

Article

Experimental Accuracy Evaluation of UAV-Based Homography for Static and Dynamic Displacement Monitoring of Structures

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Abstract

Structural displacement monitoring is an essential component of structural health monitoring of bridges, providing valuable information for performance evaluation, numerical model validation, and damage detection. While conventional contact-based sensors provide high accuracy, their installation is often complex, costly, and disruptive to traffic. Recent developments in unmanned aerial vehicle (UAV) platforms and vision-based measurement techniques offer a flexible, non-contact alternative; however, platform motion remains a major source of uncertainty. This study evaluates the accuracy and operational feasibility of UAV-based homography for static and dynamic displacement monitoring. The proposed approach is validated through three complementary experimental campaigns: a controlled calibration field test, a beam static load test, and bridge monitoring under traffic loading, with direct comparison to LVDT and RTS measurements. Under controlled conditions, sub-millimetre vertical precision was achieved, with RMSE values below 0.3 mm. In full-scale bridge applications, the method captured traffic-induced displacement trends with errors generally within 1–2 mm compared to LVDT data and with RMSE values below 1.4 mm. The results demonstrate that, when appropriate reference point configuration and imaging geometry are ensured, UAV-based homography provides a practical and sufficiently accurate solution for bridge displacement monitoring which is especially important in applications where sensor installation is difficult or unsafe.

Keywords: UAV; homography; photogrammetry; displacement measurement; static displacements; dynamic displacements; LVDT; RTS

1. Introduction

The maintenance and preservation of structural integrity across the construction phases and the service life of critical infrastructure—such as bridges, high-rise buildings, and industrial facilities—is a cornerstone of modern structural engineering. Given the inevitable degradation of materials, escalating traffic loads, and the intensifying impact of climate change [1,2], the implementation of systematic Structural Health Monitoring (SHM) has transitioned from a recommendation to a technical imperative to ensure quality, safety, and serviceability. Among various response parameters, structural displacements provide one of the most direct indicators of global structural behaviour, supporting performance evaluation, numerical model validation, damage detection, and long-term condition assessment [3–5].

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Conventional displacement measurement techniques, including Linear Variable Differential Transformers (LVDTs) [6], robotic total stations [7,8], GNSS-based positioning [9], precise levelling [10], and terrestrial laser scanning [11,12], are capable of achieving high accuracy. Their application in field conditions, however, is frequently constrained by demanding installation procedures, the requirement for stable reference points, limited accessibility, and, in many cases, disruption to traffic flow [13,14].

Recent developments in vision-based measurement techniques, together with rapid advances in unmanned aerial vehicle (UAV) platforms, have enabled new possibilities for non-contact displacement monitoring [15]. UAV-based systems provide rapid deployment, flexible sensor positioning, and high spatial resolution, making them particularly attractive for bridge inspection and structural testing. Nevertheless, reliable displacement measurement from UAV imagery remains challenging, primarily due to unavoidable platform motion. Camera vibrations, rotations, and translational movements introduce apparent displacements into image sequences, which can significantly obscure the true structural response [16–18].

Displacement estimation from UAV imagery relies on a range of vision-based techniques, including three-dimensional reconstruction using structure-from-motion (SfM), planar motion compensation through homography-based correction, digital image correlation (DIC), and feature-based tracking of image sequences [19–22]. These approaches differ in computational complexity, robustness to platform motion, and suitability for field deployment, particularly under real-world environmental and operational constraints. While SfM and multi-image based methods enable full three-dimensional reconstruction, they often require dense image acquisition and significant computational effort, whereas homography-based techniques provide an efficient alternative for planar displacement monitoring in scenarios dominated by in-plane structural motion.

To mitigate UAV-induced motion effects, homography-based image stabilization techniques have been increasingly adopted. By estimating planar projective transformations between consecutive frames using stable reference points, homography allows effective compensation of camera motion without the need for explicit camera calibration or full three-dimensional reconstruction [16,23,24]. Despite encouraging results reported in previous studies, several practical challenges remain, particularly regarding reference point availability, geometric sensitivity, and robustness under real-world operating conditions.

This study investigates the accuracy and operational feasibility of UAV-based homography for monitoring static and dynamic structural displacements. Particular emphasis is placed on systematically investigating the influence of reference point configuration and their number on measurement accuracy, aspects that have received limited attention in previous studies [25,26]. The importance of measurement point configuration has also been recognized more broadly in structural health monitoring research, particularly in studies addressing optimal sensor placement and sensitivity analysis for damage identification in bridge structures [27]. Although these studies focus on different monitoring objectives, they similarly demonstrate that the spatial distribution of measurement points significantly influences identification reliability and overall system performance. This broader perspective further supports the need to systematically examine reference point configuration effects within homography-based displacement monitoring. The proposed method is evaluated through three complementary experimental campaigns, encompassing a controlled calibration test field, a static load test of the beam, and full-scale monitoring of a bridge subjected to traffic-induced dynamic deformations which enabled assessment of the method under both controlled and realistic operating conditions. The main contributions of this study can be summarized as follows:

- Experimental validation of UAV-based homography across three different campaigns.

- Systematic investigation of the influence of reference point number and spatial configuration on displacement accuracy.
- direct quantitative comparison with high-precision LVDT and RTS measurements under both controlled and operational conditions.
- Practical evaluation of methodological limitations and operational constraints relevant to real-world bridge monitoring.

The paper is structured as follows. Section 2 presents the experimental setup and measurement methodology, including the homography-based displacement estimation framework. Section 3 describes the three experimental campaigns and corresponding results. Section 4 discusses the accuracy, reference point configuration effects, and practical limitations of the proposed approach. Finally, Section 5 summarizes the main conclusions and outlines directions for future research.

2. Materials and Methods

2.1. Experimental Test Fields

This section describes the experimental setups used to evaluate the accuracy and applicability of the UAV-based homography method under controlled and real-world conditions. First, a controlled calibration field experiment was used to assess the influence of reference point configuration on homography stability. Second, a beam static load test enabled a direct comparison between UAV-derived displacements and high-accuracy LVDT measurements. Finally, a dynamic bridge test was conducted under real traffic loading to evaluate performance in field conditions with uncontrolled dynamic influences.

2.1.1. Calibration Field Test

The first part of the testing was done at the Institute for Photogrammetry's photogrammetric calibration field in Zagreb. This facility was used to calibrate all sensors used in this study. The calibration field is in a covered garage area, providing a stable geometric configuration and lighting conditions during taking images. There were 36 targets mounted on the walls and columns placed along the bisectors of the load-bearing columns (shown by red marks in Figure 1) and the rear walls (shown by white marks in Figure 1). There were three height levels for the targets: 0.5 m, 2.0 m, and 3.5 m arranged in a regular grid. This setup made sure that all images will have uniform image coverage and favourable photogrammetric geometry.



Figure 1. Calibration field—position of 36 targets.

The coordinates of all targets were determined using a high-precision total station (Leica TPS1201) (Leica Geosystems AG, Heerbrugg, Switzerland) through repeated observations, achieving a positional accuracy of less than 1 mm. This level of accuracy fully meets the requirements for high-precision photogrammetric calibration and lens distortion assessment.

In this phase, three imaging systems were utilized: a Nikon D800E camera (Nikon Corporation, Tokyo, Japan) mounted on a tripod with a SIGMA RF20/1.8 lens, a DJI Matrice 300 RTK UAV (DJI, Shenzhen, China) equipped with a DJI Zenmuse P1 camera, and a DJI Phantom 4 UAV (DJI, Shenzhen, China) featuring an FC330 camera. The significant difference in horizontal Field of View (FOV_h) between the Zenmuse P1 camera (FOV_h = 54.30°) and the other two (NIKON D800E FOV_h = 83.81°; DJI Phantom 4 FC330 FOV_h = 81.03°) leads to a significant difference in object-to-camera distance (see Table 1). Following the calibration, each sensor was tested in the same test field to evaluate the precision of displacement determination from images and video sequences by applying homography transformation. The controlled environment of the calibration field allowed for the isolation of the effects of camera calibration quality and the distribution of reference points on the precision of the coordinates derived from homography.

Table 1. Overview of sensors and imaging parameters used for displacements determination at the calibration field test.

Sensor	Mode	Resolution	Frame Rate	Distance to Object	Pixel Size on the Object	Sensor Stability
Nikon D800E + SIGMA RF20	Photo	7360 × 4912	-	~13.0 m	3.2 mm	Tripod-mounted
	Video	1920 × 1080	29.97	~15.3 m	12.7 mm	
DJI Matrice 300 RTK + Zenmuse P1	Photo	8192 × 5460	-	~22.2 m	2.8 mm	UAV hovering
	Video	1920 × 1080	59.94	~23.6 m	11.9 mm	
DJI Phantom 4 + FC330	Photo	4000 × 3000	-	~13.9 m	5.9 mm	UAV hovering
	Video	3840 × 2160	29.97	~13.5 m	6.0 mm	

2.1.2. Beam Static Load Test

The second part of the experimental investigation was conducted on a simply supported reinforced concrete beam with a length of 36 m. UAV photogrammetric measurements were conducted during the static load test of the beam in five different loading phases. Phase 1 was unloaded initial phase, in Phase 2 the beam was loaded with 14.88 tons (25% of total load), in Phase 3 with 29.76 tons (50% of total load), in Phase 4 with 44.64 tons (75% of total load) and in Phase 5 with 59.52 tons (100% of total load). A total of 24 pallets, each weighing 2.48 tons, were used for the loading (Figure 2).

Beam deflections during the load testing were tracked by the photogrammetric measurements at 7 signalized monitoring points (points 2–8 in Figure 2). Homography transformations were computed using a selected subset of reference points, including points located on the beam (points 1 and 9) and nominally stable points located beneath the beam (points 10–14). The same physical reference targets were used throughout all loading phases. As reference points are, in principle, required to remain stationary, their stability was continuously assessed during the experiment. Points 1 and 9 exhibited small but measurable displacements during loading; therefore, their object-space coordinates were updated using the corresponding LVDT measurements before homography transformation. Reference points 10–14 were considered stable throughout most of the loading process. However, during the final loading phase (Phase 5), minor vertical movements were detected at points 12 and 13 because of the beam settlement under the load. In order to preserve the geometric consistency of the homography transformation, their object-space coordinates were updated in Phase 5 based on simultaneous robotic total station

(RTS) measurements. The homography matrix was subsequently recalculated using these corrected object coordinates, while the image coordinates remained unchanged.

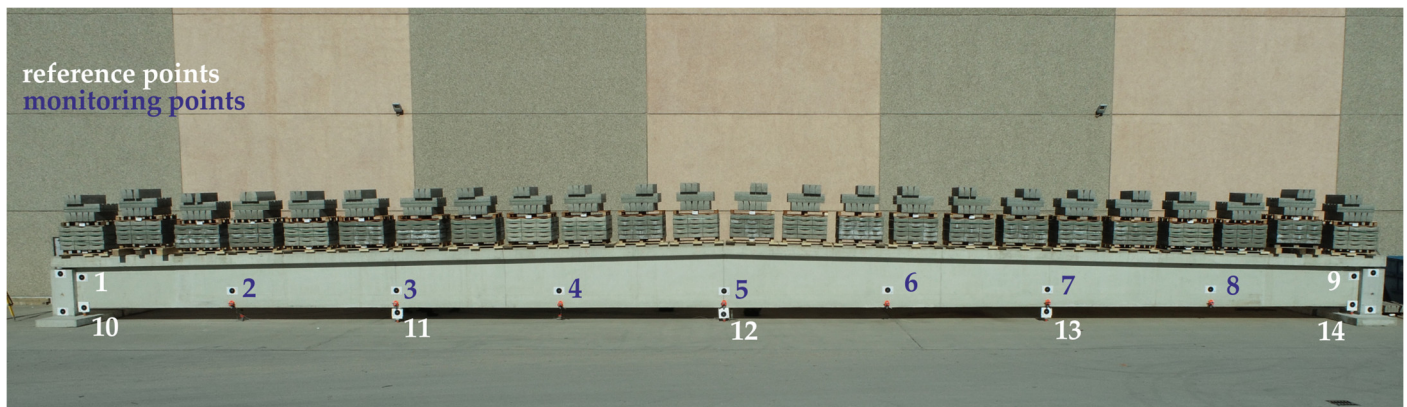


Figure 2. Position of the UAV and LVDT monitoring points on the beam and reference points.

In contrast to previous studies employing a static ground-based camera setup [20], the present experiment utilized a UAV platform for data acquisition. A DJI Phantom 4 Pro equipped with a 20-megapixel camera (focal length 8.8 mm, pixel size 2.4 μm) was operated at a hovering altitude of approximately 2 m and 22.5 m distance from the beam, maintaining a camera view oriented towards the centre of the concrete beam. The UAV was positioned to capture the entire beam and surrounding reference frame within a single field of view.

Images were captured at discrete loading phases corresponding to 0%, 25%, 50%, 75%, and 100% of the design load.

In each loading phase, ten consecutive photographs were captured (resolution 5472 $\times$ 3648 px). Because the load was static and the beam remained motionless within each phase, the repeated images enabled an assessment of the measurement repeatability. For every signalized point, the dispersion of image coordinates across the 10 images was used to quantify precision, while the averaged values provided a more robust estimate of the points displacements in each loading phase.

To provide an independent and high-accuracy reference for displacement validation, six LVDT sensors were installed in monitoring points 1–5 and 9 as shown in Figure 3. The sensors were mounted on a rigid steel reference frame anchored to the ground and on the beam supports, ensuring that measured displacements were not affected by structural movement of the beam. The LVDT sensors (HBM, model type WA) continuously measured the vertical displacement with a resolution of 0.01 mm in all loading phases. Additionally, to LVDT the UAV displacements were compared to the displacements determined using a robotic total station Leica TPS1201, with a direction measurement accuracy of 1" and a distance measurement accuracy of 2 mm + 2 ppm. By RTS, displacements were measured in seven monitoring points (points 2–8) identical to those from UAV measurements.

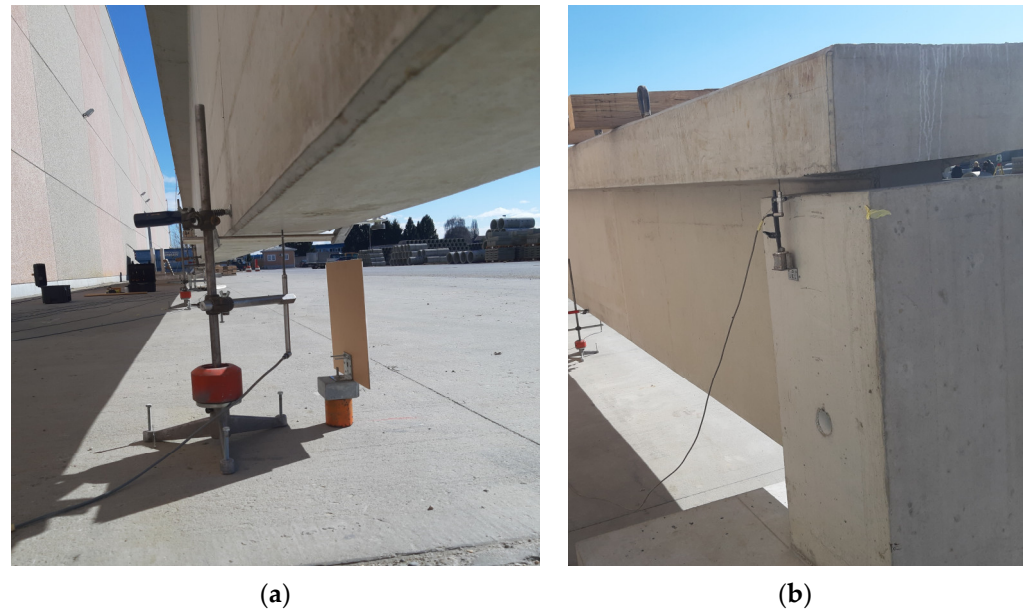


Figure 3. Setup of the LVDT sensor beneath the beam in measuring point 3 (a) and on the beam support in measuring point 1 (b).

2.1.3. Dynamic Bridge Test

The third set of measurements were performed in real conditions during exploitation on the Podsused bridge in Zagreb, Croatia, where the traffic load that took place over the bridge was used for the dynamic load.

The new Podsused Bridge (Figure 4) was constructed on the piers of the former railway-road bridge. It features a continuous static system with a constant superstructure height across nine spans of 37.15 m each. The bridge has a total length of 334.35 m and a width of 14.7 m. The load-bearing structure consists of two steel box girders connected by transverse beams, while the deck is a steel orthotropic slab. Following damage caused by strong water currents, the bridge piers were reinforced and repaired between 2016 and 2018.

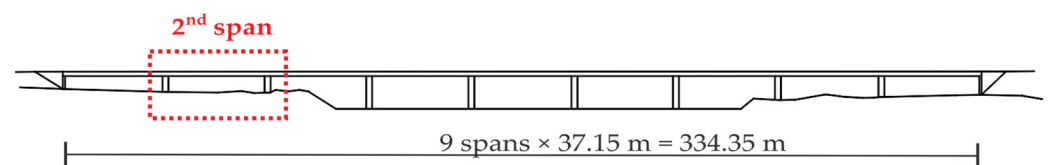


Figure 4. Longitudinal section of the new Podsused bridge.

The measurements were carried out by monitoring ambient traffic flow specifically capturing the passage of heavy vehicles (trucks and buses) at speeds ranging from 40 km/h to 70 km/h. Measurements were carried out in the second span of the bridge from the direction of city of Samobor.

Six measuring points were stabilized on the bridge structure using 27 cm diameter circular targets marked in Figure 5 with numbers from 1 to 6. At these points, the dynamic displacements of the structure were determined from video captured from UAV platform and ground-based camera. Points 7 and 10 were placed on the pillars of the bridge and points 8 and 9 were placed on a tripod on the ground below the point stabilized in the middle of the span (point 2) and served as additional reference points (in addition to points 7 and 8) for homography transformation. Those points were stabilized using 15 cm diameter circles.



Figure 5. Position of the measuring points in the 2nd span of the bridge.

To validate the results, reference measurements were conducted via direct displacement sensing using LVDT sensors, which were installed in measuring point 2 and point 4 (Figure 6). Since the measurement accuracy of LVDT sensors significantly exceeds the accuracy of camera used in this study, displacements obtained by LVDT sensors were used as a reference.

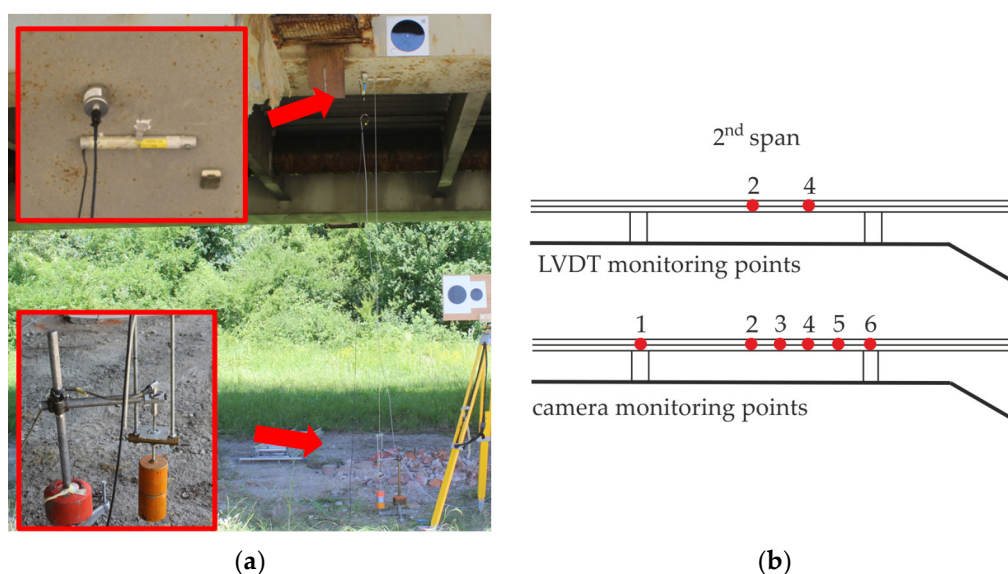


Figure 6. LVDT sensor in measuring point 2 (a), location of UAV measuring points (points 1–6) on bridge (b).

The dynamic displacements of the bridge at different measuring points signaled within 2nd span were measured with Nikon D800E camera and UAV Phantom 4 (see Table 2).

Table 2. Imaging parameters for the bridge measurement campaign.

Sensor	Mode	Resolution	Frame Rate	Distance to Object	Pixel Size on the Object	Sensor Stability
Nikon D800E + SIGMA RF20	Video	1920 × 1080	29.97	~18 m	20.6 mm	Tripod-mounted
DJI Phantom 4 + FC330	Video	3840 × 2160	29.97	~24 m	13.3 mm	UAV hovering

Both systems recorded video sequences, later decomposed into individual frames for displacement extraction.

2.2. Displacement Measurement Methodology

While Section 2.1 describes the experimental setups, this section presents the methodology used to derive structural displacements from UAV imagery using homography-based transformation.

2.2.1. Methodology of the Homography-Based Displacement Measuring

Prior to acquiring photographs and video sequences to track the deformation of the observed object, all cameras used in this research were calibrated on the test field, as it is explained in Section 2.1. These calibration data, in particular the parameters of radial and tangential distortion, were used to remove their impact on further measurements by reprojecting them to distortion-free ones. Signalized targets placed in reference and monitoring points were tracked in successive image frames using sub-pixel feature detection using a custom Python 3.12. implementation based on the OpenCV 4.8.0 library. Initial target localization was performed using multi-scale template matching to ensure scale invariance under varying UAV-to-object distances. The detected target positions were subsequently refined to sub-pixel accuracy using an iterative Least Squares Matching (LSM) algorithm, optimizing translation and scale parameters. Image preprocessing steps, including grayscale conversion and contrast enhancement, were applied to improve robustness under varying illumination conditions. From video sequences, image coordinates were extracted independently for each frame, forming time series of image-space displacements prior to homography transformation. The frame rate (29.97 fps) of video sequences was fixed during individual measurement campaigns and chosen to ensure sufficient temporal resolution for capturing traffic-induced displacement responses dominated by low-frequency components. Since the focus of this study was on displacement amplitude accuracy rather than detailed spectral analysis, higher frame rates were not required. In one configuration, a higher frame rate was additionally tested to evaluate potential accuracy degradation; however, this was not observed in the processed results. Acquired images were projected onto the monitored object's plane by homography transformation using image coordinates measured by DIC and object coordinates measured manually by robotic total station. Finally, structural displacements were obtained by computing frame-to-frame differences in transformed object-plane coordinates relative to the initial reference frame. The resulting displacement time histories were evaluated using mean absolute displacement, maximum displacement, and Root Mean Square Error (RMSE), depending on the test scenario. The main steps of deformation measuring on the structural objects are shown in the following flowchart (Figure 7).

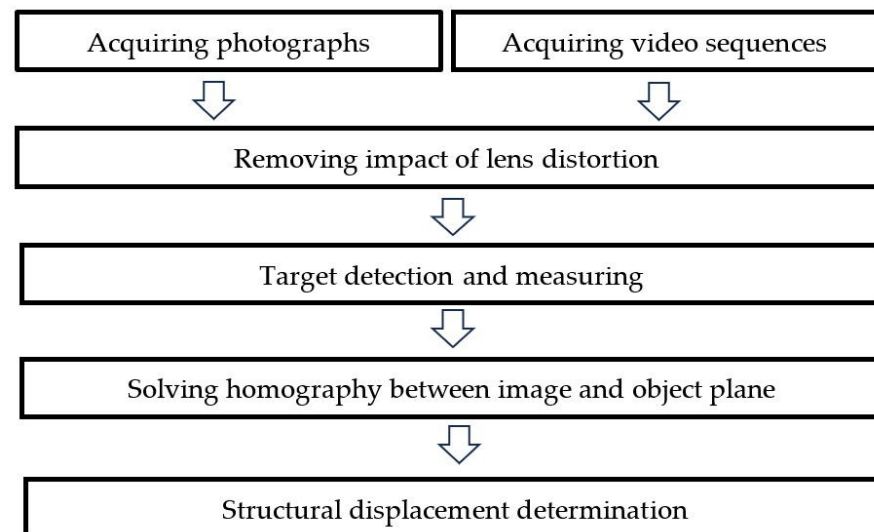


Figure 7. Image processing flowchart.

2.2.2. Principle of the Homography Based Displacement Measurement

A comprehensive review of the use of the homography-based displacement measurement method can be found in [28], where points measured on images are projected to the reference image by homography. To have displacement properly scaled, we suggest using homography to transfer points from every image to the object plane. The key assumption of the method is that both reference points and the points of interest on the monitored structure lie approximately in the same plane. In UAV-based monitoring, camera motion and vibration during flight introduce false apparent displacements. To remove this effect, the image pairs are geometrically aligned to the plane, where lies the monitored structure, using the homography matrix derived from fixed reference points. After alignment, the residual movement of the signalized points corresponds exclusively to the true structural deformation.

Homography transformation of images is typically characterized as the projection mapping relationship between photographs of an identical planar object captured from various positions by two distortion-free cameras. It delineates the transformation relationship between two planes. In our case, it represents the homographic transformation between the image and the object plane (Figure 8).

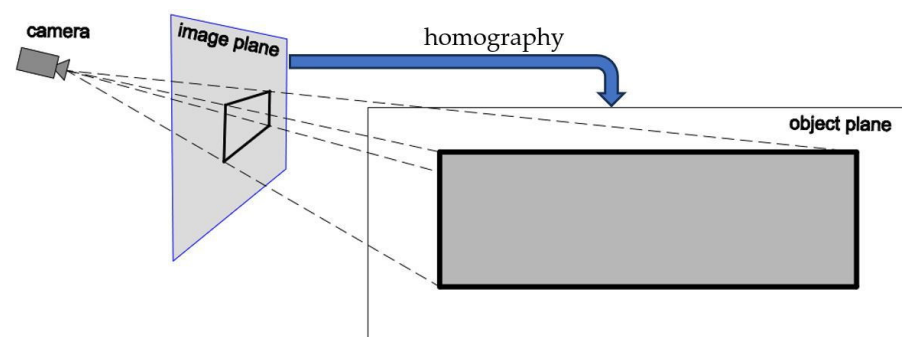


Figure 8. The principle of homographic transformation from image to object plane.

This coordinate transformation can be expressed as:

$$\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = H \begin{bmatrix} x \\ y \\ 1 \end{bmatrix}, \quad (1)$$

where

X, Y are coordinates of the object in the object plane

x, y are image coordinates of the object

H is the homography matrix

$$H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{bmatrix}. \quad (2)$$

Expanding Equation (1) we can get:

$$X = \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}} \quad Y = \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}}. \quad (3)$$

Finally, by multiplying the denominator of both equations to their left and moving the left side of the equation over the right side, we get:

$$0 = (h_{11}x + h_{12}y + h_{13}) - (h_{31}Xx + h_{32}Xy + h_{33}X), \quad (4)$$

$$0 = (h_{21}x + h_{22}y + h_{23}) - (h_{31}Yx + h_{32}Yy + h_{33}Y), \quad (5)$$

or in matrix form:

$$0 = Ah = \begin{bmatrix} x & y & 1 & 0 & 0 & 0 & -Xx & -Xy & -X \\ 0 & 0 & 0 & x & y & 1 & -Yx & -Yy & -Y \end{bmatrix} \begin{bmatrix} h_{11} \\ h_{12} \\ h_{13} \\ h_{21} \\ h_{22} \\ h_{23} \\ h_{31} \\ h_{32} \\ h_{33} \end{bmatrix}. \quad (6)$$

where h is a nine-dimensional vector consisting of coefficients of the homography matrix H . Because the homography matrix is a 3×3 homogeneous matrix, its h_{33} element is normalized to 1 so that it has only 8 degrees of freedom. To find the solution for the homography matrix, a minimum of four pairs of corresponding points on the object and the image are needed. If there are more than four pairs of corresponding points, the final solution is obtained by Direct Linear Transformation (DLT) [29] or Singular Value Decomposition (SVD), minimizing the errors in determination of the homography coefficients caused by measuring noise present in object and image coordinates.

3. Results

This section presents the results obtained from three experimental setups: the calibration test field, the static load beam test, and the dynamic bridge test. Each setup was designed to analyze specific aspects of the UAV-based homography approach. The calibration field experiment focused on evaluating the influence of reference point configuration and camera stability on the accuracy of homography-based transformations. The beam test verified the method's performance under controlled static load, while the bridge test extended the assessment to dynamic displacements induced by real traffic loads.

3.1. Influence of Reference Point Configuration on Homography Accuracy—Calibration Field Test

To evaluate the accuracy of the homography transformation in relation to the number and spatial distribution of reference points, a detailed test was performed using a static calibration field (Figure 9). The test was conducted at the same test site used for the interior calibration of all imaging sensors included in this study. Ten monitoring points were

signalized within the calibration field using circular targets with a diameter of 16 cm, as illustrated in Figure 9. These points were selected to represent typical object points monitored in structural applications, while ensuring a well-defined and repeatable image geometry.

Three different imaging systems were employed: (i) a DJI Phantom 4 UAV, (ii) a DJI Matrice 300 RTK UAV equipped with a Zenmuse P1 camera, and (iii) a Nikon D800E ground-based camera mounted on a rigid tripod. For each sensor, 15 still images and one video sequence were acquired under static conditions, ensuring that all detected displacements originate exclusively from image measurement noise and homography estimation errors rather than from actual object motion.

The accuracy evaluation was performed on three monitoring points (3, 5 and 6). For each image, the coordinates of these points were transformed using four different homography configurations (Figure 9):

1. Case 1—edge-only configuration (points 1, 2, 8, 10):

Represents the most common scenario in field measurements of structures such as bridges, where reference signals can only be installed near image boundaries (e.g., bridge abutments or piers).

2. Case 2—edge configuration + one additional edge point (points 1, 2, 8, 10 + 9)

Used to evaluate whether an additional reference point near the image boundary improves geometric stability.

3. Case 3—edge configuration + one central point (points 1, 2, 8, 10 + 7):

Assesses whether introducing a single interior point reduces perspective distortion and improves overall transformation accuracy.

4. Case 4—edge configuration + two central points (points 1, 2, 8, 10 + 4 and 7):

Represents an optimized layout with improved spatial coverage.

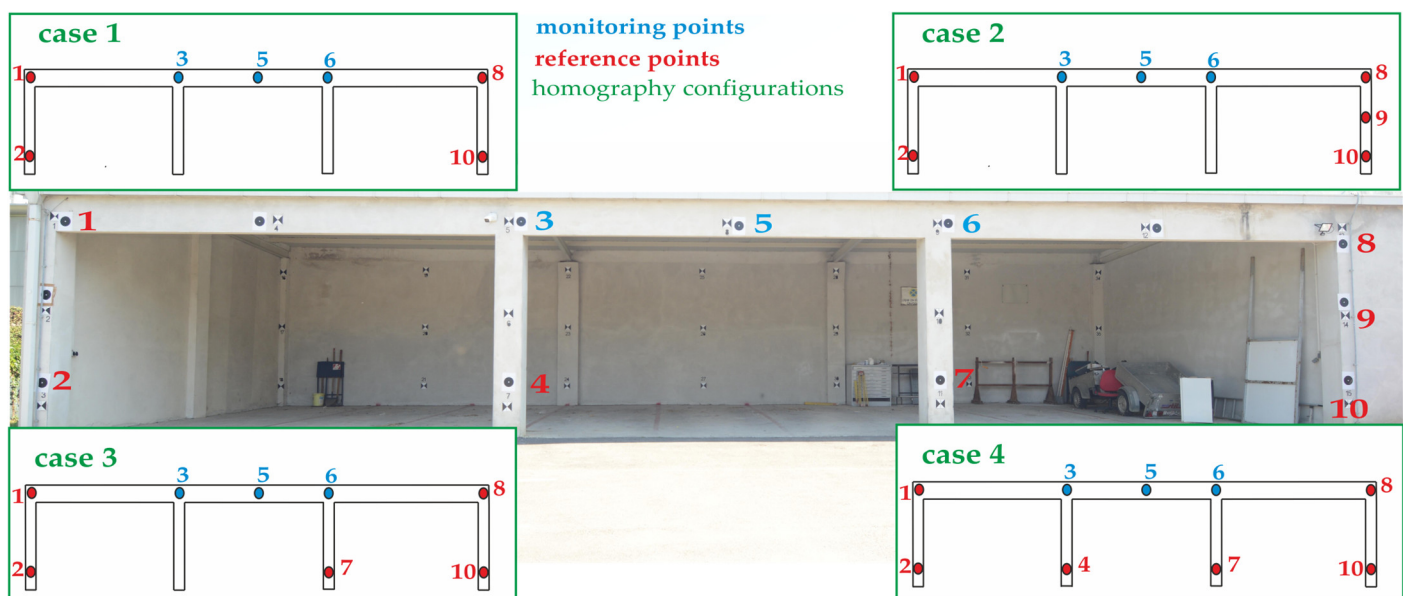


Figure 9. Calibration field with signalized points and a schematic representation of four different homography configurations.

For each sensor and homography configuration, the RMSE was computed based on the apparent displacements of monitoring points 3, 5, and 6. Since no actual structural motion occurred during image acquisition, the true displacement of all monitoring points was zero. Consequently, the apparent displacements obtained from successive images

represent measurement errors resulting from image noise, subpixel localization uncertainty, and imperfections in the homography transformation.

The RMSE values were calculated from the displacement time series derived from image coordinates relative to the initial reference position. Any deviation from zero displacement was therefore interpreted as a measurement error, allowing the RMSE to serve as a direct indicator of the internal precision and stability of the homography-based displacement estimation.

The maximum RMSE values obtained for the Nikon D800E camera were 0.12 pixels (Case 2), while for the DJI Phantom 4 and DJI Matrice 300 RTK systems the maximum RMSE values reached 0.25 pixels and 0.28 pixels, respectively, observed in both Case 1 and Case 2 (Table 3). When considering the corresponding object-space pixel sizes listed in Table 1, these values indicate that the achieved displacement accuracy is in the order of a few tenths of a millimetre for the ground-based system and within a millimetres for the UAV-based systems.

Table 3. RMSE (pixels) of homography transformation for different reference point configurations.

Case	Reference Points	Nikon D800E		DJI Phantom 4		DJI Matrice 300 RTK	
		RMSE X	RMSE Y	RMSE X	RMSE Y	RMSE X	RMSE Y
1	1–2–8–10	0.11	0.01	0.25	0.04	0.28	0.08
2	1–2–8–10–9	0.12	0.01	0.25	0.04	0.28	0.07
3	1–2–8–10–7	0.03	0.02	0.12	0.04	0.13	0.07
4	1–2–8–10–4–7	0.04	0.02	0.09	0.04	0.12	0.07

These results confirm that homography-based correction enables subpixel-level displacement precision even under UAV hovering conditions, provided that a sufficient number of well-distributed reference points is available.

Also, the results clearly show that configurations including one or more central points (Cases 3 and 4) reduce RMSE values compared to edge-only configurations (Cases 1 and 2). The inclusion of centrally located reference points minimizes perspective-induced warping and provides better geometric control, particularly along the X-axis, while the Y-axis results remain largely stable regardless of configuration. The reduced sensitivity observed in the Y-direction can be attributed to a more favourable vertical distribution of reference points within the image, providing sufficient geometric control even in edge-only configurations.

Analysis of Video Sequences

To further evaluate the applicability of the homography transformation method for dynamic monitoring, the same analysis procedure was extended to video recordings. The video sequences were decomposed into individual frames, each processed independently using homography transformation based on the defined set of reference points.

The analyzed video datasets consisted of (1) 920 frames recorded with the DJI Phantom 4 (3840 × 2160 px resolution and 29.97 fps), (2) 460 frames recorded with DJI Matrice P1 (1920 × 1080 px resolution and 59.94 fps) and (3) 920 frames recorded with Canon D800E camera (1920 × 1080 px resolution and 29.97 fps). Since no load was applied to the observed object, all apparent displacements represent measurement noise caused by UAV motion, image stabilization imperfections, and subpixel localization uncertainty and residual homography estimation errors.

The computed displacements of monitoring points 3, 5 and 6 are illustrated in Figure 10 for the Phantom 4 video sequence. The figure presents both horizontal and vertical coordinate variations obtained from the video sequence before and after applying homography

transformation. For the monitoring point, the corrected trajectory is nearly linear, confirming that homography successfully compensates UAV-induced camera motion.

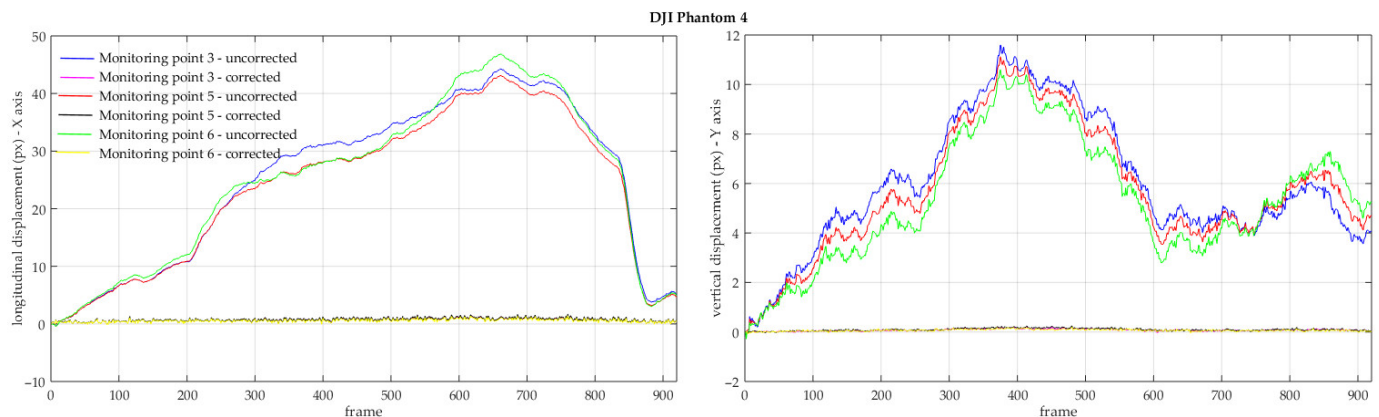


Figure 10. Displacements of monitoring points 3, 5 and 6 before (uncorrected) and after (corrected) applying homography correction in DJI Phantom 4 video.

The computed apparent displacements for monitoring points 3, 5 and 6 after applying homography transformation are illustrated in Figure 11 (DJI Phantom 4), Figure 12 (DJI Matrice 300 RTK) and in Figure 13 (Nikon D800E camera). Each figure presents both horizontal and vertical coordinate variations obtained from the video sequence for Case 1 and Case 3 homography configurations. Only Case 1 and Case 3 configurations are presented in the figures, since Cases 1 and 2 as well as Cases 3 and 4 produced nearly identical results, indicating that the inclusion of additional reference points did not further improve transformation stability.

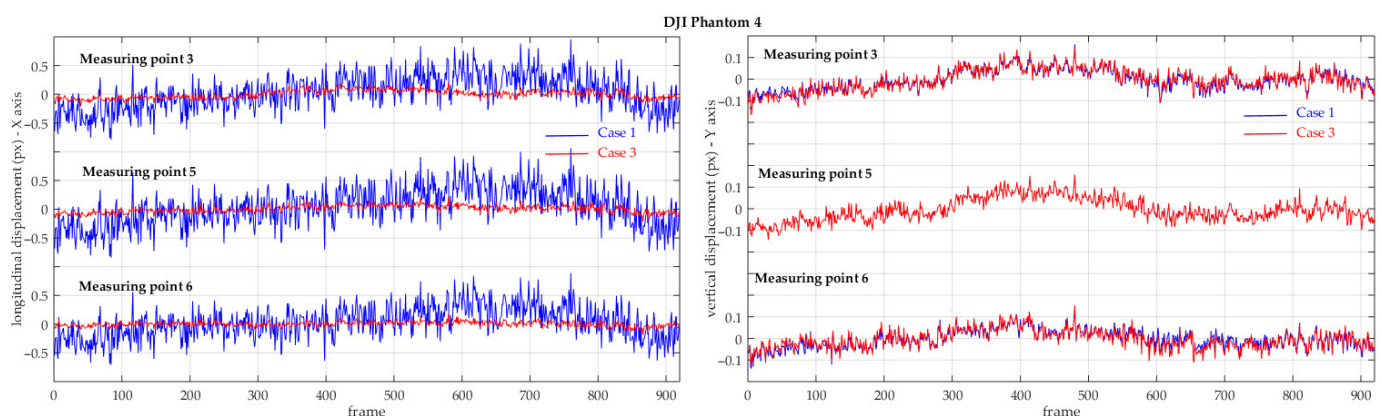


Figure 11. Longitudinal and vertical displacements of measuring points 3, 5 and 6 derived from DJI Phantom 4 video after homography transformation (Case 1 and Case 3).

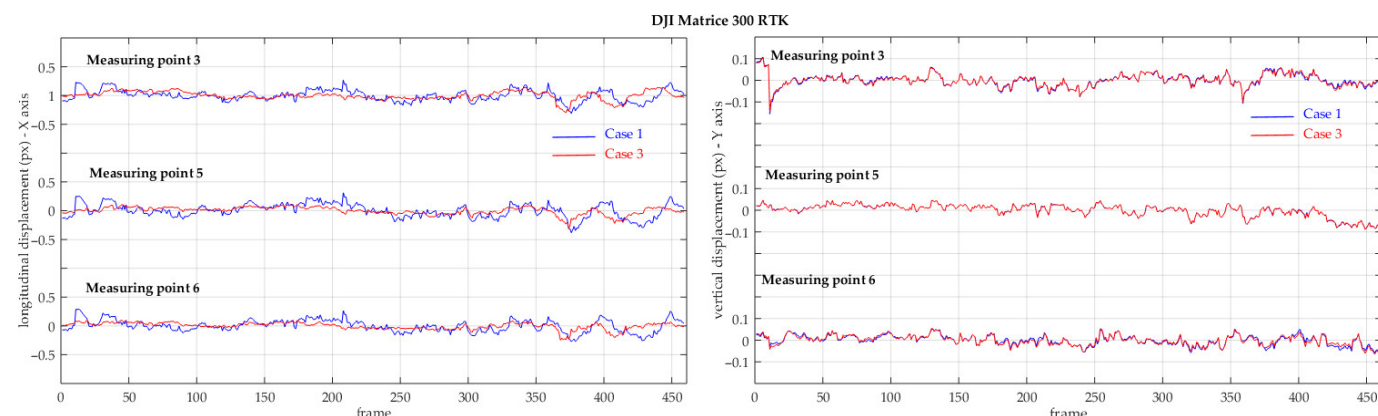


Figure 12. Longitudinal and vertical displacements of measuring points 3, 5 and 6 derived from DJI Matrice 300 RTK video after homography transformation (Case 1 and Case 3).

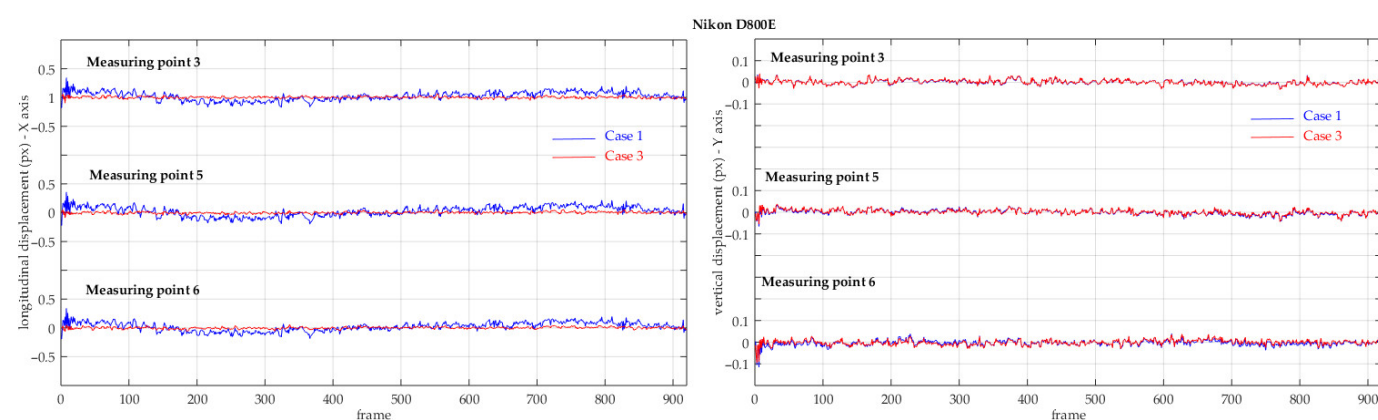


Figure 13. Longitudinal and vertical displacements of measuring points 3, 5 and 6 derived from Nikon D800E video after homography transformation (Case 1 and Case 3).

The results presented in Table 4 summarize the displacements obtained from video sequences for three monitoring points (points 3, 5, and 6) and four homography configurations. For each camera system and homography case, three statistical indicators are reported for both the longitudinal (X) and vertical (Y) directions: the mean of the absolute displacement values, the maximum absolute displacement, and the RMSE. The results allow a quantitative comparison between different homography configurations as well as between the UAV-based camera systems and the tripod mounted camera.

Table 4. Comparison of apparent displacement statistics obtained from UAV-based and ground-based camera systems under static conditions (pixels).

Case	Monitoring Point	Axis	DJI Phantom 4 (920 Frames)			DJI Matrice 300 RTK (460 Frames)			Nikon D800E (920 Frames)		
			Mean	Max	RMSE	Mean	Max	RMSE	Mean	Max	RMSE
1	3	X	0.24	0.96	0.30	0.08	0.32	0.10	0.06	0.35	0.08
		Y	0.04	0.16	0.05	0.02	0.16	0.03	0.01	0.04	0.01
	5	X	0.27	1.03	0.32	0.10	0.39	0.12	0.07	0.36	0.09
		Y	0.04	0.16	0.05	0.02	0.09	0.03	0.01	0.07	0.01
	6	X	0.22	0.88	0.28	0.09	0.29	0.11	0.06	0.34	0.08
		Y	0.04	0.14	0.04	0.02	0.06	0.02	0.01	0.11	0.01
2	3	X	0.25	0.95	0.30	0.08	0.32	0.10	0.06	0.35	0.08
		Y	0.04	0.16	0.05	0.02	0.16	0.03	0.01	0.04	0.01
	5	X	0.27	1.05	0.33	0.10	0.40	0.12	0.08	0.37	0.09

3	6	Y	0.04	0.15	0.05	0.02	0.09	0.03	0.01	0.07	0.01
		X	0.22	0.88	0.27	0.08	0.31	0.10	0.07	0.34	0.08
		Y	0.03	0.16	0.04	0.02	0.06	0.02	0.01	0.12	0.02
	3	X	0.06	0.21	0.07	0.06	0.30	0.07	0.01	0.10	0.02
		Y	0.04	0.17	0.05	0.02	0.15	0.03	0.01	0.04	0.01
	5	X	0.05	0.22	0.06	0.05	0.32	0.07	0.01	0.09	0.02
		Y	0.04	0.16	0.05	0.02	0.09	0.03	0.01	0.05	0.01
	6	X	0.03	0.19	0.04	0.05	0.25	0.06	0.01	0.06	0.02
		Y	0.03	0.15	0.04	0.02	0.07	0.02	0.01	0.10	0.01
	4	X	0.06	0.21	0.07	0.07	0.27	0.08	0.01	0.08	0.02
		Y	0.04	0.18	0.05	0.02	0.15	0.03	0.01	0.04	0.01
	5	X	0.05	0.22	0.06	0.05	0.24	0.06	0.01	0.06	0.02
		Y	0.04	0.16	0.05	0.02	0.09	0.03	0.01	0.05	0.01
	6	X	0.03	0.19	0.04	0.05	0.23	0.06	0.01	0.07	0.02
		Y	0.03	0.15	0.04	0.02	0.06	0.02	0.01	0.09	0.01

The results presented in Table 4 confirm the trends observed in the still-image experiment. For all three imaging systems, homography configurations including centrally located reference points (Cases 3 and 4) yield substantially lower mean, maximum, and RMSE displacement values compared to edge-only configurations (Cases 1 and 2) in the longitudinal (X) direction. Also, results in the Y-direction remained stable in all four homography configurations, indicating that the vertical geometry of reference points already provides sufficient control even in simplified layouts.

Results presented in this section indicate that, under controlled geometric conditions, the homography-based approach achieves sub-millimetre precision. The stability observed across different reference point configurations confirms the robustness of the transformation when adequate spatial distribution is ensured.

3.2. Static Load Test of the Reinforced Concrete Beam

This section presents the results obtained from the static load test of a reinforced concrete beam. The aim of this experiment was to evaluate the accuracy of UAV-based homography photogrammetry under controlled static loading conditions and to compare the UAV-derived displacements with reference measurements obtained using LVDTs and RTS.

The beam was loaded in four incremental loading phases corresponding to 25%, 50%, 75%, and 100% of the design load. For each loading phase, displacements were measured independently using UAV photogrammetry, LVDTs, and RTS observations. Three different homography reference point configurations (Figure 14) were applied, analogous to those used in the calibration field experiment, in order to assess the influence of reference point selection on displacement accuracy.

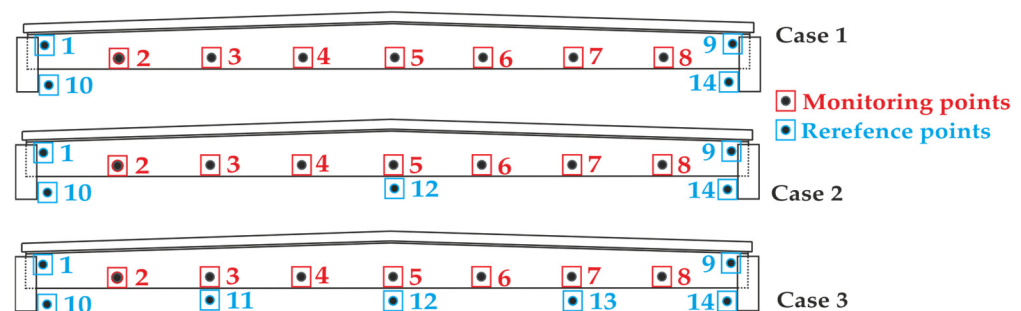


Figure 14. A reinforced concrete beam with positions of signaled points and three different homography configurations.

Figure 15 presents the measured displacements for all monitoring points in the fifth loading phase, corresponding to the maximum applied load, using the edge-only homography configuration (Case 1).

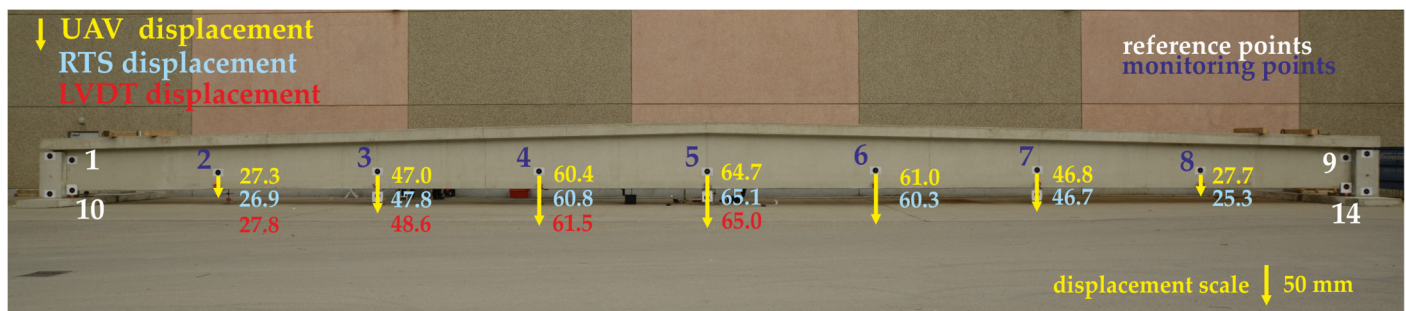


Figure 15. Measured vertical displacements (mm) by UAV, LVDT and RTS in Phase 5.

The results show a consistent deformation shape obtained by all three measurement systems. The displacement differences between the UAV-derived measurements and the reference RTS and LVDT measurements for all loading phases are summarized in Table 5. The results show no systematic increase in discrepancies with increasing load level. Instead, the differences remain relatively consistent across all loading phases, indicating stable homography performance even at higher displacement amplitudes.

Table 5. The displacement differences between the UAV-derived measurements and the reference RTS and LVDT measurements for Case 1 (mm).

Reference Measurement	Loading Phase	Monitoring Point						
		2	3	4	5	6	7	8
RTS	F2	−2.8	−3.7	−3.1	−1.8	−2.2	−3.6	−0.5
	F3	1.6	−0.6	0.0	0.4	−0.4	−1.2	0.4
	F4	−1.4	−2.9	−3.5	−2.7	−1.9	−2.6	0.5
	F5	−0.5	0.8	0.4	0.4	−0.6	−0.1	1.6
LVDT	F2	−2.6	−4.0	−3.5	−2.3	−	−	−
	F3	2.0	0.0	0.3	−0.1	−	−	−
	F4	−0.7	−2.3	−3.1	−3.1	−	−	−
	F5	0.5	1.6	1.0	0.3	−	−	−

A statistical accuracy evaluation was performed for all three homography configurations by comparing UAV-derived displacements against both RTS and LVDT reference measurements. The results are summarized in Table 6.

Table 6. The UAV displacement differences statistics for a different homography reference point configurations (mm).

Case	Reference Measurement	No of Displacements	Mean	Max.	St. dev.	RMSE	
						mm	px
1	RTS	28	1.5	3.7	1.6	1.9	0.26
	LVDT	16	1.7	4.0	2.0	2.1	0.28
2	RTS	28	1.3	3.2	1.5	1.7	0.23
	LVDT	16	1.5	3.5	1.8	1.9	0.26
3	RTS	28	1.3	3.1	1.4	1.6	0.22
	LVDT	16	1.4	3.3	1.7	1.8	0.24

The analysis shows a gradual improvement in measurement accuracy with increasing number and spatial coverage of reference points. Case 3 achieved the lowest RMSE values for both RTS and LVDT comparisons, confirming that the inclusion of additional reference points improves homography stability. However, the observed differences between configurations remain relatively small, indicating that even simplified reference point layouts can provide acceptable accuracy under controlled static loading conditions.

From the results, we can conclude that observed agreement with LVDT measurements demonstrates that the method remains reliable under controlled static loading conditions, although minor deviations become more noticeable with less favourable reference point configurations.

3.3. Influence of Reference Point Configuration on Homography Accuracy—Podsused Bridge

Two UAV video sequences acquired using the DJI Phantom 4 were analyzed to evaluate the applicability of homography-based displacement correction under real traffic loading conditions on the Podsused bridge. The first video sequence (Video 1), with a duration of 83 s, captured three distinct traffic-induced loading events, clearly visible in the UAV-derived displacement records. The second video sequence (Video 2), lasting 25 s, recorded the passage of a heavy truck with a trailer. All detected events are illustrated in Figure 16.



Figure 16. Traffic-induced loading events in recorded videos.

Each video was decomposed into individual frames and processed using a DIC-based tracking approach. For each frame, the image coordinates of all ten signaled points were determined. Subsequently, homography transformations based on the selected set of stable reference points were applied independently to each frame in order to remove false displacements caused by UAV motion.

Figure 17 presents the longitudinal (X-direction) and vertical (Y-direction) displacements of four monitoring points on the bridge (points 2, 3, 4 and 5), both before and after homography transformation in Video 1. Prior to correction, the displacement signals exhibit significant apparent motion dominated by UAV instability. After applying homography transformation, the false global trends are removed, and the remaining displacement patterns clearly correspond to traffic-induced dynamic structural behaviour.

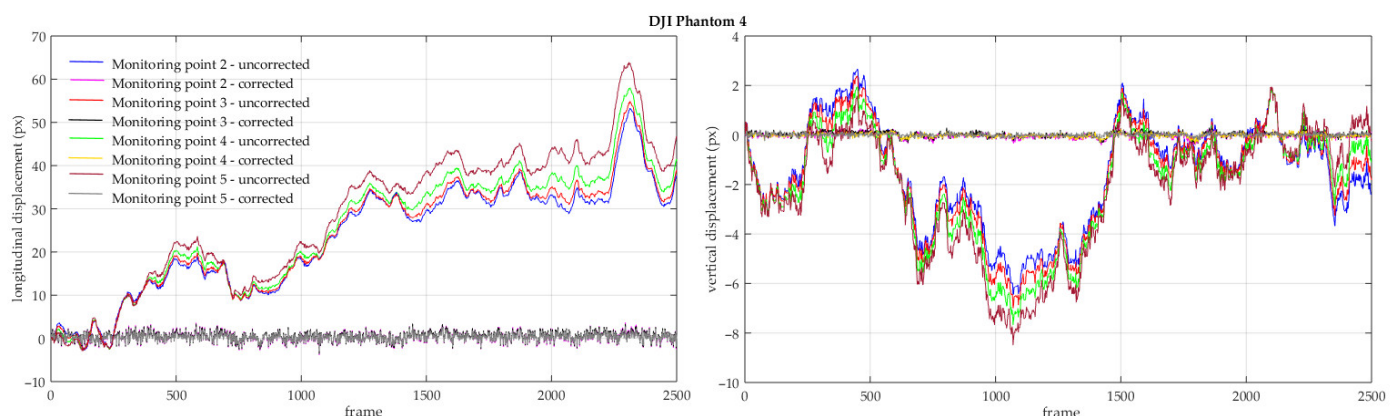


Figure 17. Displacements of monitoring points on the bridge before (uncorrected) and after (corrected) applying homography correction in Video 1.

To assess the measurement accuracy, UAV-derived vertical displacement were compared against reference measurements obtained using an LVDT sensor installed at measuring points 2 and 4. Since the UAV and LVDT records were neither synchronized nor sampled at the same rate, an event-based time alignment was applied by matching the maximum absolute displacement values corresponding to the same loading event. This event-based alignment approach is straightforward and well suited to low-frequency dynamic response. However, it may introduce minor temporal uncertainties, particularly due to measurement noise present in the UAV-derived signal and the limited temporal resolution of visually identified peak values. For applications involving higher-frequency dynamic response, more advanced synchronization techniques (e.g., cross-correlation-based alignment) could provide improved temporal accuracy. In the present study, given the predominantly low-frequency dynamic response of the loading events, the adopted procedure was considered adequate for comparative accuracy assessment. The records were then truncated to a common time interval, vertical offsets were removed by equalizing the mean displacement in the unloaded state, and the LVDT signal was linearly interpolated to the UAV time stamps. The displacement differences were subsequently used to quantify the measurement accuracy.

Due to differences in acquisition start times and sampling rates between the UAV video and LVDT recordings, only the overlapping portions of both signals were used for accuracy analysis. Consequently, although Video 1 had a total duration of 83 s, the comparison was performed over a 60 s interval corresponding to the common time window with available LVDT data, while for Video 2 the overlapping interval was limited to 20 s.

Figures 18 and 19 illustrates the comparison between UAV and LVDT-derived vertical displacements at measuring points 2 and 4 for both video sequences. A very good agreement in displacement trends and peak values is observed for both loading scenarios, confirming the ability of the UAV–homography approach to capture dynamic bridge displacements under real traffic conditions.

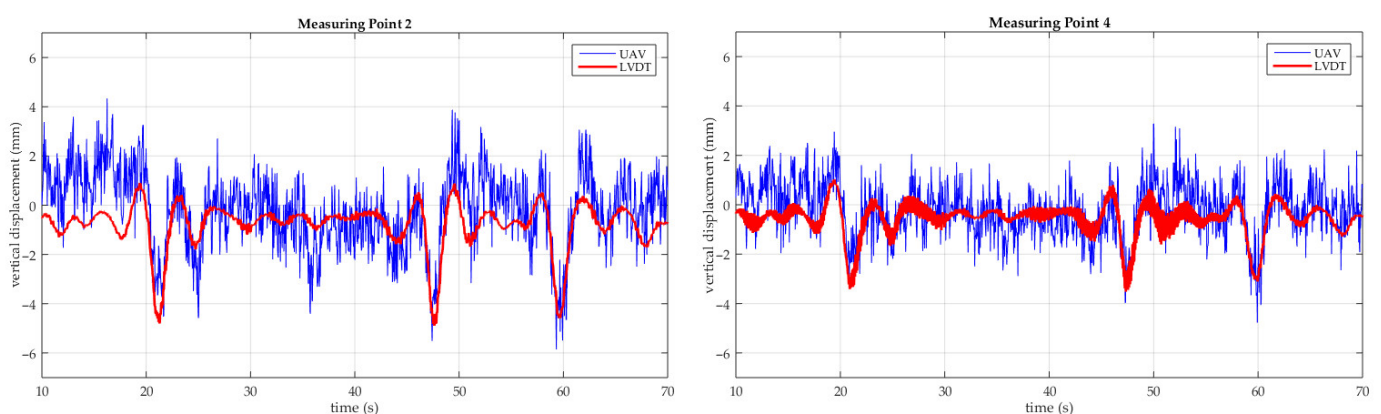


Figure 18. Vertical displacements of measuring point 2 and measuring point 4 derived from Phantom 4 UAV Video 1 and from LVDT sensor.

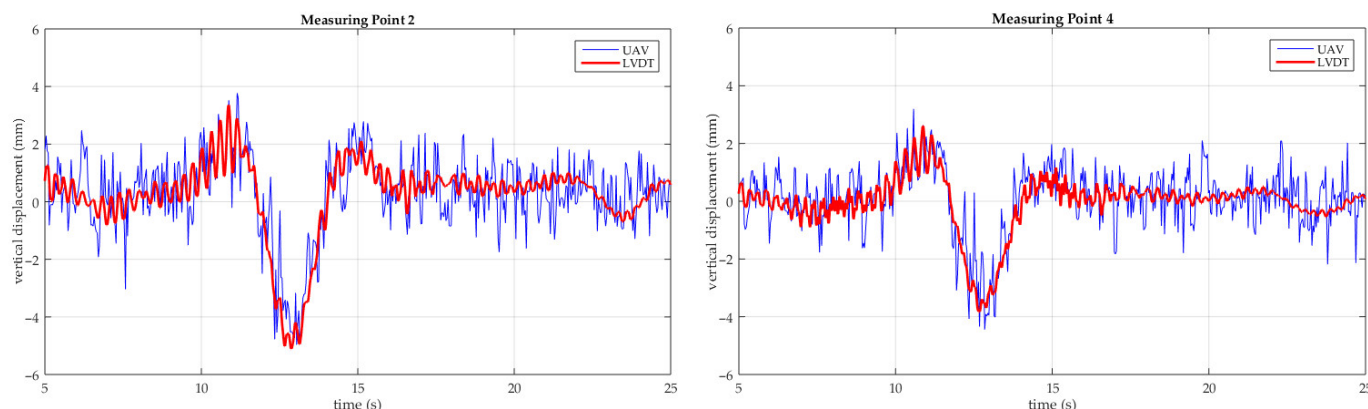


Figure 19. Vertical displacements of measuring point 2 and measuring point 4 derived from Phantom 4 UAV Video 2 and from LVDT sensor.

Table 7 summarizes the statistical indicators computed from the displacement differences relative to the LVDT reference values for both video sequences. The results show RMSE of 1.38 mm and 1.01 mm for monitoring points 2 and 4 in Video 1 and 0.88 mm and 0.76 mm in Video 2. When expressed in image space, these values correspond to subpixel-level accuracy, with RMSE values at approximately 0.1 pixels, considering that one pixel represents approximately 13.3 mm in object space.

Table 7. Accuracy analysis of UAV displacement measurements compared to LVDT values (mm).

	Measuring Point	Frames	Mean	Max.	St. dev.	RMSE	
						mm	px
Video 1	2	1856	1.10	4.66	1.24	1.38	0.10
	4		0.80	3.83	0.94	1.01	0.08
Video 2	2	634	0.70	3.03	0.88	0.88	0.07
	4		0.57	3.23	0.75	0.76	0.06

Despite the fact that the maximum traffic-induced displacements observed in both video sequences reached values of less than half a pixel in image space, the UAV-based measurements were able to reliably capture and reproduce these small-amplitude structural responses. All characteristic loading events identified visually in the recorded videos, including the passages of heavy vehicles illustrated in Figure 16, are clearly recognizable in the corresponding displacement time histories. This confirms the high sensitivity of the homography-corrected photogrammetric approach and demonstrates its capability to detect dynamic bridge displacements of very small magnitude under real traffic conditions.

In accordance with the findings from the calibration field and beam experiments, the homography transformation in the bridge test was not limited to the minimum number of four reference points. In addition to the primary reference points 1, 6, 7, and 10 (Figure 5), two additional centrally located reference points (points 8 and 9) were introduced for Video 2, resulting in a six-point homography configuration. The UAV-derived displacement results obtained using both four-point and six-point configurations are shown in Figure 20.

The comparison reveals that the inclusion of additional central reference points did not lead to a significant improvement in vertical displacement accuracy. The displacement time histories obtained using four and six reference points are nearly identical, and the resulting accuracy metrics remain at the same level for both configurations. This indicates that, under favourable geometric conditions and with well-distributed boundary reference points, a minimal homography configuration can already provide sufficient stability

for reliable displacement monitoring. These findings are consistent with the results obtained in the calibration field and beam experiments, where additional reference points improved robustness but did not always yield substantial accuracy gains.

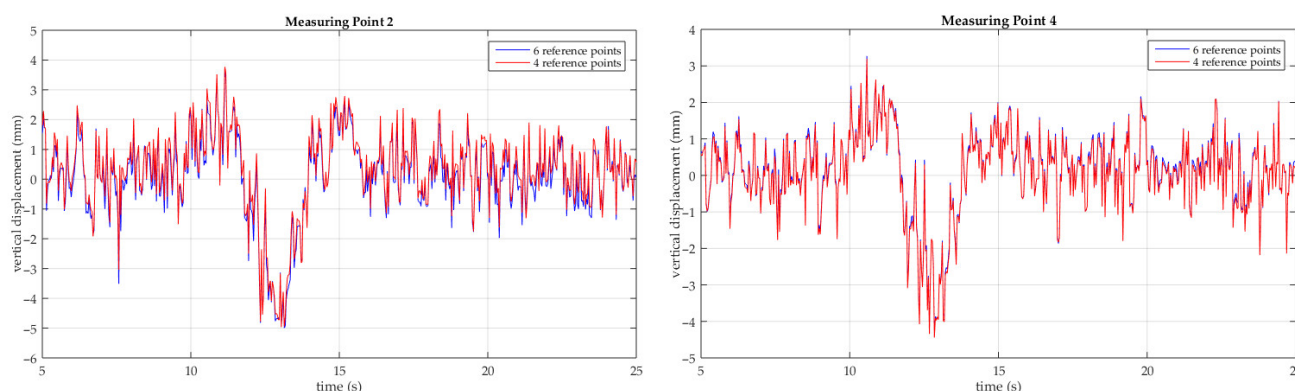


Figure 20. Vertical displacements of measuring points 2 and 4 from Video 2 after homography transformation by 6 reference points and 4 reference points.

In addition to UAV measurements, bridge deformations were also measured with a Nikon D800E camera mounted on a solid and stable tripod. Figure 21 illustrates the comparison between camera and LVDT-derived vertical displacements at measuring points 2 and 4.

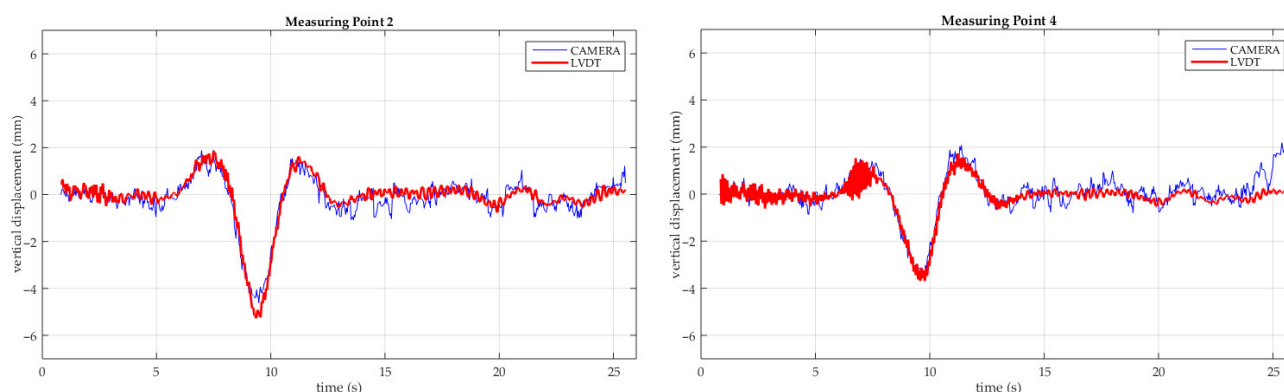


Figure 21. Vertical displacements of measuring point 2 and measuring point 4 derived from Nikon D800E video sequence and from LVDT sensor.

Due to the superior recording quality, longer focal length, and complete elimination of camera movement, the tripod mounted camera achieved significantly higher accuracy compared to UAV measurements. The resulting RMSE values were below 0.5 mm, confirming the potential of vision-based displacement measurement under ideal imaging conditions (Table 8).

Table 8. Accuracy analysis of camera displacement measurements compared to LVDT values (mm).

		Measuring Point	Frames	Mean	Max.	St. dev.	RMSE	
							mm	px
Video 1	2	4	742	0.30	1.29	0.37	0.38	0.02
	4			0.33	2.12	0.42	0.45	0.02

These outcomes establish a benchmark for evaluating UAV-based measurements, highlighting the impact of camera stability and image geometry on achievable accuracy. The

tripod mounted camera is more precise; however, it is impractical for actual bridge monitoring scenarios due to its inability to access appropriate locations or operate under suitable conditions. Conversely, UAV-based systems offer numerous practical advantages.

From the UAV results, we can conclude that although environmental variability and UAV platform motion introduce additional noise, the overall displacement trends show satisfactory agreement with reference sensors, confirming the practical applicability of the approach in field conditions.

4. Discussion

4.1. Accuracy and Consistency of UAV–Homography Displacement Measurements

The experimental results obtained from the three performed tests demonstrated that UAV-based homography can provide precise measurements of static and dynamic structural displacements in monitoring projects with different spatial scales and operational conditions.

At the calibration test field, very high internal precision was achieved. The maximum RMSE values of the vertical displacements were below 0.08 pixels, corresponding to approximately 0.25 mm in object space for the UAV-based systems and about 0.10 mm for the ground-based camera system. Lower accuracy was observed in the longitudinal direction, which can be attributed to less favourable imaging geometry and reduced geometric sensitivity along this axis. In this direction, RMSE values remained on the order of a few tenths of a millimetre for the ground-based system and within one millimeter for the UAV-based measurements. Since vertical displacements are typically of primary interest in bridge load testing and serviceability assessments, the achieved accuracy is considered highly satisfactory. These results confirm that homography-based correction successfully compensates UAV-induced camera motion and enables subpixel-level displacement precision, provided that a sufficient number of well-distributed reference points is available.

The measurements during the static load test of the beam validated the accuracy of the proposed approach through direct comparison with high-precision LVDT measurements. The close agreement observed between UAV-derived and reference displacement confirms the capability of the method to capture vertical static displacements with an accuracy of approximately 2 mm. Compared to the calibration test field measurement results, a reduction in accuracy was observed, which can primarily be attributed to less favourable imaging geometry and reference point configuration. Additional factors included longer observation distances and variable illumination conditions. Nevertheless, considering that the maximum displacements during the final loading stage reached 27.3 mm at the beam edges and up to 64.7 mm at midspan, the achieved accuracy corresponds to relative errors of approximately 7% at the supports and 3% at midspan. This level of accuracy is particularly suitable for long-span and flexible structures, where expected displacements align with the precision thresholds necessary for reliable structural assessment. Moreover, in comparison with conventional contact-based sensors, the UAV-based approach enables significantly simpler deployment and provides full-field displacement information along the entire beam length.

In the third test, measurements were performed on a full-scale bridge during regular traffic operation in order to capture dynamic displacement response induced by heavy vehicle loading. The UAV-based measurements successfully reproduced the characteristic displacement patterns, with RMSE values of approximately 0.1 pixels, corresponding to up to 1.38 mm in object space. Although the absolute accuracy was reduced compared to the calibration test field, the temporal evolution and magnitude of the measured displacements showed good agreement with the LVDT reference data, and all characteristic loading events were clearly identified. This confirms the operational feasibility of the proposed approach for real-world bridge monitoring, where operational constraints inevitably

affect measurement quality (further discussed in Section 4.3). A direct comparison between UAV-based and ground-based camera measurements in this test further highlights the importance of camera stability and quality. The ground-based system achieved significantly higher accuracy, with RMSE values below 0.5 mm, confirming that camera stability and image geometry play a critical role in achieving higher displacement measurement precision.

4.2. Influence of Homography Reference Point Configuration

Additionally, in this study, the systematic investigation of the influence of reference point number and spatial configuration on homography-based displacement accuracy was done. The calibration test field measurements clearly indicate that both the number and geometric distribution of reference points affect the stability and precision of the estimated displacements.

Based on the conducted experiments, several practical principles for reference point selection and arrangement can be summarized. First, reference points should be located on geometrically stable parts of the structure or on externally stable elements whenever possible. Any movement of reference points directly affects homography stability and may require coordinate correction.

Second, reference points should be (as much as possible but reasonable) uniformly distributed across the image. Concentrated or nearly collinear arrangements decrease the reliability and accuracy of homography. Furthermore, the inclusion of centrally located reference point compared to edge-only configurations, minimizes perspective-induced warping and provides better geometric control along the X-axis, while the Y-axis results remain largely stable regardless of configuration. At all three measurement locations we had a more favourable vertical distribution of reference points within the image, which provided sufficient geometric control even in edge-only configurations.

Third, an adequate number of reference points should be used to provide redundancy and improve robustness against individual point tracking errors. However, increasing the number of points does not automatically guarantee higher accuracy if their spatial distribution is unfavourable.

These findings highlight a limitation of homography-based displacement monitoring in practical field applications, where the availability of suitable stationary reference features is often constrained. Unlike controlled environments, real-world bridge sites rarely offer ideally distributed reference points within the camera field of view. Consequently, careful planning of UAV positioning, camera orientation, and reference points selection becomes essential to achieve reliable displacement estimation.

4.3. Practical Limitations and Operational Considerations

Several practical aspects constrain the performance of UAV-based homography displacement monitoring in real-world applications. In particular, the method is sensitive to UAV drift, wind-induced platform instability, illumination variability, camera calibration errors, and motion blur. Platform instability may introduce geometric inconsistencies that affect homography estimation accuracy, while reduced illumination or strong shadows can decrease image contrast and the number of reliably detectable features, increasing susceptibility to matching errors. Uncorrected lens distortion and calibration inaccuracies may further introduce spatially varying errors across the image domain.

In the present study, these effects were mitigated by performing measurements under favourable weather and lighting conditions, applying prior camera calibration, and ensuring stable hovering during image acquisition. Nevertheless, such operational factors remain critical when evaluating the robustness and reliability of UAV-based displacement monitoring in practical bridge applications. Beyond these environmental and platform-

related influences, the method assumes predominantly planar structural motion, and significant out-of-plane displacements may introduce projection-related errors. Measurement accuracy also strongly depends on imaging geometry, camera resolution, and flight stability, emphasizing the importance of careful mission planning and flight control.

Moreover, the requirement for stationary reference points remains a major operational challenge, especially for long-span bridges or complex structural layouts. However, this challenge can be addressed by employing aerial manipulators designed to mount targets and sensors directly onto the structure, a process that eliminates the need for specialized inspection trucks and costly road closures [30]. Also, recent advances in reference-free vision-based methods, including feature tracking and digital image correlation techniques, show promising potential. However, such approaches are often more sensitive to illumination variability, texture quality, and environmental disturbances. Therefore, the use of controlled reference targets currently provides improved geometric stability and measurement robustness in field applications. Although the proposed UAV-based approach requires the placement of reference and monitoring targets, the installation effort remains significantly lower compared to traditional contact sensors such as LVDTs. In bridge load testing scenarios, LVDTs typically require stable external supports, mounting frames, wiring, and physical access beneath the structure, which can be time-consuming and sometimes impractical for large spans or over-water crossings. In contrast, the installation of lightweight photogrammetric targets can be performed rapidly and without the need for heavy supporting equipment. Nevertheless, for very large-scale infrastructure or structures with restricted access, the installation of artificial targets may still present logistical challenges. Taking into account the above, future developments may involve the integration of multi-camera UAV platforms, onboard inertial measurement units, and hybrid photogrammetric–inertial correction frameworks to further enhance robustness and reduce reliance on external reference points. Such advancements could significantly extend the applicability of UAV-based displacement monitoring for routine structural health assessment and long-term monitoring campaigns.

5. Conclusions

This study investigated the accuracy and operational feasibility of UAV-based homography photogrammetry for monitoring static and dynamic displacements of civil engineering structures. The results demonstrated that sub-millimetre precision was achievable under controlled conditions, while full-scale bridge monitoring showed displacement errors generally within 1–2 mm compared to LVDT measurements. The results confirmed that reference point number, spatial distribution, and stability significantly influence homography-based displacement accuracy. Importantly, the vertical displacement accuracy remained largely insensitive to reference point configuration, which is particularly relevant for bridge load testing, where vertical deflections are typically of primary interest and the identification of suitable stationary reference features often represents a practical challenge.

Despite the encouraging results, several challenges remain. Measurement accuracy is still affected by environmental conditions, illumination variability, and UAV platform stability. Moreover, the assumption of predominantly planar structural behaviour limits the direct applicability of the method in scenarios involving complex three-dimensional deformations. Future research will therefore focus on extending the proposed framework toward multi-camera UAV configurations, enhanced real-time stabilization strategies, and the integration of advanced computer vision and machine learning techniques to improve robustness under demanding field conditions. While the present study focused primarily on displacement reconstruction accuracy in the time domain, future work will also extend the validation framework toward frequency-domain analysis and potentially

modal parameter identification, further assessing the applicability of UAV-based methods in structural dynamics monitoring. Overall, the findings demonstrated that UAV-based homography provides a flexible, contactless, and sufficiently accurate alternative to conventional displacement sensors, particularly in applications where sensor installation is complex or access is limited.

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Abbreviations

The following abbreviations are used in this manuscript:

UAV	Unmanned Aerial Vehicle
LVDT	Linear Variable Differential Transformers
SHM	Structural Health Monitoring
RTS	Robotic Total Station
DIC	Digital Image Correlation
SfM	Structure-from-Motion

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