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Review Article

Tunnel inspection using photogrammetric techniques and image processing: A review

Leanne Attard[a], Carl James Debono[a,*], Gianluca Valentino[a], Mario Di Castro[b]

[a] Department of Communications and Computer Engineering, University of Malta, Msida, Malta
[b] Engineering Department, CERN, Meyrin, Switzerland

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ABSTRACT

During the last few decades many tunnelling projects were conducted in order to use limited land surface area more efficiently. Such underground constructions are used for transportation such as for railways, subways and roads, to host equipment used for experiments like particle accelerators, as well as for pipelines and mines. Independent of their purpose, tunnels should be regularly inspected in order to avoid accidents resulting from structure failure and to simultaneously extend their lifetime by identifying deterioration at an early stage and perform the required maintenance. Traditional methods of tunnel inspection rely on manual vision monitoring and sensing equipment that requires installation and contact with the tunnel surface. Apart from being time consuming, tedious and expensive, manual inspection is also highly dependent on human subjectivity and exposes inspection personnel to possible dangerous environments. Taking these issues into consideration, various systems were proposed to automate different procedures of tunnel inspection using photographic equipment to capture photos of the tunnel environment, apply photogrammetric and computer vision (CV) techniques and conduct image processing (IP) on them to achieve different surveying goals. This manuscript provides a collective review of the current state of the art in tunnel inspection based on photogrammetric techniques and IP.

1. Introduction

A considerable amount of tunnelling was performed in the last few decades, and concerns have been raised over the need to improve the current methods employed in civil construction management, monitoring and inspection in general. The use of photogrammetry and CV is already being utilized to provide better automated approaches for these tasks. Using IP techniques, 3D maps are generated to help with Building Information Modelling (BIM) Eastman et al. (2008) as in Ptrucean et al. (2015) and Martin et al. (2016). Continuous area monitoring to analyse the progress on a construction site is also being improved by the introduction of CV systems Lukins et al. (2007). Over time, much of the infrastructure shows signs of deterioration due to ageing and stresses which may eventually cause problems in structural integrity. Consequently, to ensure safety in concrete tunnels, periodic inspections have to be conducted.

Currently, structural tunnel inspection is predominantly performed through periodic visual observations by trained inspectors. They try to detect structural defects such as cracking, spalling and water leakage as well as to identify possible changes in the infrastructure with respect to a previous survey. It is important that such inspections are made without creating a negative effect on the structure itself. Thus non-destructive (ND) inspection methods are commonly used other than destructive ones. ND methods (Montero et al., 2015; Boving, 1989) can be divided in visual observation, strength-based, sonic and ultrasonic, electrical, thermography, radar and endoscopy methods, each requiring specific equipment. In order to conduct such methods, presently, personnel often are required to be physically present in the tunnel and move around with the equipment. This approach has several drawbacks including the cost involved for hiring and training personnel to do the inspections and the considerable amount of time necessary to perform them. In addition, it is highly dependent on human subjectivity leading to possible inaccuracies, false and missing detections. Furthermore, tunnel inspections may demand personnel to access hazardous environments characterized by lack of light, inadequate temperatures, dust and possibly lack of adequate ventilation or presence of poisonous gases. For these reasons, research on automated health monitoring of tunnel structures has received significant attention in recent years in order to facilitate the process of visual inspection as in Balaguer et al. (2014) and Montero et al. (2015).

The use of cost-effective photographic equipment and photogrammetric techniques and CV (Linder, 2013; Förstner and Wrobel, 2016;

* Corresponding author.
E-mail address: carl.debono@um.edu.mt (C.J. Debono).

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Ikeuchi, 2014; Szeliski, 2011) techniques implemented through IP has led to various solutions that deal with different aspects of automated tunnel inspection. Such systems aim to achieve time-saving automated surveying solutions with fast data acquisition, identification and documentation of cracks as well as detection of structural changes. This publication reviews the use of CV to facilitate and automate tunnel inspections. Although reviews on general crack identification, image mosaicking and change detection are available in literature, these generally focus on natural scene images. In contrast, this paper provides an extensive survey of previous works presented within the whole image-based tunnel inspection spectrum, including tunnel profile monitoring, crack and leakage detection as well as tunnel surface documentation and visualization.

The remainder of this article is structured as follows. Section 2 reviews the state of the art with respect to techniques used for tunnel profile measurement and deformation monitoring. Section 3 gives an overview of methods for tunnel interior visualization. The latter includes both image mosaicking of the tunnel wall as well as 3D reconstruction. Section 4 discusses works related to crack and defect detection using different methods. Image-based water leakage detection systems are reviewed in Section 5. Section 6 investigates change identification systems. Future trends are then discussed in Section 7. A summary of the state of the art in tunnel inspection using CV concludes this publication.

2. Tunnel profile deformation

The deformation of a tunnel's cross-section indicates the structural condition of the tunnel in general. Measurement and monitoring of the tunnel profile are thus critical proactive maintenance activities to ensure tunnel safety. Several methods can be used to measure tunnel profiles such as mechanical gauge, tape extensometer, Terrestrial Laser Scanning (TLS) (van Gosliga et al., 2006; Jian et al., 2012; Kang et al., 2012) and geodetic instruments.

A tunnel profile measurement system that makes use of physical indicators was proposed in Scaioni et al. (2014). Relative deformations of traversal cross-section of tunnels are achieved by installing targets on the tunnel vault and measuring their coordinates in images captured along the wall. First, targets are independently measured on the images with the Least Square Template Matching (LSTM) Gruen (1985) algorithm. The 3D coordinates of the targets are then estimated using free-net bundle adjustment Luhmann et al. (2013). Finally, the scale ambiguity is removed using an invar wire and gauge as shown in Fig. 1 and the relative distances between the targets are computed. Photogrammetric levelling using a calibrated camera and photogrammetric rods and three circular targets as shown in Fig. 2 is then used for the measurement of vertical deformations. In these experiments, the camera was set on a topographic tripod to avoid blurring effects, making it inadequate for moving platforms.

A solution that installs physical objects in the tunnel is not an

Fig. 1. The invar wire and the gauge used to remove the scale ambiguity in Scaioni et al. (2014). Reprinted by permission from: Springer Nature Earth Science Informatics (Photogrammetric techniques for monitoring tunnel deformation, M. Scaioni, L. Barazzetti, A. Giussani, M. Previtali, F. Roncoroni, M. Alba), © (2014).

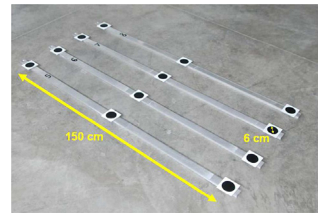

Fig. 2. An example of the basic operational scheme of 'photogrammetric levelling' as used in Scaioni et al. (2014). Reprinted by permission from: Springer Nature Earth Science Informatics (Photogrammetric techniques for monitoring tunnel deformation, M. Scaioni, L. Barazzetti, A. Giussani, M. Previtali, F. Roncoroni, M. Alba), © (2014).

optimal one as it is installation and the maintenance is time consuming, especially in long and wide tunnels. The following works, instead focused on using laser light projections to create 'virtual targets' instead of physical ones.

The tunnel cross-section measurement method proposed in Wang et al. (2010) makes use of the profile-image method proposed earlier in Wang et al. (2009). This method uses laser pointers to beam the surface and capture the resulting tunnel profile using a camera. It is important that the planes of the laser-lit profile and the camera image are parallel, thus, Wang et al. (2010) parallelizes the image, by locating all the calibration points on the periphery of the profile as shown in Fig. 3 instead of adjusting the camera orientation as in Wang et al. (2009). The transformation relationship of the global 3D coordinates and the local 2D coordinates is found using perspective projection.

Multiple structured light projectors and cameras mounted on a dedicated vehicle, were used for 3D tunnel clearance inspection in Shen et al. (2015). The optical triangulation principle is used to reconstruct the 3D metric information of the tunnel. This is achieved by a global calibration, whereby the intrinsic and extrinsic parameters of each neighboring camera are found using the pinhole camera model. Based on this, the mapping of a 3D world point $P = (x\ y\ z\ 1)^T$ to a 2D image point $p = (u\ v\ 1)^T$ can be described by:

$$sp = A(R\ T)P, \quad A = \begin{bmatrix} \alpha & \gamma & u_0 \\ 0 & \beta & v_0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where s is a non-zero arbitrary scale factor, A contains the intrinsic parameters, including α and β which are the scale factors in the image axes u and v. The principal point is represented by (u_0, v_0) and γ is the skew of the two image axes. The extrinsic parameters are represented by R for the rotation and T for the translation. The equation of the structured light plane is then used together with the latter found parameters to obtain the global model.

Similarly, in Ai et al. (2016), a set of CCD cameras and a laser emitter were placed on a cart fitted with a distance encoder. The laser emitter generates a plane perpendicular to the longitudinal axis of a metro tunnel and when the cart reaches a predefined location, the cameras are synchronously triggered to acquire images of the profile. Using photogrammetry-based algorithms and the related geometry equations, features of the sectional profile are obtained using a transmissive projection system. First, the calibration of the coordinate system transformation is conducted using an exterior target. Two neighboring cameras capture a picture of the target. Next, IP is applied on the acquired images to convert the color image to grayscale. Binary images are obtained using thresholding (TH) segmentation and used to extract the geometric information. The coordinates of points from the obtained profile are fitted to an ellipse using the Least-Squares method and the severity of the deformation is directly analyzed. The accuracy of the this system is about ± 25 mm at a speed of at least 5 km/h.

The use of laser pointers and cameras is becoming increasingly common to measure tunnel profiles as a cheaper, simpler and faster method to conduct than using targets, gauges and geodetic instruments.