Review

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Review

2D Vision-Based Measurement for Experimental Characterization of Planar Compliant Mechanisms: A Comprehensive Review

Rohan R. Ozarkar [1,*], Nilesh P. Salunke [2], Prajitsen G. Damle [3], Kundan V. Patil [1], Tushar K. Girase [1], Suchita M. Badgujar [1] and Gaurav S. Chavhan [1]

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Abstract

In planar compliant mechanisms, single-input dual-output (SIDO) displacement amplifiers driven by piezoelectric actuators are frequently used in precision positioning, micro/nano manipulation and biomedical microdevices. Accurate experimental verification of these mechanisms still remains challenging because traditional contact sensors can add excess stiffness and impact structure normal behavior, and single-axis interferometers cannot measure multiple points simultaneously. In contrast, 2D vision-based measurement offers a non-contact an alternative capable of capturing full planar motion and synchronized displacement tracking within a single image frame. This paper reviews the literature on camera calibration, homography-based planar reconstruction, sub-pixel edge extraction, vision-based characterization of compliant mechanisms, and benchmarking of vision systems against laser interferometers and coordinate measuring machines (CMMs). In the review, the SIDO-CDAM developed by Ozarkar et al. [1] based on the Instantaneous Center Building Block (IC-BB) approach has been chosen as the target characterization system. The reviewed studies confirm that the major technical components needed for a high precision 2D vision framework have been independently validated. However, there seems to be a lack of an integrated framework designed for synchronized dual-output SIDO-CDAM characterization. To overcome this gap, a seven-layer 2D vision-based characterization framework is proposed for scalable inspection of prototype-scale and MEMS-scale compliant mechanisms.

Keywords: 2D measurement; machine vision; camera calibration; digital image correlation; OpenCV; kinematic characterization; planar mechanism; compliant mechanism

1. Introduction

Planar compliant mechanism systems, in which all elements are constrained to move in a single plane, are found in a variety of engineering domains, including robotic manipulators and automotive suspension systems to precision positioning stages and biomedical microdevices. Accurate experimental characterization of such systems is essential for validation of kinematic and dynamic models, determining the existence of manufacturing induced deviations from the intended design and enabling reliable iterative optimization. In compliant mechanisms, where motion is obtained through elastic deformation rather than traditional rigid-body joints. Therefore, the displacement, velocity and force distribution in a planar mechanism must be measured with sufficient accuracy and spatial resolution to distinguish finite element analysis (FEA) predictions from actual physical behavior.

Conventional contact-based instruments such as linear variable differential transformers (LVDTs), rotary encoders, dial gauges, and strain gauges can achieve high measurement accuracy. However, they face several limitations when applied to compliant mechanisms. Any sensor (contact probe or strain gauge) physically attached to the mechanism provides a stiffness and mass loading and thus affects the structural response to be measured. Further, a single sensor detects only one displacement component. The 2D output field (primary displacement along with parasitic lateral displacement) of a dual output mechanism requires two sensors for characterization, and each of individuals can add their own loading and installation error, indicating that their engagement is often complex and time consuming. Sequential sensor measurements cannot capture the correlated and synchronized motion behavior of dual-output compliant systems. Moreover, contact instruments are generally limited in measurement range and can be costly in terms of instrumentation and maintenance. Therefore, contact-based measurement becomes less suitable for compliant mechanism characterization, especially at micrometer scale displacement levels.

Recently, vision-based measurement systems have emerged as an effective non-contact alternative for planar motion analysis and precision metrology. A 2D vision-based measurement framework tackles many of the limitations of contact sensors. The motion of several tracking points in the same image frame can be recorded with a single calibrated camera, without disturbing the mechanism under study. Modern sub-pixel image processing algorithms allow the feature position to be determined with a precision much smaller than the native pixel resolution, and the homography-based planar reconstruction allows an accurate conversion between image coordinates and real-world coordinates. The primary advantage of vision-based systems comes from the capability of performing remote, simultaneous and multi-point measurements of displacements without affecting the structural behavior of the system under study. These devices are therefore very well suited for experimental mechanics, structural monitoring and compliant mechanism characterization.

This review is motivated by the specific mechanism, which is the Single-Input Dual-Output Compliant Displacement Amplification Mechanism (SIDO-CDAM) introduced by Ozarkar et al. [1]. This mechanism is a monolithic planar compliant body that turns the small stroke of a single piezoelectric stack actuator into two simultaneous, symmetric amplified displacements at distinct output ports. The design utilizes the Instantaneous Center Building Block (IC-BB) synthesis method in which compliant dyad building blocks (CDBs) are systematically integrated to achieve the desired kinematic behavior. A structured two-stage multi-response optimization approach was employed to simultaneously maximize geometric advantage (GA) and minimize structural stiffness, followed by finite element validation of the optimized configuration. Since compliant displacement amplification mechanisms fundamentally follow energy conservation principles, an increase in geometric advantage ($GA = \delta out/\delta in$) is accompanied by a proportional reduction in output force. Accurate measurement of geometric advantage in a fabricated prototype therefore requires a non-contact, simultaneous, multi-point characterization methodology capable of resolving both primary and parasitic displacements.

For the characterization framework considered in this review, three key experimental requirements arise directly from the SIDO-CDAM configuration: (a) simultaneous tracking of the input point and both output ports within a single image frame; (b) displacement measurement resolution better than 2 μm across the full operating range; and (c) validation of the measured results against a traceable reference instrument such as a laser interferometer or precision stage. To the best of the authors' knowledge, a unified framework integrating camera calibration, planar homography, motion compensation, sub-pixel feature extraction, simultaneous dual-output tracking, and uncertainty-oriented validation for SIDO-CDAM characterization has not yet been systematically reported in the literature. The primary gap identified in existing studies is therefore integrative rather than purely technical.

The major contributions of this review are summarized as follows: (1) systematic review of vision-based measurement methodologies relevant to planar compliant mechanisms; (2) critical comparison of precision metrology approaches used for compliant mechanism characterization; and (3) proposal of a seven-layer 2D vision-based characterization framework specifically intended for SIDO-CDAM applications.

This paper is organized as follows. Section 2 reviews camera calibration and homography-based planar tracking methods. Section 3 discusses sub-pixel edge detection techniques and their achievable measurement accuracy. Section 4 reviews vision-based characterization approaches for compliant mechanisms. Section 5 examines compliant displacement amplification mechanisms and associated experimental measurement challenges. Section 6 compares vision-based systems with other approaches for precision metrology. Section 7 identifies major research gaps in the current literature. The proposed seven-layer characterization framework and the uncertainty-oriented methodology are presented in Section 8. Finally, Section 9 concludes with an summary of the major findings and directions in future research.

2. Camera Calibration and Homography-Based Planar Tracking

2.1. Camera Calibration Basics

Camera calibration refers to the process of estimating the intrinsic and extrinsic parameters that describe how a camera observes the physical world. These parameters are the focal length, the principal point, the lens distortion coefficients, and the position and orientation of the camera with respect to the measurement plane. Zhang's checkerboard-based calibration method [2] remains preferred, as it requires just a couple of images of a planar calibration target captured from different angles and is easy to implement in computer vision libraries such as OpenCV. For the characterization of the planar compliant mechanism, accurate lens distortion correction is specifically crucial, as uncorrected distortion can cause considerable position errors at a boundary of the image that affects the accuracy of displacement measurement. This effect becomes more critical when micrometer-level displacement resolution is required. The application of telecentric optics can significantly minimize the perspective distortion and magnification variation within the field of view, thereby improving the measurement uniformity.

Arellano-González et al. [3] investigated the performance of homogeneous and non-homogeneous Direct Linear Transformation (DLT) calibration methods for the motion tracking of planar mechanisms and reported comparable findings for both methods under controlled laboratory conditions. Their study showed that with appropriate calibration procedures, reliable planar motion tracking can be achieved using low-cost machine vision hardware. This observation is important for the characterization of compliant mechanisms, it indicates that high-precision planar tracking is achieved without highly specialized optical instrumentation.

Figure 1 presents the typical workflow of a 2D vision-based characterization system, which includes camera calibration, homography estimation, planar reconstruction, and simultaneous multi-point tracking.

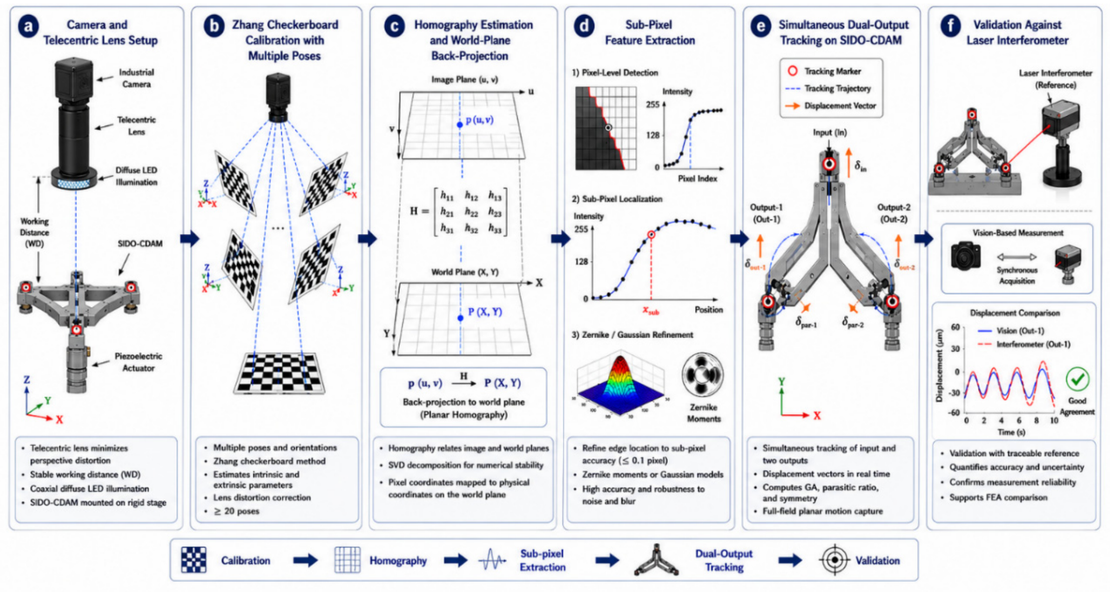

Figure 1. Pipeline of the 2D vision-based measurement framework. (a) Camera and telecentric lens arrangement; (b) Zhang checkerboard calibration using various poses; (c) Homography estimation and world-plane back-projection; (d) Simultaneous dual-output marker tracking on a CDAM.

2.2. Homography- Translating Image Pixels to Real-World Coordinates

Planar motion can be reconstructed using homography transformation once the camera is calibrated. In the case of strictly planar motion, the projective mapping between the image coordinates and corresponding real-world coordinates on the measurement plane can be obtained by a homography matrix H. Unlike a simple pixel-to-millimeter scale conversion, homography-based reconstruction compensates for perspective effects and non-uniform magnification across the image.

Wu et al. [4] recommended a homography characteristic matrix method in which the homography matrix is decomposed using singular value decomposition (SVD) to directly recover translational and rotational motion components. The method was used on a three-degree-of-freedom robotic stage and provided higher accuracy and better repeatability than conventional methods based on scale factor. The scale-factor method assumes a constant ratio of pixels to distance throughout the image and hence is not accurate for larger fields of view or non-telocentric optical systems.

Chen et al. [5] proposed a high-resolution stage measurement based on 2D-DFT phase estimation approach using grating patterns with a nanometer-scale measurement resolution. Another study by Chen et al. [6] showed long-range planar position detection by machine vision with high linearity (0.04%) over broad travel ranges (40 mm). These studies collectively indicate the feasibility of using homography based vision systems for both short-range high-precision measurement and larger scale planar motion tracking applications.

2.3. Compensation for Camera Motion and Environmental Disturbances

One practical problems in vision measurement at the laboratory scale is the unintentional motion of camera due to environmental vibration, disturbance of optical table or thermal drift. Even small camera movements in the micrometer range can appear as incorrect structural displacement during compliant mechanism characterization. Since compliant displacement amplification mechanisms typically operate in displacement ranges of only a few hundred micrometers, compensation of the camera motion is important for reliable experimental measurement.

To address this problem, Jiao et al. [7] proposed a vision-based motion correction strategy based on fixed reference markers on the stationary base structure. The apparent displacement of the reference markers in each image frame is used to estimate unintended camera motion and it is removed from the measured displacement of the moving structure. It is a combination of Random

Sample Consensus (RANSAC) for outliers rejection and Efficient Second-order Minimization (ESM) for robust homography estimation and sub-pixel tracking performance.

For SIDO-CDAM characterization, several (4–6) reference markers can be positioned on the fixed base plate outside the active deformation region of the mechanism. The measured motion of these markers can then be used for drift compensation on a frame-by-frame basis to minimize the effect of environmental vibration and thermal instability on displacement estimation. As the target measurement uncertainty approaches the sub-pixel range, this motion compensation becomes ever more important.

Table 1 summarizes representative studies from the reviewed literature on camera calibration, planar reconstruction, and accuracy of vision-based displacement measurement.

Table 1. Camera calibration and planar measurement accuracy benchmarks reported in the reviewed studies.

Study	Method	Calibration Error	Accuracy	Application
Wu et al. (2023) [4]	Homography + SVD	Sub-pixel	High accuracy & repeatability	3-DOF robot stage
Arellano-González et al. (2021) [3]	DLT calibration	Equivalent	Trajectory tracking	Four-bar mechanism
Chen et al. (2016) [5]	2D DFT phase / grating	< 1 pixel	3.5 nm (X), 8 nm (Y)	Planar stage encoder
Jiao et al. (2021) [7]	RANSAC + ESM homography	Sub-pixel	< 1 pixel	Structural displacement
Moru & Borro (2019) [8]	Vision2D sub-pixel	0.06 pixel	±0.020 mm	Gear inspection
Nogueira et al. (2023) [9]	Monocular sub-pixel edge	—	0.008 mm mean	Mechanical part dimensions.

3. Sub-Pixel Edge Detection

3.1. The Resolution Gap and Sub-Pixel Methods

In machine vision systems, the native spatial resolution is fundamentally limited by the camera sensor and optical magnification. For example, in the case of an 80 mm × 80 mm compliant mechanism imaged with a conventional 4 MP industrial camera, one pixel corresponds to about 32 µm of real distance. Such resolution is not sufficient for experimental characterization of CDAM.

This limitation is overcome by sub-pixel edge detection algorithms which estimate the edge location at a fraction of a pixel by modelling mathematically the local intensity distribution around the edge region. Instead of treating the edge as a discrete pixel boundary, they are interpolate the gray-scale intensity transition to determine a more precise edge position. Under suitable illumination and imaging conditions, the localization precision of modern sub-pixel approaches can reach 0.05–0.10 pixels, corresponding to a micrometer-level physical resolution depending on the optical magnification and field of view.

The achievable accuracy of a sub-pixel measurement system depends not only on the algorithm itself, but also relies on practical imaging parameters, such as signal-to-noise ratio, stability of illumination, optical distortion, quality of the marker and mechanical vibration. Hence, algorithm selection must be considered in the context of the overall imaging configuration rather than as a stand-alone image processing step.

3.2. Comparative Assessment of Sub-Pixel Edge Detection Methods

3.2.1. Coarse-to-Fine Hybrid Methods

Among the reviewed studies, coarse-to-fine hybrid methods appear to be especially suitable for compliant mechanism characterization as they provide a trade-off between computational efficiency and measurement accuracy. Xie et al. [10] proposed a two stages strategy for edge extraction. Firstly, a fast Roberts operator is used to search the rough edge location. Then an improved Zernike moment calculation is used to refine the edge location to sub-pixel accuracy. Otsu's method sets intensity threshold automatically. The hybrid strategy was shown to have increased precision and better computational efficiency compared to traditional Zernike-only implementations. This method is especially suitable for CAMD because the output markers and flexure boundaries tend to be smooth linear or mildly curved geometries produced by wire-EDM or precision CNC machining.

3.2.2. Zernike Moment and Gray-Level Moment Methods

Zernike moment methods estimate the edge position and orientation by fitting orthogonal polynomial functions to the local image intensity distribution. One advantage of this approach is that edge location and directional information can be acquired simultaneously, which is useful for tracking curved flexure boundaries and components of rotational motion.

Guo et al. [11] used a sub-pixel method based on Zernike matrix for dimension measurement of flange disc parts and showed good agreement with coordinate measuring machine (CMM) measurements. Ding et al. [12] further improved the Zernike approach for curved-edge extraction, which is relevant for compliant mechanisms employing circular notch hinges or curved flexure geometries. Dynamic displacement tracking has also been explored using Gray-Level Moment (GLM) methods. Hagara et al. [13] demonstrated that edge localization based on the GLM model can successfully track displacements of less than one pixel in the case of partially blurred imaging conditions. This capability is particularly important for compliant mechanism testing near resonance frequencies where motion blur can degrade the performance of conventional edge extraction.

3.2.3. Gaussian Integral Method

Gaussian-based edge modelling methods approximate the image intensity transition across an edge using the integral form of a Gaussian function. Duan et al. [14] used a Gaussian integral fitting (least-squares) method for the precision measurement of gear tooth profiles, and the maximum measurement error was about 1.9 μm.

Compared to higher order polynomial approaches, the Gaussian fitting approaches generally have a lower computational complexity with good accuracy for relatively smooth edge geometry. However, their performance can degrade for very irregular or noisy edge profiles. Hence, Gaussian approaches may be more suitable for straight or slightly curved marker boundaries than complex flexure contours for the characterization of compliant mechanisms.

3.2.4. Hessian-Based Methods (Canny-Steger)

Hessian-based methods determine the edge locations are by using second order image intensity derivatives. Cheng et al. [15] reported 3 μm accuracy and 2 μm repeatability on shaft parts by coupling Canny edge detection with Steger's Hessian-based method.

A benefit of Hessian-based methods is that their ability to accurately detect edges along regions of maximum intensity curvature, and hence are useful for curved flexure hinges and circular notch geometries which are common in compliant mechanisms. However, these methods are usually more computationally expensive and can be sensitive to image noise if the illumination conditions are not well controlled.

3.2.5. Deep Learning-Based Sub-Pixel Methods

Recent work has studied the application of deep learning for sub-pixel edge localization. A CNN-based approach for sub-pixel line-edge angle detection was proposed by Pang et al. [16], which improved accuracy over traditional methods for inclined edges. Deep learning approaches offer potential benefits for illumination variation, surface texture irregularities, and complex edge conditions. However, they often require extensive labelled training datasets and high computational resources. In addition, their measurement uncertainty characteristics are often less interpretable than analytical edge models. At the current stage, the adoption of deep learning based sub-pixel methods in the precision CDAM characterization is still at an early stage and not yet recommended for primary measurement use.

3.3. Practical Factors Affecting Sub-Pixel Measurement Accuracy

In addition to algorithm selection, various practical imaging factors strongly influence the achievable measurement accuracy of a vision-based characterization system.

- Illumination Conditions: The surface finish of the wire-EDM or CNC machined planar mechanisms is typically semi-reflective, which results in illumination-dependent intensity variation and unstable edge localization. Diffuse coaxial LED illumination is generally preferred because it minimizes specular reflection and provides consistent edge contrast throughout mechanism motion.
- Optical Configuration: Optical Configuration: Telecentric lenses are most suitable for precision planar measurement as they offer almost uniform magnification in the field of view and significantly minimize perspective distortion. This leads in a stable pixel-to-distance relationship over the entire measurement space, which simplifies calibration and improves reconstruction accuracy.
- Thermal Drift and Sensor Stability: Industrial CMOS sensors may exhibit thermal drift during the initial operation. Proper warm-up time prior to measurement can alleviate image instability caused by drift. For long-term experiments, this helps keep sub-pixel measurements consistent when used with reference marker-based drift correction.
- Marker design: The quality of edge extraction is closely linked to the marker contrast and geometry. For prototype-scale compliant mechanisms, circular and square markers, laser engraved or ink printed, usually provide sufficient contrast for reliable sub-pixel tracking without significantly impacting structural performance. Optical tracking of MEMS-scale mechanisms may require lithographically patterned markers or etched surface features.

These practical considerations demonstrate that micrometer-scale experimental characterization relies on the combined performance of optics, illumination, calibration, mechanical stability and image-processing algorithms, instead of relying solely on sub-pixel algorithms. Table 2 summarizes representative sub-pixel edge detection methods and the reported measurement performance in the literature reviewed.

Table 2. Overview of sub-pixel edge detection accuracy in reviewed studies.

Study	Algorithm Family	Max Error	Repeatability	Application
Xie et al. (2019) [10]	Roberts + Zernike hybrid	< 2 μm	< 1 μm	Industrial parts (general)
Cheng et al. (2025) [15]	Canny-Steger + Hessian	3 μm	2 μm	Shaft dimension measurement
Duan et al. (2018) [15]	Gaussian integral	1.9 μm	N/R*	Gear tooth profiles
Guo et al. (2024) [11]	Zernike matrix method	Sub-pixel (vs. CMM)	Sub-pixel	Flange disk dimensions
Hagara et al. (2024) [13]	Grey-level moment (GLM)	< 2 pixels dynamic	< 0.5 pixel	Vibration monitoring
Nogueira et al. (2023) [9]	Sub-pixel monocular	0.013 mm (circular)	0.006 mm	Planar part dimensions

* N/R = not reported.

4. Vision-Based Experimental Characterization of CDAM

4.1. Need for Non-Contact Characterization in CDAMs

Compliant mechanisms produce motion by utilizing elastic deformation of flexure members rather than traditional rigid-body joints. Therefore, their structural response is highly sensitive to the imposed constraints and loading conditions. Inequalities in finite element predictions and experimentally measured results may occur during experimental validation because contact force applied by a displacement sensor may alter the mechanism's deformation characteristics.

This issue becomes more crucial for compliant displacement amplification mechanisms where large output displacement is obtained by distributed elastic deformation. Accurate experimental evaluation therefore requires measurement of input displacement, amplified output displacement and parasitic motion simultaneously while affecting the mechanism itself minimally as possible. Conventional contact based instruments are often not suitable for this purpose as they typically tend to measure only a single displacement component. It may influence the effective stiffness of the compliant structure under test.

Many vision-based measurement systems overcome these limitations, enabling remote, noncontact and multi-point displacement tracking. With a single calibrated camera, it is feasible to monitor multiple locations on the compliant structure simultaneously in the same image frame. This feature is especially beneficial for dual output compliant mechanisms where simultaneous motion of multiple output ports needs to be experimentally validated.

4.2. Microscopic Vision for MEMS-Scale Mechanisms

Yao et al. [17] propose a microscopic vision system based on multi-scale Lucas-Kanade optical flow on high magnification image sequences for a compliant nano-positioning stage. The system achieved an absolute measurement accuracy of 0.06 μm when validated against a laser interferometer, which is among the highest accuracies reported for vision-based characterization of compliant mechanisms in the literature reviewed.

Similarly, Su et al. [18] used particle swarm optimization (PSO) combined with successive three-step search (S-TSS) template matching to a three-degree-of-freedom compliant micro-stage and obtained sub-micrometer measurement accuracy with high computational efficiency. These studies together demonstrate the capability of microscopic vision systems for precision characterization of MEMS scale compliant mechanisms.

For the prototype-scale SIDO-CDAM developed by Ozarkar et al. [1] microscopic optics are not required, as the mechanism dimensions are significantly larger, with output ports separated by several tens of millimeters. The working displacement range of mechanism is about 50–700 μm. A standard telecentric lens with a working distance of 100–200 mm can typically achieve 2–5 μm measurement accuracy, which is enough to resolve the FEA discrepancy observed experimentally in the operating range of the mechanism. This observation highlights an important advantage of the proposed framework, that the same vision-based characterization methodology can be used for both macro-scale and MEMS-scale compliant mechanisms, primarily by adjusting the optical magnification.

4.3. Force–Compliance Testing Using Vision Systems

Hricko and Havlík [19] proposed a practical experimental procedure called 'vision-way testing', in which loads are applied incrementally and images are captured at each loading step. The displacement gathered from the images to plot force-compliance curve. The method captures actual flexure behavior, including nonlinear deformation effects and geometric imperfections which may not be fully captured by finite element models assuming ideal beam behavior. The methodology is directly applicable to characterization of SIDO-CDAM. For example, the voltage of the piezoelectric actuator can be increased stepwise from 0 to 100V and one image can be acquired at each loading step. The measured geometric advantage is then calculated as a continuous function of actuator voltage from the tracked input and output positions.

4.4. Full-Pose Vision for Kinematic Calibration

Renaud et al. [20] that the full kinematic calibration of a parallel robotic mechanism can be achieved with a single camera instead of precise physical calibration targets. Position and orientation full-pose vision measurements of end-effector that allow identification of optimal kinematic calibration models without high-precision physical targets. Their analysis of identifiability shows which parameters of the mechanisms can be identified from the image data only. The response for planar mechanisms includes GA, parasitic displacement ratio and positions of output ports. Hence, a properly calibrated vision system provides users a complete kinematic characterization of the SIDO-CDAM, without the need for additional displacement sensors.

4.5. Stereo Vision and Digital Image Correlation

Fuentes-Juvera et al. [21] implemented a low-cost stereo vision approach for kinematic validation of a 3D compliant gripper mechanism, reporting errors below 10% compared to FEA predictions. For strictly planar CDAMs, stereo calibration complexity and sensitivity to baseline misalignment outweigh the benefits of the third dimension — single-camera planar homography is both simpler and more accurate for this application.

Sutton et al.[22] presented a comprehensive review of Digital Image Correlation (DIC), a full-field displacement measurement technique based on random speckle pattern tracking. Commercial DIC systems such as Aramis and Vic-2D are widely used in experimental mechanics and material testing. However, several limitations arise when these systems are applied to miniaturized compliant mechanisms: (a) difficulty in applying high-quality speckle patterns to sub-millimeter flexure surfaces without affecting structural behavior; (b) high computational cost limiting real-time implementation; and (c) dependence on high-magnification optics that reduce the available field of view. For planar CDAM characterization, marker-based homography tracking therefore represents a more practical and computationally efficient solution.

For quasi-static characterization, such as piezoelectric voltage ramp testing below 1 Hz, a standard industrial camera operating at 25–60 fps is generally sufficient because the mechanism remains effectively stationary during image acquisition. The trade-off between imaging bandwidth, illumination intensity, and sub-pixel measurement accuracy remains insufficiently explored in existing CDAM characterization literature and represents a potential direction for future investigation.

5. Compliant Displacement Amplification Mechanisms: Design and the Measurement Problem

CDAMs employed to transform the small input displacement of a piezoelectric actuator into a larger usable output displacement through elastic deformation of flexure members. Various amplification topologies have been reported in the literature, including lever-type, bridge-type, Scott-Russell, toggle-based, and hybrid compliant mechanisms. The amplification performance of these mechanisms is commonly evaluated using geometric advantage, which is defined as the ratio of output displacement to input displacement. Other important design considerations other than amplification capability include output stiffness, parasitic displacement, stress concentration, dynamic response and manufacturability.

The mechanism of Ozarkar et al. [1] as shown in Figure 2 is based on a dual building block topology with dual symmetric output ports (Single Input Dual Output configuration). For a meaningful experimental validation of such a mechanism, the following quantities have to be measured simultaneously: (a) input displacement obtained from the piezoelectric actuator, (b) amplified displacement at output port 1; (c) amplified displacement at output port 2; (d) parasitic

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displacement components at both output ports; and (e) symmetry of motion between the two output branches.

A 2D vision based framework is particularly appropriate for this application as all measurement points can be captured within a single synchronized image frame using a common coordinate system. In comparison to sequential contact measurement approaches, simultaneous optical tracking synchronizes both output ports and limits the structural disturbance during testing.

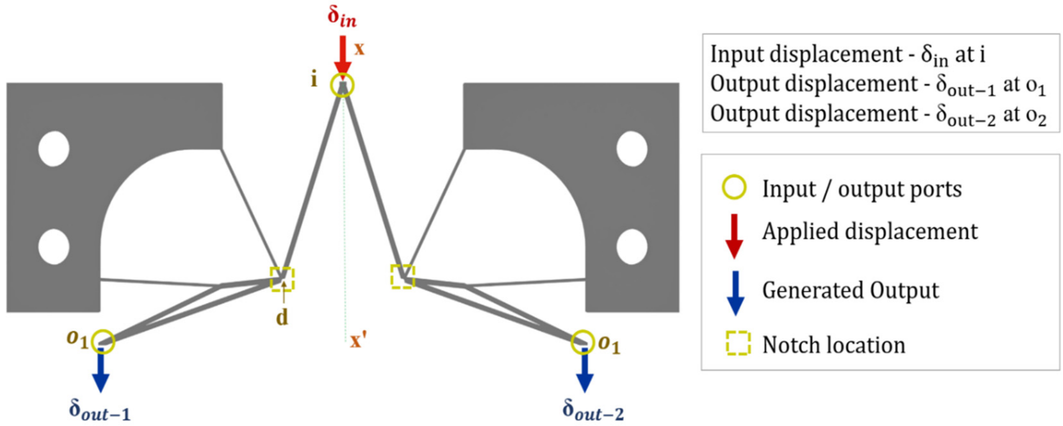

Figure 2. Schematic of single input port, two symmetric output ports (left and right) and notch at d and d’ of SIDO-CDAM (Ozarkar et al. [1]). The same topology applies at prototype scale (mm) and miniaturized MEMS scale (µm). The vision framework is adjusts via lens magnification selection.

6. Benchmarking of Vision-Based Systems with Alternative Precision Metrology Techniques

Cui et al. [23] reviewed the accuracy hierarchy in precision displacement metrology, including laser interferometry (LI, sub-nanometre), grating interferometry (GI, approximately 1 nm), and time-grating sensors (TGS, approximately 1 nm). n comparison, vision-based systems typically achieve measurement accuracy in the range of 0.06–5 µm. Although laser interferometers provide substantially higher absolute accuracy than vision systems, they generally measure displacement only along a single axis at a time. or a SIDO-CDAM with two output ports, simultaneous measurement of six displacement quantities (X and Y displacements at three tracking locations) would require multiple independently aligned laser heads, making the setup experimentally complex and impractical for compact laboratory-scale compliant mechanisms. A single calibrated camera, however, can simultaneously capture all in-plane displacement components within the same image frame.

Yao et al. [17] directly validated a microscopic vision system against a laser interferometer. The microscopic vision system was less accurate than the laser interferometer on the primary axis, but it simultaneously measured the transverse (parasitic) motion that could not be captured using a single-axis interferometer alone. Clark et al. [24] demonstrated an alternative indirect metrology approach in which a passive compliant mechanism converted 3D motion into three measurable 1D displacements. The method achieved near-interferometric resolution but required fabrication of an additional precision mechanism specifically designed for measurement. Such an approach becomes impractical when compliant mechanism geometries change frequently during iterative design optimization.

Strain gauges [25] provide continuous, high-bandwidth displacement feedback but introduce stiffness loading. For miniaturized compliant mechanisms with flexure thicknesses in the range of 0.2–0.5 mm and overall stiffness between 1–10 N/µm, a typical foil gauge rosette can change the dynamics and resonance behavior of the mechanism. The vision-based characterization completely avoids this loading and is not subject to any mechanical perturbation to the system under study.

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Coordinate Measuring Machines (CMMs) provide traceable 3D dimensional metrology with sub-micrometer accuracy. However, CMMs require contact probing, are generally limited to quasi-static measurements, and cannot capture the dynamic force-displacement behavior during the actuation of the mechanism. Nogueira et al. [9] validated machine vision measurements against CMM measurements and observed a mean dimensional error of about 0.008 mm, which indicates that vision systems can provide CMM equivalent accuracy for static planar dimensional measurements under suitable calibration conditions.

Kim et al.[26] demonstrated a hybrid interferometric and angular sensing system for 2D stage evaluation, achieving approximately 40 nm straightness uncertainty and angular accuracy near 0.14″. Traxler et al.[27] compared four optical inline measurement technologies, including stereo vision, photometric stereo, laser triangulation, and structured light systems. Their study reported lateral resolution in the range of 50–200 μm with temporal noise between 0.1–1 μm depending on the sensing configuration.

For CDAM characterization, structured light and photometric stereo approaches may provide improved sensitivity to out-of-plane deformation and flexure buckling effects. However, these methods require substantially more complex optical calibration and illumination control compared with planar homography-based tracking. For strictly planar SIDO-CDAM characterization, single-camera 2D vision systems therefore provide a more practical balance between measurement accuracy, implementation simplicity, and simultaneous multi-point tracking capability. Table 3 summarizes the major advantages and limitations of different measurement approaches for SIDO-CDAM characterization.

Table 3. Measurement method comparison for SIDO-CDAM characterization.

Method	Accuracy	Simultaneous DOFs	Contact	Dynamic	Suitable for SIDO CAMD
Laser interferometer	< 1 nm	1 per head	No	Yes (kHz)	No — needs 6 heads for SIDO
Grating/time-grating	~1 nm	2 (X+Y)	No	Yes	Partial — requires scale attachment
CMM contact probe	~0.5 μm	3D sequential	Yes, loads	No	No — stiffness loading; quasi-static only
Strain gauge	~0.1 μm	1–3	Yes, loads	Yes (kHz)	No — alters resonance frequency
Passive CDAM meter [24]	< 10 nm	3 (indirect)	No (indirect)	Limited	No — requires secondary mechanism
2D Vision (proposed)	1–5 μm	All in-plane DOFs	No	Yes (high-speed)	Yes — full SIDO characterization
Microscopic vision [17]	0.06 μm	All in-plane DOFs	No	Limited	Yes for MEMS; over-specified for prototype

* DOFs = degrees of freedom.

7. Research Gaps

The reviewed literature confirms that all the individual components required for a capable 2D vision-based characterization framework already exist and have been independently validated. Zhang's checkerboard calibration combined with homography characteristic matrix decomposition and singular value decomposition (SVD) achieves sub-pixel planar tracking accuracy [4]. Zernike hybrid sub-pixel extraction methods achieve measurement uncertainty in the range of 1–3 μm [10]. RANSAC-ESM homography tracking successfully compensates for camera vibration and laboratory drift [7]. Microscopic vision systems achieve 0.06 μm measurement accuracy for MEMS-scale compliant stages, while optical measurement of force–compliance behavior has also been experimentally demonstrated [17,19]. Vision systems have been shown to provide laser-trackerequivalent workspace characterization [28] and CMM-equivalent dimensional measurement accuracy for planar components [9].

However, so far, no reported work has integrated all of these individual techniques into a single experimentally validated framework specifically intended for dual-output compliant displacement amplification mechanisms (SIDO-CDAMs). The primary research gap identified in literature is therefore integrative rather than purely technical. Table 4 summarizes the major research gaps identified from the reviewed studies together with their implications for SIDO-CDAM characterization.

Table 4. Prioritized research gaps in 2D vision characterization of SIDO-CDAMs.

SR	Gap	Consequence	Priority
1	No end-to-end validated framework for SIDO-CDAM characterization	No experimental validation of agreement between FEA and physical prototype response, symmetric amplification behavior not fully validated	Critical — primary contribution
2	Simultaneous dual-output measurement not demonstrated	Sequential single-point measurements cannot detect cross-port coupling and synchronized motion behavior	Critical
3	Out-of-plane flexure deflection error not quantified	Homography assumes planar motion and 10 um out of plane deformation leads to ~1 um apparent in plane error at a working distance of 100 mm.	High
4	Dynamic testing bandwidth versus illumination trade-off unresolved	Resonance-frequency testing requires synchronized illumination or high-speed imaging; no standard CDAM implementation exists currently	High
5	Absence of a standardized validation protocol	Different studies report different error metrics (maximum error, mean error, RMS error), which makes cross-study comparison difficult.	Medium
6	FEA model updating using vision data not demonstrated	Experimental multi-point displacement data have not been fully exploited to identify dominant error sources in compliant mechanism models	Medium — further work

8. Proposed Seven-Layer 2D Vision-Based Characterization Framework

The research gaps identified from the literature review motivate us to propose a seven-layer 2D vision-based characterization framework for experimental validation of SIDO planar CDAMs. The framework combines the camera calibration, planar homography reconstruction, the sub-pixel displacement extraction, the motion compensation, the synchronized multi-point tracking and the uncertainty-oriented validation in a unique experimental methodology.

The proposed framework is mainly aimed at the design of prototype-scale planar compliant mechanisms actuated by piezoelectric stacks. But the same method is applicable to MEMS-scale compliant mechanisms with necessary modifications in optical magnification and imaging setup. Figure 3 illustrates the general structure of the presented seven-layer framework.

For prototype-scale SIDO-CDAM characterization, a 12–20 MP monochrome camera is usually enough for micrometer-scale displacement measurement. The telocentric lens reduces the perspective distortion and ensures that the magnification almost constant in the measurement region.

The second layer performs the intrinsic and extrinsic calibration using Zhang’s checkerboard calibration method. The calibrated parameters are subsequently used to accurately generate a pixel-to-world coordinate transformation and to compensate for lens distortion effects.

The third layer is the planar homography reconstruction using reference markers mounted on the fixed base structure. The reconstructed coordinates of the moving output ports are expressed in the stationary base frame, which enables the synchronized evaluation of the amplified displacement, parasitic displacement and output symmetry.

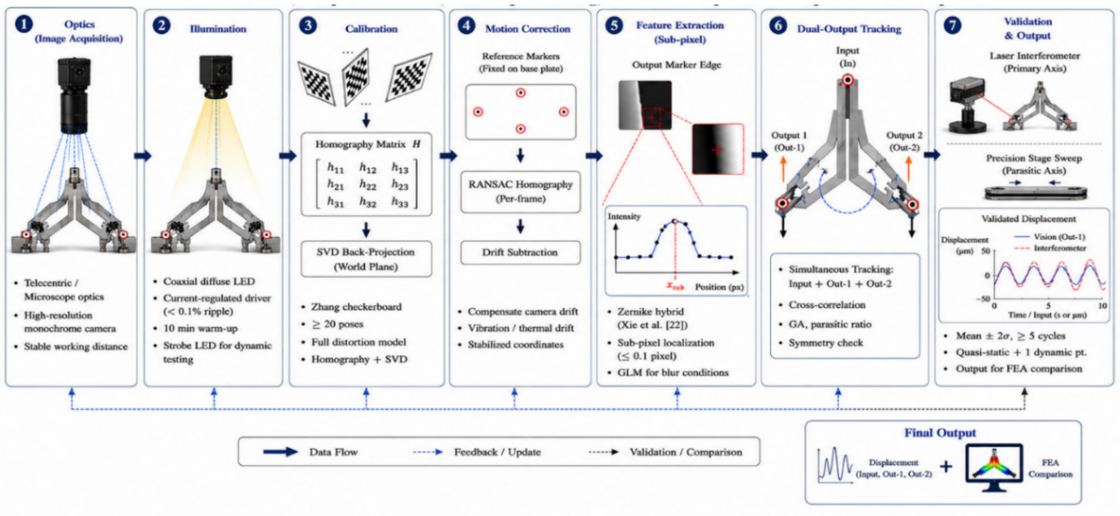

Figure 3. Architecture of the proposed seven-layer framework. Data flow from raw image acquisition to calibration, motion correction, sub-pixel extraction, dual-output tracking, validated displacement output and FEA comparison.

The fourth layer uses a hybrid Zernike based edge extraction for sub-pixel feature localization. Fiducial markers located near the actuator input and output ports are tracked in the image sequence. In general, under appropriate imaging conditions, localization accuracy of about 0.05–0.10 pixels can generally be achieved.

The fifth layer compensates for environmental vibration, thermal drift and unintentional camera movement. The measured drift is compensated using RANSAC assisted homography compensation by simultaneously tracking stationary reference markers and the markers on the moving mechanism from the displacement data.

The sixth layer implements multi-point actuator input, dual-output ports, and reference markers tracking synchronized in the same image frame. Simultaneous measurement enables direct evaluation of geometric advantage, parasitic displacement, and coupled deformation behavior and motion symmetry.

The final layer performs uncertainty estimation and experimental validation using ISO-GUM-based root-sum-square (RSS) uncertainty propagation. Major uncertainty sources include calibration error, lens distortion residuals, sub-pixel localization uncertainty, illumination variation, vibration, and thermal drift. Validation may be performed using a laser interferometer, calibrated translation stage, or micrometer actuator reference system.

For the prototype-scale SIDO-CDAM developed by Ozarkar et al. [1], an overall expanded uncertainty within approximately 1–5 μm is generally sufficient to resolve experimentally observed finite element analysis (FEA) discrepancies.

The proposed framework integrates all major stages required for synchronized, non-contact, and uncertainty-aware characterization of SIDO-CDAMs within a single experimentally implementable methodology. Table 5 gives the full specification.

8.1. Illustrative Prototype-Scale Estimation

For the prototype-scale SIDO-CDAM developed by Ozarkar et al. [1], having an output port separation of approximately 60 mm and an operating displacement range of 50–700 μm, the proposed framework is expected to achieve measurement uncertainty within approximately 1–5 μm under suitable calibration and illumination conditions.

A 12 MP industrial camera and a telocentric lens at 1× magnification remains to a typical spatial resolution of about 20 μm/pixel. The localization accuracy of the Zernike-based sub-pixel extraction is at the level of 0.05-0.10 pixels, resulting in an effective displacement resolution approximately 1–2 μm after calibration and drift compensation.

In accordance with the microscopic vision-based measurements reported by Yao et al. [17], the replacement of the telocentric lens with microscopic objectives (e.g., 5×–10× magnification) can further enhance spatial resolution into the sub-micrometer range for MEMS-scale compliant mechanisms.

Table 5. Proposed seven-layer vision framework — applicable to both prototype and miniaturized MEMS-scale CDAMs.

Layer	Specification	Reference	Gap addressed
1: Optics	Telecentric lens 25–50 mm (prototype) or microscopic objective (MEMS); 12–20 MP monochrome sensor; WD 100–200 mm (prototype) or 5–20 mm (MEMS)	Nogueira et al. [9]; Cheng et al. [15]; Yao et al. [17]	Gaps 1, 3
2: Illumination	Coaxial diffuse LED + current-regulated driver (< 0.1% ripple); 10 min warm-up. Strobe LED for dynamic testing at resonance frequency.	Xie et al. [10]; Hagara et al. [13]	Gaps 1, 4
3: Calibration	Zhang checkerboard (≥ 20 poses); full distortion model; homography characteristic matrix + SVD back-projection	Wu et al. [4]; Arellano-González et al. [3]	Gaps 1, 5
4: Motion correction	Fixed reference markers on base plate; per-frame RANSAC homography drift subtraction	Jiao et al. [7]	Gaps 1, 3
5: Feature extraction	Coarse-precise Zernike hybrid (Xie et al. [10]) on output marker edges; GLM for dynamic blur conditions	Xie et al. [10]; Hagara et al. [13]	Gap 1
6: Dual-output tracking	Simultaneous: input port + Output Port 1 + Output Port 2; cross-correlation → GA + parasitic ratio + symmetry check	Ozarkar et al. [1]; Clark et al. [24]	Gap 2
7: Validation	Primary axis: laser interferometer. Parasitic axis: precision stage sweep. Report mean ± 2σ, ≥ 5 load cycles, quasi-static + one dynamic point.	Yao et al. [17]; Clark et al. [24]	Gaps 4, 5

9. Conclusions

This paper reviews the literature survey of 2D vision-based measurement, sub-pixel extraction methods, compliant mechanism characterization and precision metrology. The SIDO-CDAM developed by Ozarkar et al. [1] considered as the target application for experimental characterization.

The review confirms that all major technical components for a capable 2D vision-based characterization framework have been independently verified in previous studies, including Zhang-based homography calibration, Zernike hybrid sub-pixel extraction, RANSAC-ESM camera motion compensation, and microscopic vision-based compliant mechanism measurement with good accuracy reaching. However, no study has been reported that combines these techniques into a single experimentally validated framework for dual-output SIDO-CDAM characterization. Therefore, the main contribution and future work of this work is the development and validation of such an integrated system.

The reviewed studies also indicate that FEA predictions and experimentally measured responses of CDAMs are frequently different because of manufacturing tolerances, material nonlinearity, assembly conditions, and boundary constraint uncertainties. A synchronized vision-based framework capable of capturing multiple displacement quantities within the same image frame provides sufficient experimental information to separate and investigate these error sources more effectively than conventional single-axis measurement systems.

The proposed seven-layer framework further demonstrates scalability across both prototype-scale and MEMS-scale compliant mechanisms. For prototype-scale systems, a telocentric imaging configuration combined with sub-pixel edge extraction is expected to achieve micrometer-scale uncertainty suitable for resolving experimentally observed FEA discrepancies. For MEMS-scale mechanisms, replacement of the telocentric lens with high-magnification microscopic objectives enables sub-micrometer measurement capability consistent with the best results reported in the literature.

Future work should therefore focus on: (a) experimental implementation and validation of the proposed seven-layer framework using the fabricated Ozarkar et al. [1] SIDO-CDAM prototype with laser interferometer benchmarking; (b) quantification of out-of-plane reconstruction error using tilted-plane calibration approaches; (c) development of synchronized illumination strategies for dynamic testing near resonance frequencies; and (d) utilization of captured multi-point displacement data for finite element model updating and identification of dominant sources contributing to the experimentally observed FEA discrepancy.

Overall, the present review establishes that vision-based experimental characterization provides a practical, scalable, and uncertainty-aware methodology for synchronized dual-output evaluation of compliant displacement amplification mechanisms.

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Abbreviations

The following abbreviations are used in this manuscript:

SIDO	Single Input Dual Output
CDAM	Compliant Displacement Amplification Mechanism
GA	Geometrical Advantage
FEA	Finite element analysis
DOF	Degrees of Freedom

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