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Detecting healthy concrete surfaces

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A R T I C L E I N F O

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A B S T R A C T

Teams of engineers visually inspect more than half a million bridges per year in the US and EU. There is clear evidence to suggest that they are not able to meet all bridge inspection guideline requirements due to a combination of the level of detail expected, the limited time available and the large area of bridge surfaces to be inspected. Methods have been proposed to address this problem through damage detection in visual data, yet the inspection load remains high. This paper proposes a method to tackle this problem by detecting (and disregarding) healthy concrete areas that comprise over 80–90% of the total area. The originality of this work lies in the method's slicing and merging to enable the sequential processing of high resolution bridge surface textures with a state of the art classifier to distinguish between healthy and potentially unhealthy surface texture. Morphological operators are then used to generate an outline mask to highlight the classification results in the surface texture. The training and validation set consists of 1028 images taken from multiple Department of Transportation bridge inspection databases and data collection from ten highway bridges around Cambridge. The presented method achieves a search space reduction for an inspector of 90.1% with a risk of missing a defect patch of 8.2%. This work is of great significance for bridge inspectors as they are now able to spend more time on assessing potentially unhealthy surface regions instead of searching for these needles in a mainly healthy concrete surface haystack.

1. Introduction

Bridges are the most critical and complex structures in a road network, both technically and strategically. Weight-limitations or closures have negative consequences on the economic success of a country as well as on the user satisfaction. Bridge inspections need to be carried out to know the bridge condition, to collect information about damages and to make appropriate operational or maintenance decisions (load limitations, maintenance needs or closure). A team of engineers inspect a bridge manually on site regularly (typically every two years a general, purely visual inspection, every five years a more detailed in-depth inspection from a touching distance including the use of tools) [33].

Bridge inspection guidelines require engineers to visually identify both small and large defects (e.g. down to 0.3 mm in width for cracks) on all bridge element surfaces [33]. Our datasets show that the concrete surface area of an average highway bridge taken around Cambridge is 2440 square meters, equal the size of almost six basketball courts. Inspecting this takes more than 20 h if allowing for 30 s inspection time per square meter to identify potentially unhealthy areas, closely examine these areas, taking measurements and documenting the defects in writing and visually. Moreover, this is the pure inspection time, not accounting for time required to perform safety measures, walking and climbing to get into a solid inspection position or rest periods. In addition, there usually exists a serious issue of accessibility where some areas to be inspected are not easily accessible. Image timestamps of 399 inspections were analysed to learn about inspection duration. The time span between the first and last image allows a conclusion on the duration of the visual part of an inspection based on the assumption that an inspector regularly takes images during a visual inspection. The average time for a general inspection was 19 min and for an in-depth inspection 72 min. It is therefore questionable whether an inspector is able to inspect the entire bridge surface with the required level-of-detail and from a distance from which all defect types can be identified. Inspectors have to make a trade-off between inspection time and inspection distance. They do it in two ways: (1) Inspectors might look from a distance where they are unable to see small details or (2) inspectors might skip some surface parts because it is too time-consuming to get into a position from where the surface is visible. As a result, bridge condition information is incomplete.

Missing out small details leads to missing minor defects. Preventive maintenance, which means to maintain minor defects before they become major, can reduce costs by up to 65% [18]. More importantly, skipping surface area completely bears the risk of missing major defects which can lead to major closings or a complete loss of structural

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integrity and fatal accidents [35].

1.1. State of practice

Inspectors perform two tasks during an inspection: First, they identify which areas of a bridge are prone to and critical for defects. This is done empirically and based on a subjective structural interpretation; no defined rules exist. Typical areas are the ones close to a support (e.g. the connection between column and girder) or with maximal bending (e.g. middle of span). Second, an inspector looks for potentially unhealthy spots in the critical areas. Only these potentially unhealthy spots are examined more closely by conducting four steps: take a close look to identify the defect type and possible cause; take measurements of the relevant defect properties; give a condition rating based on the measurements and the inspection guidelines and finally document findings in writing and figurative in a sketch or an image [30]. This second step typically affects only a minor surface area; most of the surface is non-deficient concrete.

1.2. State of research

Technologies for collecting the as-is raw data of a bridge exist: Laser scanning or Structure from Motion (SfM) can provide high-precision dense point cloud data with registered imagery. Methods for manual or automated as-is modelling exist [13,22]. High resolution imagery can be used for texturing elements. Textures are stored in common 2D image formats such as jpeg or png. UV mapping is the process of applying a flat, two-dimensional image onto a three-dimensional shaped object [27]. With these methods, a fully textured as-is digital representation from a real structure can be compiled such as the one shown in Fig. 1. The textures include very small surface details from the real surface such as cracks, aggregate and spider nets. Hence, these models can be used to research, if they are sufficient for manual or automated defect detection.

Any method, automated or manual, has to achieve at least the same inspection quality as the state of practice: a team of human inspectors on site. Two metrics define the level of inspection quality for the scope of this work: the risk of missing a defect and the ability to generalize over healthy and potentially unhealthy areas.

Determining the performance of existing inspection schemes regarding the risk of missing a defect is difficult. No up-to-date study exists. Phares et al. [28] did an investigative study to evaluate the performance of bridge inspectors. They found out that inspectors tend to miss documenting 46% of the defects. Authorities adopted inspection schemes since then. One of the adoptions was to change from a component inspection level to an element inspection level. A performance evaluation of the new scheme is missing. Hence, any automated inspection method has to have a considerably lower risk of missing a defect than the one determined by Phares et al. The second metric, generalization, is difficult to measure quantitatively for the scope of this work. Nevertheless, it is an absolute requirement for the evaluation. Human inspectors generalize well, as they are able to identify and examine suspicious areas based on their experience even if inspection guidelines do not list rare, untypical types of defects.

1.2.1. Appearance of healthy and potentially unhealthy concrete

A general definition of the appearance of potentially unhealthy or healthy concrete does not exist. Newly build reinforced concrete is approximately homogeneously coloured. The admixed aggregate and sand appear as small spots in different colours (depending on the mixture, white, shades of brown, almost black).

Multiple influences immediately change the appearance of a concrete surface already during construction. For example, shrinkage during hardening and design loads plus gravity, traffic and environmental loads lead to initial capillary cracks in the concrete. These cracks are difficult to see with the naked eye and do not constitute a defect, hence are not to be considered as potentially unhealthy. Formwork marks, minor corroding metal pieces (e.g. nails left from construction) and differences in concrete texture are also common and occur frequently on concrete surfaces. Environmental influences such as rain, vegetation or dirt change the concrete surface texture over time. These influences vary depending on the location and exposure. Momentary environmental conditions during the data collection, such as strong sun or rain, have an additional effect on the image texture. Fig. 2 shows multiple examples of such normal patterns: (a) dust and spider webs, (b) formwork marks, (c) water stains and (d) strong shadows.

Potentially unhealthy areas are all areas relevant for an inspector to take a close look for the scope of this work. These are primarily concrete defects, but also include signs of vandalism, graffiti and littering. Inspection manuals list typical examples of concrete defects. Huethwohl et al. [11,12] analysed multiple inspection manuals from different continents. Spalls (e), cracks (f), rust stains (g), efflorescence (h), scaling and abrasion/wear are the most common ones and pictured in Fig. 2.

Methods for detecting potentially unhealthy/healthy concrete use a two-dimensional image as input. The three-dimensional shape is irrelevant for most considered defect classes, as long as the texture image is undistorted. Abrasion/wear is the only defect class that primarily affects the shape. Abrasion/wear is excluded for the scope of this work as these defects are not visually detectable in 2D images and state of the art as-is models do not model such minor shape deformations.

1.2.2. Research on concrete defects

The research community has shown interest in tackling the challenge of separating potentially unhealthy from healthy concrete, yet has not been able to entirely address the problem for bridges. General approaches directly address the problem of distinguishing potentially unhealthy and healthy areas in one step by using a single metric for all possible potentially unhealthy candidates. McRobbie et al. [25] tested fifteen different feature descriptors such as entropy, standard deviation, mean value of area, quadtree decomposition and different edge

Fig. 1. 3D as-is model of fully-textured RC highway bridge, deck view on the left, bottom view on the right.