Shape-from-Shifting: Uncalibrated Photometric Stereo with a Mobile Device

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***Abstract*—Surface shape scanning techniques, such as laser scanning and photometric stereo, are widespread analytical tools used in the field of cultural heritage. Compared to regular 2D RGB photos, 3D surface scans provide higher fidelity of an object's surface shape which assist conservators, art historians, and archaeologists in understanding how these artworks and artifacts are made and to digitally document them for purposes of conservation. However, current state-of-the-art 3D surface scanning tools used in art conservation are often expensive and bulky- such as light dome structures that are often over 1 m in diameter. In this paper, we introduce mobile shape-from-shifting (SfS): a simple, low-cost and streamlined photometric stereo framework for scanning planar surfaces with a consumer mobile device coupled to a low-cost add-on component. Our free-form mobile SfS framework relaxes the rigorous hardware and other complex requirements inherent to conventional 3D scanning tools. This is achieved by taking a sequence of photos with the on-board camera and flash of a mobile device. The sequence of captures are used to reconstruct high quality normal maps using near-light photometric stereo algorithms, which are of comparable quality to conventional photometric stereo. We demonstrate 3D surface reconstructions with SfS on different materials and scales. Moreover, the mobile SfS technique can be used "in the wild" so that 3D scans may be performed in their natural environment, eliminating the need for transport to a laboratory setting. With the elegant design and low cost, we believe our Mobile SfS can greatly benefit the conservation community by providing a user-friendly and cost-effective solution for 3D surface scanning.**

***Index Terms*—3D Surface Shape Reconstruction, Photometric Stereo, Image-Based Modeling, Reflectance Transformation Imaging, Scale-invariant Feature Transform, Near-Light Position Calibration.**

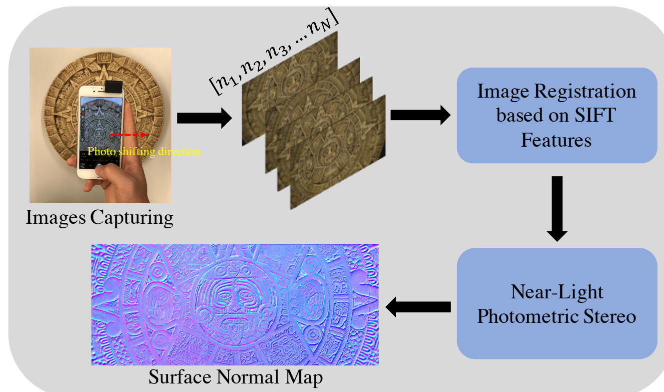


Fig. 1. **Overview of Shape from Shifting:** Our shape-from-shifting technique uses a mobile device camera to capture images around the object with the built-in flash used as a source of illumination. SIFT-based image registration renders the images to the same viewpoint but each with a unique illumination direction. The synthesized images are further processed by uncalibrated photometric stereo to acquire dense surface normal vector maps.

I. Introduction

3D imaging techniques have had an explosive growth in both industry and academic research during the last decade with a variety of applications, such as visual effects in movies and video games [3], computer-aided-design for rapid prototyping, quality inspection [4], and biological imaging [5], [6]. In the community of cultural heritage, 3D imaging has gained widespread popularity as a tool for documenting object condition [7]. 3D imaging methods can be loosely divided into two groups: passive and active 3D imaging. Passive based 3D imaging, such as photogrammetry relies on the reflected radiance from an object lit with ambient illumination to reconstruct the object's 3D surface shape. Active 3D imaging, such as photometric stereo (PS) [8], uses a controlled light source, such as a flash light, to illuminate the object and recover the 3D surface shape. PS is a highly sensitive technique that is capable of recovering 3D surface shape information on the scale of micrometers. For this reason, it has been widely used for the visualization of works of art and artifacts. While PS has been explored extensively, it still faces many fundamental challenges that limit its ease of use and has prevented its widespread adoption as a collection survey tool in the cultural heritage community.

PS estimates the surface normal/shape from photos taken by a fixed position camera but with varying lighting position and direction. By modeling the measured image intensity as a function of the incident lighting angle, one can recover the surface normal and material reflectance of each point on the object. The depth information of the object can then be recovered by integrating the reconstructed surface normals. The material's reflectance can also be interactively manipulated by the users for the purposes of visualization and may be integrated into virtual reality (VR) head-mounted displays (HMDs) or augmented reality (AR) displays. Conventional PS reconstruction techniques use a far-light assumption, which assumes the position of the illumination light source is infinitely far away from the object. In practice, this assumption is frequently violated due to the space limitations of the acquisition setup. Without proper correction of the forward model, the violation

TABLE I
COMPARISONS OF SPECS BETWEEN OUR PROPOSED MOBILE SFS AND TWO STANDARD TECHNIQUES.

Imaging Techniques	Price	System Complexity	Capturing Time	In the Wild	Portable
Laser Scanner [1]	$$$$	High	Hours	Yes	No
PS with Dome [2]	$$$	Medium	$\sim$ 30 Minutes	No	No
Mobile SfS	$	Low	$<$ 1minute	Yes	Yes

of this assumption introduces errors in the reconstruction of the surface normal.

We previously introduced [9] a near-light model that automatically estimates the light source positions at the same time as the surface normal estimations increasing the accuracy of both. However, to achieve these results a light dome and a high-end digital single-lens reflex (DSLR) cameras, remote triggers and flash lights were required. In this paper, we ask the question: Is it possible to achieve the same results as achieved in [9] using a simplified imaging setup that is user friendly operation and portable enough to be used in remote locations?

To this end, we recently proposed a dual camera setup and near-light model for PS reconstruction [10]. In this setup, DSLR cameras and a flash are synchronized together: a fixed camera is used for PS capture and a second camera is attached to a flash to estimate lighting direction. A sequence of photos are taken as the second camera is moved along an arbitrary path in 3D space. Detected features on the object in each image are fed into a Structure from Motion (SfM) algorithm, which recovers the pose of the second camera, and in turn provides the 3D position of the flash fixed to this camera. High-quality surface normals are then recoverd using a near-light PS algorithm, such as the one proposed in [9]. In addition, a course point cloud recovered from SfM is fused with the recovered surface normals, producing a high quality depth map.

In this paper, we draw inspiration from this previous work to simplify photometric stereo acquisitions and innovate a simpler un-calibrated method for surface acquisition of works of art. Here we introduce a near-light PS technique that uses just a single camera for surface normal reconstruction. We propose mobile shape-from-shifting (SfS), a robust 3D surface shape recovery framework that can be used on a mobile device as shown in Figure 1. SfS uses just a mobile device and a custom 3D printed widget fitted with crossed polarization filters placed respectively in front of the camera lens and on the flash LED. Hand-held capturing is possible due to the compact size of the mobile device. The polarization filters are used to separate diffuse and specular reflectance, in order to suppress normal reconstruction errors caused by specular reflections. During capture, users simply turn on the built-in flash and capture a sequence of images of the object surface. These images are pre-processed using scale-invariant feature transform (SIFT) [11] to register object features in each frame. Then, a near-light PS algorithm is used to recover surface normals from these pre-processed images. In Table I, we summarize and compare the proposed Mobile SfS with the 3D imaging techniques frequently used in cultural heritage. Our proposed method significantly reduces the complexity of PS acquisition so that images may be captured in nearly any setting. We show that our method produces similar quality 3D surface normal reconstructions to those achieved using a lighting dome in a laboratory. Our contributions are summarized below.

- **A novel PS surface normal reconstruction framework (SfS):** In this paper, we propose a novel PS surface normal reconstruction framework that uses only a single camera and flash on a mobile device. We develop an image processing pipeline and near-light PS reconstruction algorithms for the novel framework.
- **A Simple, Cost-effective Solution:** Our technique requires only a mobile device. Optionally, an add-on widget may be used to increase performance for highly specular objects. Previously, polarization has been widely used in light dome setups [2] to improve normal reconstruction, but calibrating polarizing filters is time-consuming and error-prone. Mobile SfS uses a 3D printed widget with just two polarizers, making it cost effective and easy to use.
- **Portability and Accessibility:** Since Mobile SfS only requires a mobile device, such as an iPhone, and a small widget, it is very portable and user friendly. We believe Mobile SfS will be a powerful tool for conservators because it drastically simplifies the 3D surface acquisition process by allowing objects to be scanned in their natural environment and without the need of calibration hardware such as a mirrored ball.
- **Mobile SfS for different materials and scales:** In this paper, we have demonstrated that Mobile SfS can work for ceramic, stone and paper objects of various physical proportions.

II. RELATED WORKS

A. Image-Based modeling and Photogrammetry

Developed in the 1990s, image-based modeling is a technique that utilizes a collection of images to create a three dimensional model [12]. To determine the 3D location of points within a scene, traditional photogrammetry methods require the 3D location and pose of the cameras, or the 3D location of a series of control points to be known. Structure-from-Motion (SfM) [13] removed this requirement, simultaneously reconstructing camera pose and scene geometry through the automatic identification of matching features in multiple images.

B. Photometric Stereo

Photometric stereo is often used to recover surface shape from image intensity. The original formulation by Horn [8] assumed lights are infinitely far away, the camera is orthographic, and the object surface is Lambertian and convex (i.e. no shadows or inter-reflections). Since photometric stereo was originally introduced, several researchers have sought to generalize the technique for more practical camera, surface and lighting models. Belhumeur *et al.* [14] discovered that with an orthographic camera model and uncalibrated lighting, the objects surface could be uniquely determined to within a bas-relief ambiguity. Papadhimitri and Favaro *et al.* [15] recently pointed out that this ambiguity is resolved under the perspective camera model. Several researchers have also sought to remove the Lambertian reflectance assumption and incorporate effects such as specular highlights and shadows. New techniques have been introduced based on non-Lambertian reflectance models [16]–[18] or sophisticated statistic methods to automatically filter non-Lambertian effects [19]–[21]. However, less attention has been paid to removing assumptions on the lighting model. Several other researchers [9], [22], [23] recently investigated removing the far-light assumption to improve the accuracy of photometric stereo.

C. Reflectance Transformation Imaging

As a visualization technique, reflectance transformation imaging (RTI) uses multiple photographs to probe the appearance of the object under arbitrary illumination conditions. In 2001, the polynomial texture mapping (PTM) was first introduced by Malzbender *et al.* [24] for computational relighting. By fitting the pixel intensity with a polynomial basis function, PTM could enable a virtual light source to be controlled by the user to relight the scene. Later, in order to reduce the directional bias, the hemispherical harmonics (HSH) version of RTI was proposed by Elhabian *et al.* [25]. Originally, RTI is merely a visualization technique which could not provide direct access to 3D information. Palma *et al.* [26] estimated surface normal using PTM by fitting the pixel intensity to a local bi-quadratic function of the lighting angles and then find the direction of the brightest pixel. In the last few years, RTI has become popular among conservators through the use of CHI RTI Builder and Viewer software suites [27]. Conservators use the software not only to document the historical collections with the interactively image relighting fashion but also explore the surface normal map for further analysis.

D. Separation of Diffuse and Specular Reflections

Surface reflectance is a well studied research problem in computer graphics. In 1985, Shafer [28] proposed the Dichromatic Reflectance model and utilized color images analysis to separate surface reflection into ”diffuse” and ”specular” components. Because of the different spectral distributions for diffuse and specular reflection under dielectrics, the method easily separates them in RGB color space. Klinker *et al.* [29] also developed a method based on color histograms. To get more accurate and concise results, researchers kept pushing the color-based methods to the limit. [30]–[36] In addition to color-based techniques, several hardware-based approaches have been introduced. Lamond *et al.* [37] use controlled illumination to exploit specific frequency behaviors of reflectance functions for separating diffuse and specular components. Polarization can also be used to separate diffuse and specular reflections. Wolff [38] demonstrated the use of cross-polarized filters, using two images captured with vertical and horizontal polarizers in front of the camera to efficiently separate diffuse and specular reflection components. Nayar *et al.* [39] combined polarization and color information to separate diffuse and specular reflections. Significant work from Ma *et al.* [40] described the use of polarization differential images and spherical gradient illumination to perform photometric stereo for acquiring high quality surface normal with a small number of images.

III. Mobile SfS

A. Hardware Setup and History Collection Samples

Hardware Setup: Two polarizers with opposite polarization directions (marked with blue boxes in Figure 2(a)) were attached to the camera and flash light on an iPhone 6 through a custom 3D printed add-on component as shown in Figure 2(b). Specifically, these two polarizers were cut from the same polarization film. The polarizer on the flash light was first glued on the add-on component, and the orientation of the polarizer on the camera was carefully tuned and fixed at the position of extinction. The total cost for the polarizers and 3D printed component is less than 5 USD.

Historcal Artworks: Three artworks with different materials and scales were evaluated with our prototype Mobile SfS. The first sample is a duplicate (Figure 3(a)) of Aztec calendar stone [41] which dates back to 15^{th} century in Mexico and is housed in the Mexico National Anthropology Museum as shown in Figure 3(b). The second sample is a portion of wall of Bahá’í Temple [42] (Figure 3(c)) built in the 1930s and located in Evanston, IL. The third sample is a parchment page of a French illuminated manuscript as shown in Figure 3(d), Suffrages from a Book of Hours [43], dating from the 1460s-1490s, which belongs to the permanent collection of the Isabella Stewart Gardner Museum in Boston.

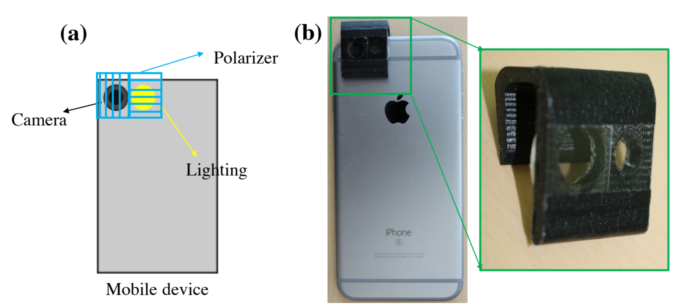
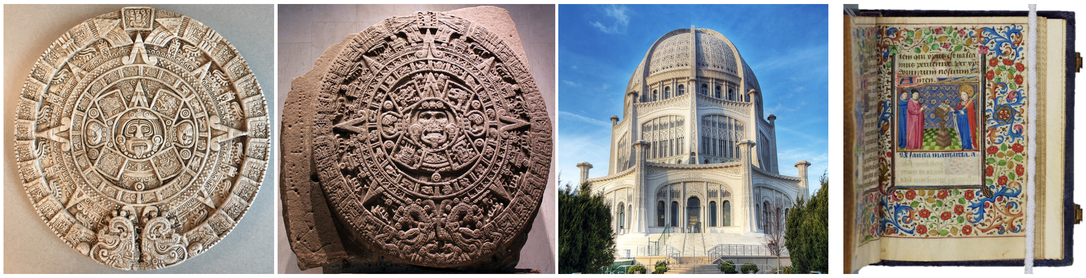


Fig. 2. **Mobile SfS hardware:** (a). two polarizers with opposite polarization are attached to the camera and the flash light of the mobile device, respectively; (b). photo of our prototype Mobile SfS with an iPhone 6 and a custom 3D printed widget.



(a). A duplicate of Aztec calendar stone (b). Original Aztec calendar stone (c). Bahá'í Temple (d). French illuminated manuscript

Fig. 3. **Samples for evaluation with Mobile SfS:** A duplicate (a) of Aztec calendar stone (b); a portion of the wall of Bahá'í Temple (c); and a page of an old manuscript (d).

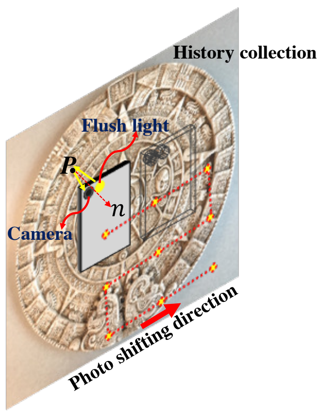


Fig. 4. **Acquisition procedure with Mobile SfS:** Hand-held Mobile SfS faces to the object. Slightly shift the phone and take one image at each position. Nine images are taken in this paper for the surface normal reconstruction.

B. Acquisition Procedure

As shown in Figure 4, the phone is held by hand at about 30 cm from the samples (depending on the size of the imaging area and the scale of the surface profile). A sequence of photos (9 images in this paper) are captured by sequentially moving the camera marked with a dash line in the figure. During capture, the focus, white balance and exposure of the phone camera are set to manual. Due to the limited power of the iPhone flash, the examples shown were captured in a dark room or in the evening to minimize the effect of ambient light.

C. Reconstruction Algorithms

Using this pipeline, we have acquired a set of diffuse reflection images where each surface point is illuminated by k lights and k different viewpoints $[I^1_{raw}, ..., I^k_{raw}]$. In order to establish the conditions necessary to measure the surface shape by photometric stereo, all the images need to be captured from the same point of view. Likewise, a Lambertian surface will diffusely reflect light with an intensity proportional to the cosine of the illumination angle, regardless of the observer's angle of view. We meet these requirements by performing a geometric transformation to render each captured image with a single viewpoint as shown in Figure 5.

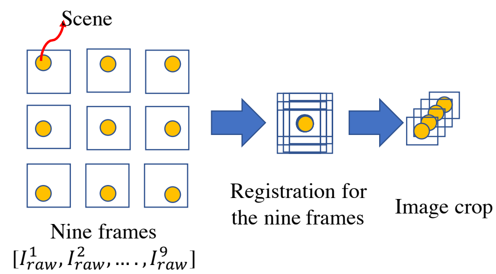


Fig. 5. **Image pre-processing:** Step 1: nine images are captured; Step 2: images are registered with the SIFT function; Step 3: images are cropped to display the same region.

The transform is calculated by identifying a set of features in each of captured image $[F^1_1, ..., F^k_j]$ using the SIFT feature detection algorithm [11]. Correspondencies between features in all images, as well as identification of outliers, is found using RANSAC [44]. With these data as inputs, the transform between the source and target images is used to estimate a homography matrix $[H_1, ..., H_{k-1}]$. Once each image is trasnformed through the homography matrix, the collection of images is thus registered $[I^1_{reg}, ..., I^k_{reg}]$ to the target viewpoint.

Next, the registered images $[I^1_{reg}, ..., I^k_{reg}]$ are used as the input into a near-light uncalibrated PS algorithm to accurately recover surface normal vector and albedo images. Similar to Xiang *et al.* [9], we assume the mobile phone camera to be linear and model surface intensity by minimizing the following energy function:

$$E(L_k, e_k, N_p, p, A'_p) = \sum_{p,k} \left(I_{pk} - \frac{N_p^T (L_k - p)}{\|L_k - p\|^3} e_k A'_p \right)^2 . \quad (1)$$

where p is the each surface point, $\hat{N} = (\hat{N}_x, \hat{N}_y, \hat{N}_z)$, $A'_p = (A'_{px}, A'_{py})$, denote the surface normal and albedo, L_k denotes the 3D position of the k-th light source and e_k is represented the lighting intensity. To simplify and accelerate the reconstruction process, we also take the 3D position from homography estimation as the initial 3D lighting position. The 3D lighting position would interactively update while estimating the albedo and surface normal.

Note that conventional photometric stereo usually requires more than 10 images to get a quality surface reconstruction. With Mobile SfS, we are able to use only 9 images to reconstruct the surface geometry.

IV. Experiments and Results

Three case studies using artworks, as described above, are performed with our prototype Mobile SfS setup to demonstrate the reconstruction of surface normal vector maps, and its versatility on a variety of materials.

A. Plaster Replica of an Aztec Calendar Stone

To qualitatively evaluate our mobile SfS, we first performed the experiment with the replica of an Aztec calendar stone and compared our normal map reconstruction to one captured, from the same object, in a light dome. The Mobile SfS device was placed about 30 cm away from the object surface facilitating a small region of interest to be captured but at high resolution. Larger fields of view can be captured, albeit with the trade off of lower resolution. The same region of the stone was imaged with the light dome. We also compared the normal map reconstruction with the same mobile phone, with and without polarizers. Sequences of nine images are used for the normal map reconstruction for our Mobile SfS, while eighty-one images are used for the normal map generation for photometric stereo with light dome.

In Figure 6(a) an RGB photo of the imaged portion of stone is shown with a close-up view of nose region. Normal maps produced respectively from a light dome and by Mobile SfS without polarization filters are shown in Figure6 (b) and (c). Compared to the normal map from the light dome (Figure 6(b)), the normal map generated using the proposed method (Figure 6(d)) retains the global shape information of the test sample. There are however some notable difference in all three captures. Specularly reflected light from the object is removed for the normal map reconstruction in Figure 6(d), via polarizing filters, to avoid introducing errors in the normal map generation. Thus when compared to Figure 6(c), where specular reflections are strong, fewer high frequency fine details such as the lines on the close-up nose region may be observed in Figure 6(d). Likewise, the light dome capture in Figure6 (b) also lacks these high frequency details but for the reason that the camera is placed much farther away from the surface than in the SfS setup.

If we reconsider the mathematical model for photometric stereo, most algorithms, including the one described in this paper, assume that the object has a Lambertian surface. However, no object in the real world is purely 'Lambertian'. Therefore, our proposed method takes advantage of crossed-polarization to suppress specular reflections to better obey the cosine illumination conditions imposed by the photometric stereo model. Using the SfS setup, we are thus achieving improved accuracy of the reconstructed normal map as will be discussed below in more detail.

B. In-Situ Measurement of Architectural Elements: Bahá'í Temple

To evaluate the Mobile SfS on different materials and its capability for imaging 'in the wild', we performed experiments on the wall of Bahá'í Temple located in Wilmette, Illinois. Nine images were taken at night, placing the camera about 30 cm from the wall as had been done in the last example.

Compared to RGB photo (Figure 7(a)), the surface information of the wall can be generated with our proposed method as shown in Figure 7(b). The surface information matches with the RGB photo, and the proposed method provides fine surface information about the wall structure. Another important observation is that the generated surface shape reveals more detail than the RGB image which lacks contrast and texture.

Since the normal map of the sample is generated, the object can be rendered as shown in Figure 7(c). All structure and fine details can be seen from the 3D rendering. This helps digitally document the priceless artwork and protect the samples.

C. Surface Shape Measurement of An Illuminated Manuscript Page

To assess the capability of the Mobile SfS to discern features no larger than a few hundred micrometers across, we performed a further experiment on a mid-to-late 15th-century French illuminated manuscript page. Nine images were extracted from a much larger array of images acquired by a macro web-camera rastered across the surface. The overall RGB image is shown in Figure 8(a). These shots were acquired at about 2-centimeter away from a page of the manuscript. The technique makes it possible to observe individual brush strokes and obtain in-depth information on how the manuscript was technically constructed as shown in Figure 8(b). We can also apply the 3D rendering to show the objects topography by separating color from surface shape, which allows us to determine the presence and extent of 19th-century restorations. Hence, using these techniques it may be possible to differentiate between the original illuminations and later restorations by correlating these topographic differences with the stylistic variations.

V. Discussion

Many historical artworks have specular surface such as those made of plaster, paper, and stone materials. The intensity of these specular reflections is often too strong to make accurate surface shape reconstructions of these materials. The reason for this is that in photometric stereo, the surface of the object is assumed to be characterized by a Lambertian model so that photons can be collect from different illumination angles and the intensity photons directed to the camera is only effected by the angle of the incoming illumination. It thus follows that under conditions where specular relfections dominate the photometric stereo will not produce an accurate assesment of the surface shape. In practice, reconstruction made using devices such as a light dome simply ignore specular reflections and assume that Lambertian relfections dominate the total light received by the camera. Clearly, this

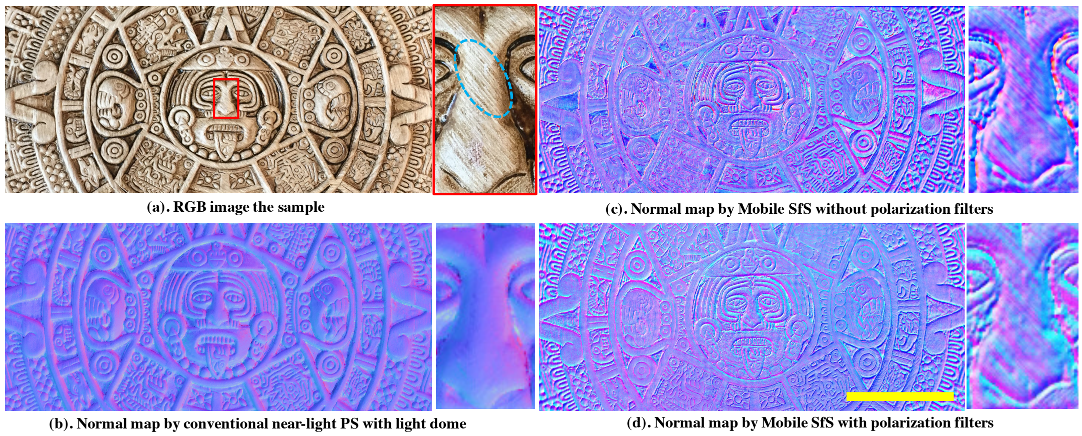


Fig. 6. **Surface normal for the plaster replica of an Aztec calendar stone:** (a). the photo of the imaged sample; (b). the surface normal generated with near-light PS using light dome; (c). the surface normal generated using mobile SfS but without polarizers; (d). the surface normal reconstructed with the proposed mobile SfS. Close-up images shows the ”nose” on the plate. Scale bar: 5 cm.

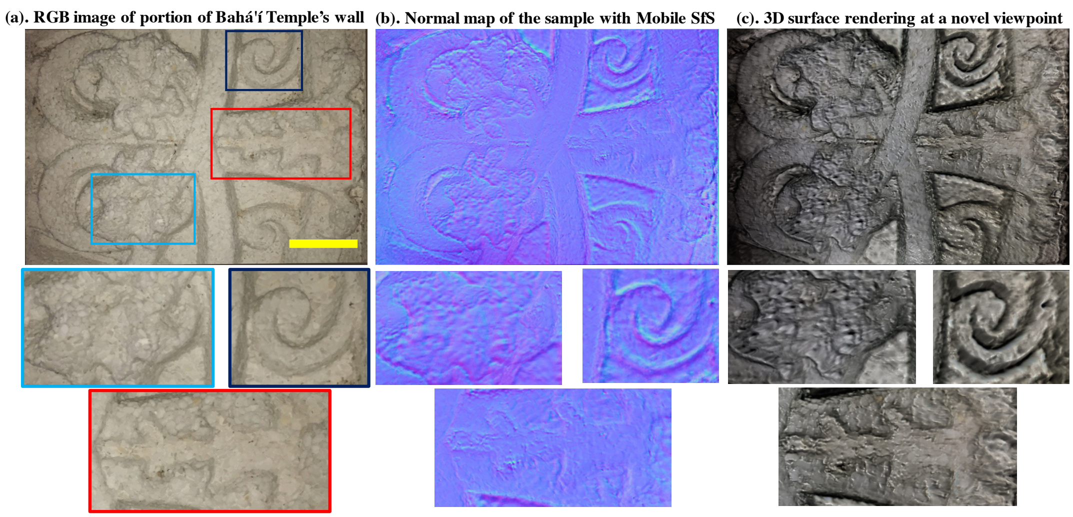


Fig. 7. **Surface normal for the architectural elements:** (a). photo of the region of Bahá’í Temple which is been scanned; (b). the surface normal generated with mobile SfS; (c). the rendering with surface normal generated with mobile SfS. Close-up shows the detailed feature on the stone. Scale bar: 10 cm.

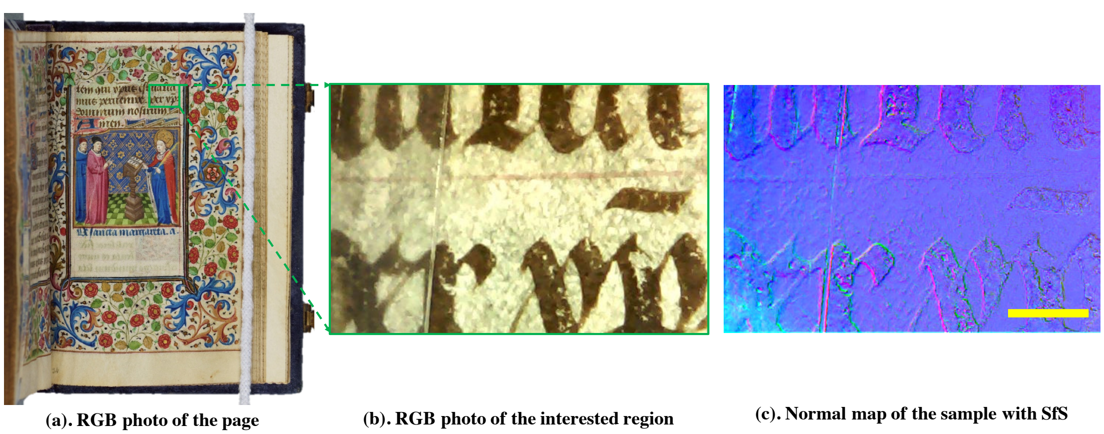


Fig. 8. **Surface normal for a page of the manuscript page:** (a). the RGB photo of portion of the page of the manuscript; (b). the surface normal reconstruction with mobile SfS for that region. Scale bar: 5 mm.

practice introduces error to the reconstruction. We show that it is possible to eliminate this source of error using the mobile SfS framework described here. In our set-up the specular reflections are removed by the crossed polarizers covering the light source and detector. From the visualization point of view, specular information is desirable since it contains high high-frequency information on the surface shape of the object. Based on this observation, we are currently designing a method to separate the diffuse and specular reflection, but record both of them to be used for accurate rendering of object surfaces.

We have evaluated the prototype mobile SfS on different materials as described above. Since artworks are made with different materials as well as stored and/or situated in different areas, it is very useful for the cultural heritage community to develop methods which can work under these varied conditions. We believe that our method affords conservators an accurate and precised surface shape evaluation method with simple and widely available tools– a smart phone device. We believe this methods will improve the efficiency of art conservators to document the condition of many works of art rapidly .

We also note that taking photos with flying drone has gained popularity and attention recently. It allows researchers to take photos of landscapes that were once difficult to reach, such as the top of the Bahá'í temple. However, these regions are critical for the conservation since conservators can not check frequently and ignore the problem due to the limited access. Since only a small piece of add-on component is needed in our proposed method, we can combine our small-size setup with the flying drone to provide a solution for the conservators to check the 3D surface of those regions. We believe this would benefit the community of architectural conservation who often need high-resolution data to assess a building's condition.

VI. Conclusion

In summary, we have proposed a portable and cost-effective surface-shape imaging technique with an off-the-shelf mobile device. Our proposed method is demonstrated to scan historical artworks with different materials and scales. Moreover, our Mobile SfS can be operated in the wild which greatly assists for the conservation of artworks in the wild. We believe our Mobile SfS can be a very useful tool for the community of historical artworks.

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