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Feature extraction of a concrete tunnel liner from 3D laser scanning data

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ABSTRACT

Underground structures require routine inspections and maintenance processes for their optimal use. In particular, the practical inspection of tunnels commonly relies on human-based methods that entail inherent limitations. The applications of laser technology are rapidly expanding, with decreased cost and increased accuracy. This study attempted to investigate the feasibility of applying laser scanning technology to the management of infra-structures. A trial model of a laser-based tunnel scanning system was developed to facilitate an automated tunnel inspection process. The trial model scanner scans a tunnel in the time-of-flight manner, and delivers the scanned data in ASCII files containing x, y and z coordinates. In addition, this paper proposed an algorithm to extract the information for tunnel management from the data set acquired from the trial model. The proposed algorithm extracts installations on the liner and the physically damaged parts of a tunnel liner using the geometric and radiometric features of the scanning data. The algorithm was tested and evaluated by using the scanned data set from an operating railway tunnel and a concrete box with various diameters of pipes attached on one wall of the box. Due to the mechanical and laser sensor limitations, the developed trial model is limited with respect to the identification of cracks and installations; cracks and installations having a gap or width of less than 5 mm are not detected well. This limitation, however, will be overcome by upgrading the scanning system and through increased density of the point cloud.

1. Introduction

Tunnels used for traffic require regular inspections in order to avoid incidents resulting from the failure of the tunnel liner and to extend the life cycle of the structure. Many tunneling projects have been conducted in order to more efficiently use limited land area, resulting in more than 1000 km of tunnels in South Korea, including railway, subway, and road tunnels. As the successful maintenance of tunnels is crucial during the operation of railways and roads, efficient and accurate tunnel inspections are mandatory. Tunnel inspection includes not only identification of the surface characteristics of tunnel liners but also an internal integrity check of the liners [1–5]. Physical damage on a tunnel liner includes cracks, spalls, and damage induced by deterioration of the concrete resulting from unexpected earth pressure, geological conditions, etc. Although automated crack detection practices such as image processing techniques have been introduced and recently applied in tunnel inspections, this type of detection still needs human support during the decision making process of damage identification. Additionally, tunnel inspection via the naked eye is labor intensive, and the inspected results are manually recorded on inspection sheets, entailing the limited use of databases, which are not typically stored in digital formats.

Through efforts to overcome the disadvantages of manual inspection by the human eye, the development of interdisciplinary technologies has accelerated various applications of tunnel maintenance. This technology includes the use of line-sensor cameras for image capturing [1,5], as well as radar technology [6]. Haack et al. [3] and Richards [4] presented detailed technical reviews of the tunnel inspection methods. Among available methods, image and laser scanning technologies are effective ways to monitor the surface of a tunnel. Image scanning technologies use captured images of a tunnel by line cameras or video recorders. The images are processed to find cracks and spalls on the surface of concrete liners. The image processing technique has high accuracy and resolution depending upon the capacity of the camera and the running speed of the vehicle onto which the image capture device is mounted. However, the image scanner requires a constant and sufficient supply of light from illuminants. Cracks are then detected on the basis of the difference in contrast between cracked and uncracked areas [7] or using an edge detection algorithm [8].

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Compared to image scanning methods, at the current state of laser scanner technology development, laser scanning technology is still less accurate with lower resolution. Laser technology, however, is rapidly growing and has great potential of increased accuracy and decreased cost with computer technologies. In addition, the data from laser scanning has a broader range of application compared to image scanning data, including facial scanning, since the laser scanning data simultaneously provides geometric and radiometric information of objects, facial morphology [9,10], rock joint surface roughness scanning [11], laser profilometer [12], and structural modeling [13]. The geometric data, the *x*, *y* and *z* coordinates of the objects, are recorded by the principle of time-of-flight, which calculates the distance between the laser scanner and the target with the traveling time of the laser or via the phase difference of the laser rays. Through accurate geometric information provided by laser data and high sampling density, precise information regarding the three-dimensional (3D) features of structures can be provided.

In addition to the geometric information of 3D spatial coordinates, some laser scanners provide intensity that is a radiometric property of backscattered laser signals. In this study, radiometric properties are effectively used for feature extraction. O'Shea et al. [14] explained that the terminology "intensity of the laser" is "the amount of power radiated per unit solid angle." The physical amount of radiated energy is converted into an 8-bit digital number (DN) through a laser system. According to Baltsavias [15], when it is assumed that the illuminated and the received areas are identical, the physical amount of power received at the sensor can be simplified

$$P_r = \rho \frac{M^2 A_r}{\pi R^2} P_T \qquad (1)$$

where P_r denotes the power collected by the receiver, ρ is the object reflectance, M is the atmospheric transmission, A_r is the receiver area ($A_r = (\pi D_r^2/4)$), D_r represents the receiver diameter, R is the range or the distance between the sensor and the target, and P_T denotes the transmitted power. In Eq. (1), the factors affecting the physical amount of the backscattered laser signal are summarized into three groups: object reflectance, atmospheric transmission, and range. As the object of this study is a tunnel, which is a constraint underground structure, the effects of the atmospheric transmission and distance in Eq. (1) can be ignored in this study. Consequently, the surface characteristics of the objects are the main cause of the intensity variation. Ahokas et al. [16] also found that the main cause of the intensity is the reflectance of materials. The intensity images generated from scanned data, hence, are a viable source of information regarding the identification of objects. The resolution of the image produced from radiometric data depends on the interval between the scanning points (i.e., the density of the points).

In this study, the application of a laser sensor was introduced for automated tunnel inspections. This study discusses the features of the laser as well as those of 3D laser scanning, as well as the development of a trial model of a laser-based tunnel scanner and a detection algorithm that can be used for tunnel installations, instances of damage, and the concrete liners of tunnels with scanned multiple data points. The proposed algorithm uses radiometric and geometric information simultaneously to extract features of the laser-scanned tunnel.

2. Development of a trial model of a laser-based tunnel scanner

2.1. System requirements for a railway tunnel scanner

A tunnel scanning system must have sufficient durability to overcome the unfavorable conditions encountered in railway tunnels such as temperature and humidity variation, corrosion, and electromagnetic interference. In addition, accuracy, precision, resolution, and repeatability of the measurements should be assured in the system, implying that its structure should be robust and simple. Based upon these structural requirements, the functional requirements of the system are as follows: (1) measurement of the internal dimensions of a tunnel; (2) detection of the restriction boundary of the tunnel; (3) construction of a 3D model; (4) control of the measurement resolution; (5) automated detection of tunnel installations and damages; (6) detection of any tunnel deformations; (7) acquisition of internal tunnel images; and (8) 3D rendering of the scanning results. At the current stage of the development of the tunnel scanning system, a trial model for laser scanning was manufactured. Since data analysis is necessary to distinguish the points reflected from the concrete liner, the damaged parts of the concrete liner, and installations such as steel pipes and catenary wires, the latter part of this study will cover the algorithm employed for data analysis.

A tunnel scanning system can be either stationary or locomotive. A close-range laser scanning system is an example of a stationary system, which is a typical type of laser scanner used for 3D ranging. A stationary scanning system scans the inside of a tunnel under stationary conditions and covers some range of measurements depending on the ranging capacity of the laser rangefinder of the scanner system. For a long tunnel, the entire process of tunnel scanning is completed in several scanning steps at different locations in the tunnel. Fig. 1 shows an example of typical scanning results produced by a stationary scanning system. This figure shows the scanned results of the Jipyung tunnel, a railway tunnel in Korea. The scanner type used was an ILRIS-3D from Optech. The ranging of the scanner is 350 m and the modeling accuracy of the system is 3 mm at 50 m range. The distance between the tunnel portal and the scanner is about 20 m. Total acquired data points are 8,000,000 and the averaged point density is 1 point/cm^2. Scanning was conducted at the left and right sides of the portal. Fig. 1 is produced from the combined data set scanned at the left and right sides of the tunnel. The black and white image was produced with backscattered intensity values of each laser point. Since the tunnel is a long and slender structure, the distances between the scanner and each target point, that is, the ranges, varied along the axis of the tunnel. In other words, the

Fig. 1. Scanning results illustrated by using backscattered intensity of the Jipyung tunnel.