Contactless Precise In-Plane Dynamic Displacement Measurements of Structures Using ArUco Markers

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ABSTRACT

This paper presents the use of ArUco markers as alternative optical-digital instruments for remote displacement measurements with submillimeter accuracy for in-plane movements. The research primarily focuses on computer vision techniques for recording dynamic loading of specimens on a seismic table. The examined specimen consists of a single-story infilled reinforced concrete frame with a strong slab and base, which is part of the GREENERGY project. The main physical displacement measurement instruments are draw-wire displacement sensors, two at the slab level and two at the base of the connecting beams to the seismic table. Two alternative sizes of real-scale ArUco markers are examined, 80mm and half-sized 40mm, corresponding to image resolutions of 1.6mm/px and 2mm/px respectively. Using the OpenCV library and the cornerSubPix function, the measurement accuracy is refined to less than 1mm. A digital camera with 1920x1080 video resolution and 60Hz recording frequency is used to capture the measurements. The measurements are conducted under various shading and lighting conditions to verify the adaptability of the predefined ArUco markers algorithm in OpenCV. The effectiveness of the measurements is verified by comparing them with measurements from the draw-wire displacement sensors at the two aforementioned positions of the specimen, which show complete alignment for the 80mm targets.

Key Words: ArUco marker, Contactless displacement Sensor, OpenCV, Digital camera

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Ανέπαφες Ακριβείς Μετρήσεις Δυναμικών Μετατοπίσεων Κατασκευών στο Επίπεδο με τη Χρήση ArUco Στόχων

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ΠΕΡΙΛΗΨΗ

Στην παρούσα εργασία γίνεται παρουσίαση της χρήσης των ArUco στόχων ως εναλλακτικά οπτικο-ψηφιακά όργανα για μετρήσεις από απόσταση, με υποχιλιοστομετρική ακρίβεια, εντός επιπέδου μετακινήσεων. Η έρευνα επικεντρώνεται κυρίως στις τεχνικές υπολογιστικής όρασης για καταγραφές δυναμικών φορτίσεων δοκιμίων σε σεισμική τράπεζα. Το εξεταζόμενο δοκίμιο αποτελείται από μονόροφο τοιχοπληρωμένο πλαίσιο οπλισμένου σκυροδέματος με ισχυρή πλάκα και βάση που αποτελεί μέρος του ερευνητικού έργου GREENERGY. Τα κύρια φυσικά όργανα μετρήσεων μετακινήσεων είναι οι αισθητήρες μετατόπισης καλωδίων έλξης, δύο στο επίπεδο της πλάκας και δύο στη βάση των δοκών σύνδεσης με τη σεισμική τράπεζα. Εξετάζονται δύο εναλλακτικά μεγέθη των ArUco στόχων πραγματικής κλίμακας, των 80mm και υποδιπλάσια των 40mm, που αντιστοιχούν στην ανάλυση της εικόνας 1.6mm/px και 2mm/px. Χρησιμοποιώντας τη βιβλιοθήκη της OpenCV και τη λειτουργία του cornerSubPix αναπροσαρμόζεται η ακρίβεια των μετρήσεων σε μικρότερη του 1mm. Για τη λήψη των μετρήσεων χρησιμοποιείται ψηφιακή κάμερα με ανάλυση βίντεο 1920x1080 και συχνότητα καταγραφής 60Hz. Οι μετρήσεις πραγματοποιούνται σε διάφορες συνθήκες σκίασης και φωτισμού για να εξακριβωθεί η προσαρμοστικότητα του προκαθορισμένου αλγορίθμου των ArUco στόχων στην OpenCV. Η αποτελεσματικότητα των μετρήσεων επαληθεύεται με μετρήσεις από τους αισθητήρες μετατόπισης καλωδίων έλξης στις δύο προαναφερόμενες θέσεις του δοκιμίου, οι οποίες βρίσκονται σε πλήρη ταύτιση για τους στόχους των 80mm.

Λέξεις Κλειδιά: ArUco στόχος, Ανέπαφος αισθητήρας μετακίνησης, OpenCV, Ψηφιακή κάμερα

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1 INTRODUCTION

ArUco stands for *Augmented Reality University of Cordoba* published by Garrido-Jurado et al. (2014) [1], initially designed for augmented reality applications. Since then the application for distance measurement has enhanced significantly, especially in laboratory environments [2]. Additionally, the use of sub-pixel accuracy across diverse industries enable for practical application in structural monitoring and robotics. The technology's significance lies in its ability to provide non-contact, multi-point measurements with real-time processing capabilities, fundamentally changing how engineers approach structural health monitoring and precision measurement tasks [3,4]. Recent developments have demonstrated successful applications ranging from millimeter-level bridge deflection monitoring [5] to micrometer-level precision manufacturing [6], establishing ArUco markers as a mature alternative to traditional contact-based sensors. ArUco markers are synthetic square fiducial markers consisting of a black border surrounding an inner binary matrix that encodes unique identifiers as depicted in Figure 1 and enable 6 - Degree of Freedom (DOF) pose estimation.

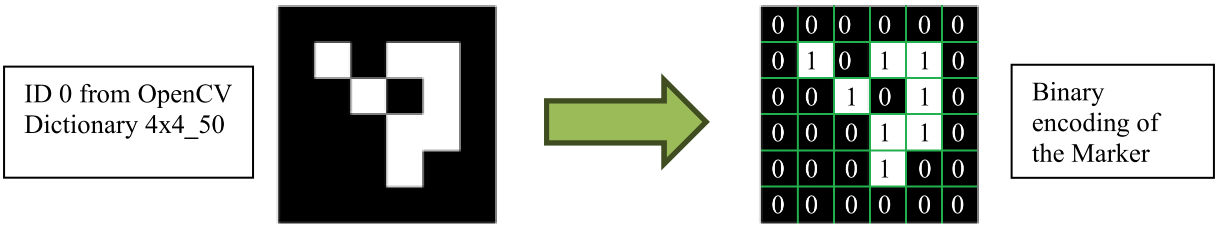


Figure 1: ArUco marker with ID 0 from Dictionary 4x4_50 and the binary encoding sketch

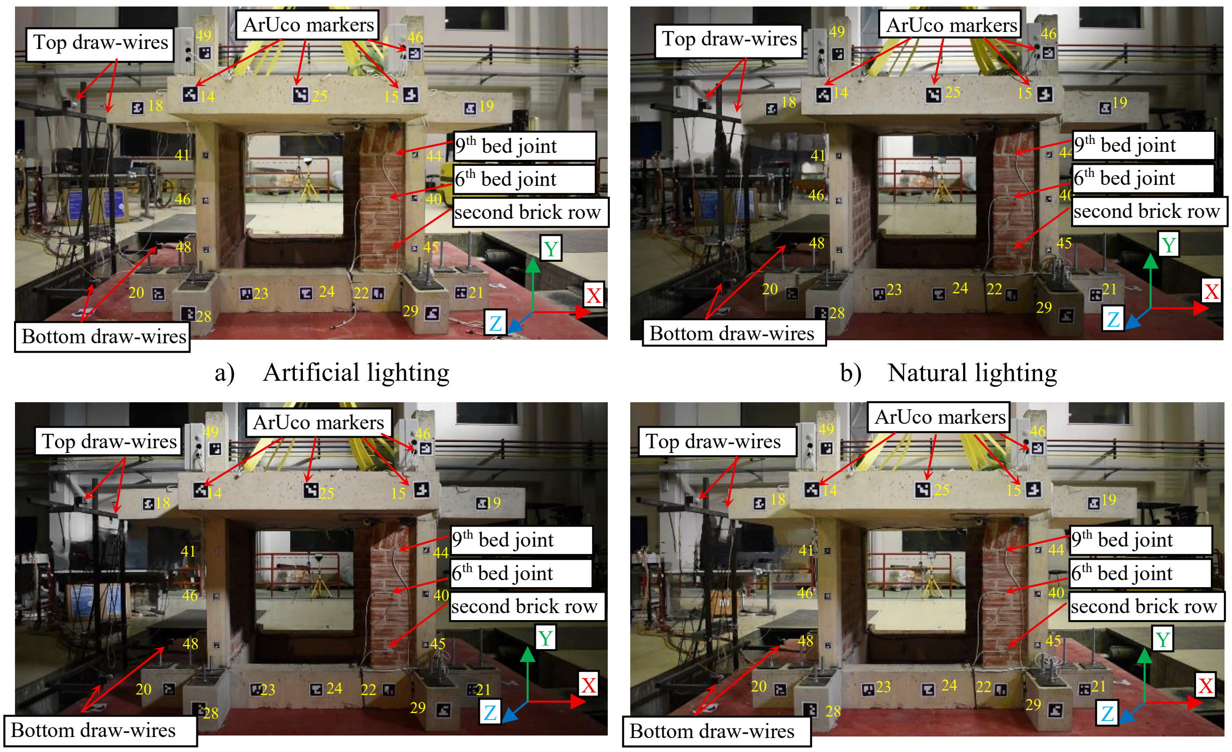
However, like all other optical metric systems, ArUco markers also have lighting sensitivity that affects performance under varying illumination conditions. To address this performance issue, advanced algorithms that use deep learning have been developed to overcome these challenges, such as DeepArUco++ [7]. The typical operating range extends from 30-50 meters when using optical enhancements total station [8]. Occlusion issues from partial or complete blockage can cause measurement gaps, requiring multiple camera positions or redundant marker placement [1]. Weather dependencies including rain, fog, and wind can affect outdoor applications, though validation studies demonstrate successful operation in various environmental conditions [9]. The technology works best when integrated strategically with traditional sensors rather than as complete replacements, particularly for critical applications requiring extreme accuracy or harsh environment operation [2].

In the current study, the in-plane displacement recording results from Phase A of the GREENERGY project using ArUco markers are presented. Initially, the experimental setup is presented, with a brief description of the geometry of the specimen, alongside the seismic table configuration, camera and draw-wire position and specifications. Then, the ArUco marker implementation is described for the marker design, the OpenCV library integration, and the cornerSubPix algorithm details. Furthermore, the image processing pipeline is explained with the marker detection algorithm, the enhancement and homogenization methods as well as accuracy refinement procedures. In the results and analysis section, the accuracy comparison of ArUco versus draw-wire sensors is discussed alongside the performance under varying conditions. Finally, in conclusion, a summary of key findings is provided with future research directions.

2 METHODOLOGY

2.1 Experimental Setup

The experimental specimen is a reinforced concrete structure that has 1000 mm clear height (measured from top of the foundation beam to the bottom of the slab). The cross-section of the columns is 130×130 mm² and the foundation beams is 200×250 mm². The slab has a mean thickness of 200 mm. The openings are partially filled in the loading direction and fully filled in the perpendicular direction with clay bricks of 60 mm thickness. More details about the specimen including the reinforcement details can be found in [10]. The draw wires are positioned at the approximate mid-height of the foundation beam to measure the introduced seismic excitation intensity and at the approximate middle of the slab thickness to measure the storey intensity response. In each elevation, there are two draw-wire sensors introduced to double-check the recorded data and provide insights for any potential rotational movement of the specimen. The specimen is fully fixed to the seismic table with proper anchoring so the base moves as a rigid body connected to the seismic table's top metal base. The seismic table has maximum displacement capacity for dynamic loading of ±130 mm and can operate under maximum acceleration of 1.6g (8 ton). The specimen was illuminated with natural light (for the majority of the test sequences) except in cases of afternoon testing when artificial lights of the laboratory were used (minimal cases) see Figure 2.



a) Artificial lighting
b) Natural lighting
c) Natural lighting
d) Natural lighting

Figure 2: Different lighting conditions during recordings of the tests a) artificial lighting and b), c), d) natural lighting (yellow numbering indicating the IDs of ArUco markers from OpenCV)

Two sizes of ArUco markers were used 80 mm (large) and 40 mm (small). The ids of all markers used in this experimental setup are depicted in Figure 3. The ArUco large markers were placed at almost midspan of the slab thickness at the top as triplets at the extension of 600 mm of the slab in +Z direction and one at each visible position for the -X and +X directions. Two markers were positioned on the 500 mm extension of the columns almost at the middle of their length. Five same large size markers were placed at the bottom foundation beam alongside the X direction and two more in the extension of the perpendicular foundation beam in the +Z direction. Additionally, markers of 40 mm were placed almost in the middle of the bed joint in the inclined brick (9th bed joint), one in the 6th bed joint and one in the second row of the bricks. Their position in the Y axis (with Y=0 assumed at the top of the seismic table metal slab) is provided in Table 1.

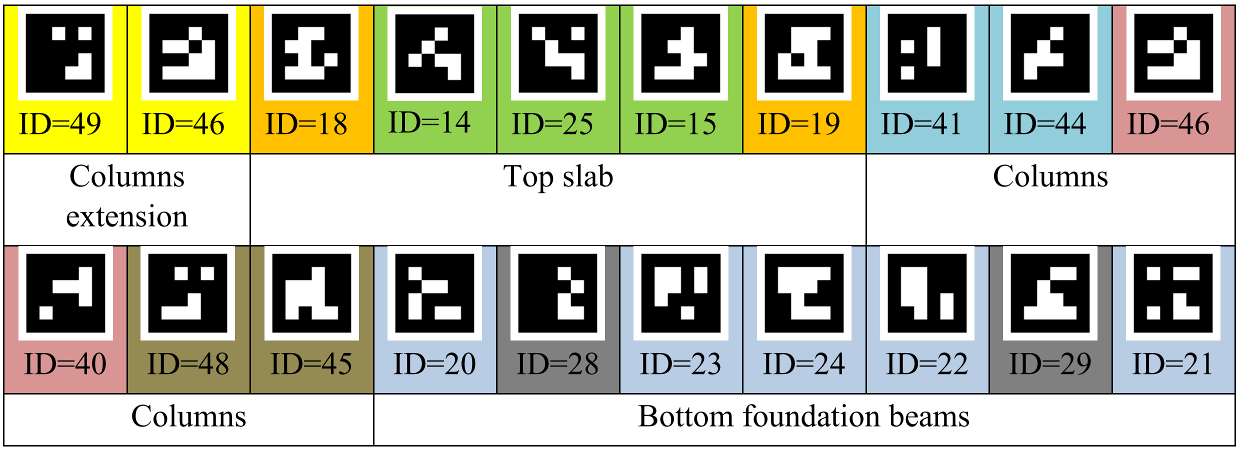


Figure 3: ArUco markers that were used in the experiment in order from left to right from top to bottom as depicted in Figure 2 (markers with same color are located at the same plane defined by Z axis)

Table 1: Position (mm) of the ArUco markers in the specimen

Marker ID	Center Y Coordinates	Marker ID	Center Y Coordinates	Marker ID	Center Y Coordinates	Marker ID	Center Y Coordinates
49	1700	15	1350	40	745	23	125
46	1700	19	1350	48	405	24	125
18	1350	41	1045	45	405	22	125
14	1350	44	1045	20	125	29	125
25	1350	46	745	28	125	21	125

The Nikon D3500 DSLR camera was selected for its stability and ability to provide consistent performance under various lighting conditions to properly capture the dynamic uniaxial displacement measurements during seismic table testing. The camera was positioned at a fixed distance from the specimen to achieve at least image resolutions of 1.6mm/px for the 80mm markers and 2.0mm/px for the 40mm markers. The video files were stored in .MOV file format using H.264 compression encoding. This format preserves the necessary image quality for subsequent OpenCV processing and proper cornerSubPix function implementation. Technical information about the camera can be found in Table 2.

Table 2: Nikon D3500 Video Recording Specifications for ArUco Marker Detection.

Parameter	Specification	Impact on ArUco Detection	Requirements Met
Video Resolution	1920 × 1080 (Full HD)	Provides sufficient pixel density for marker corner detection	Enables 1.6mm/px and 2.0mm/px accuracy
Recording Frame Rate	60 fps	Captures dynamic motion with adequate temporal resolution	Suitable for seismic table testing frequencies
Image Sensor	24.2 MP APS-C CMOS	High resolution sensor ensures clear marker boundaries	Supports submillimeter displacement accuracy
Video Format	.MOV (H.264)	Compressed format maintains quality while reducing file size	Compatible with OpenCV processing pipeline
Image Processor	EXPEED 4	Fast processing reduces motion blur during recording	Ensures stable video capture under varying conditions

The reference measurement system consists of WayCon SX50-300-10V-KA05 draw wire displacement sensors, strategically positioned to provide ground truth data for validating the ArUco marker measurements. This model designation indicates a 300 mm measurement range with 0...10V analog voltage output, connected via a 5-meter axial cable configuration. The sensors utilize a hybrid potentiometer sensing element with a stainless steel V2A draw wire (Ø 0.5 mm) and provide measurement linearity of ±0.15% of full scale. The sensors are capable of handling dynamic loading conditions with maximum velocity of 8 m/s and acceleration up to 150 m/s², making them well-suited for seismic table testing applications. The extraction force ranges from 3N to 3.6N, ensuring reliable mechanical coupling to the specimen.

2.2 ArUco Marker Implementation

The image processing pipeline implements a multi-stage approach designed to achieve sub-millimeter measurement accuracy (see Figure 5) while maintaining computational efficiency for real-time applications. Initially, user defined frame is exported from the video in JPEG file format and used for further manual region of interest (ROI) definition based on known marker position and ID (see Figure 4).

extracted frame

user defined ROIs

Figure 4: Frame extraction and ROI definition

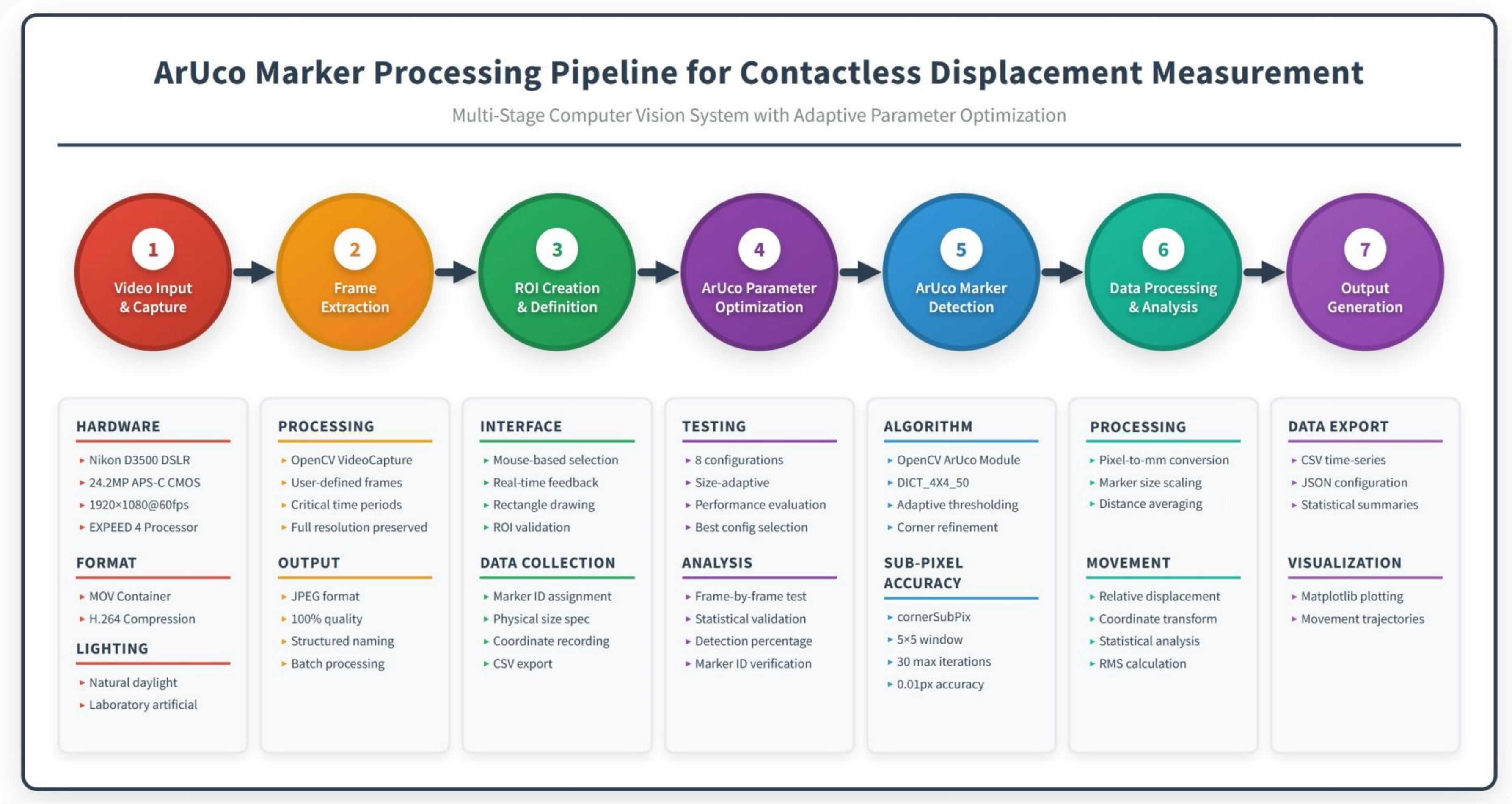


Figure 5: ArUco marker pipeline implementation

After, intervals corresponding to the critical loading phases identified in the experimental protocol is defined for each video. Then, the extraction process maintains full image resolution (1920×1080) to preserve spatial accuracy and load them directly to computer RAM for fast processing. The preprocessing pipeline is intentionally minimal to preserve the original image characteristics essential for robust ArUco detection. Each ROI is extracted from the full frame and converted from BGR color space to grayscale using OpenCV's standard color conversion, as required by the ArUco detection algorithm. This approach relies on the inherent robustness of the optimized ArUco parameter configurations to handle illumination variations rather than applying potentially destructive image enhancement techniques.

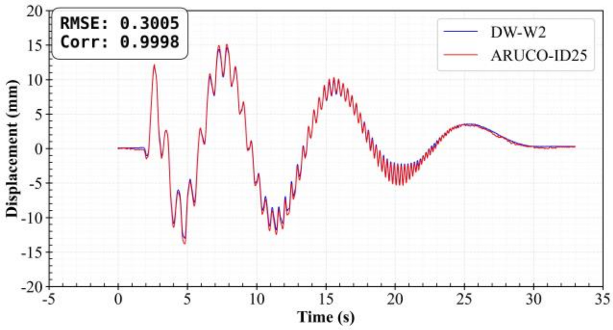
The core detection algorithm employs adaptive thresholding with dynamically adjusted parameters based on local image characteristics. The implementation utilizes the cornerSubPix function with optimized parameters: Window size: 5×5 pixels for corner refinement, Maximum iterations: 30 for convergence optimization, Minimum accuracy: 0.01 pixels for sub-pixel precision, Zero zone: (-1,-1) to disable dead region. Individual ROIs are processed independently using their optimized ArUco parameter configurations determined during the calibration phase. This approach enables simultaneous processing of markers under different local conditions while maintaining computational efficiency. When markers are successfully detected, the corner coordinates and timestamps are stored for subsequent analysis. Frames where detection fails are simply skipped, resulting in a dataset containing only successful detection events. This approach prioritizes data quality over temporal completeness, ensuring that all recorded measurements represent genuine marker detections rather than interpolated or estimated values. After the detections the pixels measurements are converted to mm measurements. Scale calibration is performed individually for each ROI using a straightforward approach based on the known physical marker dimensions. The system calculates the pixel-to-millimeter conversion factor by measuring the average pixel distance between adjacent marker corners (corner 0 to corner 1) across all successful detections, then dividing the known marker size by this average pixel distance. All displacement measurements are computed relative to the mean position of each marker throughout the detection sequence. This relative measurement approach eliminates absolute positioning requirements while providing precise tracking of marker movement patterns.

3 RESULTS AND ANALYSIS

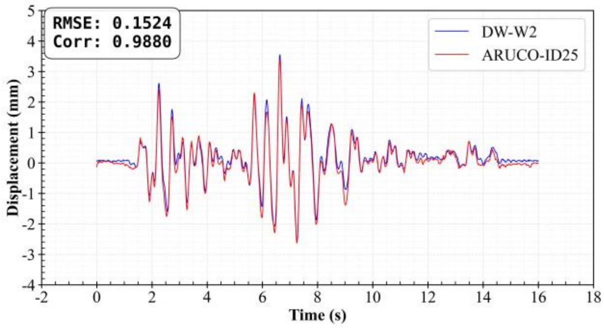
The experimental campaign consists of 5 seismic excitations of different intensity from the Thessaloniki (Volvi) 1978 earthquake and 6 white noise signals (see Table 3).

Table 3: Complete Test Sequence (11 total tests)

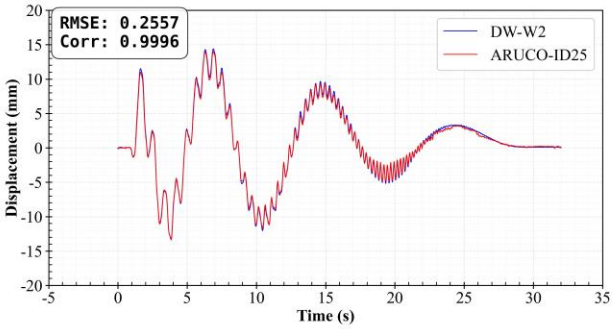
Test No.	Name	Type	Intensity	Test No.	Name	Type	Intensity
ST1	WNb0.1g	White noise	0.08g	ST7	WNb0.8g	White noise	0.08g
ST2	EQ0.1g	Earthquake	0.10g	ST8	EQ0.8g	Earthquake	0.80g
ST3	WNb0.2g	White noise	0.08g	ST9	WNb1.1g	White noise	0.08g
ST4	EQ0.2g	Earthquake	0.20g	ST10	EQ1.1g	Earthquake	1.10g
ST5	WNb0.5g	White noise	0.08g	ST11	WNa1.1g	White noise	0.08g
ST6	EQ0.5g	Earthquake	0.50g				



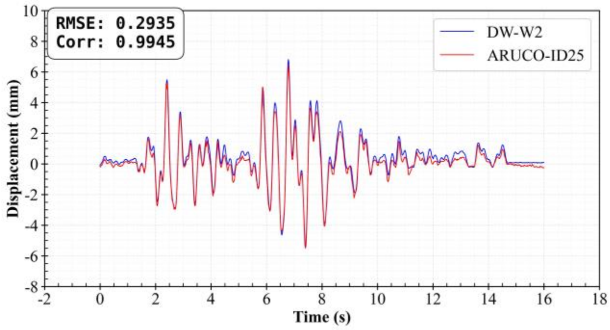
ST1 –White Noise 0.08g



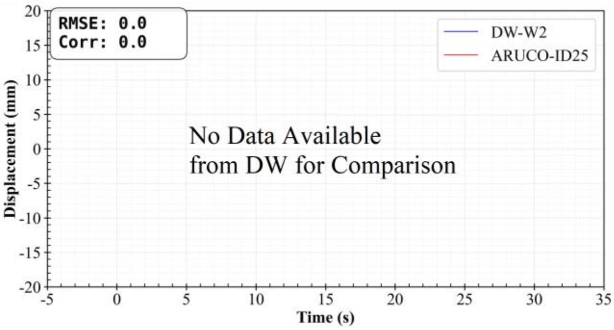
ST2 – Earthquake 0.10g



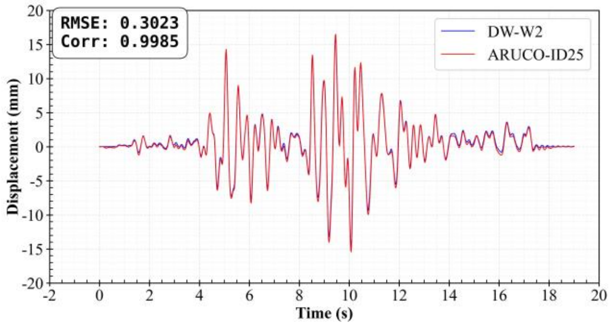
ST3 –White Noise 0.08g



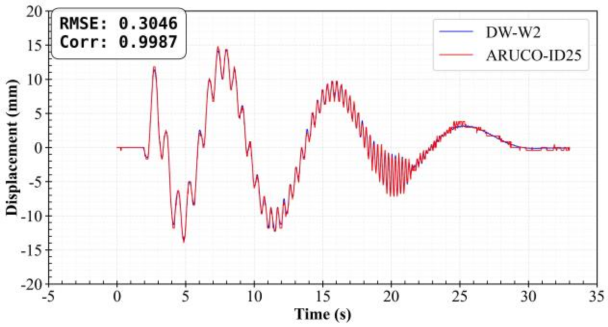
ST4 – Earthquake 0.20g



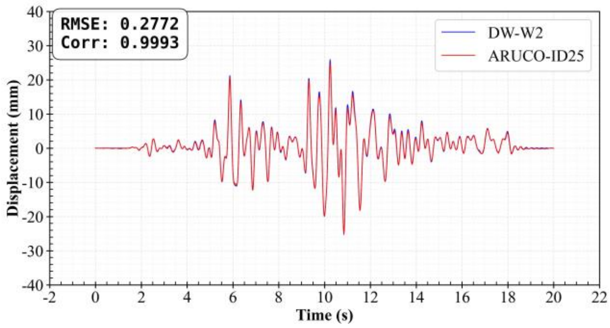
ST5 –White Noise 0.08g



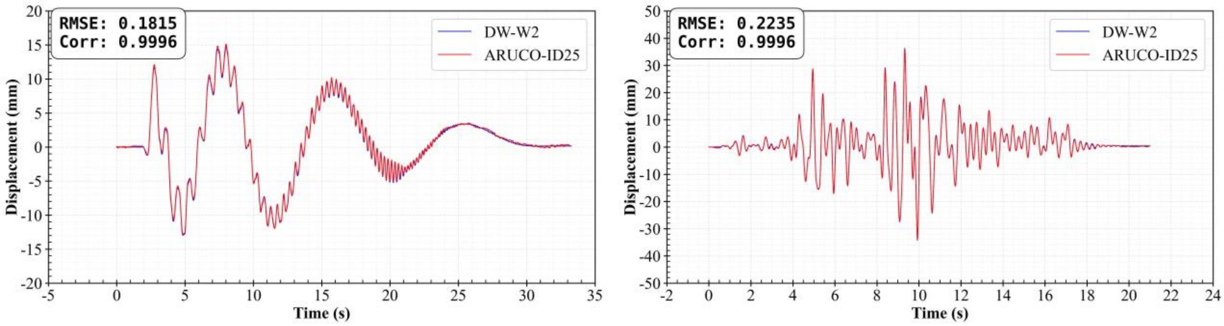
ST6 – Earthquake 0.50g



ST7 –White Noise 0.08g



ST8 – Earthquake 0.80g



ST9 –White Noise 0.08g ST10 – Earthquake 1.10g

Figure 6: Detailed comparison of ArUco results with W2 Draw-Wire sensor recordings

In this study results of ArUco marker with ID 25 are discussed in detail (see Figure 6). The marker is compared to Draw-Wire W2 results. From the eleven test sequences, the nine were fully captured with the optical recording camera. Two main indicators were used to identify the similarity of the recording. For the shape similarity the Pearson Correlation Coefficient was used that quantifies the degree of linear relationship between two datasets. It ranges from −1 to +1.

$$r = \frac{\sum_{i=1}^{N}\left(y_i^{DW} - \overline{y^{DW}}\right)\left(y_i^{ARUCO} - \overline{y^{ARUCO}}\right)}{\sqrt{\sum_{i=1}^{N}\left(y_i^{DW} - \overline{y^{DW}}\right)^2} \cdot \sqrt{\sum_{i=1}^{N}\left(y_i^{ARUCO} - \overline{y^{ARUCO}}\right)^2}} \quad (1)$$

where: $\overline{y^{DW}} = \frac{1}{N}\sum_{i=1}^{N} y_i^{DW}$ be the mean of DW data $\overline{y^{ARUCO}} = \frac{1}{N}\sum_{i=1}^{N} y_i^{ARUCO}$ be the mean of ARUCO data

For the pattern and amplitude similarity the Root Mean Squared Error (RMSE) was used. It is a standard way to measure the average magnitude of error between two sets of values — in our case, between the ARUCO measurements and the DW ground truth.

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(y_i^{ARUCO} - y_i^{DW}\right)^2} \text{ where:} \quad (2)$$

y_i^{DW} be the ground truth displacement from the DW sensor at time index i

y_i^{ARUCO} be the displacement from ARUCO tracking at the same time index i

N be the number of valid (synchronized and interpolated) data points

Based on Figure 6 results, the ArUco marker ID 25 demonstrates strong agreement with the reference draw-wire sensor W2 across nine successfully captured test sequences. The correlation coefficients consistently exceed 0.98 for all tests, with most achieving values above 0.99, indicating strong shape similarity between ArUco and draw-wire measurements. RMSE values remain below 1mm for most test conditions, with the lowest errors observed during white noise excitations (RMSE ≈ 0.18-0.31mm) and slightly lower errors during earthquake simulations (RMSE ≈ 0.15-0.3mm). The 80mm ArUco markers successfully captured both low-intensity white noise signals (0.08g) and higher-intensity earthquake excitations (up to 1.1g), demonstrating robust performance across varying dynamic loading conditions.

4 CONCLUSIONS AND FUTURE WORK

To the best of the authors' knowledge, this is the first time that ArUco markers are used in seismic table testing with reinforced concrete structure under real seismic excitation history. This study successfully demonstrates the effectiveness of ArUco markers as contactless displacement measurement instruments capable of achieving submillimeter accuracy for in-plane structural movements. The experimental validation against draw-wire sensors shows strong agreement, with correlation coefficients consistently exceeding 0.98 and RMSE values below 1mm across various seismic loading conditions from 0.08g to 1.1g intensity. The visual comparison reveals that ArUco measurements closely follow the displacement patterns of the reference sensors, validating the submillimeter accuracy capabilities of the optical measurement system for structural health monitoring applications. Future research should focus on extending the methodology to multi-directional displacement measurements. The integration of advanced image enhancement techniques and machine learning algorithms could further improve detection reliability and expand the operational range of the system.

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