https://doi.org/10.2352/issn.2168-3204.2025.22.1.29

MISHA3D - Three-dimensional surface capture with the MISHA multispectral imaging system

James Ferwerda[†], Juilee Decker[‡], David Messinger[†]; [†]Chester F. Carlson Center for Imaging Science, [‡]Museum Studies Program; Rochester Institute of Technology; Rochester, NY, USA.

Abstract
In this paper we introduce MISHA3D, a set of tools that enable 3D surface capture using the MISHA multispectral imaging system. MISHA3D uses a novel multispectral photometric stereo algorithm to estimate normal, height, and RGB albedo maps as part of the standard multispectral imaging workflow. The maps can be visualized and analyzed directly, or rendered as realistic, interactive digital surrogates using standard graphics APIs. Our hope is that these tools will significantly increase the usefulness of the MISHA system for librarians, curators, and scholars studying historical and cultural heritage artifacts.

Introduction
MISHA (Multispectral Imaging System for Historical Artifacts) is a low-cost, open-source, multispectral imaging system designed for historical and cultural heritage applications [1]. Figure 1 shows the system, which consists of a high-resolution monochrome camera, a pair of LED light panels, a supporting frame, and image capture and analysis software. The system has been designed and documented to enable librarians, curators, and scholars with limited budgets and technical expertise to build their own systems to study their collections. MISHA systems have been constructed by a diverse range of organizations, and have resulted in an increasing body of scholarship directed toward the investigation of historically and culturally significant artifacts [2].

The primary goal of the MISHA project is to enable the widespread use of multispectral imaging in the analysis of library and museum collections, and while this has been successful, many of the artifacts in these collections also have complex and important geometric properties that are not represented in the multispectral data. In this project, we have added three-dimensional surface capture capabilities to the MISHA system. This MISHA3D system uses slightly modified LED panels and custom software to implement a novel multispectral photometric stereo algorithm that produces three-dimensional surface models as part of the standard multispectral imaging workflow. The model/maps are encoded in standard digital image files and can be viewed and analyzed directly, or combined and rendered to produce realistic digital surrogates using standard 3D graphics pipelines.

In the following sections we describe the components of the MISHA3D system, demonstrate its capabilities, discuss its limitations, and outline directions for future work.

Figure 1. The MISHA multispectral imaging system.

Background
Photometric stereo is an image-based surface capture method introduced by Woodham [3]. The method leverages Lambert's law, which states that the light intensity reflected from a matte surface is proportional to the cosine of the angle between a vector normal to the surface and a vector pointing in the direction of the light source illuminating the surface. With a minimum of three linearly-independent light vectors, the three-dimensional orientation of the surface at a point can be determined from differences in the reflected intensities. In the imaging domain, a point-by-point normal map of a three-dimensional surface can be calculated by comparing three or more images of the surface illuminated from different directions.

While the normal map represents the varying tilts of a surface at different points, most three-dimensional surfaces also vary in height from point to point. A variety of techniques have been developed for estimating surface height maps from normal maps [4].

Taken together, the normal and height maps constitute a discrete three-dimensional model of a surface that can be analyzed in its own right, or used with standard graphics APIs to render realistic images of the surface that can be viewed from different directions, illuminated under different conditions, and manipulated interactively [5].

The ability to create faithful digital surrogates of historical and cultural heritage artifacts would likely be of great benefit to

Figure 2. Standard MISHA light panel modified to allow single LED illumination. The inset shows the 22 light direction vectors estimated from images of a mirrored ball.

librarians, curators, scholars and other stewards of these collections. In the following section we describe how we have implemented this capability within the MISHA system.

System

The MISHA system was designed to enable multispectral imaging of library, archive, and museum artifacts. To implement photometric stereo surface capture, we slightly modified the hardware of the MISHA system and developed a new set of software tools. The system described below is a prototype that for practical reasons uses a different camera than the standard MISHA system and has disabled some of the multispectral imaging functionality, future versions of the system will fully integrate the multispectral imaging and surface capture capabilities.

Hardware components

The standard MISHA system includes two LED light panels which each contain an array of LEDs that emit across a range of UV, visible, and near-IR wavelengths The design of these panels is detailed elsewhere [6], however one of the design goals was to provide uniform illumination across the surface of the artifact being imaged. To achieve this, the two panels are arranged to illuminate the artifact from opposite sides, and many of the LEDs in each panel are paired, or in one case tripled, to approximate diffuse illumination. Since the photometric stereo approach requires illuminating the surface from a set of distinct directions, we modified the LED panels by taping over all but one of the LEDs of each wavelength and controlling the panels separately so that together, the two boards could illuminate the surface from 22 distinct directions. One of the modified panels is shown in Figure 2.

In addition, because it was the only camera available, the prototype system used a 1.3 Mpix color camera (Point Grey BFLY-PGE-13E4M-CS) in monochrome mode rather than the MISHA-recommended 20+ MPix monochrome camera. Incorporating the higher-resolution camera should allow the creation of more detailed models.

Neither of these changes to the system hardware permanently disable the multispectral imaging functions of the system. We are currently revising the design of the LED panels to allow individual control of the LEDs, and acquiring a high-resolution monochrome camera so that the next iteration of the system will seamlessly support both multispectral imaging and surface capture functions.

Software components

Since photometric stereo algorithms typically assume the use of "white" lights, significant effort was required to adapt the method to the multispectral imaging context. To do this we first determined the directions to each light, by imaging a mirrored ball (1" gaming pinball) placed on the imaging stage, and then processed the images to determine the lighting directions. The map of lighting directions is shown in the inset in Figure 2. We then calibrated the lights radiometrically, by taking images of a Spectralon puck and using an XRite ColorMunki spectrophotometer and the Argyll CMS software package to measure both the absolute XYZ tristimulus values and spectrum of each light in the visible range. (We had previously eliminated the UV and IR lights from consideration because they produced dark images and low instrument readings with the camera we are using). We then estimated the average values of each Spectralon image and calculated scale factors that were used to scale the camera images, effectively equalizing the light source intensities so that the image values only represent the effects of surface reflectance and light source direction. In addition, we estimated the spectrum of "white" light produced by turning on all the LEDs by summing the spectra of the LEDs and then normalizing the result relative to the value at 560nm.We then used images subjected to the calibrations described above to estimate normal, height, and RGB albedo maps for imaged surfaces.

To calculate the surface normals, we implemented Woodham's algorithm in matrix form and used least-squares methods to estimate the normal map. We then transformed the bipolar x,y,z normals produced by the method to 0-255 RGBs and saved the normal map as an image. Importantly, we observed that even though the surface is only illuminated from the left and right sides, because the lights are coming from 22 unique directions, the data provides sufficient constraints to allow estimation of a full range of surface normals.

The standard method to estimate surface heights is to integrate the normals, but we found that this produced systematic distortions in the height maps, so we turned to the Generalized Least Squares method [7] which produced better results, but which still showed global curvature errors. To minimize these errors, we fit a fifth-order polynomial surface to the height map and then subtracted the height values defined by this surface from the map heights, and saved the result as a grayscale image where image intensity is proportional to surface height.

Finally, we estimated the surface albedo in RGB, by first averaging the pairs of images taken under corresponding LEDs from the two panels. We then formed an image cube where each z-plane of the cube represented the average image at one of the LED wavelengths. The cube was then interpolated, producing 81 planes representing reflected intensity every 5nm from 380-780nm. We then took the spectrum represented at each pixel and calculated the corresponding XYZ tristimulus values using the color-matching functions of the 1931 CIE 2^{o} standard observer, and the LED "white" we had estimated earlier as the illuminant. We applied a chromatic adaptation transform to refer the values to the D65 standard illuminant, and converted the XYZs to the sRGB color space. The resulting albedo map was saved as an RGB image.

Results

Figures 3 and 4 show two surfaces and the models estimated using the system. In reading order, they are a) reference photograph,

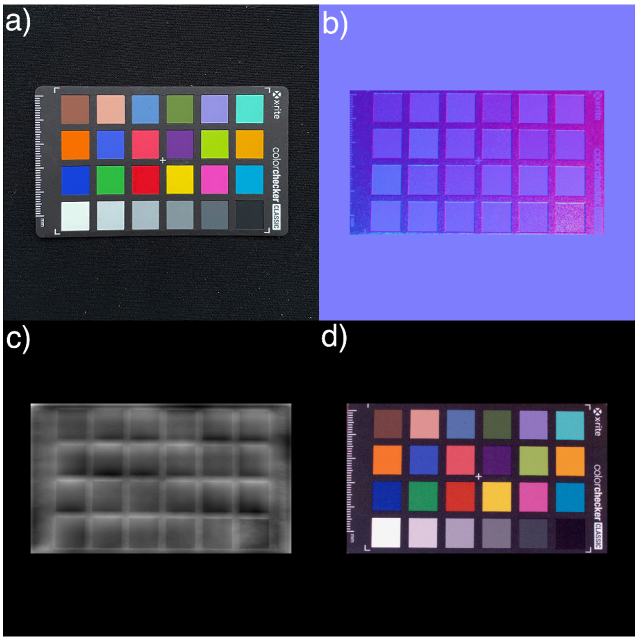

Figure 3. Surface model of an Xrite ColorChecker chart. a) photograph of the chart, b) normal map, c) height map, d) albedo map. See Figure 5 for a rendered version of the model.

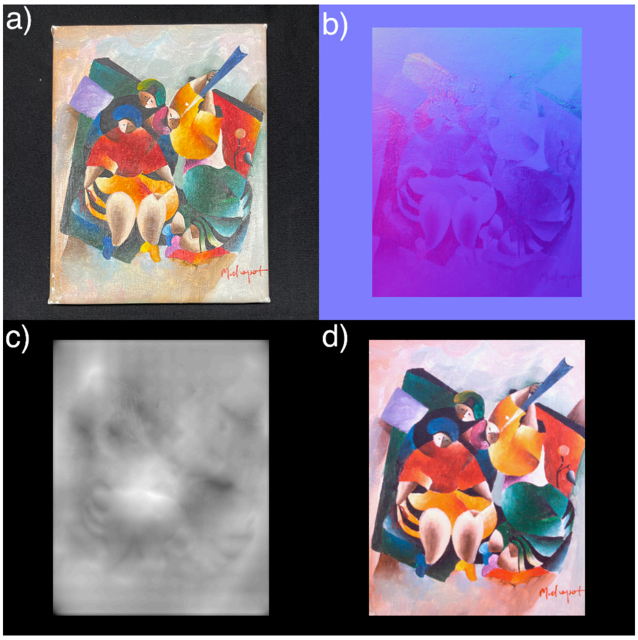

Figure 4. Surface model of an acrylic painting. a) photograph of the real painting, b) normal map, c) height map, d) albedo map. Note the crenellations in the paint that are captured in the normal and height maps. See Figure 5 for a rendered version of the model.

b) normal map, c) height map, d) albedo map. Figure 5 shows the models rendered as digital surrogates using an image-based lighting and physically-based rendering application we developed in threeJS for another project [8]. The application supports real-time rendering, and direct interaction with the surfaces, in a standard web browser.

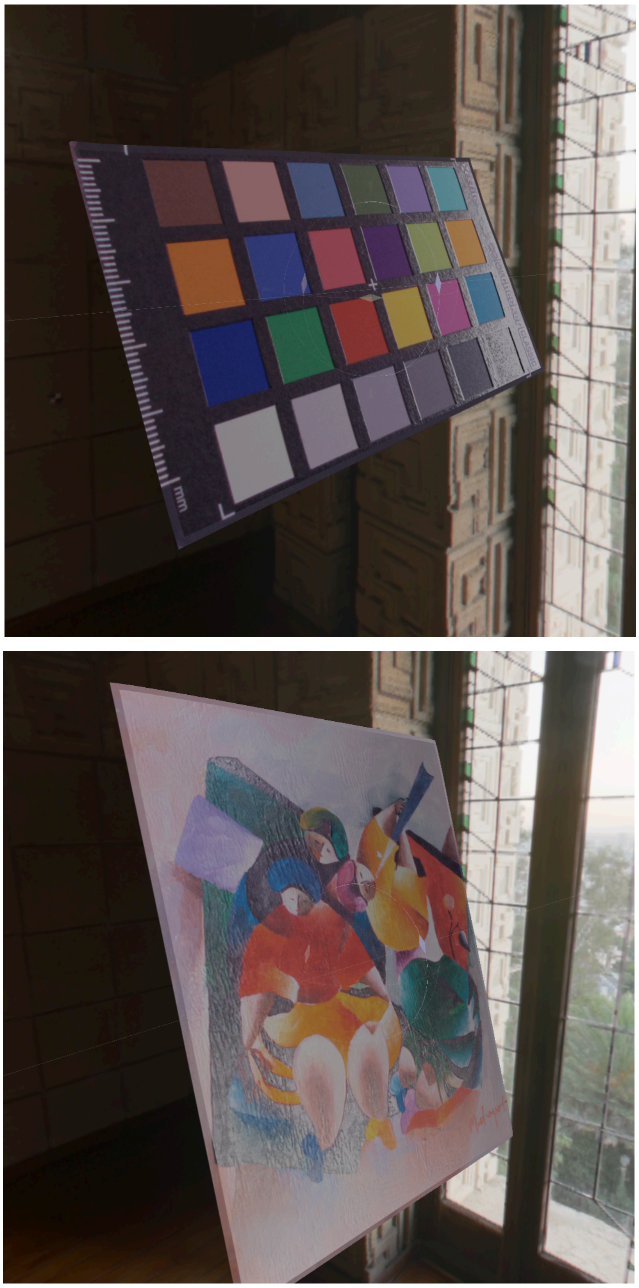

Figure 5. Computer graphics renderings of the ColorChecker and painting models.

Conclusions and future work

In this paper we have described efforts to add surface capture capabilities to the MISHA multispectral imaging system. The MISHA3D system allows 3D surface models to be created as part of the standard multispectral imaging workflow. The model components (normal, height, albedo maps) can be visualized and analyzed directly, or rendered as interactive digital surrogates. While the results appear to be accurate, validation with respect to ground-truth measurements still needs to be performed. In addition, a full surface model should include a more complete description of surface material properties such as gloss and translucency. Finally, the lights and camera of the MISHA3D prototype differ from the standard MISHA system. To support the two modalities, we are in the process of redesigning the light panels to allow individual control of each LED, and acquiring a higher resolution monochrome camera. This should allow the creation of even more faithful models of complex surfaces. Our hope is that the features we have added in MISHA3D will significantly increase the usefulness of the MISHA system for librarians, curators, and scholars studying historical and cultural heritage artifacts.

References

[1] Kleynhans, T., Carr, M. L., & Messinger, D. W. (2021). Low-cost, user friendly multispectral imaging system for the recovery of damaged, faded or palimpsested historical documents. In *Algorithms, Technologies, and Applications for Multispectral and Hyperspectral Imaging XXVII* (Vol. 11727, pp. 46-52). SPIE.

[2] https://www.rit.edu/chipr/misha

[3] Woodham, R. J. (1980). Photometric method for determining surface orientation from multiple images. Optical engineering, 19(1), 139-144.

[4] Ackermann, J., & Goesele, M. (2015). A survey of photometric stereo techniques. Foundations and Trends in Computer Graphics and Vision, 9(3-4), 149-254

[5] https://threejs.org/

[6] Barrios, C., Kleynhans, T., & Terdal, R. (2021). MISHA - Multispectral Imaging System for Historical Artifacts: From Prototype to Production, unpublished manuscript.

[7] Harker, M., & O'Leary, P. (2022). Surface reconstruction from gradient fields: grad2Surf version 1.0. MATLAB Central File Exchange.

[8] Ferwerda, J. A., & Darling, B. A. (2013). Tangible images: Bridging the real and virtual worlds. In *Computational Color Imaging: 4th International Workshop, CCIW 2013, Chiba, Japan, March 3-5, 2013. Proceedings* (pp. 13-24). Springer Berlin Heidelberg.

Acknowledgements

Development of the MISHA system was supported by NEH grant PR-268783-20, "Low cost End-to-End Spectral Imaging for Historical Document Discovery”.

Author Biographies

James Ferwerda is an Associate Professor in the Chester F. Carlson Center for Imaging Science at the Rochester Institute of Technology. He received a B.A. in Psychology, M.S. in Computer Graphics, and a Ph.D. in Experimental Psychology, all from Cornell University. The focus of his research is on building computational models of human vision from psychophysical experiments, and developing advanced imaging systems based on these models.

Juilee Decker is Professor of History at the Rochester Institute of Technology where she directs the Museum Studies program. She earned her Ph.D. from the joint program in art history and museum studies at Case Western Reserve University/Cleveland Museum of Art. She co-directs the Cultural Heritage Imaging Lab at RIT.

David Messinger received a B.S. in Physics from Clarkson University and a Ph.D. in Physics from Rensselaer Polytechnic Institute. He is currently a Professor, and the Xerox Chair in the Chester F. Carlson Center for Imaging Science at the Rochester Institute of Technology. He is a Fellow of SPIE. His personal research focuses on projects related to spectral image analysis with applications to remote sensing and cultural heritage.