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CONDITION DIAGNOSTICS OF STEEL WATER TANKS USING CORRELATED VISUAL PATTERNS

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Abstract: Insufficient, unreliable, and delayed condition assessment of steel water tanks is causing poor maintenance planning, wastes of maintenance resources, and unexpected structure failures. Visual inspection of water tanks heavily relies on engineers' experiences for achieving comprehensive and reliable condition assessments. Recent studies reveal the potential of using imaging technology for improving the efficiency and comprehensiveness of capturing visual conditions of large civil infrastructures, but manual interpretation of imagery data still impedes engineers from reliable awareness of structural conditions. On the other hand, some studies show that deteriorations of structures result in correlated visual patterns that can assist engineers in structural diagnosis. The objective of the research presented in this paper is to examine correlated deformation patterns of a steel tank based on analyzing 3D laser-scanned point clouds collected in the field. Specifically, the authors aim at identifying correlated shape change patterns of a water tank through various 3D data analysis algorithms, and synthesize these 3D data patterns as knowledge for guiding data-driven condition assessment of the water tank. The authors examined two 3D data analysis approaches for revealing the deformation patterns of the studied tank. The first approach calculates the deviations of the 3D data points from as-designed shapes of the water tank for identifying structural deformation and defects. The second approach visualized anomalous variations in local shape descriptors, such as curvature, for identifying defects of structures. Correlations between the patterns could then reveal systematic changes of the tank for helping engineers conduct more reliable condition assessments.

1 INTRODUCTION

Many civil engineering structures are prone to damages and deformations. Structural damage evaluation has become very important part of maintenance. Statistics estimate that to eliminate the deficit bridges by 2028, the nation has to spend minimum of $20.5 billion per year by, however only $12.8 billion is being spent for design, construction, replacement, and rehabilitation of bridge structures (Cooper and Munley 1995). To accommodate these funds in a right way there is a need for a systematic approach that can find the root cause and avoid unnecessary repair work behind these structural failures. Detailed geometric assessment of civil infrastructure is essential for reliable maintenance planning and public safety. Non-destructive testing such as visual inspection of a structure only offers a broad view of the structures' current state, but fails in providing the root cause of the structural damage. Hence, comprehensive geometric data is essential for effective structural rehabilitation. Using imagery sensors to capture meticulous data of a structure precise to 2mm range distance can support detailed structural assessment. Such detailed data could help in eliminating unnecessary repair work of an infrastructure by exactly identifying area that requires structural renovation. However, manual interpretations of such detailed geometric data require professional experience and are sometimes error prone. Correlated deformation patterns can assist engineers in accurate visual data interpretation and achieving reliable structural assessment. For example, collective growths of cracks and deformations on interconnected components reveal the changes of loading paths across a structure and likely defects. Formalizing these correlated visual patterns as signatures of structural health conditions hold strong potential in reducing the reliance on engineers' experiences in structural health monitoring.

Building surveyors play a key role in maintaining the structural integrity of the building during and after construction process. Surveyors use high quality optical instruments such as Total Stations for geometric measurements of a structure (Fröhlich and Mettenleiter 2004). These measurements include distance, horizontal and vertical angles and the coordinate information of the measured component. However, the density of the measured data completely relies on surveying time (Erickson, Bauer, and Hayes 2013). Furthermore, the instrument should move several times in order to get the complete structure and have portability limitations. Additionally the instrument requires a licensed professional to operate and record the measurements. Moore et al. (2001) highlights the limitations of visual inspection for surveying highway structures. Currently LIDAR (Light Detection and Ranging) technology has gained popularity over the conventional surveying systems (Jaselskis and Gao 2003). Researchers used 3D laser scanning technologies to analyze the deformations of bridges and identified the advantages of capturing geometric details for achieving more effective Finite Element Modeling (FEM) and analyses of existing facilities (Dai et al. 2013; Park et al. 2007).

However, reliable visualization of the captured data and accurate conditional geometric assessment is still error prone. Goor 2011 stated that registration errors and measurement errors could affect the quality of deformation analysis. He proposed using Iterative Closest Point (ICP) algorithm for accurate surface matching to eliminate registration errors. However, this approach is manual and requires lot of time to process. Many of the existing research indicate the challenge of reliably associating data collected from the laser scanner with the as-designed model of a building structure (Kalasapudi, Turkan, and Tang 2014). This association will aid in deformation detection by identifying changes between as-is condition and as-designed condition. Yet, identifying the root cause of detected deformation of a structure is still unreliable as many factors may cause the structure to undergo such deformations.

This paper focuses on formalizing the data processing procedures to detect deformation patterns for efficient structural health monitoring of water tanks to improve the 3D data interpretation in assessing a water tank. Initially, the authors detected the deviations of 3D as-is laser-scanning data with the as-planned model of water tank structure to analyze its spatial changes (Section 4). This step identifies various defects and deformation of every individual component of the tank. The authors then correlated the detected deformations to identify patterns that lead to systematic changes of the tank during its service period (Section 5). This detailed geometric assessment of the structure can help reduce the incorrect decisions of building maintenance, and reduce unnecessary costs or propagative errors.

2 APPLICATIONS OF 3D IMAGERY TECHNOLOGY IN STRUTURAL INSPECTION

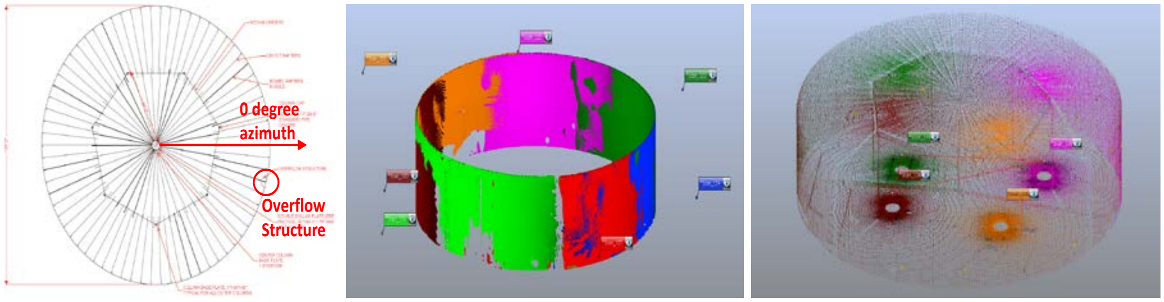
Previous studies in the domain of construction and infrastructure management examine the technical feasibilities of using 3D imaging systems in geometric assessments of various buildings and structures. Park et al. 2007 carried out an experiment for health monitoring of a simply supported steel beam and compared to the results obtained from other diagnostic techniques such as electric strain gauges, long-range fiber optic sensors etc. Lee and Hyo 2013 estimated the maximum stress in a steel beam structure using a 3D coordinated data from a laser scanner. Allard et al. explored the potential of using 3D imagery data for mechanical damage inspection on an aircraft. They stated that the major advantage of using Laser scanning is to minimize the total time of inspection of the aircraft by fast decision making along with immediate on-site results. Lemmon (2011) has explained the feasibility of using laser-scanning technology for structural geometric calibration and deformation detection of large storage tanks.

Various 3D data processing algorithms developed in the past that can process the data obtained from a laser scan (Yang, Wang, & Chang, 2010, Tarsha-Kurdi, 2007, Girardeau-Montaut, 2011). Some algorithms are computationally efficient enough to achieve real-time data processing that support decision making process of engineers (Girardeau-Montaut 2011). In this paper, the authors analyzed the 3D scans of the steel tank using existing algorithms and developed an approach for efficient geometric assessment of the large steel tank to correlate detected deformations. The following section details the data collection and processing procedure, and describes the diagnosis approach.

3 OVERVIEW OF THE TEST SUBJECT AND THE DATA COLLECTION PROCEDURE

In order to analyze the feasibility of using LIDAR data for geometric assessment, the authors selected an existing Steel Water Tank as a test subject. This Steel Water Tank is a combination of a cylinder at the bottom and a cone at the top. According to the as-built drawings, the tank has a radius of 21.34 meters and a height of 11.43 meters in total, in which 9.75 meters is of cylindrical part, and 1.67 meters is of the conical part. To identify the defects/deformations the authors use a cylindrical co-ordinate system.

The cylindrical co-ordinate system use ‘Radius’, ‘Azimuth’, and ‘Elevation’ to locate 3D points in space. The azimuth starts with 0 degree and ends with 360 degree to form a circle representing the cylindrical body of the tank. The authors define the East Direction as zero azimuth that serves as the origin to the cylindrical coordinate system (Figure 1 (a)). The authors collected eleven scans that comprise of four interior (inside the tank) and seven exterior scans. To filter the redundant data from the collected 3D scans, the authors pre-processed them for accurate data processing. Data pre-processing is an important step for obtaining efficient results. Scans collected for the Steel Water tank contains lot of redundant information, which influences the accuracy of geometric assessments. They contain large amount of noises such as reflections, unwanted background, movements of people, or other objects surrounding the test subject etc. The authors filtered the actual data from the noise and then executed the data processing algorithms in order to extract accurate information from the raw data. Most the pre-processing algorithms are available in many of the commercial software. The authors used Faro Scene (FARO Technologies Ltd.) pre-processing algorithm to filter the scans. The authors then performed the registration of all the 3D point cloud data collected at multiple locations together into a global coordinate system from their respective local coordinate axis (Figure 1(b) and Figure 1(c)).



(a) (b) (c)

Figure 1: (a) 0° Azimuth Location. (b) 3D Point Clouds Collected outside the Tank after 3D Registration and Data Cleaning. (c) 3D Point Clouds Collected inside the Tank after 3D Registration and Data Cleaning

4 GEOMETRIC AND DEFORMATION ANALYSIS OF 3D LASER SCAN DATA

The proposed framework involves segmentation of 3D Laser scan data of the steel tank into several individual components. Such components include roof, floor, rafters, and columns of the steel water tank. For analyzing the deformations of the tank, the authors aligned the registered 3D point cloud data against a cylinder with a radius of 70 feet. To compute the deviations of 3D data points, the authors extracted a cylinder from the point clouds. Such fitted model is a perfect cylinder, and deviations from it indicate possible local deformations of the tank. Figure 2 shows the comparison of the 3D point cloud and the fitted model. This figure visualizes the deviations along the radial direction: red colors show “positive deviations” pointing outward the surface of this cylinder; blue colors show “negative deviations” pointing inwards the surface of this cylinder.

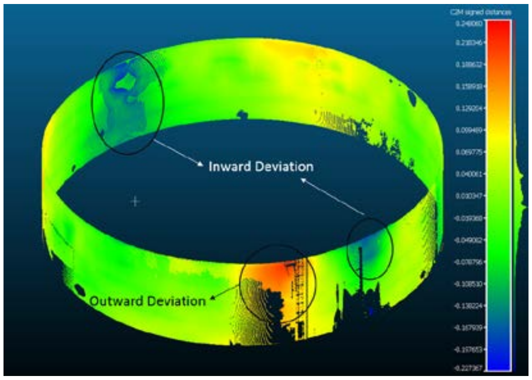


Figure 2: Comparison between 3D point cloud and fitted model

Table 1 shows the list of all the analyzed components and their respective detected deformations (Figure 3). Major conclusions for the geometric analysis include:

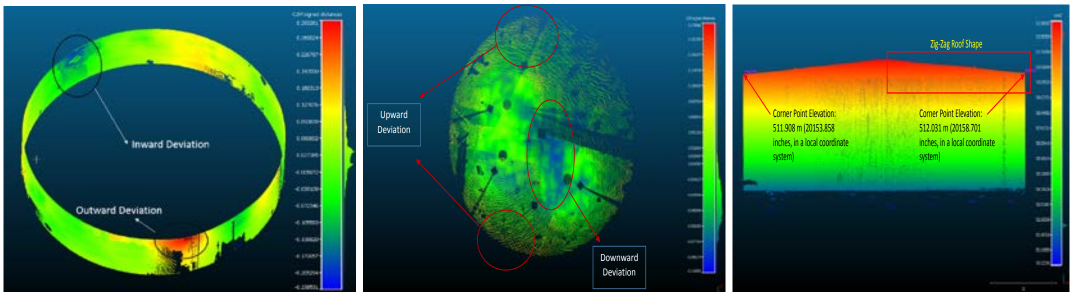
- The tank does not have obvious tilt, but the floor has a slight tilt that makes the West part of the floor lower than the East part. In addition, the central part of the floor observed to have higher elevation than the parts closer to the shell. Hence, these analyses may indicate settlements of the tank.

- The wall of the tank has elevation differences between the east part and the west part, such that the east slope of the roof is only 3.27 degree, smaller than the 4.42 degree slope specified in the as-built drawings

- Both the conical shapes of the roof and floors have a smaller height than the as-built cones of the roof and the floor. The authors also detect that the central region of the floor is flat and horizontal, most of the slope angles measured on these two conical shapes are smaller than their as-built values, and the settlement of the central column may be the reason for such observations.

- The authors detected a Zigzag pattern on some rafters that are located on East part of the roof. The turning point of that Zigzag is around the connection between the internal rafters and the girders supported by internal columns.

- Curvature analysis of the roof shows that three regions on the roof have relatively larger curvatures possibly caused by deformations of the roof and girder.



(a) (b) (c)

Figure 3: Observed Deformations of the steel water tank

Table 1: 3D data analysis procedure and the observations

	ANALYSIS PROCEDURES	OBSERVATIONS
EXTERIOR SURFACE ANALYSIS	Deviation of the exterior surface from a cylinder extracted from exterior point cloud	The maximum outward deviation and inward deviation is 0.248 m (9.76 inches) and -0.227 m (8.937 inches) respectively
	Exterior radius distribution analysis along the height of the tank	The radius of the tank increases gradually from the bottom to the top except it decreases drastically at the top of the tank.
INTERIOR SURFACE ANALYSIS	Interior floor flatness analysis	1. Two small regions at the North and South borders of the floor surface are about 8 cm above the surface of the cone. 2. The central part of the floor has higher elevations compared with the parts close to the tank shell, the central part of the interior floor surface is flat and horizontal, while the North and South sides have some deformations Above two observations seem to be indicators of the settlement of the central column (or the relative faster settlement of the central column compared with the shell of the tank)
	Elevation and slope analysis of the roof	The as-design slope is 4.42 degree; average slope of the east roof is about 3.96 degree. The west side of the roof has a slope of 3.27 degree. Both sides have slope angles smaller than the as-designed value, while the West side's slope is steeper and closer to the as-designed model The east roof and rafters seem to be "Zig-Zag," and the turning point of this Zig-Zag is around the internal rafters' connection with the "internal circle" of girders connecting interior columns
	Curvature analysis of the roof	Curvature values of the roof interior surface are larger for three regions: External rafters from -90-degree to -45-degree (Southeast, using the 0-degree azimuth coordinate system described before). Internal rafters from -135 degree to -45-degree (South). Internal rafters from -30-degree to 45 degree (East).
RAFTERS	Curvature of roof girders (5 Rafters that are observed to be warped)	Two of the 5 warped rafters have highest value of curvatures. (0.0378 and 0.0418) Three regions on the roof have relatively larger curvatures possibly caused by deformations of the roof and girder.

5 CORRELATIONS BETWEEN THE OBSERVED DEFORMATIONS OF THE WATER TANK

Correlated deformations between components of a structure occur if those components are connected, are in a similar environmental condition, or have same axis of orientation etc. Connected components move together under load conditions that cause correlated changes in them. For instance, the cylindrical body and the floor of the water tank show similar variations under loading conditions. The observed inward and outward deviations of the cylindrical surface (Figure 3(a)) of the tank correlate with the upward and downward deviations of the floor (Figure 3(b)) of the water tank. Similar environmental conditions can also lead to correlated deformation patterns. For example, common soil settlements have led to correlated tilt in the floor and roof of the water tank. The combined deformations of the roof and girders have caused the floor to undergo relatively large curvature changes at certain points, which have same axis of rotation.

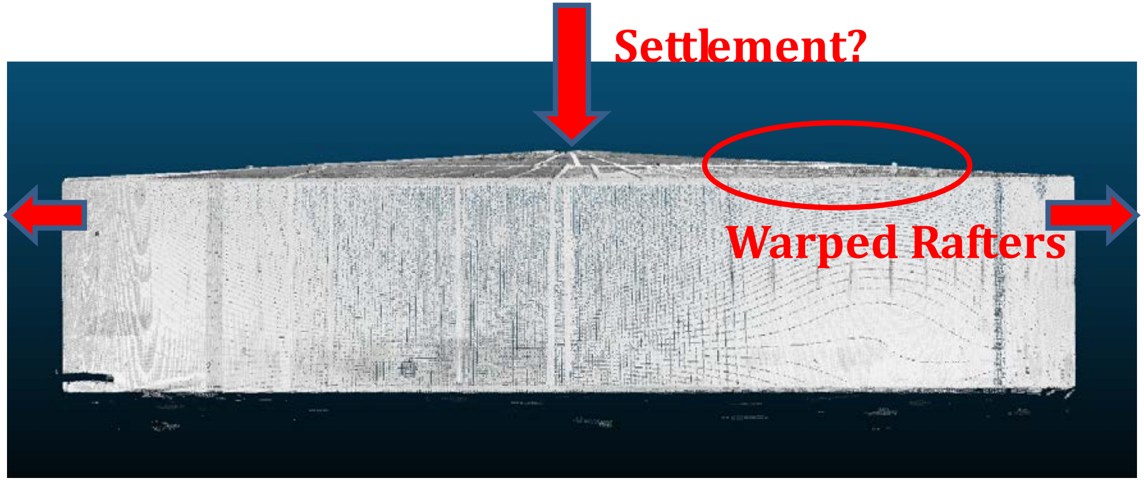


Figure 4: Combined column settlement and warping of rafters

Figure 4 shows the correlated deformation of the central column and the rafters of the tank. The authors observed that the differential settlement of the central column has caused the connected rafters to warp under axial compression. These warping of the rafters correlate with the inward and outward deviations of the cylindrical surface of the tank. In addition to the warped rafters and the surface deviations, the central column settlement correlates with the deviations of the floor of the water tank. The authors have tabulated (Table 2) all the observed correlations between individual segmented components to identify systematic shape change pattern of water tank for geometric diagnosis.

Using such correlated deformation patterns, the authors identify certain traits that can help in reliable geometric diagnosis. For example, thermal variations around the water tank can lead deformations in its exterior cylindrical surface. Since these deformation correlate with those of warping of rafter, such variations in temperature of the tank can further deteriorate the condition of the rafters. Further deviations in the cylindrical surface can predict the future warping of the rafter, which will be inaccessible during the service of the water tank. Similarly, the differential settlement of the exterior surface of the water tank could place the rafters in axial compression causing lateral bowing. Thus, predicting the long-term deformations of the inaccessible components of the water tank using their correlated deformation pattern with other accessible components can help in reliable life-cycle maintenance cost optimization.

Table 2: Observed Correlations

COMPONENT	CORRELATED COMPONENT	REASON FOR CORRELATION	DEFORMATION CORREALTION
Cylindrical Surface	Floor	Connected	The outward and inward deviation of the cylindrical surface correlates with the upward and downward deviation of floor
	Roof	Connected	The deformation on the cylindrical surface closer to the roof correlates with the Zig-Zag pattern and the elevation difference of the roof
	Rafters	Connected	Warping of certain rafters correlate with the deviations of the connected cylindrical surface
	Column	Same Axis	Settlement of the central column will eventually push the cylindrical surface to the outward direction
Floor	Roof	Same Axis	Both the floor and roof have slight tilt from its original axis
	Column	Connected	Differential settlement of the column caused upward and outward deviations in the floor
Roof	Rafters	Connected	Zig-Zag patterns on the roof relates with the warping of the rafters
	Column	Connected	Elevation difference (smaller height that as-planned) correlate with settlement of the central column
Rafters	Column	Connected	Central column settlement is likely the cause for warping of the rafters

6 CONCLUSION AND FUTURE WORK

This paper explores the technical feasibility of diagnosing a water tank structure based on analyzing correlated visual change patterns of the water tank structure. The studied structure underwent certain deformations during its life cycle. A 3D laser scanner captured detailed as-is condition of the structure to analyze the changes in structures geometry when compared to its as-designed model. The developed approach in this paper shows clear potential of aiding engineers in observing and diagnosing correlated deformation patterns for supporting the maintenance decision making of the structure. Based on these explorations, the authors determined systematic change patterns in the components of a water tank for detecting anomalous spatial changes from the 3D point cloud data for identifying structural risks.

This data-driven study of a water tank indicates that 3D laser scanning technology can help in reliable documentation of accurate as-built conditions of as structure in short time with high level of detail. Using the presented approach, the authors plan to develop automated geometric diagnosis of the structure from the data collected from a 3D laser scanner. This step includes generating algorithms that can automatically detect deviations of a structure, identify correlations between the identified deviations and create deformation histories for risk assessments. Detailed scans before, during and after renovation can provide an approximate disaster pattern of the structure. This study will also help in identifying the root cause of the damage to a structure and in proper resource allocation and rehabilitation planning.

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