

Application of Photometric Stereo 3D Reconstruction Algorithm in Non-destructive Detection of Artworks

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Abstract: This paper examines the theoretical basis and potential applications of photometric stereo 3D reconstruction for surface documentation and deterioration assessment in artwork conservation. A methodological framework is developed by linking image acquisition under multiple illumination directions, robust weighted normal estimation, Poisson integration, and geometric feature analysis. Ancient Chinese paintings and calligraphy, lacquerware, and stone and jade artworks serve as representative categories for examining how reflectance, texture, and local relief affect reconstruction and interpretation. Conceptual figures illustrate the acquisition workflow and the representation of surface geometry. The theoretical analysis identifies reflectance as a factor affecting the reliability of normal estimation and explains how gradients, curvature, and height residuals can provide complementary cues for observing cracks and local deformation. The framework provides a methodological basis for non-contact documentation and analysis before conservation treatment. Its accuracy and range of application require further experimental evaluation for specific materials.

Keywords: Digital Conservation; Photometric Stereo; 3D Reconstruction; Cultural Heritage; Artwork Inspection

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Introduction

With the development of computer vision and 3D imaging technologies, photogrammetry, structured light, laser scanning, and multi-view 3D reconstruction have gradually been applied to cultural heritage digitization. A method combining SFM-MVS photogrammetry with reflectance transformation imaging can improve the geometric reconstruction quality of low-texture cultural heritage objects^[1]. For complex surfaces such as rock art, photometric stereo can also recover morphology and color information of conservation value under unknown illumination conditions^[2]. The combined use of geometric and photometric reconstruction further shows that multi-view information is suitable for recovering overall shape, whereas multi-illumination information is advantageous for highlighting subtle relief and local surface details^[3]. However, for millimeter- or even submillimeter-scale local structures such as fine cracks, shallow reliefs, and variations in ink, pigment, or lacquer-layer thickness, conventional multi-view methods may still be limited by the density of image feature matching, resulting in surface smoothing and loss of detail.

Photometric stereo estimates pixel-level surface normals from variations in surface brightness under different illumination conditions while keeping the camera fixed and changing the incident-light direction, thereby acquiring high-density surface geometric information in a non-contact manner. For non-Lambertian reflection in real materials, neural inverse rendering and

interreflection modeling can improve normal recovery under complex reflection conditions^[4]. Robust outlier-suppression methods can reduce the interference of specular highlights and shadow observations on normal estimation^[5]. Adaptive reflectance modeling and adaptive inlier acceptance under unknown illumination conditions also provide new technical approaches for stable reconstruction of complex material surfaces^[6-7].

This paper examines photometric stereo imaging and analysis for artwork surface documentation and deterioration assessment. Robust weighting and regularization address normal-estimation stability, Poisson integration provides height recovery, and geometric features support interpretation of surface anomalies. Ancient Chinese paintings and calligraphy, lacquerware, and stone and jade artworks, including Tianhuang stone objects, jade artifacts, and inkstones, are considered in relation to reflectance and surface structure. The theoretical framework links image acquisition, geometric reconstruction, and conservation interpretation to inform acquisition design and experimental validation.

1. Photometric Stereo 3D Reconstruction for Inspection

1.1 Conceptual Nondestructive Artwork Inspection Framework

Photometric stereo image acquisition combines a fixed camera with controlled illumination. The artwork and camera remain stationary while the incident-light direction changes, producing an image sequence of the same region under different lighting conditions. Stable imaging geometry and sufficiently varied illumination directions provide the basis for surface-normal estimation. This acquisition approach is consistent with the need for non-contact documentation and surface-detail capture in cultural heritage digitization^[8-9].

The number and positions of light sources and the illumination arrangement should reflect the size of the inspected region and the material reflectance. Both a movable light source and a fixed array can provide illumination from multiple directions. The acquisition framework can therefore accommodate different equipment configurations, provided that the resulting intensity observations satisfy the model assumptions.

Figure 1: Schematic workflow of photometric stereo for artwork surface inspection



As shown in Figure 1, images acquired under different illumination directions are preprocessed to estimate surface normals. Integration then yields a height field, which supports surface-condition analysis using local geometric features.

Acquisition parameters should balance image quality, illumination stability, and conservation requirements. Exposure settings and working distance should account for the object size and reflectance, while light positions and illumination intensity should reflect the material sensitivity to light. Stable and repeatable acquisition within these requirements improves the comparability of images obtained under different illumination directions.

1.2 Photometric Stereo Imaging Model

Under ideal Lambertian reflection, the grayscale intensity of a pixel on the object surface under the k th light source can be expressed as:

$$I_k(x, y) = \rho(x, y) l_k^T n(x, y) + \varepsilon_k(x, y) \quad (1)$$

where $I_k(x, y)$ denotes the image intensity at pixel (x, y) under the k th light source; $\rho(x, y)$ is the surface albedo; $l_k = [l_x, l_y, l_z]^T$ is the calibrated unit illumination direction; $n(x, y) = [n_x, n_y, n_z]^T$ is the unit surface normal to be estimated; ε_k represents errors caused by image noise, specular highlights, shadows, and complex reflections.

Under the ideal Lambertian model with calibrated illumination, at least three linearly independent illumination directions are required to solve for the surface normal. Additional valid observations provide redundancy when highlights and shadows

affect the measurements. Lacquerware and polished stone or jade surfaces may exhibit strong specular reflection, while ink, pigments, and paper or silk substrates in Chinese paintings and calligraphy have different reflectance properties. Normal estimation should therefore account for material characteristics when identifying anomalous intensity responses and reducing their contribution through weighting.

1.3 Robust Weighted Normal Estimation

The brightness values of the same pixel under all light sources are assembled into the observation vector i , and the illumination directions are assembled into the matrix L . To suppress outliers caused by specular highlights and deep shadows, the diagonal weight matrix W is introduced, and the vector g is calculated using a weighted least-squares model with a regularization term:

$$g = (L^T W L + \lambda I)^{-1} L^T W i, \quad n = g / \|g\|_2, \quad \rho = \|g\|_2 \quad (2)$$

where $i = [I_1, I_2, \dots, I_m]^T$ is the grayscale observation vector generated by m light sources; L is the $m \times 3$ illumination-direction matrix; $W = \text{diag}(w_1, \dots, w_m)$ is the robust weight matrix; λ is the regularization parameter; I is the identity matrix; $g = \rho n$ contains both albedo and normal information. In this study, w_k is dynamically adjusted according to the residual between the current brightness and the model-predicted brightness; highlight or shadow observations with larger residuals receive smaller weights.

Weighted estimation reduces the contribution of anomalous intensities while retaining valid observations, providing a basis for addressing complex reflection on Chinese paintings and calligraphy, lacquerware, and polished stone or jade. Robust outlier handling and adaptive inlier selection offer related approaches to normal estimation on non-Lambertian surfaces. A 3×3 neighborhood median-consistency constraint can subsequently suppress isolated outliers, with the degree of smoothing adjusted to preserve local structures such as crack edges.

1.4 3D Height-Field Recovery

Photometric stereo first yields a unit normal field, whereas artwork defect analysis requires a 3D surface with explicit height relationships. Therefore, the surface gradients in two directions are calculated from the normal vectors:

$$\begin{cases} p(x, y) = -n_x(x, y) / n_z(x, y) \\ q(x, y) = -n_y(x, y) / n_z(x, y) \end{cases} \quad (3)$$

where $p(x, y)$ and $q(x, y)$ respectively represent the first-order rates of change of the 3D height function $z(x, y)$ along the horizontal and vertical image directions; n_x , n_y and n_z are the components of the recovered normal along the three coordinate axes.

To reduce the accumulation of local normal errors during point-by-point integration, global Poisson integration is adopted, and 3D height recovery is expressed as:

$$z^* = \underset{\Omega}{\operatorname{argmin}} \int \left[(\partial z / \partial x - p)^2 + (\partial z / \partial y - q)^2 \right] dx dy \quad (4)$$

where Ω is the artwork region to be inspected; z^* is the final 3D height field; $\partial z / \partial x$ and $\partial z / \partial y$ are the gradients of the reconstructed height field in the two directions, respectively. By minimizing the difference between the estimated gradients and those converted from the normal field over the entire inspection region, 3D surface drift caused by accumulated local errors can be reduced, allowing microcracks and local relief variations to be represented continuously under a unified height reference.

1.5 Artwork Surface Defect Identification

Dark ink or pigment textures can be confused with cracks in two-dimensional grayscale images. Reconstructed surface geometry provides complementary information for distinguishing these features. A composite defect response can be constructed by normalizing local slope, curvature, and height residual:

$$D(x, y) = \alpha \hat{G}(x, y) + \beta C(x, y) + \gamma \hat{R}(x, y) \quad (5)$$

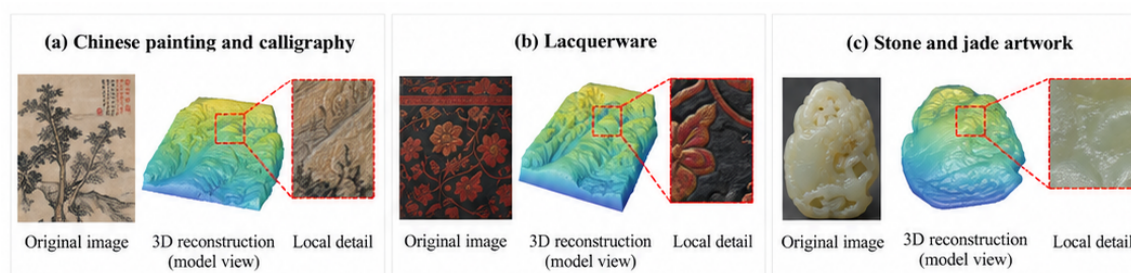
where the defect response combines normalized surface-gradient magnitude, normalized local mean curvature, and the height residual relative to a reference plane fitted to the local neighborhood. The three coefficients are nonnegative weights that can be selected for the application and calibrated when reference data are available. The gradient describes height changes at features such as crack edges; curvature characterizes local forms associated with grooves, protrusions, and lifting or flaking of

pigment or lacquer layers; and the height residual describes broader deformation such as bulging, warping, and depressions. These features provide complementary descriptions of surface anomalies at different scales. Their weights should reflect the material characteristics and inspection objective.

Joint analysis of geometric features can provide complementary cues for distinguishing color texture from surface deformation. Multi-directional photometric-stereo images have demonstrated the complementary value of shadow and reflection variations for defect detection on complex surfaces^[10]. The defect response can be overlaid on a 3D model in pseudocolor to identify regions for closer inspection. Following scale calibration and region segmentation, connected-component and height information can be used to estimate crack length, mean width, maximum depth, and the area of local deformation.

Figure 2 uses Chinese paintings and calligraphy, lacquerware, and stone and jade artworks to illustrate the relationship between surface images, representations of 3D geometry, and local detail views.

Figure 2: Conceptual illustrations of surface geometry and local details for three artwork categories



2. Illustrative Application and Discussion

2.1 Representative Artwork Categories

The application analysis considers Chinese paintings and calligraphy, lacquerware, and stone and jade artworks as representative categories; the latter include Tianhuang stone objects, jade artifacts, and inkstones. Differences in substrate flexibility, gloss, texture, and relief inform the comparison of imaging conditions, reconstruction suitability, and surface interpretation.

For paintings and calligraphy, features of interest include paper or silk undulations, brushwork, pigment accumulation, and local changes associated with ageing. For lacquerware, fine cracks, lifting between layers, and shallow deformation are relevant, while surface gloss can introduce pronounced non-Lambertian reflection. For stone and jade artworks, the analysis may address carving traces, shallow relief, and wear, while accounting for highlights on polished regions. Reconstruction should be interpreted alongside material structure and manufacturing techniques to distinguish original workmanship from changes associated with the condition of the object.

2.2 Qualitative Interpretation of 3D Surface Information

Photometric stereo estimates dense surface normals from intensity changes under multiple illumination directions, providing geometric information for local surface observation. In height or normal maps, microcracks may appear as abrupt changes within narrow regions, while bulges and depressions may produce broader height variations. Geometric representations can also provide clearer cues for identifying shallow carving and brushwork relief. These features can assist surface-condition assessment before conservation treatment, with interpretation informed by material knowledge and professional examination. Figure 2 illustrates the observation priorities for different materials. For paintings and calligraphy, non-contact surface representations may help identify subtle relief in paper, silk, and pigment layers. For lacquerware, geometric changes must be distinguished from intensity changes caused by specular reflection. For stone and jade artworks, carving, wear, and local relief are relevant, with particular attention to highlights on polished regions. Interpreting 3D information in relation to material properties helps connect geometric analysis with specific conservation questions.

2.3 Potential Role in Defect Observation and Digital Conservation

Three-dimensional surface information can document the condition of artworks and support comparisons of the same region over time when acquisition conditions are comparable and the data are registered. A defect-response map combining

gradients, curvature, and local height residuals can provide geometric cues for observing cracks in the presence of color texture and identify regions requiring closer inspection. The nature and conservation significance of these features should be assessed in relation to material condition and professional judgment.

Combining geometric information with knowledge of art materials and manufacturing techniques supports analysis of the relationship between surface form and condition. Non-contact acquisition and local-detail representation can provide visual records for digital humanities, art history, and cultural heritage research, together with a common spatial reference for documentation before treatment and subsequent comparisons.

2.4 Scope and Future Verification

This study develops a theoretical analysis of photometric stereo imaging, reconstruction, and material suitability, with figures illustrating the workflow and the representation of surface information. Subsequent experiments can use this framework to design acquisition protocols for specific materials. Equipment parameters, illumination geometry, calibration procedures, and spatial resolution should be documented, and reconstruction should be evaluated against independent reference measurements and repeated acquisitions.

Validation can begin with mock-ups or replicas to examine the stability of normal estimation and height recovery, followed by independent reference measurements, such as laser profilometry, to assess height errors. Once acquisition conditions and the range of application have been established, selected cultural objects may be examined without contact under conservator supervision. This staged process links performance evaluation with conservation requirements.

Quantitative evaluation may include height root mean square error (RMSE), crack-detection precision, and processing time, together with the reference data, evaluation region, and repeat-measurement conditions. These metrics require reproducible measurements. The theoretical analysis and conceptual figures in this paper explain application principles and features of interest; they do not establish detection performance.

Further work should also relate geometric anomalies to the condition of the object through expert examination, establishing a basis for interpreting reconstruction in deterioration screening, treatment documentation, and long-term monitoring.

3. Conclusions

This paper examines the theoretical basis of photometric stereo for nondestructive artwork inspection and develops a framework linking image acquisition under multiple illumination directions, robust normal estimation, height recovery, and geometric feature analysis. The discussion of Chinese paintings and calligraphy, lacquerware, and stone and jade artworks identifies the roles of reflectance, texture distribution, and local structure in imaging and interpretation. Gradients, curvature, and height residuals describe surface changes at different scales and provide complementary cues for observing cracks, relief, and local deformation.

Photometric stereo offers an approach for investigating non-contact surface documentation and analysis before conservation treatment. Conceptual figures illustrate acquisition and geometric representation, while performance requires evaluation using measurements from different materials. Further work can address acquisition protocols for specific materials, independent reference measurements, repeatability, and expert interpretation to establish the conditions under which the method can support digital conservation.

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Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

Reference

- [1] Morita, M. M., Loaiza Carvajal, D. A., González Bagur, I. L., et al. (2024). A combined approach of SFM-MVS photogrammetry and reflectance transformation imaging to enhance 3D reconstructions. *Journal of Cultural Heritage*, 68, 38–46.
- [2] Crabu, E., Pes, F., Rodriguez, G., et al. (2025). Color reconstruction by photometric stereo with unknown lighting of rock

art carvings found in two Sardinian Domus de Janas. *Journal of Cultural Heritage*, 71, 320–327.

- [3] Laurent, A., Couprie, B., Brument, B., et al. (2025). Combining geometric and photometric 3D reconstruction techniques for cultural heritage. *Journal of Cultural Heritage*, 73, 43–51.
- [4] Yang, Y., Liu, J., Fu, Y., et al. (2024). Non-Lambertian photometric stereo via neural inverse rendering and interreflection model. *Optics and Lasers in Engineering*, 178, 108138.
- [5] Wang, S., Cao, X., Li, J., et al. (2025). A new outlier rejection approach for non-Lambertian photometric stereo. *Optics & Laser Technology*, 182, 112142.
- [6] Fu, Y., Yang, Y., & Liu, J. (2025). UPS-HSG: Uncalibrated photometric stereo based on adaptive hybrid Spherical Gaussian. *Optics and Lasers in Engineering*, 195, 109360.
- [7] Li, W., Ma, L., Liu, H., et al. (2026). Inlier differential acceptance for non-Lambertian photometric stereo. *Optics & Laser Technology*, 193, 114141.
- [8] He, J., & Jia, Q. (2025). Opti3D for low light enhancement and calibration free 3D digitization of cultural relics. *npj Heritage Science*, 13, 357.
- [9] Jia, Q., & He, J. (2026). High-fidelity 3D reconstruction of cultural heritage via super-resolution and progressive Gaussian splatting. *npj Heritage Science*, 14, 84.
- [10] Wu, L., Ran, Y., Yan, L., et al. (2025). A dataset for surface defect detection on complex structured parts based on photometric stereo. *Scientific Data*, 12, 276.