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Laser-based surface damage detection and quantification using predicted surface properties

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ABSTRACT

Damage due to age or accumulated effects from hazards on existing structures poses a worldwide problem. In order to evaluate the current status of aging, deteriorating and damaged structures, it is vital to accurately assess the present conditions. It is possible to capture the in situ condition of structures by using laser scanners that create dense three-dimensional point clouds. This paper investigates the use of high resolution three-dimensional terrestrial laser scans coupled with images to capture geometric range data of complex scenes for surface damage detection and quantification. Although using images with varying resolution to detect cracks is an extensively researched topic, damage detection using laser scanners with and without color images is a new research area that holds many opportunities for enhancing the current practice of visual inspections. Thus, this paper mainly focuses on combining the best features of laser scans and images to create an automatic and effective surface damage detection method, which will reduce the need for skilled labor during visual inspections and allow automatic documentation of related information. A novel surface normal-based damage detection and quantification method that uses the local surface properties extracted from laser scanner data along with color information is presented. Color data provides information in the fourth dimension that enables detecting damage types such as cracks, corrosion, and related surface defects that are generally difficult to identify using only laser scanner.

1. Introduction and background

In 2013, the American Society of Civil Engineers (ASCE) released the most recent ASCE Report Card for America's infrastructure; this report depicts the current condition and performance of the nation's infrastructure [1]. In this report, the average grade for all infrastructure types was a D +. This result demonstrates the importance of accurately assessing the current status of aging, deteriorating and damaged structures and taking necessary precautions based on these up-to-date assessment results.

In recent years, applications of improved non-destructive testing methods for assessing the current conditions of structures have become more frequent. The traditional methods along with the new techniques have been increasingly used for determining and tracking structural integrity and assessing the nature of damage in a structure; some of the common methods include tap tests, impact-echo, ultrasonic measurements, acoustic emissions, gamma-ray radiography, ground penetrating radar, etc. [2,3].

Even though non-destructive evaluation technologies for structures have improved significantly, visual inspection is still the primary tool to assess conditions of structures such as bridges and transportation infrastructure, power generation and transmission systems, above-ground pipeline systems, rail systems, dams and levee systems, and other exposed infrastructure. These inspections are important to track any changes that occur on structures during two successive inspections and also to ensure that the structures satisfy all applicable serviceability requirements. However, the results obtained through visual inspections may lack consistency that is essential to assess the current condition of structures effectively; moreover, such inspections are time consuming and even dangerous in some cases.

This research investigates the use of high resolution three-dimensional terrestrial laser scanners with image capturing abilities as tools to capture geometric range data of complex scenes for structural sensing and surface damage detection. These strategies use camera-integrated laser scanners as an inspection tool that performs damage detection and characterization. Since the camera-integrated laser scanners are capable of capturing point clouds that provide information on the entire structure, in contrast to the current strategies, it is possible to develop a quantitative and systematic inspection strategy that involves no human/computer interaction. This approach allows the inspection

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information to be retained for future investigation, and it provides opportunity for comparative investigation over time.

Laser scanning capabilities have advanced significantly in recent years and have gained more recognition as a tool for applications in numerous fields. In the civil engineering domain, laser scanning technology has been used for several applications that include health monitoring, damage detection, etc. Recently, work has been done exploring the use of lasers for tracking in-situ deformation of undamaged structural components, such as beams and columns [4–6]. In another study, in order to monitor civil infrastructure systems such as long span bridges and to obtain direct measurements of absolute displacement time history at predefined locations (laser tracking references), a new vision-based approach, which consists of high-resolution depth cameras, has been developed [7].

Another commonly investigated application for laser scanners is to track changes, mostly during construction, by comparing two successive scans that are recorded throughout the process. In some studies, the algorithms attempt to locate objects in the as-built geometry based on the BIMs of the as-designed geometry. Tracking of components within a point cloud during construction has been investigated in Bosche and Haas [8] and Chi et al. [9]. In another study, laser scanners are used to conduct quality assurance. In their work, the model is compared to the as-is condition of the structure to identify potential errors in the model [10,11].

A more recently developed application is to capture in situ damage or collapse of a structure by using laser scanners, in which individual laser scans of a scene may be captured from different viewpoints to permit the creation of a complete 3D record of a damaged structure [12]. In Anil et al. [10,11], laser scanners are used to represent crack information on the surface of structures using a BIM approach. They also developed a building-information-modeling–based earthquake damage assessment methodology for reinforced concrete walls [13]. Teza et al. [14] used terrestrial laser scanner datasets to perform concrete surface damage recognition using mean and Gaussian curvatures of the surface of structures. These types of applications enable localization and quantification of surface damage in order to enhance the current visual inspection strategies.

Laser scanning technology is also used for condition assessment of wide areas as well. The terrestrial-LIDAR technologies are used to visualize the surface and structural deformations in Kayen et al. [15]. Olsen and Kayen [16] discussed the challenges and benefits of using 3D laser scanning on post-disaster reconnaissance efforts. Protopapadakis et al. [17], Stentoumis et al. [18] and Verykokou et al. [19] focused on UAV-based autonomous, computer vision based, robotic inspection strategies for both inspection and disaster modeling. Kashani et al. [20] used terrestrial laser scanners to perform damage assessment on structures affected by tornados and to use this information to estimate wind speeds. Yamada et al. [21] introduced a mobile robot system for road surface damage detection in order to reduce the workload of human workers engaged in road maintenance.

Even though texture-mapped point clouds have been used in several applications, their usage for localization and quantification of surface damage is still an advancing research area. In this paper, a new method that uses a combination of surface normals, which reflects local geometric properties, with or without the recorded intensity value at a given point for detecting damage, is proposed. This proposed method is then tested on several experimental and in-situ setups and the results are presented in the subsequent sections.

This paper includes a portion of the developed methodologies and corresponding results of research that aims to establish automated inspection strategies for large-scale structures and infrastructure systems, including bridges and transportation infrastructure, power generation and transmission systems, above-ground pipeline systems, rail systems, dams and levee systems, and other exposed infrastructure, and to propose a new automated strategy for damage quantification and documentation that will enhance current practice for infrastructure inspection. The purpose of this research is to provide solutions for different damage types and states that can be organized into three categories: small deformations, large deformations with no change in topology, and large deformations with localized change in topology. The main focus is to use texture-mapped point cloud data for locating and quantifying surface damage. In this paper, first, a novel surface-based damage detection strategy was shown to efficiently locate and quantify the targeted defect types, which include cracks, corrosion, ruptures, and spallings. The model properties of the detected surfaces, objects, or both were then used to locate the defective areas on the structural surfaces. Once the defected regions are located, a clustering methodology was developed to group the detected defect point into individual damage clusters. In order to group the related clusters, a silhouette-based cluster evaluation method was used to optimize the final number of defect clusters. Finally, a new mesh-grid based damage quantification system was developed to quantify both area and volume of the detected damage. Thus, the primary aim of the work is on enhancing current visual inspection methods and developing automated geometry reconstruction and damage detection strategies to locate and quantify the surface defects that fall under the listed damage categories by using advanced sensing technologies, including terrestrial laser scanners and sensor-integrated unmanned aerial vehicles (UAVs).

The organization of this paper is as follows: first, Section 2 presents information of the available datasets and also the different laser scanners used for data collection; Section 3 then, outlines key steps required for processing of point clouds with a focus on information needed for laser-based surface damage detection; Section 4 outlines the steps of the developed surface-normal based damage detection methodology; Section 6 focuses on the results and discussion; Section 7 then provides conclusions on this work.

2. Available datasets

In this research, several datasets are used for both structural sensing and damage assessment. These datasets can be listed as a concrete frame that was tested at 1/8 scale, a bridge in Dekalb County, Illinois, and the Bowker Overpass in Boston, Massachusetts.

2.1. Concrete testing frame

The concrete testing frame dataset was collected from an experimental test specimen that was used to predict the progressive collapse resistance of a 1/8th scale 2D physical model of a reinforced concrete structure in 2007 [22,23]. The test setup is a 114″ by 63″ frame that consists of 3 stories with 4 equal length spans. The beam and column legends for the testing frame are shown in Fig. 2.1.

A FARO Focus3D scanner was used to capture 10 scans around the test setup at varying elevations, where each scan took approximately 7 min. These separate scans and images collected during scanning were later registered by the Faro Scene software in order to get the complete texture-mapped point cloud dataset for the concrete testing frame. The

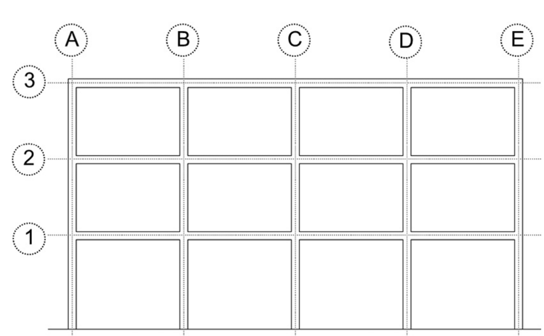

Fig. 2.1. Beam and column legends of the testing frame.