A review on 3D motion magnification

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Target Journals

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- Journal of Sound and Vibration
- Mechanical Systems and Signal Processing
- Engineering Structures
- Measurement

Abstract

This review paper explores the field of 3D motion magnification, a computer vision technique that enhances the visibility of subtle motions and vibrations in three dimensions. This technology is crucial for applications such as structural health monitoring, damage detection, and the design of vibration control systems. Current methods for 3D motion magnification include using time-varying radiance fields with a moving camera, combining stereo-photogrammetry with phase-based motion magnification, and using a single camera with a Finite Element model. Other methods include combining Fringe Projection with DIC, using binocular vision with deep learning, and extending phase-based motion magnification to 3D volumetric data.

While these methods show promise, significant challenges remain. Both 2D and 3D Digital Image Correlation are sensitive to lighting variations and speckle pattern quality, which affects measurement accuracy. Feature-matching algorithms have limitations in the number of points that can be analyzed, impacting the quality of generated meshes. Some methods are computationally intensive or require multiple viewpoints, limiting their practical application. Many methods also rely on highly calibrated camera setups, complicating their implementation. The lack of methods for using affordable DSLR cameras in 3D applications also presents an obstacle. Future work should focus on developing robust, efficient, and flexible techniques that address these limitations.

1 Introduction

Vibration measurement plays a critical role in structural and mechanical analysis. It facilitates modal identification and characterization by revealing the dynamic properties of structures, such as natural frequencies, mode shapes, and damping ratios. These insights are vital for understanding how structures respond to loads and excitations. Additionally, vibration measurement is used for operational deflection shape identification, which combines multiple mode shapes and proves valuable when determining individual mode shapes is challenging [1, 2].

This technique is indispensable for structural health monitoring and damage detection, as changes in vibration patterns, frequencies, or mode shapes can signal issues like cracks, loose connections, or other forms of structural damage. Furthermore, understanding vibration characteristics is essential for designing vibration control systems to reduce excessive vibrations, enhancing the performance and safety of structures and machinery. Vibration data also aids in refining and calibrating numerical models of structures, ensuring they accurately represent real-world behavior and support reliable predictive analysis [1, 2].

Traditional methods to measure vibrations use contact sensors, which have drawbacks such as difficult installation, high cost, and low efficiency. Non-contact methods like laser Doppler vibrometers and computer vision based methods have emerged as alternatives. While laser Doppler vibrometers can achieve high precision, they are expensive and difficult to operate. Computer vision based methods are advantageous because they are non-contact, provide full-field measurements, and are easy to operate. However, when vibration amplitudes are small, special computer vision techniques like motion magnification are needed [1, 2].

Motion magnification is a computer vision technique that makes subtle motions or vibrations, often imperceptible, visible. It can be based on Lagrangian or Eulerian approaches, which are used in fluid mechanics to describe motion, or based on learning approaches [1, 2].

However, motion magnification is limited to 2D, capturing only in-plane motions and failing to represent out-of-plane or depth movements. This creates issues in scenarios like 3D structural vibration analysis, depth-dependent motion, or accurate modal analysis, where full spatial motion is critical. 3D motion magnification solves this by amplifying motion in all three dimensions, using techniques like multi-camera systems to accurately capture and visualize complex 3D dynamics.

Despite the importance of 3D motion magnification, there isn't a review article on the topic. Therefore, this document fills that gap by analyzing the works on 3D motion magnification.

2 Methodology

The topic of this review article includes two components: "3D" and "motion magnification". I searched for works on 2D motion magnification, general 3D reconstructions, and consequentially feature-matching algorithms to better understand the topic. However, the main focus of this document is "3D Motion Magnification". Therefore, the majority of the works cited in the document are about this topic.

Some databases and tools were used to find the literature on these topics:

- **Web of Science**[1] : To find the first articles, I used the Web of Science using the following keywords: "Motion magnification", "3D motion magnification", "Multi view motion magnification", "3D vibration", "Multi camera motion magnification", "Stereo motion magnification", "Phase-based motion magnification", "Feature matching", "Camera calibration", "Uncalibrated Stereo", "Digital Image Correlation", "3D Digital Image Correlation";

- **Google Scholar**[2] : I used Google Scholar with the same keywords as in Web of Science;

[1]https://www.webofscience.com/wos/woscc/basic-search
[2]https://scholar.google.com/

- **Google Patents**[3] : I didn't spend much time with Google patents and I didn't find anything relevant;
- **Supervisors**: My supervisors showed me that the Department of Mechanical Engineering of the University of Aveiro has already used software for phase-based motion magnification using a single viewpoint. The papers published by the software developer are important for understanding the base theory used to create the software.
- **Litmaps**[4] : This tool helped me identify streams of thought because it links the papers to the references and citations. With this tool, it was also easier to identify the foundations of a topic, thus the more relevant old papers. Although the old papers are not relevant for the review, they are sometimes important to understand newer papers.

To filter the relevant papers, I used the following order of preference:

- Availability through b-on;
- Number of citations;
- Connection with other papers within a stream of thought;
- Relevance of the journal;

The main limitations of this research were the unavailability of source code from the referenced papers, which will make testing and comparing results significantly more challenging, and the paywall restrictions on some papers that were not accessible through B-on.

3 Preliminary Findings

3D motion magnification has been achieved using different approaches. Some focus more on the quantitative results, and others also provide qualitative results, more graphical results for an intuitive understanding of motion.

Feng *et al.* [3] proposed a method for magnifying subtle motions in 3D scenes captured by a moving camera. It uses time-varying radiance fields to represent the scene and applies the Eulerian principle for motion magnification. The method works by extracting and amplifying the variation of the embedding of a fixed point over time and uses both implicit and tri-plane-based radiance fields as the underlying 3D scene representation. Feng *et al.* [3] evaluated this method quantitatively on synthetic scenes and qualitatively on real-world scenes with various camera setups. This method generates a video moving

[3] https://patents.google.com/
[4] https://www.litmaps.com/

around the object with the motion magnified, providing a really intuitive understanding of motion. The source code of this method is publicly available.

Another way to achieve 3D motion magnification is by using stereo-photogrammetry techniques like 3D Digital Image Correlation (DIC) and 3D Point Tracking (3DPT), combined with phase-based motion magnification to measure 3D displacements and vibrations. This approach improves the Signal-to-Noise Ratio (SNR) in optical measurements, allowing for the detection of subtle motions at higher frequencies. Poozesh *et al.* [4], Molina-Viedma *et al.* [5] and Yan and Zhang [6] based their works in this approach.

Poozesh *et al.* [4] evaluated the use of motion magnification with 3D DIC and 3DPT to extract high-frequency operating shapes of structures. It shows that the method is effective for measuring small vibrations and extracting 3D operating shapes with low SNR. This was tested on a cantilever beam and a wind turbine blade.

Molina-Viedma *et al.* [5] explored measurements using 3D DIC in stereoscopic sets of magnified images for 3D Operational Deflection Shapes (ODSs) characterization. It validated that motion magnification helps to reveal ODSss from low amplitude tests and at high frequencies. This was evaluated on a cantilever beam and a curved panel.

Yan and Zhang [6] combined phase-based motion magnification and 3D-DIC to obtain high-frequency vibration modes. The method is validated by separating the first five out-of-plane vibration mode shapes of a cantilever beam under a single hammer excitation, and also applied to identify the out-of-plane vibration modes of a real engine pipe.

Xuan Le *et al.* [7] proposed a framework for 3D noncontact stereovision-based cable vibration measurement using Phase-based Video Motion Magnification. It magnifies micro-vibrations of a cable and uses a centroid-based bounding-box tracking technique. This method has been validated by comparing its results with accelerometer-based measurements.

Another method, presented by Renaud *et al.* [8], uses a single camera and a Finite Element model of the structure to measure the vibrations in 3D. The method involves identifying the camera's intrinsic and extrinsic parameters, projecting numerical deflection shapes and normal modes onto the camera's image frame, and comparing the motion of targets seen by the camera with the motion of the Finite Element model. By comparing the motion of targets in the video with the projected FE model motion, the method estimates the time evolution of modal amplitudes.

Felipe-Sesé *et al.* [9] combined Fringe Projection, which measures out-of-plane shape, with DIC, which tracks in-plane motion. Phase-Based Motion Magnification is then applied to enhance the visibility of subtle movements in the image sequences. The method independently magnifies both the fringe patterns used for FP and the speckle patterns used for 2D DIC. This allows for the measurement of small vibrations and deformations. By correcting for in-plane distortions caused by out-of-plane displacement, accurate 3D maps can be obtained. The technique has been validated against 3D DIC and Scanning Laser Doppler Vibrometer, showing its ability to measure operational deflection shapes and improve the SNR. The approach also provides simultaneous qualitative and quantitative information of the motion and displacement.

Shao *et al.* [10] introduced a novel method for measuring 3D vibrations without the need for artificial targets. The system uses a binocular vision system with two cameras to capture the motion of the structure. A phase-based motion magnification algorithm is then applied to the recorded videos to amplify small motions. This enhances the SNR and makes it possible to measure vibrations that would otherwise be imperceptible. Deep learning techniques are used to achieve target-free measurements and to detect and match key points. The SuperPoint network detects key points, and the SuperGlue algorithm matches these key points between images. Then, a polynomial triangulation approach is used to calculate the 3D vibration displacements. The accuracy of the system has been validated through experimental tests, including tests on a steel cantilever beam and an in-field test on a pedestrian bridge. The results have been compared with measurements from physical sensors like LVDTs, laser displacement sensors, and accelerometers showing good agreement. The study also includes an analysis of the system's sensitivity and finds that motion magnification is beneficial when the peak vibration displacement is smaller than one pixel.

Southwick *et al.* [11] presented a method called Volumetric Motion Magnification, which extends phase-based motion magnification into three dimensions for the analysis of volumetric data over time. Volumetric Motion Magnification uses a 3D complex steerable pyramid to decompose volumetric frames, enabling the filtering and amplification of subtle motions within 4D datasets. This technique has been tested on synthetic data, demonstrating its ability to extract subtle motions, such as modal deformations of a cylinder.

Despite the advancements in these techniques, several challenges remain to be addressed. Both 2D and 3D DIC are highly sensitive to lighting variations and rely heavily on the quality of the speckle pattern [12, 13]. While feature-matching algorithms like SuperGlue deliver impressive results [14], faster and more efficient networks, such as LightGlue, have emerged with even better performance [15].

For instance, Shao *et al.* [10] implemented SuperGlue to identify matching points, eliminating the need for a speckle pattern. However, this approach limits the number of points that can be analyzed. The number of points matched by state-of-the-art feature-matching methods remains insufficient to generate high-quality meshes. As shown in Figure 1, a mesh created using only LightGlue is very sparse, whereas Figure 2 illustrates the results of employing a simple L^2 norm for dense matching.

The only method capable of handling occlusions effectively is the one proposed by Feng *et al.* [3]. However, this approach is computationally intensive and requires a significant number of viewpoints,

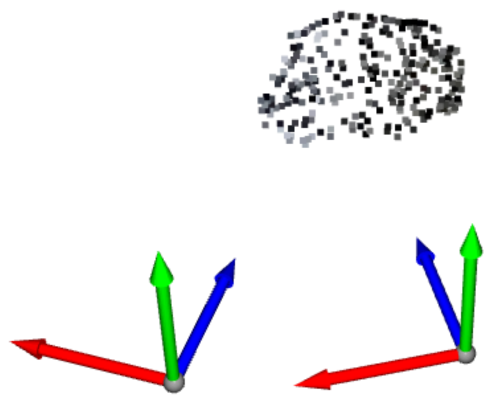

Figure 1: Implementation of LightGlue for pixel matching

making it less practical in many scenarios.

Another limitation of these methods is their reliance on highly calibrated camera setups. Developing a more flexible calibration process, potentially one that could be performed on the fly, would greatly simplify the setup and broaden the applicability of these techniques.

In the realm of 2D motion magnification, advancements have been made to bypass the need for high-speed cameras—which remain prohibitively expensive—by using DSLR cameras instead [16]. However, a similar approach has yet to be developed for 3D applications.

4 Conclusion

3D motion magnification is a valuable tool for revealing subtle motions and vibrations that are not visible to the naked eye, making it useful in structural and mechanical analysis. This review has explored various methods for achieving 3D motion magnification, including techniques that use time-varying radiance fields with a moving camera, stereo-photogrammetry combined with phase-based motion magnification, single camera setups with Finite Element models, combinations of Fringe Projection and DIC, stereo vision with deep learning, and the extension of phase-based motion magnification to 3D volumetric data.

While these techniques have shown great promise, several challenges remain to be addressed. Both 2D and 3D DIC are highly sensitive to lighting variations and the quality of the speckle pattern. Feature-matching algorithms like SuperGlue, while effective, still have limitations in the number of points that can be analyzed, which affects the quality of generated meshes. Some methods, such as the one proposed by Feng *et al.* [3], are computationally intensive and require multiple viewpoints, making them

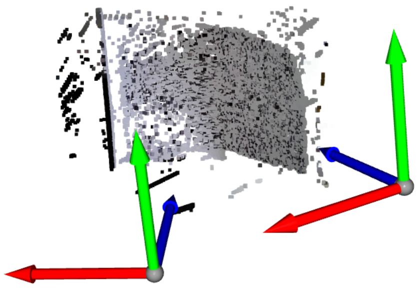

Figure 2: Implementation of L^2 norm across every epipolar line for dense matching

less practical in many scenarios. Additionally, many methods rely on highly calibrated camera setups, which complicates their implementation and limits their applicability. Finally, there is a need to develop methods for using DSLR cameras, which are more affordable than high-speed cameras, in 3D applications.

Future research should focus on creating more robust, efficient, and flexible methods. This includes developing techniques that are less sensitive to lighting and speckle pattern quality, improving the density of matched points, reducing computational costs, simplifying camera calibration, and enabling the use of DSLR cameras for 3D motion magnification.

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