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Review

Past, present and future of robotic tunnel inspection

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Nowadays, the vast majority of the tunnel inspection processes are performed manually by qualified operators. The process is subjective and the operators need to face very uncomfortable and even dangerous conditions such as dust environments, absence of light, or toxic substance exposition. Robotic technology can overcome many of these disadvantages and provide quality inspections collecting different types of data. This paper presents the key aspects of tunnel inspection and a survey of the developed robotic tunnel inspection systems up to date. Additionally, two projects regarding automation of the processes involved and future trends will be discussed.

Contents

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1. Introduction

One of the greatest challenges engineers face is the inspection, assessment, maintenance and safe operation of the existing civil infrastructure. This includes large-scale constructs such as tunnels, bridges, roads and pipelines. In the case of tunnels (water supply, metro, railway, road, etc.), they have increased in both total length and number, and will continue to do so. Furthermore, some tunnels still in service were completed over 50 years ago, with the existing construction and materials technology.

Only in Japan in 2006, the number of active tunnels was up to 9000 [1], with tunnels such as the Seikan Tunnel, which is 54 km long and partially below the seabed [2]. Fig. 1 shows the evolution of Japanese tunnels in terms of number and length until 2006.

Tunnels progressively deteriorate due to ageing, environmental factors, increased loading, change in use, damages caused by human/natural factors, inadequate or poor maintenance, and deferred repairs. Unfortunately, several incidents related to the structural condition of tunnels have taken place, such as the Big Dig ceiling collapse in 2006 in Boston [3], or the Sasago Tunnel collapse in 2012 in Tokyo [4].

These examples highlight the need of automated, cost-effective and exhaustive inspection of tunnels that prevents such disasters. In this work, we present current tendencies and future trends within this area.

This paper will describe the key aspects of the tunnel inspection procedures and the main advances in robotic tunnel inspection technology. Section 1 defines the main tunnel defects to identify and the principal methods to detect them. Section 2 describes the motivations to use robots in this task and includes a review of the robotic tunnel inspection systems developed up to date, while Section 3 describes the main drawbacks of these systems. In section 4, two relevant European projects regarding automatic tunnel inspection systems are discussed. Section 5 focuses on the future trends that can be applied to the robotic tunnel inspection area. Finally, the conclusions of the paper are included in Section 6.

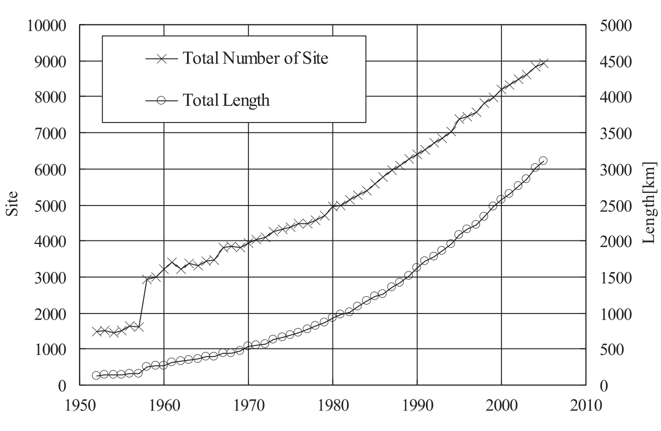

Fig. 1. Changes in the number and total length of road tunnels in Japan (2006) [1].

1.1. Tunnel defects

The first aspect of inspection that must be defined is related to the types of defects that may affect tunnels. Identifying these defects is crucial for performing a successful inspection, verifying the state of a tunnel, and performing maintenance if required.

The following list of common defects in tunnels is based upon the *TOMIE Manual* [5], created by the Federal Highway Administration (FHWA).

- Concrete structures: scaling, cracking (traverse, longitudinal, horizontal, vertical, diagonal, pattern, d-cracks, random), spalling, joint spall, pop-outs, efflorescence, staining, delamination, honey-comb, leakage
- Steel structures: corrosion, cracks, buckles and kinks, leakage, protective layer fail
- Masonry structures: masonry units (displaced, cracked, broken, crushed, or missing), mortar, shape, alignment, leakage
- Timber structures: decay, insects, checks/splits, fire damage, hollow area, leakage

The walls of most tunnels are made of concrete, though these walls may contain finishes such as ceramic tiles or metal panels. In most cases, the typical defects found in a tunnel are cracks, spalling and efflorescence/leakage [6]. Examples of this type of defects are displayed in Fig. 2. If the walls are covered by a finish, the condition of such walls is generally defined by the deficiencies of the finish on the wall surface. An analysis of the causes of these common defects in tunnels can be found in the work by C. C. Xia et al. [7].

1.2. Tunnel inspection methods

The purpose of inspection is to check if a structure that has been functional for years is still safe or not. Furthermore, it is desirable to do this without creating any negative effect on the structure or component, and this is why the non-destructive inspection (NDI) methods [5,8] are far more commonly used than destructive methods. As said before, the most common structural material in tunnels is concrete, thus the following inspection processes are usually applied to concrete tunnels. NDI methods in structures can be divided in visual, strength-based, sonic and ultrasonic, magnetic, electrical, thermography, radar, radiography, and endoscopy methods.

1.2.1. Visual methods

Visual testing is probably the most important of all non-destructive tests. It can often provide valuable information to the well-trained eye. Visual features may be related to workmanship, structural serviceability,