COVER SHEET

Title: *Evaluation of using Structure from Motion Optical Techniques for Structural Health Monitoring of Railroad Tracks for* Proceedings of the **11th International Workshop on Structural Health Monitoring 2017**

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ABSTRACT

Routinely, civil, mechanical, and aerospace structures continue to be used despite that they are approaching or have already exceeded their design life. Structural monitoring techniques have the ability to indicate the onset of or avoid failure. Conventional sensing techniques like visual inspection and sensors such as accelerometers, strain gages, and acoustic transducers produce results at only a discrete number of points. Moreover, they can be labor intensive to install, have wire and power constraints, and the correlation between the sensor signal and structural integrity is not always straightforward. In the last few years, achievements made in camera technology, optical sensors, and image-processing algorithms allowed the development of a new generation of non-contact measuring methods. One of the most promising is Structure from Motion (SfM), a photogrammetric range imaging technique which makes it possible to obtain three-dimensional (3D) renderings from a cloud of two-dimensional images. The SfM approach has been widely used for large-area aerial inspections in the field of agriculture, geosciences, environmental disaster management, and heritage documentation. What is still missing is an evaluation of its feasibility for being used as a quantitative inspection technique for Structural Health Monitoring (SHM) purposes. In this study, an estimation of the accuracy of this non-contact, optically based measurement technique is experimentally performed. In particular, a number of laboratory experiments are executed on a real-size wood model of a railroad track to determine the capability of SfM in measuring crosstie vertical displacements, structural deformation, and geometry profiles. To validate the accuracy of the SfM measurements, a back-to-back comparison is made with Digital Image Correlation measurements. The strengths and limitations of the SfM approach for SHM are discussed and the measurement accuracy is quantified.

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INTRODUCTION

Railroad tracks include several parts such as rails, fasteners, crossties (or sleepers), ballast, and an underlying subgrade, each of them having different functionalities [1]. The rails are secured to the rest of the infrastructure by means of fastening systems (e.g. bolts, clamps, joint bars, anchor, etc.) for preventing unwanted displacement. The crossties are the transversal elements that support the rails; the ballast provides resistance to vertical, lateral, and longitudinal forces to facilitate load distribution; while, sub-ballast and subgrade act as a foundation for the whole infrastructure [2].

Crosstie degradation or loss in ballast support may produce railroad track failures, which can result in a number of problems ranging from simple service interruptions to derailments. For instance, dissimilar levels of abrasions experienced at different locations of the crosstie-ballast interface can result in locally supported crossties. It may cause uneven vertical displacements as a train transits. This phenomenon, referred to as center binding conditions, is one of the most common failure mechanisms for railroad tracks [3]. The interface between the crossties and the ballast is an area extremely difficult to access. Nevertheless, it is assessing its integrity is fundamental for the stability of the whole system. For this reason, a method for performing Structural Health Monitoring (SHM) assessments of the above mentioned issues are important to reduce risks, downtime, and maintenance costs [4].

Several measurement techniques have been implemented to monitor the railroad track health. Fixed hardware and contact-type sensors (e.g. strain gages, extensometers, accelerometers, impedance-based transducer, etc.) have been widely used and are extremely common for SHM [5]. However, installation is labor intensive and they typically provide information only at a few discrete points. In recent years, a great deal of attention has been given to non-contact measurement techniques. Systems such as Acoustic Emission (AE), active and passive infrared (IR) images, Ground Penetrating Radar (GPR), Interferometric Synthetic Aperture Radar (InSAR), Light Detection And Ranging (LiDAR), and Ultrasonic Testing (UT) have shown pros and cons for monitoring purposes [6-11]. Despite that, their costs and difficulties of being used for in-situ monitoring are serious drawbacks to their application for large-area inspections. As a result, inexpensive and cost-effective novel assessment techniques are continuously sought [12].

Recent development in camera technology, optical sensors, and image-processing algorithms have made three-dimensional (3D) Digital Image Correlation (DIC) and Structure from Motion (SfM) appealing tools for SHM of railroad tracks. While the feasibility of using 3D-DIC for extracting structural deformations, full-field mechanical parameters, and geometry profiles of the crossties has already been proven in the laboratory [13-15], an evaluation of the performance of SfM techniques for railroad track assessment has not been performed yet and provides the motivation for this research. SfM is a technique that allows building a 3D description of a static scene from a dense sequence of images [16]. This means that starting from a cloud of two-dimensional (2D) images, a 3D model of the targeted object can be reconstructed and "virtually" navigated to detect structural anomalies.

SfM is a photogrammetry technique based on finding "keypoints" between images. The keypoints are defined as common points between two or more images by using algorithms for detecting features (e.g. corner points, edges with gradients in multiple directions, etc.). In practice, as several images of the same object are taken from different points of view, a cloud of retinal data is generated [17]. By processing the images, SfM algorithms look for common features from one image to the next. When two keypoints on two or more different images are found to be the same, they are matched and will generate one 3D point. As a general rule, it can be stated that the more keypoints there are, the more accurately 3D points can be computed. Therefore, the recommended overlap for most cases is equal to 75% in the frontal direction (i.e. frontal overlap) and at least 60% in the transversal direction (i.e. side overlap). For a detailed description about the mathematical models and algorithms behind this technique, interested readers can refer to papers [17, 18]. SfM has been widely used for performing large-area aerial inspections in the field of agriculture, geosciences, environmental disaster management, and heritage documentation [19-21]. The quality of the generated 3D renderings is high and allows detecting features of the targeted object. What is still missing is an evaluation of this technique to be used as a quantitative rather than qualitative inspection tool.

In this paper, the preliminary design of a novel railroad tracks examination system that detects crossties' vertical deflection using SfM techniques is described. It consists of eight cameras installed on the underside of a rail car to detect the displacements and the deformation shapes of the crosstie as loads are applied. By comparing results obtained processing a set of 2D images of railroads using commercially available SfM software, an evaluation of the performance of this technique is provided. For validating the accuracy of the SfM-generated data, and evaluating whether or not they can be used as quantitative assessment technique, a back-to-back comparison is made with 3D-DIC measurements. If fully developed, the proposed systems would enable track inspectors to perform more frequent, cheap, and cost-effective measurements of tracks while trains are moving at typical operating speeds (e.g. 60 mph).

EXPERIMENTAL SETUP

For judging the capability of SfM in performing quantitative inspection and being used as an effective SHM assessment technique, a set of tests has been performed. In the example presented in this research, a group of eight cameras were installed over the test article as shown in Figure 1a and used for capturing a sequence of images simulating the advancement of the train along the railroad. The camera employed for this experiment was a Nikon D3200 that had a zoom lens AF-S DX manufactured by Nikkor with a focal lens variable between 18 and 55 mm. Due to the camera working distances (i.e. 1.10 m and 0.84 m) and the selected focal length (i.e. 18 mm), the camera's field of view (FOV) covered an area of ~0.87 x 1.30 meters. Then, assuming a camera system installed underneath the train car similar to the conceptual one showed in Figure 2 and a train speed of 27 ms^{-1} (60 mph), images should be acquired every $\Delta t = 0.007$ s to guarantee an overlap of 0.67 m in the direction of motion (77% of frontal overlap). A frame rate of 135 Hz, which is easily obtainable with commercially available cameras, is required for performing this acquisition. In the experiments shown in this research, only a single camera was available at the time of the tests. Therefore, the advancement of the train was simulated by moving the camera by 0.20 m at each stage in an acquisition plan similar to that shown in Figure 3.

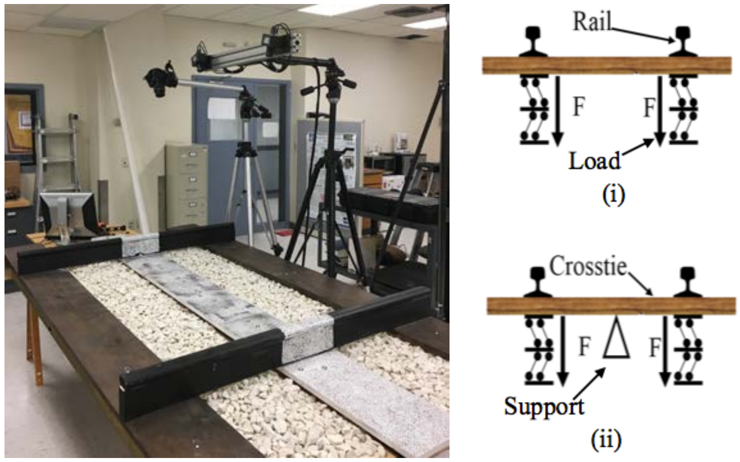

Figure 1. a) SfM and 3D-DIC cameras setup over the wooden full-scale model of a railroad track; b) Center binding conditions simulated during the performed experiments (not to scale): (i) uniform support, (ii) supported in the middle of the distance between the rails.

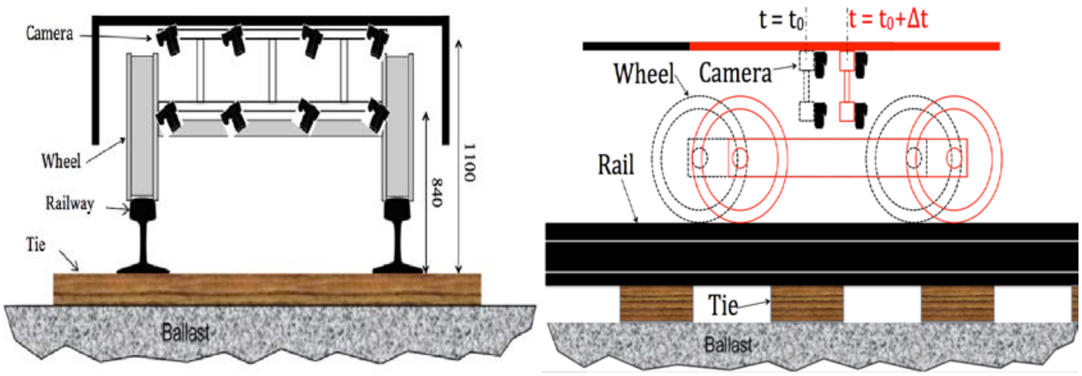

Figure 2. Conceptual setup of a SfM system that can be used to observe the tie deflection profiles attached to the underside of a moving rail car.

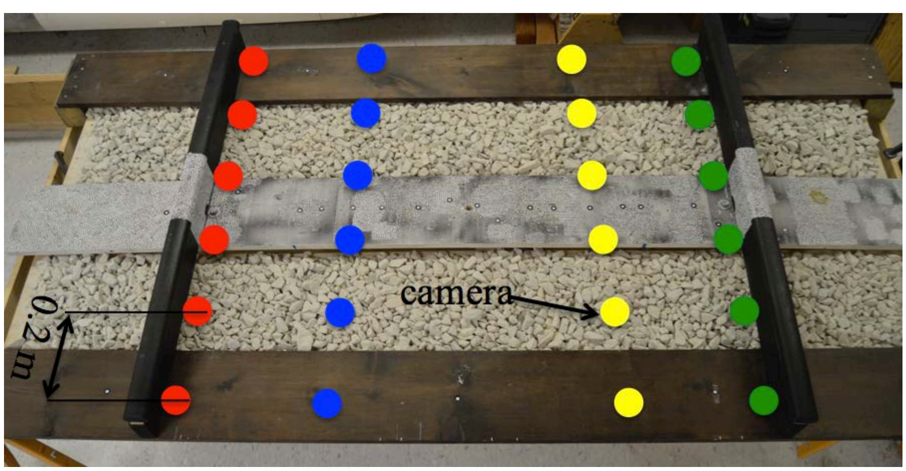

Figure 3. Image acquisition plan and location of the cameras' position over the test object.

As observed from Figure 1a, a 3D-DIC system was used for comparison purposes as a high-accuracy reference to measure the displacements of the crosstie as different loads were applied. The DIC camera sensors consisted of a pair of 2 Megapixel FWX201 series digital cameras manufactured by Baumer GmBH installed with 8.5 mm focal length lenses. The 3D-DIC system was positioned to have a working distance of 1 meter, a 36.5° separation angle, and a base distance of 0.68 m. In this configuration, the stereo-photogrammetry system allowed for measuring a limited area of 0.81 x 0.67 m. Moreover, to measure the performance of the proposed system, different center binding conditions were simulated on the middle tie of the setup shown in Figure 1a and measurements were recorded as two loading conditions (i.e. zero and 534 N) were applied to simulate the effects of the transit of a train. Figure 1b shows the two center-binding conditions replicated during the performed experiments, obtained by placing a wooden support underneath the loaded crosstie.

ANALYSIS OF THE RESULTS

The tests performed sought to evaluate the performance of commercially available SfM software to measure the out-of-plane displacement (i.e. vertical displacement Z) and deformation of the crosstie's longitudinal profile as different boundary conditions were simulated. For each of the analyzed configurations (i.e. two loads and two center binding conditions) a total of 48 pictures were taken and post-processed using the Pix4Dmapper image-processing software released by the Swiss company Pix4D SA. An example of the obtained 3D rendering is shown in Figure 4. As is it possible to observe, the generated 3D model is extremely accurate. Many features of the targeted object are recognizable, including the black-and-white optical targets stitched on the crosstie and the 3 mm speckles used as pattern for performing the 3D-DIC measurements.

As stated, the goal of the research is to evaluate the technology readiness level (TRL) for performing accurate and quantitative measurements for assessing the health status of railroads' crosstie-ballast systems. For validating the accuracy of the performed measurements, a back-to-back comparison with a 3D-DIC was performed. To process the recorded images, the Aramis software developed by GOM was used. In particular, the reference system has shown capabilities of detecting displacements on the order of $1 \cdot 10^{-5}$ m (noise floor range equal to [+0.0627; -0.0099] mm; noise floor interval amplitude equal to 0.0727 mm) as it is operated with the specifications shown in Table I. The data presented in Figure 5 shows the displacement experienced by the crosstie as different loads and the two boundary conditions shown in Figure 1b were applied. Measurements were performed in correspondence of the optical targets applied on the structure using both the 3D-DIC system and the different SfM software.

As can be observed from data reported in Figure 5, the SfM measure the zero displacement condition with an accuracy within ~± 1 mm, likewise it is able to detect with good accuracy the shape of the crosstie as it deforms. Comparisons between the results computed using the SfM technique and the measurements performed using the 3D-DIC system are summarized in Table II.

TABLE I. SETUP PARAMETERS FOR THE 3D-DIC MEASUREMENT SYSTEM

Facets		**Deviation**	
Size (pixel)	17 x 17	Calibration (pixels)	0.029
Step (pixel)	15 x 15	Scale (mm)	0.006
Speckles dimension (mm)	3	Intersection (-)	0.300

Figure 4. 3D SfM rendering of the mock railway tie laboratory experimental setup shown in Figure 1a obtained using the Pix4Dmapper image-processing software (left) and detail of the reconstructed model starting from a cloud of 48 2D images (right).

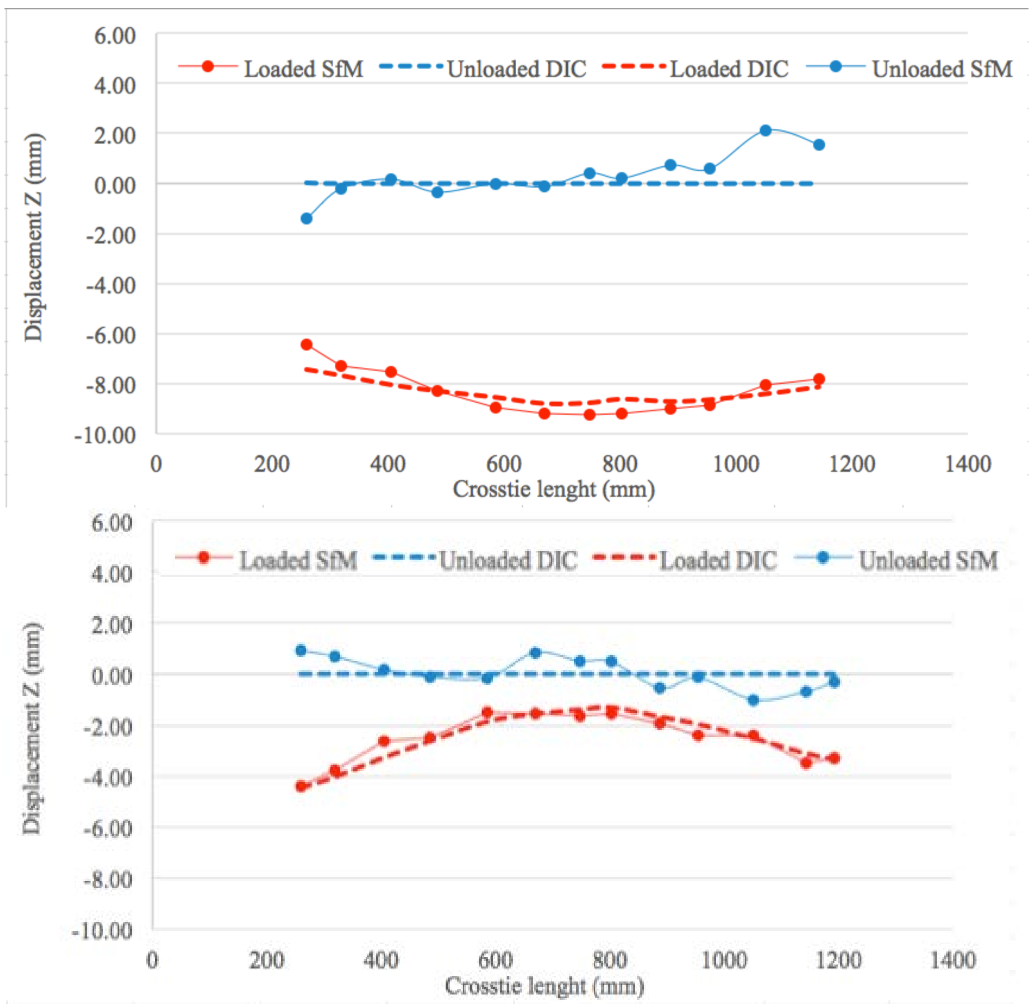

Figure 5. Comparison of the vertical displacement Z measured using the 3D-DIC and SfM systems for the two loading conditions and boundary conditions shown in Figure 1b: case i (top); case ii (bottom).

TABLE II. AVERAGE ABSOLUTE ERROR FOR THE ANALYZED SOFTWARE

Case i		**Case ii**	
Unloaded	**ε (mm)**	**Unloaded**	**ε (mm)**
Pix4D mapper	0.659	Pix4D mapper	0.506
Loaded	**ε (mm)**	**Loaded**	**ε (mm)**
Pix4D mapper	0.414	Pix4D mapper	0.246

For extremely small displacements, the accuracy of the SfM system is deviates from DIC measurement and this phenomenon could be due to the fact that displacements had the same order of magnitude of the noise-floor of the SfM software (i.e. ~± 1 mm) and cannot be detected by the system with the same accuracy of the 3D-DIC system (which has a noise floor on the order of 10^{-5}m). As the load is applied and the crosstie experiences higher displacements, the SfM detects deflections with good precision. Errors are equal on average to 0.583 mm and 0.330 mm for the unloaded and the loaded case respectively as a comparison with the higher accuracy system is performed. The results presented demonstrate that the SfM technique has good potential for performing analyses on the geometrical shape and deformation of the crossties.

CONCLUSIONS

In this study a novel system for optically assessing the condition of railroad tracks while trains are in operation is introduced. The final goal of this research is to develop a non-contact, automated, inexpensive, and fast method for identifying defects or damages before they become failures in service. By evaluating the crossties deflection profiles, an estimation of the state of the ballast and the health of the track's elements can be achieved. The system presented in this research employs Structure from Motion (SfM) techniques for obtaining three-dimensional (3D) renderings of the infrastructure from a series of two-dimensional images.

Structure from Motion is used for reconstructing a 3D model of a wooden, full-scale model representing a section of a railroad track, which can be virtually navigated to assess tracks' health. The results shown that this method is suitable for obtaining qualitative evaluations on the overall condition of the track starting from the analysis of some major features. Outcomes of the research demonstrate the efficiency of the system in highlighting defects at a macroscopic scale. The results obtained by processing the pictures recorded using a commercially available SfM software have been compared to measurements performed using a well-known and accurate technology such us three-dimensional Digital Image Correlation (DIC). The aim of these tests was to evaluate the capacity of the SfM techniques in performing quantitative assessment as the target object experienced different loading and center binding conditions. Experimental results have revealed that the accuracy of the SfM systems increases for larger crosstie displacements.

From results shown in this research, SfM has proven to be extremely promising and further investigation should be pursued to improve its functions for Structural Health Monitoring (SHM) evaluations. These might include both i) the development of machine learning algorithms for automatically evaluating the state of the track by just processing information from pictures and ii) software enhancements to increase the measurement accuracy and allow the extraction of those geometrical parameters of interest in the ballast condition assessment. Further developments of this technique could increase railway safety and reduce cost for condition-based maintenance. It would represent an easy-to-use, effective, and autonomous SHM system that would allow the detection of potentially dangerous situations while not interfering with train operations.

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