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Machine vision-based model for spalling detection and quantification in subway networks

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A B S T R A C T

Spalling is a significant surface defect that can compromise the integrity and durability of concrete structures. The detection and evaluation of spalling are predominantly conducted on the basis of visual inspection (VI) techniques. Although these methods can provide substantial inspection data, they are known to be time-consuming, costly, and qualitative in nature. The objective of this paper is to develop an integrated model based on image processing techniques and machine learning to automate consistent spalling detection and numerical representation of distress in subway networks. The integrated model consists of a hybrid algorithm, interactive 3D presentation, and supported by regression analysis to predict spalling depth. First, RGB images are preprocessed by means of a hybrid algorithm to de-noise the image and enhance the crucial clues associated with spalling. Second, a spalling processor is designed to detect distress attributes, thereby providing 3D visualization model of the defect. And third, the depth and severity of spalling distress are measured using a novel regression analysis model in conjunction with image processing techniques in intensity curve projection. The integrated model was validated through 75 images. Regarding the hybrid algorithm, the recall, precision, and accuracy attained, were 91.7%, 94.8%, and 89.3% respectively. The mean, standard deviation of error percentage in spalling region extraction were 11% and 7.1% respectively, while the variance was 25. Also, the regression model was able to satisfactory quantify the spalling depth with an average validity of 93%. The integrated model is a decision support tool, expected to assist infrastructure managers and civil engineers in their future plans and decision making.

1. Introduction

The competitiveness among big cities hinges on their capability to build up a functional public transit system. In 2009, transit-based industries boosted Quebec's economy by $1.1 billion in added value which accounts for 14,110 jobs per year [1]. Subway network has always been a main constituent of the national public asset and a major generator of tremendous economic benefits. The facilities in this network continually deteriorate which may undermine their serviceability and claim lots of money. According to the ASCE 2013 Report Card, the condition of public transit infrastructure in the U.S. is rated D, hence the total maintenance cost of these deficient systems reached $90 billion in 2010. These underground facilities are subjected to severe environmental conditions and constant heavy loads. Huge amount of water infiltration through subway systems may accelerate the deterioration mechanisms and subsequently causes the closure of their services. The structural defects facing transit authorities are derived from water intrusion, among others are corrosion of reinforcing steel bars, delamination, spalling, etc. Hence, providing cutting edge serviceability through periodic structure inspection and assessment is essential in keeping the subway network operational and avoiding catastrophic incidents, such as the collapse of concrete infrastructure which brings about numerous fatalities and injuries, loss of wealth and businesses.

Non Destructive Evaluation (NDE) techniques have demonstrated to be useful for concrete surface evaluation, thus numerous researches were conducted due to their versatile applications and efficacy. Kim et al. [2] proposed a framework to assess the dimensional and surface quality of precast concrete elements on the basis of BIM and 3D laser scanning. In a study SHRP 2 [3], as part of Strategic Highway Research Program, Infrared thermography was characterized as one of the top technologies used for detecting surface anomalies and delaminations in concrete bridge decks. Ham et al. [4] characterized micro crack damage in concrete by developing a contactless ultrasonic surface wave method. Shah et al. [5] investigated the micro and macro level of defects in concrete by computing linear and non-linear ultrasonic pulse velocity

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(UPV) factors. Dilek [6] utilized the UPV, Young's modulus of elasticity, and concrete air permeability to assess the severity of concrete damage. Scott et al. [7] used Impact Echo (IE) testing in conjunction with Fast Fourier Transform analysis to determine the location of distress, crack or discontinuity, and depth of component. Electrical resistivity (ER) technique was performed by Lataste et al. [8] to classify the damage in concrete, especially to quantify the crack width and depth. Consequently, the authors concluded that the extracted information from ER and acoustic method can be fused to yield precise diagnosis for the structure. A multi-spectral image analysis approach was presented by Valença et al. [9] to assess concrete damages and delineate automatically the deteriorated zones. Sadowski [10] presented a methodology to recognize the values of pull-off adhesion between the layers of concrete. His methodology was based on three NDE techniques (3D laser scanning, acoustic impulse response, impact-echo) and artificial neural networks (ANNs).

In practice, the detection and assessment of spalling distress is conducted on the basis of visual inspection (VI) techniques. Although these methods can provide significant inspection data [11], they are known to be labor-intensive, time-consuming and costly. They have inherent shortcomings in recognizing the structural integrity and measuring the level of defect of a facility because some parts of the structure are inaccessible by inspectors, therefore many distresses are not diagnosed until they progress and become serious. Moreover, these methods are subjective to the inspector's knowledge and experience. This underscores the necessity for automated information processing to visual data supported by computer-based approaches. Therefore, machine vision-based detection system which provides more consistent and objective output has to be developed. This system utilizes visual data to capture remotely the images, analyzes and evaluates accurately the extent of defect using computational approaches and multiple algorithms. These approaches have been leveraged in many studies to automatically evaluate different distresses in civil structures. Nevertheless, spalling distress has seldom been studied. Therefore, the ultimate goal of the current research is to develop an integrated framework for the detection and quantification of spalling distress in subway networks, by incorporating regression analysis and several filtering techniques. It endeavors to bridge the gaps pertain to current practice and to ameliorate the existing level of detection and evaluation of spalling defect.

2. Background

2.1. Previous subway assessment models

Many endeavors have been made previously to detect and/or evaluate concrete distresses in subway systems. Semaan [12] proposed a framework for the evaluation of subway stations based on Analytic Hierarchy Process (AHP) and Preference Ranking Organization Method of Enrichment Evaluation (PROMETHEE) in conjunction with Multi-Attribute Utility Theory (MAUT). As described by the author, the model was developed only for stations and cannot be applied for tunnels, auxiliary structures or the entire network. Also, this framework was capable of assessing surface defects based on visual inspection reports, thus the severity of defects was not investigated. Subsequently, another model was developed by Semaan [13] to assess the performance of subway network. This model Leveraged AHP, MAUT theory, and Weibull reliability function to construct performance prediction curves for the components of the network, followed by using series-parallel system technique. Although this was the first attempt to evaluate the condition of subway networks, it was characterized as subjective since it relied on visual inspection reports in assessing the structural performance of subways.

Kepaptsoglou et al. [14] presented a model to evaluate the functional condition of subway stations. The AHP, Fuzzy AHP techniques were utilized, in addition to MAUT to get the Metro Condition Index (MCI). Their model failed in evaluating the whole network and lacked the objectivity in estimating the severity of defects. Gkountis and Zayed [15] further enhanced this model by applying the Analytic Network Process (ANP) which attains the interdependencies among the criteria of the model. Thereafter, the additive MAUT was implemented to acquire the station's condition index. However, this model had the same limitations as the previous one in spite of utilizing the ANP technique to augment its accuracy. Abu-Mallouh [16], and Farran [17] proposed models for station rehabilitation. Since these models were developed solely for stations, they were considered as unintegrated models.

In a study by Derrible and Kennedy [18], a network design model was generated in an effort to improve the efficiency and ridership of metro networks. The study was controversial since it didn't deliver an evaluation model which tackles the structural performance of subway networks. Marzouk and Abdel Aty [19] created various subway management indicators as a solid background for their Building Information Modeling (BIM) framework. However, their system was ambiguous in describing the proposed indicators and it didn't consider any distresses or deterioration options in subway structures. Abouhamad [20] developed a risk-based asset management framework for subway networks. This study delivered recommendations to prioritize stations for rehabilitation action. However, the proposed framework was subjective due to its reliance upon the expert's judgment and feedback. In addition, as the author mentioned, it might not guarantee the coherency to in-depth analysis.

2.2. Automated defect detection and evaluation

Machine vision-based techniques have gained a lot of momentum during the last two decades which can be exposed in their multiple applications in the industry as well as in academia, specifically for the detection and evaluation of distresses in civil infrastructure. In this regard, the majority of researches pertain to the field of bridges, La et al. [21] presented a crack detection and mapping algorithm for bridge deck data collected via a robotic system. Adhikari et al. [22] proposed a model for crack quantification in bridges supported by artificial neural networks and 3D visualization models. Abudayyeh et al. [24] developed an automated bridge inspection system based on imaging data and integrated with Bridge Management Systems PONTIS.

Substantial progress has been achieved in the field of computer vision, especially when it's complemented with various non-destructive evaluation technologies. Examples of such studies can be found in the pavement defect inspection, Li et al. [25] designed an integrated framework for the detection and measurement of potholes on the basis of 2D images and Ground Penetrating Radar (GPR) data. Yu and Salari [26] introduced a laser-based detector and classifier for pavement defect inspection. Koch and Brilakis [27] presented a pothole detection method which involved image thresholding, morphological thinning, elliptic regression and texture extraction.

The remainder of studies extends through a proliferation of applications in water pipes, wastewater, road tunnels, and civil structures in general, Atef et al. [28] utilized a multi-tier technology to locate water pipes and detect leaks based on the image processing of captured Infrared (IR) and GPR images. Guo et al. [29] presented a condition assessment approach of wastewater systems grounded in visual pattern recognition techniques. Yu et al. [30] devised a system for inspecting and measuring tunnel cracks, the system comprised of a mobile robot and a crack processor. Zhu [31] retrieved critical structural defects from images and utilized multiple computational mechanics for column recognition and rehabilitation of civil infrastructure. Jahanshahi et al. [32] incorporated depth perception, image processing, and pattern recognition for the purpose of crack detection and quantification. Hutchinson and Chen [33] proposed a statistical procedure for the detection of cracks through utilizing Bayesian Decision Theory.

The previously-mentioned attempts indicate that there still remain gaps in the body of knowledge, since the mainstream of automated

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