Accurate bridge deflection measurement using drone imagery via phase-based motion analysis

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Abstract. Recent advancements in drone technology have improved bridge deflection measurement using aerial imagery. Drones offer benefits such as easier access, cost efficiency, and automation. This study introduces a novel motion analysis-based method to separate drone-induced movement from actual bridge displacement, unlike conventional image stabilization approaches. Extensive validation confirms its high precision, lower computational cost, and robustness to environmental factors. This technique holds great potential for automated inspections of aging infrastructure, addressing global sustainability and resilience challenges.

Introduction

The aging global infrastructure, particularly bridges, presents significant challenges. In the U.S. and Japan, over 40% of bridges are over 50 years old, a figure expected to surpass 55% by 2030, increasing the burden of inspection and maintenance [1]. Traditional contact-based displacement measurement methods, such as accelerometers, offer limited spatial coverage, while non-contact methods like GPS and laser Doppler vibrometer require complex installations. Image-based approaches, especially phase-based methods like the sampling moiré (SM) technique [2-4], provide high accuracy and robustness.

Recent advancements in UAV technology have enabled bridge displacement measurement using drones, reducing costs and improving accessibility [5]. However, achieving high precision remains a challenge due to drone-induced motion artifacts. This study develops a novel approach to accurately distinguish structural displacement from drone motion using phase analysis [6]. Unlike previous methods focusing on image stabilization, this technique tracks marker motion trajectories between frames while assuming minimal drone movement over short intervals. The proposed method enhances measurement accuracy, improves robustness against environmental disturbances, and increases computational efficiency, making UAV-based bridge monitoring a practical and reliable solution.

Principle

Figure 1 illustrates the configuration of the proposed drone-based displacement measurement system. The setup includes motion trackers with a regular grating pitch: two reference markers (Mk-A and Mk-B) attached to the bridge's side and one testing marker (Mk-C) at the centre. A commercial drone equipped with a high-resolution camera captures video during bridge load testing. This setup supports practical inspections where heavy truck loads cause maximum displacement at the bridge centre. Reference markers (Mk-A and Mk-B) are assumed to experience negligible displacement, allowing the establishment of a reference line for displacement calculations. The deviation of the testing marker (Mk-C) from this line determines the load-induced displacement. This systematic design effectively separates drone motion-induced artifacts from actual structural displacements.

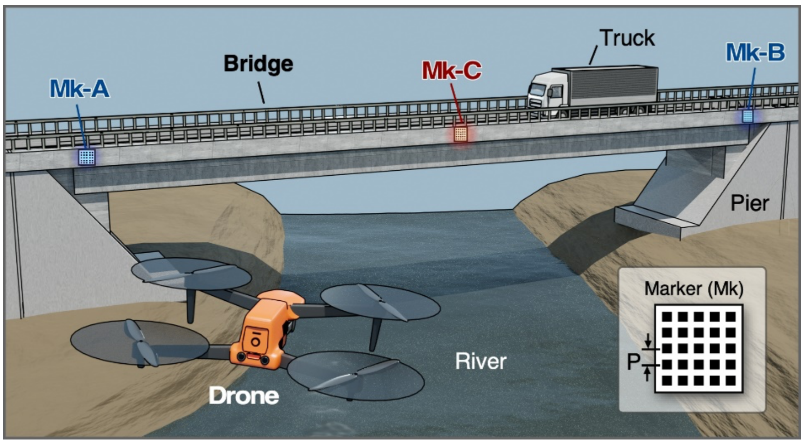

Fig. 1 System configuration of the proposed bridge deflection measurement system using drone imagery.

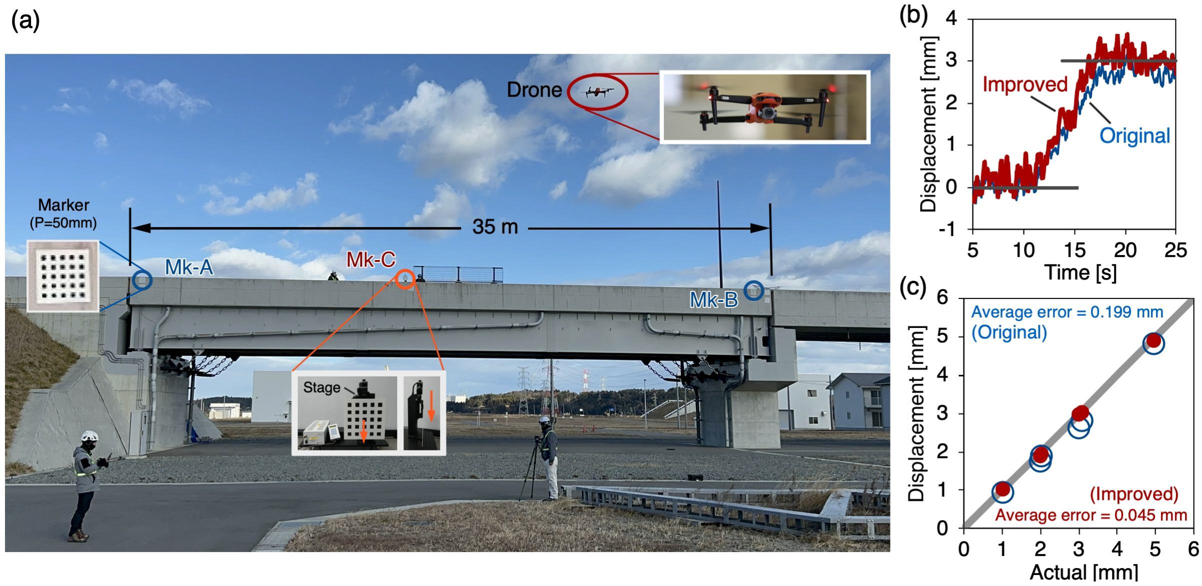

Fig. 2 Deflection measurement accuracy through a field experiment for a general 35 m-scale bridge: (a) experimental settings, (b) comparison results, and (c) overall measurement accuracy comparison.

During inspection, the drone captures multiple snapshots of the markers. At time frame t, the 3D coordinates of markers are translated into the camera coordinate system. Reference markers (Mk-A and Mk-B) define a reference line for displacement calculations, while Mk-C at the bridge centre measures maximum displacement. To simplify motion analysis, the drone is assumed to hover, reducing the camera motion model to a 4-degree-of-freedom (4-DoF) system, considering only translations (Δx, Δy, Δz) and yaw ($\Delta\theta$). This approximation effectively separates camera-induced variations from structural displacement.

Experimental Results

To validate the effectiveness of the proposed method, deflection measurement experiments were conducted on a 35-meter-long bridge at the Fukushima Robot Test Field, Japan. The study compared deflection values obtained from drone-based measurements with true displacements, precisely controlled using a high-precision linear moving stage. The experimental setup as shown in Fig. 2(a) included three moiré markers with a 50 mm grating pitch, with the drone positioned 34 meters from the bridge. A central marker (Mk-C) was displaced in increments of 1.003 mm, 2.010 mm, 2.999 mm, and 4.967 mm using a precision moving stage, with additional tests at 2.000 mm and 3.082 mm to assess reproducibility. This setup ensured an accurate comparison between drone-measured and actual displacements.

As the same with our prior study, a commercial drone (Autel EVO-II Pro) recorded 6K video at 24 fps. The results showed the improvement in measurement accuracy, as depicted in Figs. 2(b) and 2(c), reducing the average error from 0.199 mm to 0.045 mm. The proposed method approached the theoretical resolution limit of the sampling moiré phase analysis, achieving 1/100th of a pixel accuracy. These field tests confirmed that the proposed approach outperformed previous methods, demonstrating superior precision, reduced measurement errors, and improved reliability for drone-based bridge displacement monitoring.

Conclusion

This study introduces a novel UAV-based approach for high-precision bridge deflection measurement. By analysing motion tracker trajectories using instantaneous speed and phase information, the method effectively separates drone-induced movements from structural displacements. Extensive experiments confirm its superior accuracy, computational efficiency, and robustness against external factors like wind-induced drifting. Offering low cost and easy deployment, this approach enhances drone-based infrastructure monitoring, providing a reliable, autonomous, and cost-effective solution for addressing the challenges of aging bridges worldwide.

References

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