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Tunnel structural inspection and assessment using an autonomous robotic system

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ABSTRACT

This paper presents the ROBO-SPECT European FP7 project, funded under the ICT-2013.2.2 programme on Robotics use cases & Accompanying measures, a robotized alternative to manual tunnel structural inspection and assessment of cracks and other defects. Physical developments include the design and implementation of a multi-degree-of-freedom robotic system, composed by a mobile vehicle, an extended crane, and a high precision robotic arm. A semi-supervised computer vision system to detect tunnel defects, and a ultrasonic sensor (US) robotic tool to measure width and depth of detected cracks have been also developed. An overview of defect detection methods, as well as the fundamental aspects of the project architecture and design, will be presented. In addition, the developed and implemented arm tip positioning algorithm for the US robotic tool shall be detailed. Finally, experimental evidence and details on validation in a real motorway tunnel with ongoing traffic will be provided.

1. Introduction

The structural performance of tunnels is time-dependent because of the deterioration processes induced by natural and man-made impacts, changes in load criteria, or the simple effect of ageing. Therefore, inspection, assessment and maintenance are required to ensure that these constructions remain in safe condition and continue to provide reliable levels of service. Tunnels of all kinds, including water supply, metro, railway and road, have increased in both total length and number, and will continue to do so on a global scale. Some tunnels still in service were constructed over 50 years ago, and many have exceeded their intended design service life [1]. Only in Europe in 2002, the overall length for operational transportation tunnels had grown up to 15,000 km [2].

Tunnel environments are characterized by dust, humidity, absence of natural light, and the existence of toxic substances among others. Inspection and maintenance are frequently performed by human operators in these unfriendly environments. Manual inspection processes are time-consuming, and must rely on expert trained operators. Additionally, human error tend to cause poor quality inspections.

An automated, cost-effective and exhaustive inspection of tunnels will improve short and long-term security, and increase productivity [3]. In this work, we present the integrated ROBO-SPECT system, which is a promising solution to the problems described above. This paper also describes the arm positioning algorithm for placing the Ultrasonic Sensors on detected cracks, followed by experimental evidence ranging from initial simulation and laboratory testings to demonstrations in motorway tunnels with ongoing traffic. Finally, results and conclusions are presented.

1.1. Tunnel inspection methods

The majority of tunnel linings use reinforced concrete and a significant number of them contain ceramic tiles and metal panels. According to SHRP 2 projects [4], several defects in tunnel linings are hidden from view, however this work focuses on the inspection of visible defects.

Figs. 1 and 2 display the most common visible defects in tunnel lining, which are cracks, spalling and efflorescence.

- Cracks are linear fractures in the concrete caused by tensile forces exceeding the tensile strength of the concrete.
- Spalling is the detachment of hardened concrete that leave a roughly circular or oval depression.
- Efflorescence is a deposit of water-soluble calcium hydroxide that forms on the concrete surface.

In order to know if the structure is still safe without causing side

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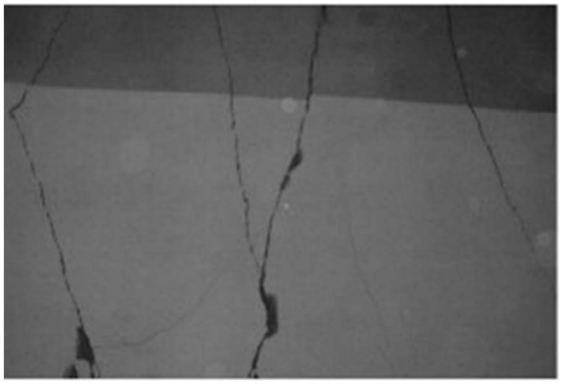

Fig. 1. Crack observed in the lining of Longxi tunnel (left) [5] and concrete spalling with exposed reinforcing steel (right) [1].

Fig. 2. Moderate cracking and efflorescence on the underside of the liner [1].

effects, it is preferable to use non-destructive evaluation (NDE) methods [6]. NDE methods in structures can be classified in visual, strength-based, sonic and ultrasonic, magnetic, electrical, thermographic, radar electromagnetic, radiographic, and endoscopy methods.

- Visual inspection, performed by inspectors, is an essential precursor to any intended non-destructive test.
- Strength-based tests measure the surface hardness of materials and provide an estimation of surface compressive strength, uniformity and quality of the structure. Examples of hardness testers include the Windsor Probe [7] and the Schmidt Hammer [8].
- In sonic methods [9], also known as impact-echo tests, hammer impacts on the wall generates waves that are reflected at discontinuities in the material and a receiver records the signals. The depth of these discontinuities is determined by analyzing the frequency spectrum of the recorded signals.
- Ultrasonic methods [10] are normally based on velocity measurements of pulses generated by a piezoelectric transducer on the material. The pulse velocity depends on the composition and maturity of the structural material and its elastic properties.
- Magnetic methods [11] are important in corrosion control since they are used to determine the position of reinforcing bars. Examples of these methods are the Magnetic Flux Leakage method or the Magnetic Field Disturbance method.
- Electrical methods [12] based on electrical resistance are used to estimate corrosion rate for reinforced concrete.
- Thermographic methods [13] measure the thermal radiation emitted by the tunnel lining and allow a visual representation of the temperature distribution on the surface. The temperature on the surface represents the thermal flow through the surface, which in turn is influenced by the mechanical and/or hydraulic discontinuities of the structure. Consequently, thermal discontinuities on a surface reflect abnormalities within the underlying structure.
- Radar electromagnetic methods [14] have been widely used to detect defects in tunnels and other structures. The most used is the Ground-Penetrating Radar (GPR), which is based on the propagation of electromagnetic energy through materials of different dielectric properties.
- Radiographic methods [15], such as those based on X-rays, gamma radiation, or neutron rays, can penetrate structural materials and therefore can be used with inspection purposes. The amount of radiation absorbed by the material is dependent on density and thickness.

1.2. Robotic systems for NDE inspection of concrete structures

In recent years, the development of concrete inspection and maintenance robotic systems has been an area of increasing research interest. These robots are expected to provide exhaustive inspections with high productivity and increased safety.

Vehicle-based systems have been developed for off-line detection of defects on the tunnel lining. A mobile robot for crack detection via computer vision algorithms is reported in [16]. A similar system to detect deformations by fusing cameras and ultrasonic sensors data is developed [17]. Suda et al. present a system composed by a truck and a robotic arm equipped with a multi-hammer that generates impact sounds to find cavities and exfoliation areas [18]. A bridge inspection system using machine vision techniques is reported in [19]. TUNCONSTRUCT teleoperated