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Measuring Displacement of Railroad Bridges using Unmanned Aerial Vehicles

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Summary

As a part of research programs funded by the Association of American Railroads' Strategic Research Initiatives, the University of Illinois at Urbana-Champaign has conducted research using unmanned aerial vehicles (UAVs) to determine the displacement of a railroad bridge during revenue service traffic, which has been related to service condition limit states. This research used computer vision techniques to extract bridge displacements from the images taken from the UAV's onboard video camera. The proposed method is composed of three main parts:

- Development of a target-free method to estimate displacements of an object in a video using commercial grade cameras.
- Estimating the motion of the UAV's camera from the recorded video by tracking background features.
- Resolving the absolute displacement of the railroad bridge from the processed video.

While awaiting Federal Aviation Administration approval to fly in the field, preliminary tests were conducted in the laboratory to validate the proposed approach. Measured vertical displacements from a pin connected truss bridge in Rockford, Illinois, were reproduced on a hydraulic simulator. The UAV was flown from a distance of 15 feet (simulating the standoff distance to not foul the track), and resulted in estimated displacements with a root-mean-square error of 0.08 inch. The precision of the displacement estimates will be a function of a number of factors, including distance from the bridge, resolution of the camera, etc. Data fusion techniques using the UAV's onboard inertial measurement unit are currently being considered to improve this accuracy of the displacements estimates; preliminary results indicate an improvement of roughly a factor of 5 is possible. Use of such displacements have been proposed to assist railroad owners in prioritizing maintenance, repair, and replacement policies.

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INTRODUCTION AND MOTIVATION

As a part of research programs funded by the Association of American Railroads Strategic Research Initiatives, UIUC has conducted research to determine the displacement of a railroad bridge under revenue service traffic using unmanned aerial vehicles (UAVs) equipped with commercial-grade video cameras.

Railroads must ensure bridge safety by conducting annual inspections and maintaining bridge management programs.[1] Inspection and rating practices recommend observing the displacement of bridges under revenue service traffic. Moreover, researchers have proposed the use of such displacements to assist railroad owners in prioritizing bridge maintenance, retrofit, and replacement strategies.[2] Indeed, determining bridge displacements under revenue service traffic has been identified as a top research priority of the railroad bridge structural engineering community in North America.[3]

While such displacements are difficult to measure due to limited access and a fixed reference being required, researchers have developed some methods, including LVDTs,[4] lasers,[4] accelerometers,[5,6] and GPS.[7] However, these methods all have limitations with respect to installation, cost, accuracy, and complexity.

This study investigates the potential use of commercially available UAVs equipped with commercial-grade cameras to measure the displacement of the railroad bridges under revenue service traffic.

PROPOSED METHOD

The underlying framework for the proposed method employing a UAV-mounted camera is comprised of three main components. The first is target-free measurement of the displacement of the bridge relative to the UAV's camera; a key feature here is that no target is required to be placed on the bridge. The second is estimating the UAV camera's motion by tracking background features in the video. The final component is resolving the signal to obtain the absolute motion of the bridge.

Target-Free Displacement Measurement

The first step in target-free displacement measurement[8] is camera calibration, which is needed to: (1) remove the radial distortion from images taken with consumer-grade cameras, and (2) construct the intrinsic matrix, in which are embedded camera properties necessary for subsequent mapping from world coordinates to image coordinates. The camera calibration process can be conducted by taking pictures of known, regular geometry from different points of view, as shown in Figure 1. Next, the dynamic response of the bridge relative to the UAV's camera is determined by analyzing the captured video frame-by-frame. Natural features that can be tracked effectively are extracted using the method suggested by Harris and Stephens.[9] After the features are selected in the initial frame, the KLT method[10] is employed to track these points for the entire duration of a video using optical flow.

Finally, the displacement of the bridge relative to the UAV's camera is obtained.

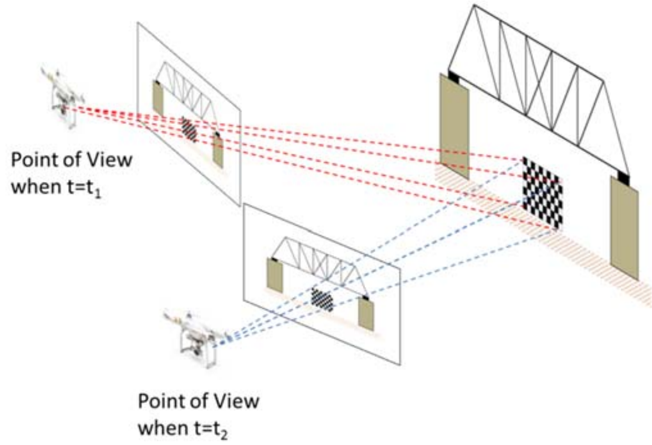

Figure 1. Camera Calibration and Ego-motion Estimation

Estimating UAV Motion

Subsequently, the 6 degree-of-freedom (6 DOF) motion of the camera on the UAV is estimated using fixed, background features. Note that the motion of the camera and UAV are related, but not identical, due to the independent action of the gimbal attaching the camera to the UAV. In the field of computer vision, the motion of a camera with respect to some reference frame is called ego-motion, herein it corresponds to the position and orientation of the UAV's camera. Together with the intrinsic matrix obtained in the camera calibration step, the ego-motion is determined by tracking selected fixed background points. The position and rotation vector for the UAV's camera is then calculated using multiple-view geometry, as shown in Figure 1.

Absolute Displacement Estimation

Once the position and the orientation of the UAV's camera is determined, the camera projection matrix, which maps the 3D points in world coordinates into image coordinates, can be calculated by combining the intrinsic matrix and estimated 6 DOF motion of the camera. Finally, by neglecting the out-of-plane bridge motion (i.e., transverse to the longitudinal axis of the bridge), the feature points in the bridge can be resolved into global coordinates using the calculated camera projection matrix. The displacement vector obtained from this process is the absolute displacement of the bridge.

LABORATORY VALIDATION

Experimental Setup

The Federal Aviation Administration has placed considerable restrictions on flying UAVs in the field. Therefore, preliminary experiments were conducted in the Newmark Structural Engineering Laboratory at UIUC to validate the proposed approach. The vertical motion of a pin connected truss bridge owned by CN near Rockford, Illinois, subjected to revenue service traffic was measured and reproduced on a servo-hydraulic motion simulator (Figure 2). The DJI Phantom 3 Professional (Figure 3) UAV mounted with a 4K resolution (4096x2160) video camera operating at 24 frames per second was used for this experiment. The UAV recorded the video at a distance of 15 feet from the motion simulator, which corresponds to the distance so as not to foul the track (Figure 4). To have a reference by which to assess the accuracy of the proposed method, a Krypton 3D measurement system with an accuracy of 10^{-3} inches was installed on the servo-hydraulic motion simulator.

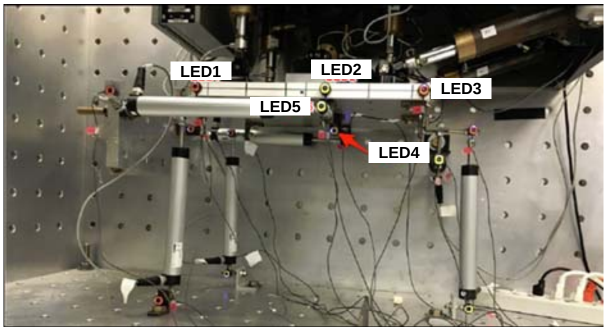

Figure 2. Motion Simulator with Krypton LEDs

Figure 3. UAV DJI Phantom 3 Professional

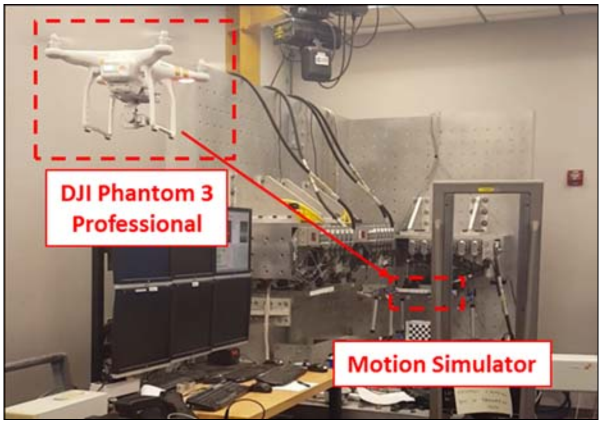

Figure 4. Experiment Setup using Motion Simulator

Experimental Result

Figure 5 shows the relative displacement of the UAV's camera with respect to the bridge estimated from the video taken with the UAV. When compared with the reference measurement of the simulated motion of the bridge, little information about the motion of the bridge appears to be contained in this signal.

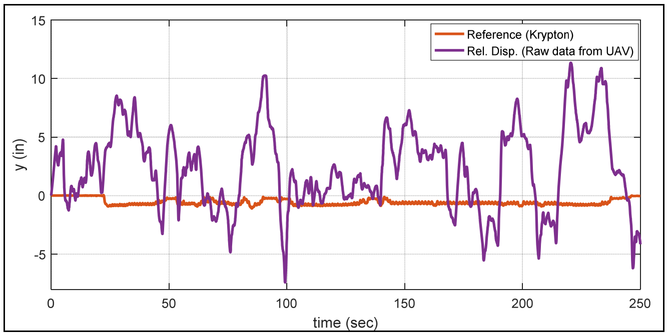

Figure 5. Relative Displacement with Respect to UAV

Using the ego-motion estimation method, the 6 DOFs of the UAV's camera were determined. As illustrated in Figure 6, the motion of the UAV and the camera is complex, as it contains significant translations and rotations.

Figure 7 shows the absolute displacement of the bridge determined using the proposed method, as compared with the Krypton 3D measurement reference. The estimated displacement matched well with the simulated vertical motion of the railroad bridge. The root-mean-square (RMS) error was 0.08 inch, corresponding to 1.2 pixels of resolution. These laboratory results demonstrate the potential of using a UAV equipped with an onboard video camera.

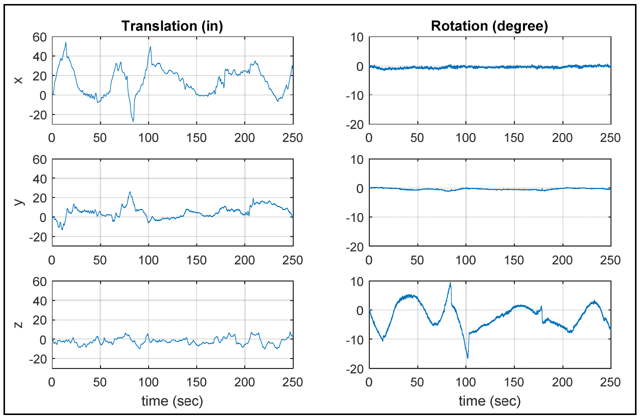

Figure 6. 6 DOF Motion of the UAV's Camera

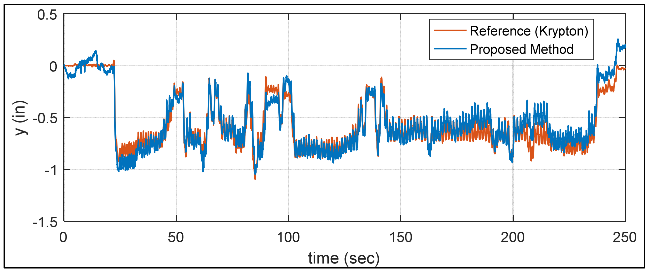

Figure 7. Absolute Displacement using Proposed Method

SUMMARY AND FUTURE WORK

This digest demonstrates the use of UAVs equipped with commercial grade video cameras for estimating the displacement of railroad bridges under revenue service traffic. Computer vision techniques were used to extract bridge displacements from the images taken from the UAV's onboard video camera. Preliminary tests conducted in the laboratory to validate the proposed framework indicate that railroad bridge displacements can be estimated with a root-mean-square (RMS) error of 0.08 inch at a standoff distance of 15 feet. The precision of the displacement estimates was found to be a function of a number of factors, including distance from the bridge, resolution of the camera, etc. Data fusion techniques are currently being considered to improve the accuracy of the displacements estimates using the UAV's onboard inertial measurement unit; preliminary results indicate that an improvement of roughly a factor of 5 is possible.

While the laboratory tests were successful, many uncertainties still exist with regard to testing in the field (e.g., wind effects, lighting conditions, etc.). Onsite field tests are currently being planned at the Transportation Technology Center.

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REFERENCES

1. Federal Railroad Administration. 2010. "Bridge Safety Standards." DOT 49 CFR Parts 213 and 237, RIN 2130-AC04, Federal Register, Vol. 75, No. 135, Rules and Regulations. pp. 41281-41309.
2. Moreu, F., B.F. Spencer Jr, D.A. Foutch, S. Scola. "Consequence-based management of railroad bridge networks." *Structure & Infrastructure Engineering* (2016): 1-14.
3. Moreu, F. & J.M. LaFave. *Current research topics: Railroad bridges and structural engineering*. Newmark Structural Engr. Laboratory. UIUC, 2012.
4. Moreu, F. et al. "Dynamic assessment of timber railroad bridges using displacements." *Journal of Bridge Engineering* 20, no. 10 (2014): 04014114.
5. Moreu, F. et al. "Reference-Free Displacements for Condition Assessment of Timber Railroad Bridges." *Journal of Bridge Engineering* 21, no. 2 (2015): 04015052.
6. Wilk, S.T., T.D. Stark, & J.G. Rose. "Evaluating tie support at railway bridge transitions." *Proc. Institution of Mechanical Engineers, Part F: Journal Rail and Rapid Transit* 230, no. 4 (2016): 1336-1350.
7. Jo, H. et al. "Feasibility of displacement monitoring using low-cost GPS receivers." *Structural Control & Health Monitoring* 20, no.9 (2013):1240-1254.
8. Yoon, H. et al. "Target-free approach for vision-based structural system identification using consumer-grade cameras." *Structural Control & Health Monitoring* (2016).
9. Harris, C. & M. Stephens. "A combined corner and edge detector." *Alvey Vision Conference*, vol. 15, p.147-151. 1988.
10. Tomasi, C. & T. Kanade. *Detection and tracking of point features*. Pittsburgh: School of Computer Science, Carnegie Mellon Univ., 1991. CMU-CS-91-132.