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Resilience Through **Community Engagement** and **Technology**

Multi-View UAV-Based Imagery for Seismic Displacement Tracking of a Full-Scale 10-Story Cold-Formed Steel Building

R. Ji¹, J. Zhang¹, E. Lo², T.J. Norton², J.W. Driscoll², F. Kuester³, B.W. Schafer⁴ and T.C. Hutchinson³

ABSTRACT

This study investigates the application of unmanned aerial vehicle (UAV)-based imagery from multiple views for seismic displacement tracking of a full-scale 10-story cold-formed steel (CFS) framed building. Multiple off-the-shelf UAV platforms with high-resolution onboard cameras were deployed at different locations around the building with the aim of tracking its displacement in 6 degrees of freedom (DOFs). The transient structural displacement is then calculated by reprojecting the 2-D image points onto the 3-D world space. Reasonable agreement between the UAV-based results and the measurements from alternative conventional sensing approaches demonstrates the effectiveness of the application of UAVs in structural displacement tracking under seismic excitations.

Introduction

Unmanned aerial vehicle (UAV) vision-based sensing has emerged as a cost-effective approach supplementing and advancing conventional data collection practices to capture the dynamic response of infrastructure, including those impacted by earthquakes [1-4]. Notable benefits of using UAV-based response monitoring include its non-invasive and remote capture potential, aspects that are particularly useful for infrastructure with large scales. Structural displacement during seismic excitations can be tracked by interpreting the image data collected using UAV-based vision sensing systems with image processing and computer vision algorithms. Key metrics, such as peak inter-story drift ratio during the seismic excitation, can be calculated from the tracked structural displacement time series and used for post-earthquake structural safety assessment and functional recovery analysis. This study investigates the application of UAV-based imagery from multiple views for seismic displacement tracking of a full-scale 10-story cold-formed steel (CFS) framed building during a series of shake table tests. The deployment layout, with multiple UAVs, aims to track the structural displacement in the complete 6 degrees of freedom (DOFs). The structural displacement is calculated by reprojecting the 2-D image points onto the 3-D world space based on the world-to-image point correspondence.

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Multi-View UAV Imagery for CFS10 Shake Table Test Program

A full-scale 10-story cold-formed steel (CFS) framed building, coined CFS10, was tested under a series of shake table tests [5, 6] at the 6-DOF Large High-Performance Outdoor Shake Table (LHPOST6) [7] at UC San Diego. The CFS10 building has a total height of 30.5 m (to the roof level) and a floor plan measuring 6.86 m $\times$ 11.58 m. A series of shake table tests with 18 multi-directional earthquake motions scaled to various hazard levels were performed on the CFS10 building [5, 8]. To integrate UAV-based imagery from multiple views for seismic displacement tracking in the complete 6 DOFs of this landmark building specimen, four off-the-shelf UAV platforms with high-resolution monocular cameras onboard were deployed at different locations around the building as shown in Figure 1 and Figure 2(a). The specifications of the UAV platforms and the camera setup for each camera view are summarized in Table 1. It is noted that the east and west elevation views were set up with the portrait orientation utilizing the true vertical shooting characteristic of the UAVs #2-4 to increase the pixel resolution of the building specimen. In total, 328 reference targets with four different black-and-white checkerboard patterns as shown in Figure 2(b) were installed on the building specimen and stationary background to provide robust image feature points for detection and tracking. As presented in Table 2, the distribution of the reference targets covered different structural (floor levels, exterior walls) and nonstructural (roof-mounted equipment) components of the building, as well as multiple objects (ground level, safety towers) in the stationary testing scene.

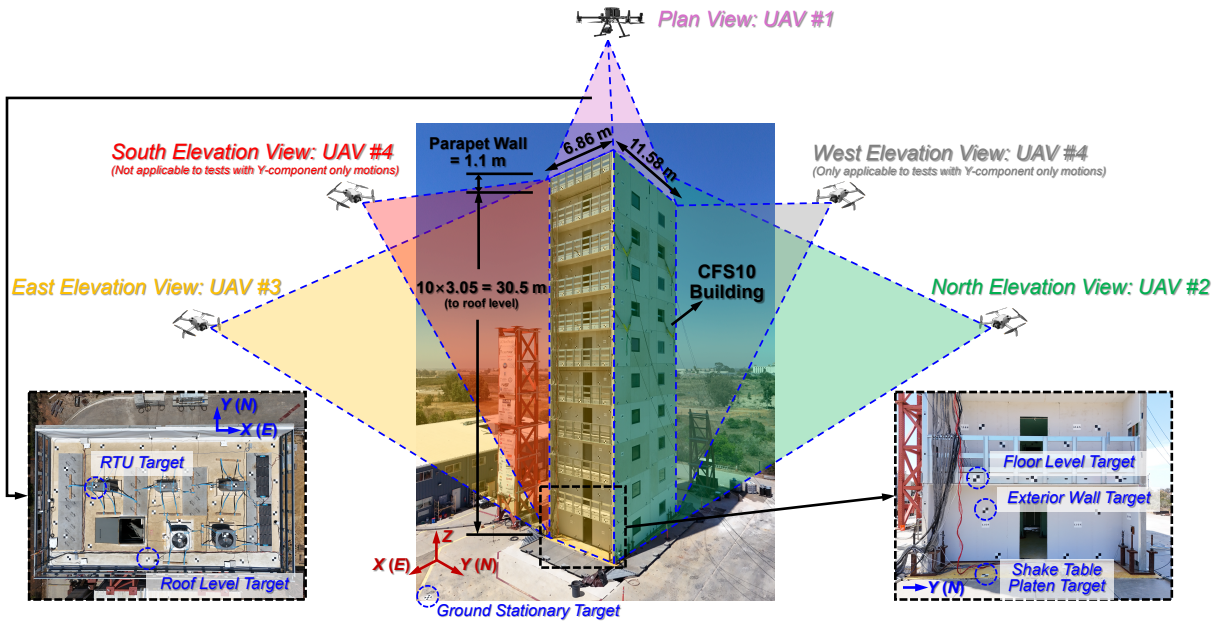


Figure 1. Overview of the experimental setup for structural displacement tracking of the CFS10 building under seismic excitations at the LHPOST6 facility.

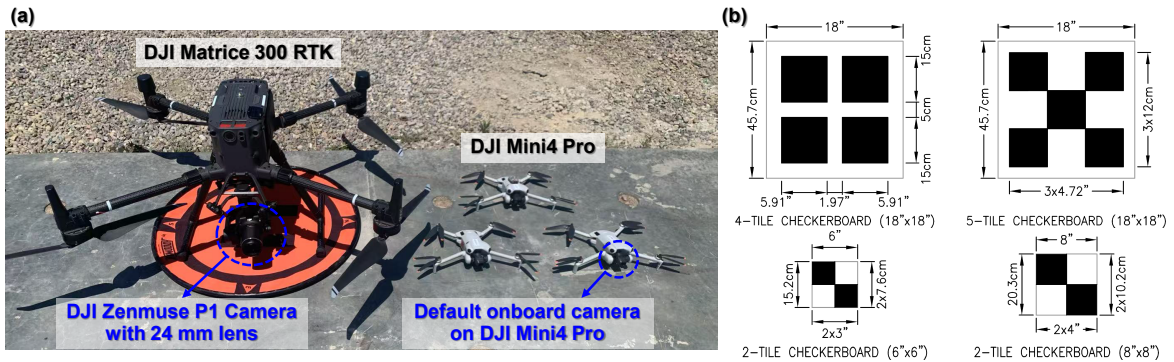


Figure 2. (a) UAV platforms deployed for CFS10 shake table test imagery, and (b) Checkerboard patterns for reference targets on the building specimen and stationary background.

Table 1. UAV platform specifications and camera view setup for CFS10 shake table test imagery [9].

Camera View	UAV Platform Specification					Camera Setup			
	UAV #	UAV Model	Unfolded Size [L×W×H-mm]	Battery Life [min]	Altitude AGL ³ [m]	Camera Model	Frame Rate [fps]	Resolution	Tilt ⁴ [deg]
Plan (XY)	1	DJI Matrice 300 RTK	810×670×430	55	55	DJI Zenmuse P1 camera (24 mm lens)	59.94	3840×2160	-90
N-Elev (XZ)	2	DJI Mini4 Pro	298×373×101	39	25	Default onboard camera	59.94	3840×2160	-12
E-Elev (YZ)	3	DJI Mini4 Pro	298×373×101	39	20	Default onboard camera	59.94	2160×3840	-12
S-Elev (XZ) ¹	4	DJI Mini4 Pro	298×373×101	39	30	Default onboard camera	59.94	3840×2160	-17
W-Elev (YZ) ²	4	DJI Mini4 Pro	298×373×101	39	22	Default onboard camera	59.94	2160×3840	-15

¹ South elevation views were not captured for tests with Y-component only motions.

² West elevation views were only captured for tests with Y-component only motions.

^{3,4} These values are target UAV altitude and camera tilt angle (AGL: above ground level).

Table 2. Reference target distribution on the CFS10 building specimen and within background scene.

Target Description	Target Location	Pattern	Dimension	Count
Stationary	Ground level	4- and 5-tile checkerboard	45.7 cm × 45.7 cm	13
	Safety towers	2-tile checkerboard	20.3 cm × 20.3 cm	22
Shake table platen	Top of shake table platen	2-tile checkerboard	20.3 cm × 20.3 cm	4
	Top of transfer plates	2-tile checkerboard	20.3 cm × 20.3 cm	8
Roof level	Roof level floor panel	2-tile checkerboard	20.3 cm × 20.3 cm	20
	Top of supplemental mass	2-tile checkerboard	20.3 cm × 20.3 cm	6
	Roof-mounted equipment (Rooftop unit, RTU)	2-tile checkerboard	15.2 cm × 15.2 cm and 20.3 cm × 20.3 cm	5
North façade	Elevation at each floor level	2-tile checkerboard	20.3 cm × 20.3 cm	66
	Mid-height of each floor	2-tile checkerboard	20.3 cm × 20.3 cm	20
East façade	Elevation at each floor level	2-tile checkerboard	20.3 cm × 20.3 cm	30
	Exterior drywall surface	2-tile checkerboard	20.3 cm × 20.3 cm	41
South façade	Elevation at each floor level	2-tile checkerboard	20.3 cm × 20.3 cm	24
	Mid-height of each floor	2-tile checkerboard	20.3 cm × 20.3 cm	20
West façade	Elevation at each floor level	2-tile checkerboard	20.3 cm × 20.3 cm	21
	Exterior drywall surface	2-tile checkerboard	20.3 cm × 20.3 cm	28
Total				328

Structural Displacement Tracking Framework

The applied UAV vision-based structural displacement tracking framework utilizes the world-to-image point correspondence to reproject the tracked 2-D image points to the 3-D world space for displacement calculation. The following key steps are adopted in the framework [10]: (1) Given the camera intrinsic parameters obtained from the camera calibrations, lens distortion correction [11] is performed on the raw video frames to remove the radial and tangential distortion of the image frames. (2) Corner points (corner-like features) from the reference targets are detected using the Harris-Stephens feature detector [12] in the reference distortion-free video frame (the first video frame) corresponding to the stationary state of the building based on a coarse pre-defined region of interest as shown in Figure 3. (3) The detected feature points are tracked over each video frame with sub-pixel level accuracy using the Kanade-Lucas-Tomasi (KLT) algorithm [13]. (4) The Perspective-*n*-Point (PnP) method [14] and Levenberg-Marquardt algorithm [15] are applied to recover the 6-DOF camera pose defined by the camera extrinsic matrix based on the correspondence between 2-D image coordinates and 3-D world coordinates (extracted from the pre-test photogrammetry model of the testing scene at the LHPOST6 facility) of stationary targets over each video frame. (5) The 3-D world coordinates of all moving targets for each video frame are reconstructed by solving the camera projection equation. Analysis using the plan-view video is conducted first to extract the XY-displacement and Z-rotation. The results will ultimately be combined with elevation-view videos to calculate displacements in other DOFs at different locations as adopted in previous work of the authors [16].

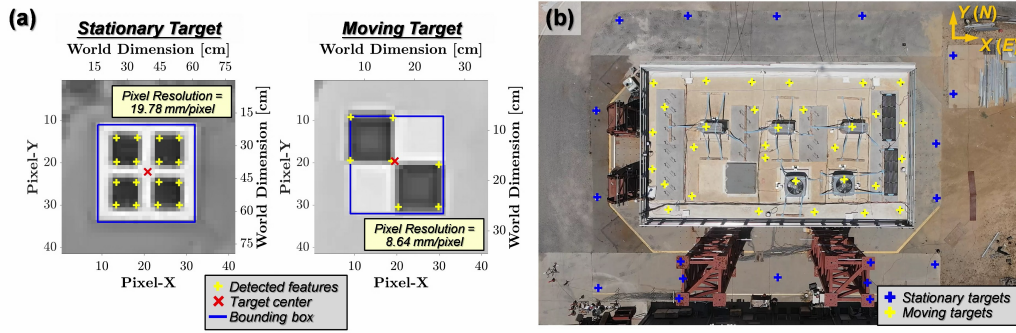


Figure 3. Reference targets detection result: (a) Detected feature points and target center in the region of interest, and (b) Detection of all the stationary and moving targets from plan-view test video.

The proposed method is implemented with the Image Processing and Computer Vision Toolbox in MATLAB R2024b [17], and its effectiveness is evaluated by comparing the displacements tracked from UAV-captured videos with the results from two conventional sensing approaches including double-integrated accelerations based on micro-electro-mechanical system (MEMS) accelerometer measurements and direct displacement measurements from global navigation satellite system (GNSS). Figure 4 presents a comparison of the tracked displacement results from the reference target installed at the SE corner on the roof level and the measurements from the accelerometer and GNSS receiver adjacent to this target during a bi-directional (XY) MCE_R-scaled Cape Mendocino earthquake test, which demonstrate the effectiveness of the proposed method, in terms of the potential to track the salient response features (e.g. during the significant duration D_{5-95} [18]) as well as the overall root-mean-square errors (RMSEs). The UAV-based results have overall RMSEs less than 10 mm compared to the ground truth measurements.

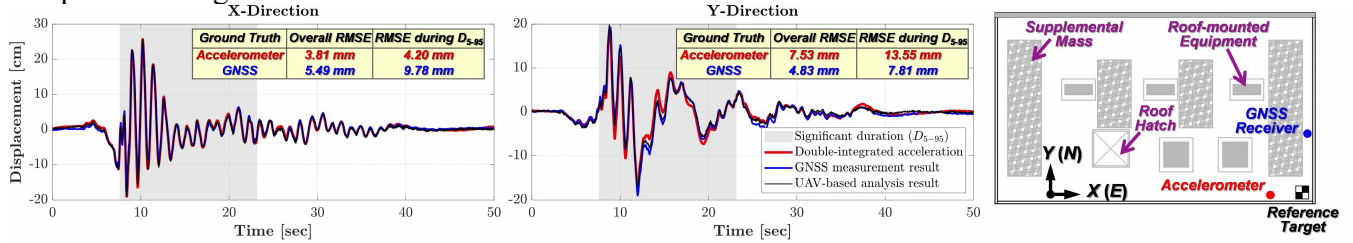


Figure 4. Example comparison between the tracked displacements and measurements from other sources.

Concluding Remarks

This study presents a multi-view UAV-based effort for seismic displacement tracking of a full-scale 10-story cold-formed steel framed building. Multiple UAVs are deployed in different views, with more than 300 reference targets, to allow structural displacement tracking in the complete 6 DOFs of this full-scale building tested on a large outdoor shake table. Structural displacement is calculated by reprojecting the 2-D image points to the 3-D world space. Preliminary results demonstrate good agreement between the UAV-tracked structural displacement results and measurements from two alternative conventional sensing approaches.

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References

1. Ge Y, Yu X, Chen M, Yu C, Liu Y, Zhang G. Monitoring dynamic deformation of building using unmanned aerial vehicle. *Mathematical Problems in Engineering* 2021; 2021 (1): 2657689. DOI: <https://doi.org/10.1155/2021/2657689>.
2. Ri S, Ye J, Toyama N, Ogura N. Drone-based displacement measurement of infrastructures utilizing phase information. *Nature Communications* 2024; 15 (1): 395. DOI: <https://doi.org/10.1038/s41467-023-44649-2>.
3. Wang X, Lo E, De Vivo L, Hutchinson TC, Kuester F. Monitoring the earthquake response of full-scale structures using UAV vision-based techniques. *Structural Control and Health Monitoring* 2022; 29 (1): e2682. DOI: <https://doi.org/10.1002/stc.2862>.
4. Wang X, Wittich CE, Hutchinson TC, Bock Y, Goldberg D, Lo E, Kuester F. Methodology and validation of UAV-based video analysis approach for tracking earthquake-induced building displacements. *Journal of Computing in Civil Engineering* 2020; 34 (6): 04020045. DOI: [https://doi.org/10.1061/\(ASCE\)CP.1943-5487.000092](https://doi.org/10.1061/(ASCE)CP.1943-5487.000092).
5. Hutchinson TC, Eladly M, Ji R, Rivera D, Cyizere Rukundo F, Singh A, Sorosh S, Zhang J, Zhang X, Padgett L, Jones H, Karns J, Schafer BW. Advancing use of cold-formed steel framing systems for mid-rise residential construction in seismic zones via full-scale shake table testing. *Proceedings of the 8th Residential Building Design & Construction Conference*, State College, PA. 2026.
6. Hutchinson TC, Zhang J., Sorosh S, Ji R, Rivera D, Zhang X, Singh A, Cyizere Rukundo F, Eladly M, Jones H, Karns J, Padgett L, Emberley R, Gernay T, Meacham B, Schafer BW. Overview of the CFS10 Program: Full-scale shake table (earthquake and fire) testing of a 10-story cold-formed steel building. *Proceedings of Structures Congress 2026*, Boston, MA. 2026.
7. McCartney JS, Van Den Einde L, Morrison M, Palermo A, Lotfizadeh K, Lai C-T, Conte JP. Multi-degree of freedom shake table testing of large-scale structural and geotechnical systems with NHERI-UCSD LHPOST6. *Frontiers in Built Environment* 2025; 11: 1573390. DOI: <https://doi.org/10.3389/fbuil.2025.1573390>.
8. Zhang J, Sorosh S, Ji R, Lotfizadeh KH, Schafer BW, Hutchinson TC. Full-scale 10-story cold-formed steel building shake table test: Protocol development and shake table performance. *Proceedings of the 13th National Conference on Earthquake Engineering*, Portland, OR. 2026.
9. DJI - Official Website. Available from: <https://www.dji.com/> (accessed on 27 September 2025).
10. Ji R, Sorosh S, Lo E, Norton TJ, Driscoll JW, Kuester F, Barbosa AR, Simpson BG, Hutchinson TC. Application framework and optimal features for UAV-based earthquake-induced structural displacement monitoring. *Algorithms* 2025; 18 (2): 66. DOI: <https://doi.org/10.3390/a18020066>.
11. Bouguet JY. Camera Calibration Toolbox for MATLAB. Available from: <https://data.caltech.edu/records/jx9cx-fdh55> (accessed on 27 September 2025).
12. Harris C, Stephens M. Combined corner and edge detector. *Proceedings of the Alvey Vision Conference*, Manchester, UK. 1988.
13. Lucas BD, Kanade T. An iterative image registration technique with an application to stereo vision. *Proceedings of the 7th International Joint Conference on Artificial Intelligence*, Vancouver, Canada. 1981.
14. Zheng Y, Sugimoto S, Okutomi M. ASPnP: An accurate and scalable solution to the Perspective-n-Point problem. *IEICE Transactions on Information and Systems* 2013; 96 (7): 1525-1535. DOI: <https://doi.org/10.1587/transinf.E96.D.1525>.
15. Schonberger JL, Frahm J-M. Structure-from-motion revisited. *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition*, Las Vegas, NV. 2016.
16. Cao P, Ji R, Ma Z, Sorosh S, Lo E, Norton T, Driscoll J, Wang X, Hutchinson T, Pei S, Kuester F. UAV-based video analysis and semantic segmentation for SHM of earthquake-excited structures. *Proceedings of the 18th World Conference on Earthquake Engineering*, Milan, Italy. 2024.
17. MathWorks - Computer Vision Toolbox (R2024b). Available from: <https://www.mathworks.com/products/computer-vision.html> (accessed on 27 September 2025).
18. Trifunac MD, Brady AG. A study on the duration of strong earthquake ground motion. *Bulletin of the Seismological Society of America* 1975; 65(3): 581-626. DOI: <https://doi.org/10.1785/BSSA0650030581>.