Systematic Use of Transport Infrastructure Non-Destructive Assessment and Remote Sensing

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ABSTRACT: For decades, remote sensing technologies and the non-destructive testing (NDT) methods have been used for the assessment of transport infrastructure, highways, railways and airfields. The existence of provisions of multi-source, multi-scale and multi-temporal based information on infrastructure conditions on one hand and the developments of hardware and software technologies in the other, have provided opportunities for the growth of the applications of NDT techniques. The outcome lends itself to be incorporated into existing infrastructure management models. This paper presents an overview of the latest developments in ground-based (Ground Penetrating Radar (GPR) and interferometric radar systems) and satellite (space-borne Synthetic Aperture Radar (SAR) interferometry) remote sensing that applied to transport infrastructures. The applications of GPR to pavements, e.g. multi-layered pavement structure and asphalt concrete (AC) density, and rail-tracks, e.g. ballast assessment are discussed. In addition, the applicability of ground-based radar interferometry and SAR for the bridge structural health monitoring and horizontal transport infrastructure is presented. A novel integrated approach is introduced to form the base of a novel intelligent transport infrastructure management system. The approach is aimed utilizing the structure condition assessment-based information collected using SAR and NDT techniques to prioritize maintenance/rehabilitation activities of transportation assets. For example, analyses of multi-temporal SAR data are used to identify areas of concern at the network level (e.g. differential settlements at bridge approaches or rail track-beds, and excessive deformation rate of pavement surface). The identified locations would be further assessed using ground-based techniques to collect more accurate data. This approach would provide an effective, efficient, and sustainable state of good repair over the life cycle of the transportation infrastructure system.

KEY WORDS: Non-destructive assessment; remote sensing technologies; interferometric synthetic aperture radar (InSAR); intelligent infrastructure management systems.

1. INTRODUCTION

Non-destructive testing (NDT) methods have been widely used for the assessment of transport infrastructure in the last decades. Several indirect non-invasive technologies have been successfully applied ad proved to enhance effectiveness and productivity of monitoring transportation infrastructural asset. This includes applications to superstructure (Joshaghani, 2019, Plati et al. 2020), subgrade (Nabizadeh et al. 2019, Xu et al. 2013) and concrete elements

(Capozzoli and Rizzo 2017, Tosti and Ferrante 2020), highways (Plati and Loizos 2012, Goktepe et al. 2006), railways (Artagan et al. 2020, Al-Qadi et al. 2016) and airfields (McQueen et al. 2001, Gopalakrishnan and Thompson, 2007).

The advancements of hardware and software technologies have generated new opportunities for the growth of the NDT techniques applications to transportation infrastructure; allowing collection of multi-source, multi-scale and multi-temporal based information on its condition. Such information can be readily available for incorporation into existing transportation infrastructure management models (AASHTO 2019, Nasimifar et al. 2019, Tosti et al. 2018, FAA 2016). To further advance current continuous and rapid measurements and enhance measurement resolution, new NDT technologies have been introduced (Artagan et al. 2020, Nasimifar et al. 2019).

Ground penetrating radar (GPR) technique has proven versatile for pavement application due to its relatively surveying flexibility, rapidity of data collection, and accuracy (Ciampoli et al. 2019, Al-Qadi and Lahouar 2005). Hence, GPR could be integrated with a deflection-based non-destructive testing (e.g., Falling Weight Deflectometer (FWD)) for the evaluation of layer structural capacity (Elbagalati et al. 2017, Crook et al. 2012). The calculated layer thicknesses from GPR measurements are used in the backcalculation of FWD data analysis to predict layer moduli. This would affect the remaining pavement service life prediction (Tosti et al. 2018, Elbagalati et al. 2017). GPR has been also successfully used in asphalt concrete (AC) pavement density estimation and part of the paving quality control (QC) and quality assurance (QA). An accurate density measurement during compaction allows for a near real-time correction to better control the compaction process (Plati et al. 2020, Zhao and Al-Qadi 2019, Killingsworth 2004).

The proper non-destructive evaluation (NDE) application mainly relies on existing inventory data and the provision of routine inspection carried out at the network level of the transportation infrastructure asset, considering a prioritization criterion. The outcome of the NDE network monitoring allows producing a dynamic priority list of critical sections that require action utilizing an optimization approach. However, such management models may be hindered by NDT resources and expertise required and available to inspect the asset network periodically, which is crucial to optimize maintenance/rehabilitation strategies.

To overcome the above limitations, remote sensing could be utilized. Remote sensing is defined as the measurement or the acquisition of information on specific properties of a target by a recording device, which is not in physical contact with the object itself (Colwell 1997). These techniques can be passive (e.g., infrared thermography) or active (e.g., RADAR, LiDAR), depending on the source of the received energy. Amongst the active remote sensing tools, satellite Synthetic Aperture Radar (SAR) can benefit from the forward motion of the orbiting satellite, resulting in an equivalent 'synthesized' large aperture to obtain adequate measurement resolution from high altitudes (Hoppe et al. 2016).

A dense array of information could be collected on the overall structural stability of the asset and the surrounding environment, using multi-scale and multi-temporal SAR images. The coverage of every image collected by SAR sensors, allows the evaluation of large infrastructures at the network level in a single data processing flow. Hence, interferometric approaches based on the comparison between multiple SAR images have proven effective in assessing transport infrastructure conditions (Tosti et al. 2021). However, individual outcome may be inevitably incomplete under different perspectives. To achieve a faster and accurate information on the transportation infrastructure asset, the integration between multi-source, multi-scale and multi-temporal datasets allows to fill individual technology gaps. Despite of the high potential for the application of this technology to transport infrastructures (Bianchini Ciampoli et al. 2020, Monserrat et al. 2014), the use of remote sensing techniques is still not implemented as a routine inspection method.

This paper presents an overview of the latest developments in GPR and interferometric radar systems, and satellite (space-borne SAR interferometry) remote sensing that applied to transport infrastructure. Successful applications of GPR are presented for pavements and rail-tracks, including the evaluation of multi-layered pavement structure, AC density, and railway ballast assessment. In addition, the paper discusses the applicability of ground-based radar interferometry and SAR for bridge structural health monitoring and horizontal transport infrastructure, respectively.

2. EMERGING TRANSPORT INFRASTRUCTURE NON-DESTRUCTIVE ASSESSMENT AND REMOTE SENSING

Major damage in transport infrastructure could occur due to reduced load bearing of pavement layers. Hence, laboratory and on-site assessment of the structural layer bearing capacity can be performed by measuring pavement progressive deformation due to applied loading (ASTM 2009a,b). Although electromagnetic properties of the material may not be related to its strength characteristics, various NDT methods may be used to indirectly relate material properties to potential damage (e.g., relating the change in the dielectric properties of a pavement layer to its potential distress). The term dielectric in the study refers to relative dielectric constant or relative permittivity.

2.1. Ground-based NDTs

Amongst the available non-destructive NDT methods, GPR has been extensively used for the assessment and health monitoring of transport infrastructure. The GPR technology relies on the transmission of electromagnetic (EM) waves through a target/medium. In case an inhomogeneity is encountered, the energy radiated by a transmitting antenna is partly reflected to the receiver and partly transmitted through the medium. However, as its propagation (amplitude, velocity, attenuation) is ruled by the dielectric properties of the illuminated medium (Jol 2009). The change in the dielectric constant due to subsurface conditions is returned in the form of EM reflection. Post-processing algorithms are usually applied to predict the dielectric constant of the medium and then to calculate the medium dimensions (2 dimensions unless 3D GPR is used).

Research on GPR has resulted in new emerging trends, including the following:

- *High-accurate AC pavement density assessment*. AC pavement density estimation from GPR measurements is based on predicting the dielectric properties of the AC material, which is obtained by applying Fresnel's law. Based on the mixing theory, the Al-Qadi, Lahouar and Leng (ALL) model (Leng et al. 2012, Leng et al. 2011) relates the AC mixture component dielectrics to the bulk density of the AC. In addition, the effect of signal noise and surface moisture are accounted for in the pre-processing of the GPR signals to ensure the model accuracy in AC prediction (Wang et al. 2020, Wang et al. 2019).
- *Railway ballast health assessment.* Railway ballast is referred to as a homogeneously graded hard-rock-derived material providing adequate support to the loads passing onto the rails and proper drainage capacity (Selig and Waters 1994). During the infrastructure life cycle, this material is likely to be polluted by different sources of ballast fouling. Fragmentation of aggregates under cyclic loading and the uprising of fine particles from the subgrade have been reported amongst the main causes that can trigger severe deformations to railways, undermining safety and operability of the infrastructure (Solomon 2001). In the last decades, GPR has been increasingly used as a fast and reliable tool for the assessment of critical railway ballast conditions (Artagan et al. 2020). It is also observed that the

research focus in this area has been progressively moved from time-domain analyses (e.g., layering and reconstruction of structural elements (Benedetto et al. 2017a, Sussmann et al. 2003, Gallagher et al. 1999)) to frequency and time-frequency analyses of the GPR signal (e.g., the evaluation of changes in the as-built ballast aggregates' arrangement) (Al-Qadi et al. 2010, Al-Qadi et al. 2008a). In this context, the spectral analyses of clay-related fouling and grading changes caused by aggregates friction are worthy of mention (Benedetto et al. 2017b, Bianchini Ciampoli et al. 2017, Al-Qadi et al. 2008a). In addition, time-frequency analyses and wavelet approaches have proven successful at relating signal scattering effects to ballast voids at different rates of fouling (Bianchini Ciampoli et al. 2020, Al-Qadi et al. 2016, Shangguan and Al-Qadi 2014, Shangguan et al. 2012, Al-Qadi et al. 2008b).

- *Health monitoring of masonry arch bridges*. Arch bridge structures are very common and historical types of asset vital to the economy, mobility and development of communities. No doubt an effective assessment and routine monitoring of bridge structures are nowadays crucial for maintenance, regardless of their historical value and mobility function. Health of bridges can be assessed using several monitoring methods and sensors (Zhou and Yi 2013, Moschas and Stiros 2011), including GPR (Solla et al. 2012, Lubowiecka et al. 2009). Due to the structural complexity of the target, stand-alone GPR applications on masonry bridges has been mostly employed for initial mapping and subsurface target locations, as opposed to a more comprehensive structural health monitoring (Saarenketo 2009). However, promising research has been recently published with a focus on the integration between GPR and other NDT method for comprehensive assessment and health monitoring (Alani et al. 2020, Biscarini et al. 2020, Solla et al. 2011).

The ground-based synthetic aperture interferometry (GB-SAR) is another emerging technology in transport infrastructure monitoring. The GB-SAR is a radar-based terrestrial remote sensing imaging system (Tarchi et al. 1997) based on a radar sensor that emits and receives a field of microwaves while moving along a rail track (Bernardini et al. 2007). The imaging capability is achieved by exploiting the SAR technique (Lin et al. 1992). The GB-SAR technique is acknowledged as a reliable tool for landslide and slope monitoring (Pipia et al. 2013), although it has proven effective for structural monitoring applications (Tapete et al. 2013). This is due to the possibility to acquire both temporal and spatial samplings as well as to a high sensitivity of this technique in detecting small displacements. In this context, the joint application of the GB-SAR and other NDT techniques can be regarded as a future prospective approach to collect information for inclusion in infrastructure management systems.

2.2. Satellite Remote Sensing

Various processing techniques have been proposed for displacement mapping from SAR imaging and, amongst these, the Permanent Scatterers InSAR (PSI) method (Ferretti et al. 2000, Ferretti et al. 2001) is one of the most acknowledged. This technique is based on a statistical analysis of the signals back-scattered from a network of phase-coherent targets, named as Permanent Scatterers (PSs). These are defined as points on the ground returning stable signals back to the satellite receiver.

In the last decade, the PSI technique has proven effective in land monitoring applications, such as landslide surveillance (Squarzoni et al. 2020, Frattini et al. 2013), pre- and post-seismic evaluations (Duan et al. 2020) and urban subsidence detection (Khorrami et al. 2020). Regarding the monitoring of transport infrastructures, recent research on emerging applications of the PSI technique is summarized below:

- *Pavement distress assessment.* Linear infrastructures in rural environment contexts are among the most reflective target in terms of SAR transmissions, triggering the generation of a high number of PSs in a PSI analysis. This implies a good potential of the PSI technique in the monitoring of major pavement distresses (e.g., rutting, deformations and settlements) in both highways (Ozden et al. 2017) and airport runways (Gagliardi et al. 2021, Marshall et al. 2018).
- *Railway track subsidence monitoring.* Similar to roads, railways are excellent scatterers for InSAR analyses. Millimetre-scale displacements can be monitored and accurately located across rail track sections using high-resolution (X-band) satellite data (Bianchini Ciampoli et al. 2020, Tosti et al. 2020), including differential displacements at the rail-abutment sections in railway bridges (D'Amico et al. 2020).
- *Bridge monitoring*. It is known that vertical and horizontal displacements at the piers of bridges may seriously compromise their structural stability. This occurrence is generally related to geodynamic (e.g., the sliding of the slope) or geotechnical aspects (e.g., oedometric subsidence of the piles). The SAR-based processing technique was successful applied for the evaluation of three major bridge features. The linear deformation trend, the height of the structure over terrain, and the thermal expansion were proven to create variations in the SAR phase (D'Amico et al. 2020, Lazecky et al. 2017, Zhao et al. 2017).
- *Assessment of tunnelling-induced subsidence*. In general, formation of vertical settlements is first observed at the tunnel construction stage, followed by an increased instability of the concerning area compared to the surrounding, once the structure is built. An accurate assessment of these two major stages is crucial for predicting any potential future subsidence expected on nearby buildings and infrastructures. Multi-temporal SAR analyses have allowed to monitor the entire construction process, and verify the future stability to ground settlements of the investigated area (Milillo et al. 2018, Perissin et al. 2012).

3. THE INTEGRATED APPROACH

Based on the potential integration of remote sensing technologies and NDT methods, an intelligent transport infrastructure management system is introduced (Figure 1). The proposed approach is developed based on the provision of inventory data, identified network elements, and as-built information. It is characterized by two concurrent routine monitoring stages at low- and high-frequency monitoring rates applied at local and network levels, respectively.

Remote sensing technologies can be used to assess the entire infrastructure network in terms of ongoing geotechnical/geodynamic processes, with a high time resolution (~10 days) permitted by the scale of analysis. In case critical spots are identified, targeted inspections can be carried out with dedicated NDT techniques to build a more comprehensive information system on the type and scale of the developing distress at the identified infrastructure sections. The information obtained at this stage and processes in distress prediction models, could assist in the maintenance/rehabilitation requirement and priority decision.

Parallel to remote sensing, ground-based NDTs would be applied to the network, but at a lower frequency rate. The testing frequency is controlled by cost, productivity, and resource availability. The main scope of this stage is to assess any potential distress in terms of severity level and extent, causes, and effects, which may not be detected by satellite remote sensing.

The outcome is a scale of priority of the maintenance and rehabilitation (M&R) activities for individual assets of the network. In case the need for an intervention is ascertained, the provision of M&R alternatives is assessed based on the compliance to safety requirements and economic constraints.

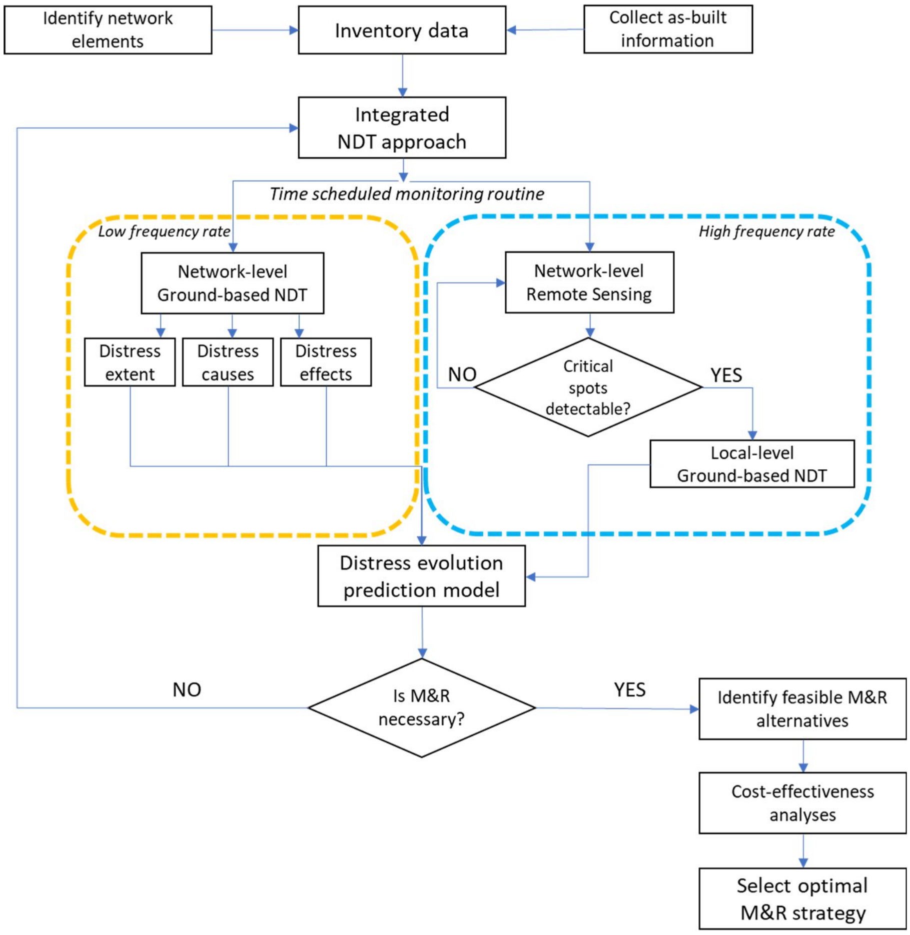

Figure 1: Proposed intelligent transport infrastructure management system

For each of the alternatives, a cost-benefit analysis is performed, leading to the selection of the optimal strategy of M&R intervention. This approach is updated periodically to continuously upgrade the prioritization list that can be dynamically used to allocate funding.

4. CONCLUSIONS

This paper presents an overview of the emerging developments in ground-based non-destructive testing (NDT) and remote sensing technologies that applied to transport infrastructure. Ground penetrating radar (GPR) and ground-based synthetic aperture radar (GB-SAR) interferometry are presented. In addition, applications of the space-borne SAR interferometry (InSAR) for infrastructure network surveillance are discussed. The use of multi-source, multi-scale and multi-temporal information is required to achieving a comprehensive knowledge of distresses and build more reliable prediction models.

An integrated approach for transport network surveillance is proposed for application to transportation infrastructure. The approach considers inventory data as input, identifies network elements and as-built information. Surveys with remote sensing technologies and NDT techniques are envisaged to be carried out at different scales and times to monitor the genesis and the evolution of the damage progression. Based on the relevant outcome, distress evolution prediction models could be developed – compared to traditional infrastructure management systems (e.g., Pavement Management Systems (PMSs)) – to define a priority scale of intervention that can be updated with a higher temporal frequency. This allows proposing alternative M&R approaches and compares then using cost-benefit analyses for optimal intervention strategy.

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