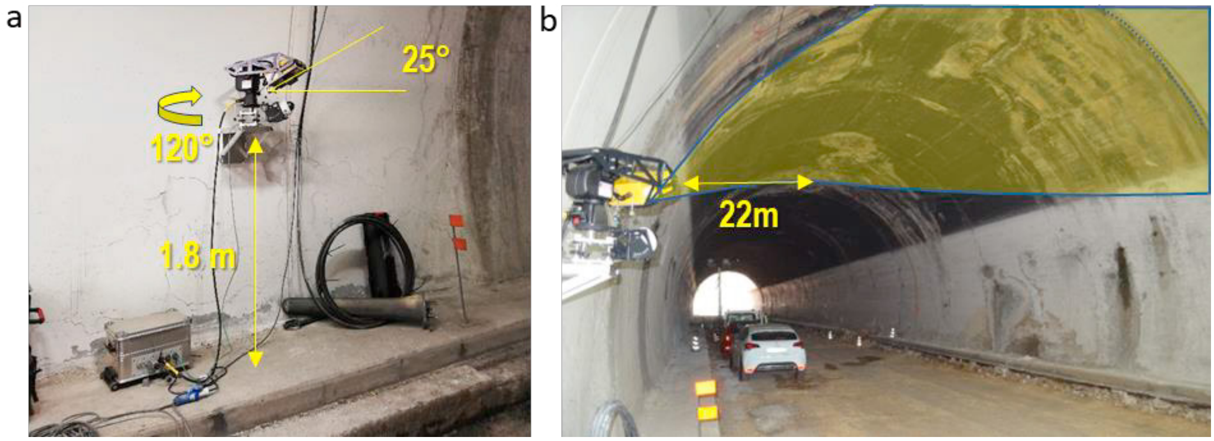

Fig. 2. (a) View of the Hydra-U installation point and (b) view of the monitored tunnel sector.

After the installation, the system was remotely controlled and operated for a whole month, acquiring images of the monitored scenario every 30 s. The acquisition process was managed by a controller software (Controller SW), which creates raw datasets that will then be post-processed by Guardian SW. Guardian SW allows for a real-time 3D interactive pointwise or areal visualization of the results and can provide the users with SMS/email alarms if specific thresholds are exceeded.

3. Results obtained and discussion

The result of the radar data processing can be represented through LOS displacement and velocity maps of the monitored scenario, i.e., the tunnel crown and sidewalls. Every pixel of these maps, characterized by a maximum spatial resolution of 0.2 m x 0.2 m, stores the variation of the measured LOS displacement and velocity over time. The analysis of the displacement time series can therefore be related to the potential deformation and convergences of the tunnel lining that occurred during the monitored period.

3.1. Analysis of the displacement maps and the time series

Fig. 3 shows the LOS displacement map superimposed over the 3D point cloud of the tunnel obtained from the laser scanner coupled with the radar sensor. Using the installation geometry previously described, a spatially continuous map of the tunnel crown and the upper portion of the sidewalls was obtained. The different colors of each pixel represent the cumulated LOS displacement measured during the period (15 days) after the completion of the stitching and sealing of the main cracks and the installation of suspended steel ribs in the monitored tunnel section. Negative displacement corresponds to a reduction of the sensor-to-target distance and corresponds to an increase in the tunnel convergence, i.e., a reduction of the diameter or a specific chord of the tunnel. The analysis of the map indicates that the LOS displacement of each pixel in the monitoring period analyzed was maintained in the range of ±1.5 mm.

In addition to the pixel-by-pixel analysis, to better analyze the displacement patterns retrieved from the monitoring, the tunnel's crown and sidewalls were subdivided into 13 different areas corresponding to specific tunnel sectors. It is worth noting that area #2 was not directly affected by the restoration works since it is enclosed in the recent tunnel extension. For all 13 areas, it was then possible to obtain a specific time series by averaging all the pixels that are included as shown in Fig.4. The time series of the LOS displacement show a direct correlation between the increases in the displacement of some areas, i.e., the onset of the acceleration, and the working phases in the tunnel as highlighted by the pink polygons in Fig. 4. This is particularly evident in areas 3, 7 11 (located at a distance of about 7-8 m from the radar system), and 9 (located at a distance of about 20 m from the radar) where the stitching and sealing of the main cracks and the installation of suspended steel ribs were completed. As can be seen from the camera pictures included in Fig. 4, different kinds of equipment as telescopic handlers and aerial platforms were used to access the tunnel crown and the upper portions of the sidewalls. The machinery remains in the radar field of view for different hours causing some of the spikes which can be seen in the time series. The areas not directly involved in the work (for instance areas 1 and 2) did not show any particular acceleration phase, and the final LOS displacement remained in the range ±0.2 mm, i.e., very close to the accuracy of the system.

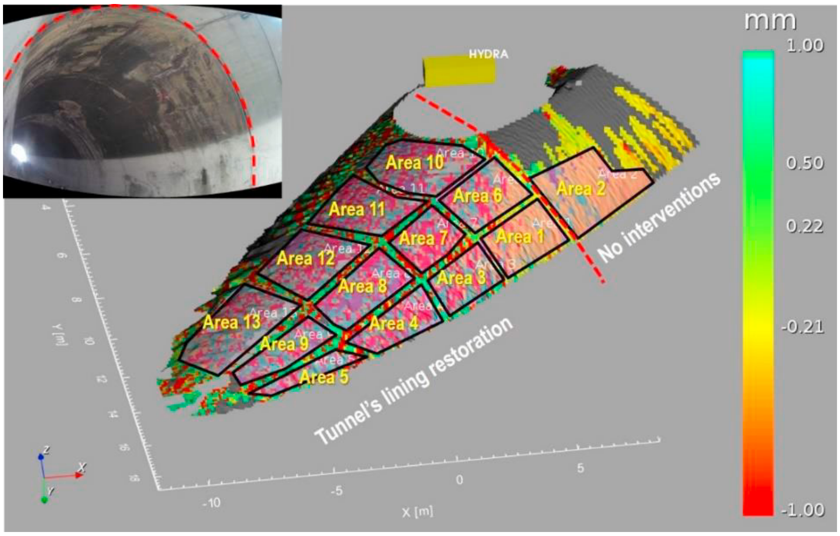

Fig. 3. LOS displacement map of the tunnel's lining projected over a 3D point cloud obtained after a monitoring period of 15 days.

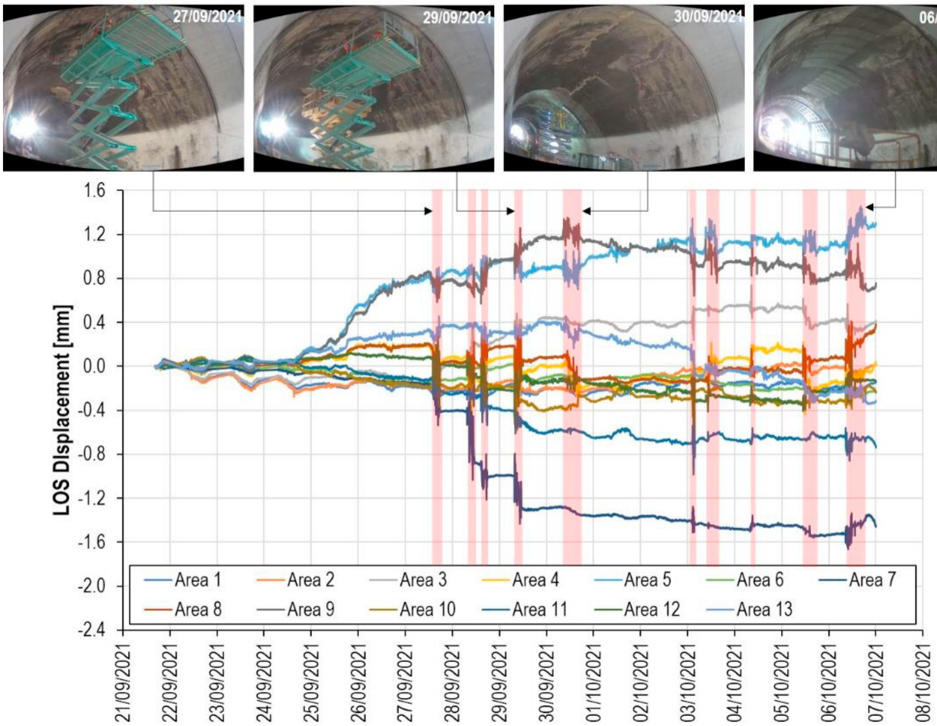

Fig. 4. LOS displacement time series of the 13 different areas of Fig. 3 (15 days) related to the main work phases carried inside the tunnel (pink polygons). Above the graph, some pictures taken by the camera during the work are shown.

It should be noted that the continuous presence of machinery and heavy equipment in the monitored scenario during the main working phases always determines a noise increase in the radar images and therefore in the time series as shown in Fig.4. This effect is caused by the high signal backscattering from the metallic surfaces of the objects that are in the radar field of view. On the contrary, objects passing in front of the radar sensor for a short period do not influence the radar measurements. Therefore, some of the spikes shown in the time series are related to the aforementioned disturbances which could determine a slight overestimation of the LOS displacement.

3.2. Operational monitoring and early warning system

From an operational point of view, when the demolition and the reconstruction of the tunnel lining are necessary, these works generally proceed from one tunnel entry to the other and they are organized to affect only one portion of the tunnel lining at a time (i.e., 10-15m). Therefore, to follow all the working phases, the radar sensor needs to be moved and reinstalled along one of the tunnel sidewalls using a quick installation kit like the one shown in this paper. Despite the range limitation to 20-25 m, the results obtained from the test described have indicated sufficient coverage of the most critical tunnel portion i.e., the tunnel's crown and the upper portion of the sidewalls through the use of a single sensor.

The tested GB-InSAR system is already engineered to allow its use for EWS purposes as shown in Fig. 5: the survey unit installed in the tunnel is operated by an industrial PC coupled with a router. Even though the system is equipped with batteries, power supply is required. The system can be managed remotely both by local users through a specific Wi-Fi connection and by remote users through the Internet. The specific software running on the PC manages and controls the radar system and processes in real-time all the acquired data to obtain displacement and velocity maps of the monitored scenario. User-defined displacement or velocity thresholds can be selected to activate the alarm notification system: whenever these thresholds are exceeded email and SMS can be sent to specific recipients and an alarm coupled with a flashing light installed in the work site can be activated. Using this configuration is then possible to warn the workmanship when anomalous trends caused by sudden lining deformations are detected. To minimize the potential disturbances of the machinery and the equipment in the SAR images and the consequent overestimation of the LOS displacement, the cumulative displacement or the average velocity of selected points or specific areas over short time intervals (6-24h) can be used despite the limitation in reconstructing the complete displacement/velocity time series on the monitored scenario.

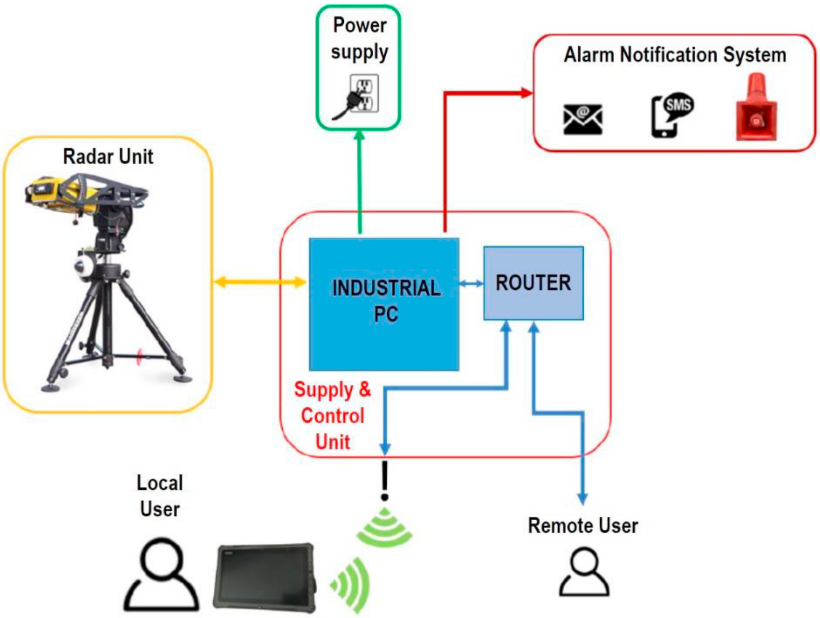

Fig. 5. Schematic outline of an EWS based on GB-InSAR monitoring to be applied to major tunnel rehabilitation works.

4. Conclusions and future development

The results obtained from the test carried out have demonstrated that the GB-InSAR technique can be satisfactorily adopted to monitor displacements in a motorway tunnel subjected to restoration works, where different equipment and machinery are present. The disturbances induced in the SAR images by such equipment are limited and therefore it was possible to monitor continuously and in real-time the displacement and convergences of different portions of the tunnel lining.

Despite the intrinsic limitation of the radar technique i.e., the possibility of measuring the displacements limited only along the LOS, the early warning capabilities of the system can assist the operators during the interventions by promptly identifying potential unexpected deformation and convergences of the tunnel linings especially along the tunnels crown and the upper portion of the sidewalls. The adoption of the GB-InSAR monitoring using specifically designed sensors can therefore mitigate the risk for the workmanship and the equipment involved in these operations.

Further development of the technique to extend the application to tunnel maintenance and repair works may concern the improvement of the wall mounting kit to reduce its overall dimensions and to facilitate the radar repositioning as well as the adoption of dynamic filtering on SAR images able to discard in real time the areas in the monitored scenario that are affected by disturbances caused by the presence of equipment and machinery.

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