Latest trends for condition assessment using non-destructive techniques

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Abstract

Bridges are one of the most vulnerable assets within the transportation network. Ageing processes in combination with changing loading conditions make these assets especially vulnerable to structural damage and material degradation. To ensure the optimal operation, appropriate maintenance practices are required, and new techniques and methods facilitating a more accurate diagnostic and safety assessment are being demanded.

IM-SAFE project aims to fill the gaps in the existing European standards regarding monitoring, maintenance, and safety of transport infrastructure. This paper gathers information about surveying technologies with a focus on optical and radar remote sensing technologies. The final purpose of this article is to support the use of these technologies in the management of bridges and tunnels, and demonstrate the value of their information for the safety assessment of in-service structures.

Keywords: Non-destructive testing, remote sensing, satellite, UAV, LiDAR, GPR, condition assessment.

1 Introduction

In recent years, the modern society has faced a rapid growth of testing, inspection, and monitoring technologies in various sectors. In the domain of transport infrastructure, intensive research has been carried out to enable the use of non-destructive data collection technologies to support asset management of bridges and tunnels.

These technologies allow realise condition survey and are therefore referred to as surveying technologies. Condition survey is the process of acquiring data and transforming it into information about the current condition of the structure with regard to its appearance, functionality and/or ability to meet the specified performance requirements [1].

The aim of condition survey is to recognise important limitations, defects, deterioration of the structures and the needed measures accordingly. During condition survey, data may be obtained by activities such as inspection, monitoring and testing through a wide range of data collection technologies.

However, accepted and harmonised approaches to condition survey are lacking to this day. This hinders asset owners and public authorities in charge of maintenance of the transport infrastructure to apply the latest developments.

This paper aims to respond to this challenge by reviewing data collection technologies used for condition survey and identifying their requirements, focusing on those technologies applicable to bridges and tunnels. The document is divided in 6 sections, being the present one which introduces the problem statement. In Section 2, a review of some non-destructive data collection technologies is made. And then, in Section 3 a discussion about the technologies analysed is made. To finalise the article, the conclusions are presented (Section 4), followed by the acknowledgements (Section 5) and the references integrated the text (Section 6).

2 Surveying technologies

The main objective of performing monitoring activities is to gather enough, valuable, and reliable information to be analysed in a posterior phase. In this analysis, possible damages affecting an asset can be detected. The surveys can be done by using non-destructive data collection technologies, destructive techniques, or semi-destructive techniques. This document is focused also on reviewing some of the most important non-destructive ones, more specifically remote sensing, ground penetrating radar (GPR) and accelerometers.

The variety of existing monitoring technologies can be defined attending to certain characteristics, which are described in this section. The definition and important aspects of each technology are also addressed.

2.1 Remote sensing technologies

Remote sensing is the term that encompasses the collection of information about the object to be measured without making physical contact with it.

2.1.1 Satellite technology

The main objective of satellite technology is to monitor the earth's surface for observation and mapping. In the infrastructure field, it is used to monitor the infrastructure network.

There are two different types of satellite, depending on the signal source used: (i) active, since they generate their own radiation and receive it bounced; and (ii) passive, which receive radiation emitted or reflected by the earth. For the latter, it depends a lot on the natural energy (solar rays) that bounces off the target.

Functioning mode

In order to capture the data, satellites employ different whit electromagnetic waves, such as: photographic ultraviolet, visible, photographic, reflective region, emissive region, reflective infrared, optical region, and microwave [2]. From the observation of the electromagnetic spectrum, certain regions might be used for different systems. Then, according to the type of energy that the systems capture, the sensors can be photographic, optical or microwave sensors.

Types

Photographic systems are those that capture images with cameras using photographic emulsions with a long-wave sensitivity (0.3-0.9 µm, UV to IR). Optical systems are the sensors that work to capture images with long waves (0.3-15 µm). Both systems capture the electromagnetic energy reflected or emitted by the ground, and the spectral response is recorded in the image. Conversely, in microwave systems (0.8 µm to 100 cm) the image is the result of the beams of waves that rebound in the terrain, called backscatter [2].

Process to be detected or monitored

Monitoring of infrastructure using satellites can be performed by measuring the land subsidence from space. The main barrier of this technology would be that it is not always possible to detect land movements in an area before the bridge or tunnel collapses or gets seriously damaged. More information about this application can be found in [3,4].

Physical quantity to be measured

The resolution of satellites limits the monitoring of infrastructure for condition assessment, being impossible to detect structural problems in detail. What satellite technology can detect and monitor are changes over time, either movement (e.g., mm/year) with radar satellites, or visual changes of a maximum of 50 cm with optical satellites.

Induced damage to the structure

As the images are taken remotely, this type of technique does not cause any damage during measurement.

General points of attention and requirements

To obtain data with an appropriate quality from satellite, it is necessary to plan the survey beforehand. The steps that must be followed can be summarised as: (i) preliminary study of the environment in which the infrastructure is placed; (ii) choice of the type of satellite image appropriate for the case study; (iii) study of the number of images required for analysis; (iv) consideration of the climatic conditions and discard images with poor quality; and (v) choice of the download platform and programs to deal with the data.

2.1.2 Unmanned Aerial Vehicles

An unmanned aircraft vehicle (UAV) is defined as a powered aerial vehicle that does not carry a human operator, making use of aerodynamic forces to fly and being piloted remotely or by means of an autonomous control [5].

In order to measure and monitor the environment, these vehicles carry optical imaging sensors, LiDAR systems, synthetic aperture radar (SAR) and NDT payloads. The measurements can be georeferenced by the navigation system and the sensors of the vehicle, generally based on global navigation satellite systems (GNSS) and inertial measurement units (IMU). The main contribution of UAVs consists of their capability to fly in difficult and inaccessible areas, lowering the risks for crews of manned aircraft.

In the last years, these systems have enabled for the so-called Aerial Robotics, that can obtain measurement and perform inspection tasks in bridges.

Functioning mode

UAVs behaviour mainly depends on system properties and, in general, their functioning mode heavily depends on their subsystems, that briefly consist of:

Frame: Main structural element of UAVs. It is the support for the rest of components. The frame should obey a trade-off between a smooth geometry with little aerodynamic resistance to fly and the need for actuating and hovering in the air.

Motors and batteries: The strong adoption of rotary-wing UAVs is partly caused by the performance and popularization of brushless motors. For heavy UAVs, there is a need to use combustion motors powered by solid combustible that can carry the payload and are more complex to use and maintain.

Propellers: The propellers convert the rotational motion of the motors into thrust following the Bernoulli's principle.

Flight control: The flight of the UAV is controlled by the so-called autopilot that performs a mission based on a planned path. The flight control strongly depends on the GNSS and IMU sensors.

Payloads and Data Processing: These are components that are not used to fly but are specific to perform the mission and its objectives. Payloads are mainly classified into optical payloads, that enable for remote sensing of the environment, and NDT payloads, that support aerial robotics [5].

Types

There are several types of UAVs and they can be classified depending on a number of their chararacteristics, such as their weight, the application, or the flying principle.

Process to be detected or monitored

UAV support the combined advantages of robot inspection and remote sensor inspection. As such, the use of this systems for documentation, inspection, and monitoring, has gained a significant focus. Visual inspection of surface defects (e.g., cracks, spalling, corrosion, etc.) based on the non-equipped eye is the most commonly used method for bridge inspection. However, this method is subjective, costly, time-consuming, and may cause safety risks [9]. Other NDT methods include image processing and LiDAR. Image processing methods using cameras are popular, speedy, and inexpensive. Several image processing studies have been done in order to detect defects automatically [7], [8], [9], [10], [11]. On the other hand, LiDAR is used for collecting point clouds. LiDAR-based methods are highly accurate and able to detect the depth of the defects [6], [12], [13] and mass losses [14], [15]. Although the initial cost of the LiDAR is high, it is a time and cost-effective method in the long term [6].

Physical quantity to be measured

The same as the previous section. This depends on the payload mounted on the vehicle.

General points of attention and requirements

Data collection and surveying using UAV needs for specific measures to prevent risky situations and obtain useful data. The steps that must be followed comprise: (i) determine the objective areas and data, (ii) revise available geographical information of the location and the operational constraints of the environment; (iii) offline flight planning; (iv) enumerate, evaluate, and foresee mitigation measures related to the operation risks; (v) study regulation constraints; notify any potentially impacted populations about when the aerial survey will start; follow the devised flight plan for data collection, and if any emergency occurs, land the UAV safely [15].

2.1.3 Terrestrial dedicated platforms

Laser scanning is a non-destructive and non-contact technology which uses a laser beam to generate a three-dimensional (3D) representation of the structure to which it is pointing at.

Functioning mode

The scanned object is represented in the space by its 3D coordinates, which are obtained by computing the distance between the LiDAR system and the target object. When the distance measurement device is combined with optomechanical systems or mirrors, which deflect the laser beam and measure the deflection angle, a 3D point cloud is obtained.

The time that it takes to a laser beam to reflect on an object and return back to the instrument is the time of flight (TOF). Knowing the velocity of the light waves, the TOF allows to evaluate the range. Measuring this time delay, the distances may be obtained directly by using short repetitive laser pulses, or indirectly by modulating the power of the wavelength of the laser beam and using phase difference

Types

Terrestrial-Static: Static scanners, also known as Terrestrial Laser Scanners (TLS), were the first type of laser scanners used as surveying for measuring 3D point coordinates. These scanners use mirrors to deflect the laser beam in the vertical plane, measuring elevation angles. With mirrors rotating around the vertical axis they measure azimuth angles. Normally, these mirrors can rotate 360º at very high speed (Figure 1). After performing the survey, a very dense point cloud is obtained in the spherical coordinate system, which will be turned into Cartesian coordinates by most of the scans. The point clouds will be formed by the mentioned coordinates (x, y, z) for each single point, as well as by some other attributes [16].

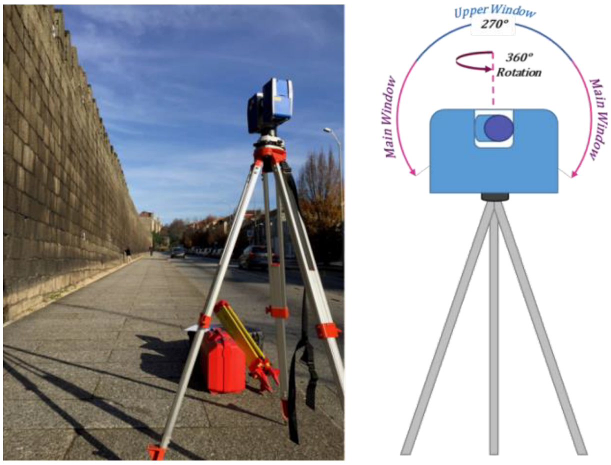

Figure 1. FARO Focus3D X 330 (left); TLS rotation angles (right)

Terrestrial-Mobile: Mobile Laser Scanners (MLS) are the more appropriate platforms for scanning large infrastructures. Yet, there are two different modes of performing this type of surveys, differing in the imaging procedure, even though the sensors are identical (Figure 2):

- Stop-and-go mode (SAG): At least one laser scanner is placed on a vehicle-borne platform. During the scanning process the scanner remains static and it is the vehicle which changes its position between scans.
- On-the-fly mode: The vehicle moves along a predefined trajectory while the laser scanner is continuously working. In addition, the monitoring of the position of the scanning system is done using of a global navigation satellite system (GNSS), combined with an inertial measurement system (IMS) and distance measurement indicators (DMI).

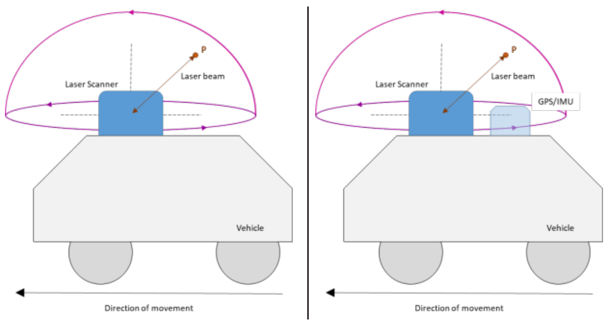

Figure 2. Acquisition modes: Stop-and-go (left) and on-the-fly (right)

Process to be detected or monitored

Laser scanner technology is employed to acquire comprehensive data about a real site, namely its layout, shape, and other information regarding its general appearance, and use it to produce a virtual representation of the scene. A single scan is discrete and thus limited to a particular time, so in order to record the effects of an event or some process occurred on the site, several scans must be acquired at different times to be compared.

Physical quantity to be measured

Geometric information: Laser scanning is used to capture the geometry of the structure. This geometry is represented by 3D Euclidean coordinates that form a 3D point cloud.

Radiometric information: Intensity data (spectral reflectance): Amount of energy reflected by an object's surface when receiving a laser beam. It depends on the reflectance characteristics of the material. This backscatter generated after the collision is recorded by most LiDAR instruments as a function of time [17,18].

General points of attention and requirements

Scanning project plan: Every survey requires a different planning to achieve the best results. This planning involves: selection of the suitable device, definition of the suitable scanning positions or trajectory, preparation and calibration of the equipment, definition of the working parameters, study of the environment in which the object/infrastructure is placed, possible occlusions. A more detailed explanation of these aspects can be found in [16,19].

2.2 Ground penetrating radar

GPR is a geophysical method that allows for the analysis of the propagation capacity of electromagnetic waves through media with different dielectric constants. The objective of this technique is to detect discontinuities at the interface between two different media (different permittivity) with sufficient dielectric contrast.

Functioning mode

A transmitting antenna emits an electromagnetic signal into the ground, which is partly reflected at the interface between two different media with sufficient dielectric contrast and partly transmitted into deeper layers. Then, the reflections produced are recorded from the receiving antenna, which is either in a separate antenna box or in the same antenna box as the transmitter. The strength (amplitude) of the reflected fields is proportional to the change in the magnitude of the dielectric constant. If the time required to propagate to a reflector and back is measured, and the velocity of the signal propagation in the medium is known, the depth of the reflector can therefore be determined. A detailed description of the methodology along with a deep theoretical background can be found in [20–22].

Types

Different GPR systems will have different capabilities according to the type of antennas and their frequency, which affect the operating speed, the resolution, the penetration, and the sampling rate [23,24]. The frequency and depth of penetration are related, with higher frequency pulses achieving lower penetration, but better resolution. Impulse GPR systems are the most widely used, with two main groups of GPR antennas, dipole and horn antennas, and with frequencies currently ranging from 10 MHz to 6 GHz. Nowadays, the most commonly used technology is the time-domain impulse radar. Additionally, several investigations point to the step-frequency radar as a potential technology for broad resolution range, although these systems do not allow real-time visualization of data during acquisition.

Process to be detected or monitored

Particularly for the diagnosis of bridges and tunnels, the GPR method has been demonstrated as effective for the detection of the characteristics in Table 1.

Table 1. Characteristics detected by GPRs in infrastructure assets

Masonry arch bridges	Concrete bridges	Tunnels
Unknown geometries	Concrete cover depth	Thickness
Evidence of restorations or reconstructions	Reinforcing bars	Cracks and voids
Cavities and fractures/cracking	Deck joints or drain gate	Moisture
Moisture	Corrosion	Reinforced elements
Bridge foundations	Cracking, spalling, delamination	Immersion joints
Infill distribution	Moisture	-
Thickness	-	-

More information about the application of the GPR method on transport infrastructures inspection can be found in [25–27].

Physical quantity to be measured

The method is based on measuring the time arrival and amplitude of the reflected waves. The magnitude of the measured amplitudes and the propagation time depend on the dielectric properties of the medium materials that can be inferred analysing the arrival time, the amplitude, and the frequency of the received signals.

General points of attention and requirements

Preparation

The most important parameters to consider when designing the GPR survey are: (i) selection of the optimal operating frequency; (ii) time window between two transmitted pulses for which the reflected signals are recorded; (iii) temporal sampling interval; and (iv) spatial sampling interval.

In some cases, for both air-launched and ground-coupled systems, calibration consists of comparing GPR data with cores. In other cases, and more particularly for air-launched antennas, calibration consists of comparing the amplitude of the reflected wave with the amplitude of the wave reflected on a metallic plate.

3 Discussion

The ultimate goal of this article is to provide information to the H2020 (CSA) IM-SAFE project for creating a standardised framework for monitoring using NDT. Under the umbrella of the project, more surveying technologies are being studied, covering a wide range of physical quantities measured and different damage processes to be detected or monitored.

Considering the information presented in this document, it seems clear that satellite is the technology that fits less for the purpose of detecting and/or monitoring damage processes. In addition, the purpose of the analysis will be linked to the sensor available on board the satellite. Each satellite has one or more instruments that allow obtaining conventional optical images, radar data, presence of pollutants, temperatures, etc.

MMS and GPR have shown good performances for condition assessment, being able to detect a large variety of damages in a bridge or tunnel thanks to their adaptation to the characteristics of the asset and environment. In addition to this, UAVs are also becoming a good alternative when facing a risky survey due to the conditions of the environment or the placement of the asset. Besides, they show an extraordinary adaptation to whatever payload is needed for surveying (cameras, LiDAR, etc.).

4 Conclusions

This paper presents a short review describing different non-destructive data collection technologies useful for the monitoring of transport infrastructure, more specifically bridges and tunnels.

This information will be used for providing a basis to the European Committee for Standardization (CEN) for performing an organised, structured, and efficient surveying of transport infrastructures (bridges and tunnels).

Upcoming, it seems these technologies are gaining ground for the condition assessment of infrastructure assets.

5 Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958171. For more information, please contact the IM-SAFE Project Coordinator, Agnieszka Bigaj-van Vliet, mailto:agnieszka.bigajvanvliet@tno.nl, or visit the project website at the following address: www.IM-SAFE.eu.

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