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Multispectral RTI analysis of heterogeneous artworks

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Abstract

We propose a novel multi-spectral reflectance transformation imaging (MS-RTI) framework for the acquisition and direct analysis of the reflectance behavior of heterogeneous artworks. Starting from free-form acquisitions, we compute per-pixel calibrated multi-spectral appearance profiles, which associate a reflectance value to each sampled light direction and frequency. Visualization, relighting, and feature extraction is performed directly on appearance profile data, applying scattered data interpolation based on Radial Basis Functions to estimate per-pixel reflectance from novel lighting directions. We demonstrate how the proposed solution can convey more insights on the object materials and geometric details compared to classical multi-light methods that rely on low-frequency analytical model fitting eventually mixed with a separate handling of high-frequency components, hence requiring constraining priors on material behavior. The flexibility of our approach is illustrated on two heterogeneous case studies, a painting and a dark shiny metallic sculpture, that showcase feature extraction, visualization, and analysis of high-frequency properties of artworks using multi-light, multi-spectral (Visible, UV and IR) acquisitions.

Categories and Subject Descriptors (according to ACM CCS): I.4.1 [Image processing and Computer Vision]: Digitization and Image Capture—Imaging Geometry I.3.3 [Computer Graphics]: Digitizing and Scanning— I.3.8 [Computer Graphics]: Applications—

1. Introduction

Multi-light image capture (MLIC), also known as Reflectance Transformation Imaging (RTI), is widely applied in the Cultural Heritage (CH) domain to analyze and document many types of artworks, such as paintings, bas reliefs or ancient books [KK13, DJB13, SBG11, EBB*11, MMSL06]. The technique consists in capturing photographs of an object with a fixed camera view and a moving light. Processed data can reveal to CH scholars relevant information about surface geometry and material appearance.

In the common practice, RTI data is analyzed and visualized by first fitting a matte model based on low-frequency reflectance functions, such as polynomial texture mapping (PTM) and hemispherical harmonics (HSH), and using it directly or augmented with specialized methods for additionally modeling high-frequency components (see Sec. 2).

Analyzing and relighting artworks using this approach has proven to offer a number of additional possibilities with respect to a single, even multi-spectral, photograph. In the most typical applications, images are relighted from directions selected to highlight specific details, and the fitting coefficients are displayed as gray-scale images inside a visualization tool to visually identify features [Mac15]. In the CH community, visualization operations are usually facilitated by the well-known and broadly used RTIViewer developed by [CHI17]. Furthermore, using the coefficients of the fit, normals can be reconstructed and, then, local image contrast can be amplified by multiplying the normals with a constant which triggers along an augmented surface gradient. Following this direction, many feature extraction techniques working on fitted coefficients or normal maps have been proposed to emphasize hidden details (see Sec. 2).

However, reliably fitting the matte model to measurements in the presence of non-Lambertian phenomena (e.g., shadows, anisotropic behaviors, gloss, specularity), and finding a reliable and repeatable separation between low- and high-frequency components is a very hard task. Recent evaluations [SWM*16], for instance, have proven how complicated BRDFs, spatially-varying materials, concave shapes, and other non-Lambertian behaviors still remain very challenging conditions even for the extraction of simple normal fields, leading to significantly distorted results. Especially in the case of specular materials, the models used not only flatten highlights, but also tend to incorrectly fit the matte part. This results in a large difference between relighted and original images as well as on failures in showing material differences and small relief details.

In this work, we propose a novel multi-spectral reflectance transformation imaging (MS-RTI) framework and demonstrate its flexibility in the analysis of heterogeneous artworks. In our approach, we compute per-pixel calibrated multi-spectral appearance profiles, which associate a reflectance value to each sampled light direction and frequency. Such calibrated information can be obtained from free-form acquisition using state-of-the-art autocalibration techniques capable to compute per-pixel lighting directions and intensities [CPM*16, GDR*15]. Visualization, relighting, and feature extraction are then performed directly on appearance profile data, applying scattered data interpolation based on Radial Basis Functions to estimate per-pixel reflectance from novel lighting directions. The generation of novel views, as well as the extraction of feature maps for enhancing object detail is performed directly on the interpolated high-frequency reflectance data, without relying on the model-dependent unreliable separation into low-frequency and high-frequency components (see Sec. 3).

We demonstrate the capabilities and flexibility of the proposed approach on two heterogeneous CH case studies, where the standard methods do not provide optimal results, i.e., a highly specular painting, whose surface exhibits materials with largely different reflectance properties, and a dark, metallic statue with a shiny BRDF (see Sec. 4). These artworks are captured with a 5-band multi-spectral signal (UV, three VIS, IR), in order to increase analysis sensitivity.

2. Related work

Multi-light multi-spectral acquisition, processing, and analysis are broad research subjects. A full review of these areas is out-of-scope for this paper. We concentrate here only on the most-related method to perform MS-RTI processing and analysis. For a wide coverage, we refer the reader to established surveys in surface reflectance capture [Sze10], multi-light computational frameworks [AG*15], digital modeling of material appearance [DRS10], and geometric analysis in cultural heritage [PPY*16].

Analytical model fitting. Since the emergence of RTI techniques [MGW01], which extended the classical Lambertian Photometric Stereo [Woo80] by proposing a flexible low-frequency representation supporting analysis and relighting, a lot of works have been presented to improve RTI-based surface representations by finding more flexible analytical models of measured reflectance. These models include discrete modal decomposition [PLGF*15], bi-polynomial functions [STMI14], spherical and hemispherical harmonics [MMC*08], and bivariate Bernstein polynomials [IA14]. The main issue is that they strongly rely on a low-frequency, matte constraints on the material behavior, so they are affected by all the non-diffuse effects (e.g., glossiness, highlights and shadows). For this reason, techniques have been presented for the separation and modeling of matte and high-frequency components. Zhang and Drew [ZD14] and Pintus et al. [PGG17], in particular, extract the diffuse signal by employing a Least Median of Squares fitting procedure to a modified 6-term polynomial model, and obtain the high-frequency component by analytically fitting RBFs to the difference between each original image and the image relighted with the low-frequency component. Nevertheless, recent benchmarks by Shi et al. [SWM*16] clearly indicate that, when the material behavior deviates from the defined analytical models, or the shape of the object is significantly concave, all state-of-the-art methods exhibit very large errors in the representation of both material and geometry.

Non-parametric approaches. Several works are moving toward more data-driven, non-parametric approaches to capture the surface reflectance properties [FKIS02, MBK, LBAD*06, SWRK11]. A series of methods are hybrid solution, where a large set of basis materials are sparsely combined to render a wider appearance space [WDR11, WWHL07]. Others avoid having an a-priori set of materials, and try to extract the bases directly from the sample being digitized [DWT*10]. Ruiters et al. [RSK12] adopt a direct on-the-fly interpolation of sparse and irregular samples by using a compact representation based on separable functions, while Zickler et al. [ZERB05] choose the same rationale but employing RBFs, and focusing of spatially-varying BRDF extraction. Our approach falls in this category of interpolation approaches. In contrast to previous work, we do not aim to recover material and geometry properties, but, rather to be able to perform visual enhancement and feature extraction on interpolated data.

Visualization and feature enhancement. The classical method to visualize RTI data is based on the relighting of images using the globally fitted reflectance functions, such as polynomial texture mapping (PTM) and hemispherical harmonics (HSH). This may help in revealing details not easily distinguishable from one single photo. The fitting parameters themselves are often used directly in visualization tools, presenting them as greyscale images for visual inspection [Mac15]. A common approach is to extract normals from coefficient in order to detect gradients or to enhance the visualization through Specular Enhancement or Unsharp masking [CHI17]. Other feature extraction methods proposed to find hidden details are related to edge detection based on PTM-derived normal maps [BCDG13] or on PTM coefficients using the Di Zenzo operator [Pan16]. These methods have proved very effective, but are not easy to apply to non-Lambertian artworks, given the difficulty in reliably extracting the parametric representation. Direct feature extraction based on image processing has thus been proposed in the MLIC literature. Raskar et al. [RTF*04] exploited multi-light images to extract depth edges with a simple heuristics and used the result to create non-photorealistic rendering methods. Fattal et al. [FAR07] used MLIC to generate enhanced images highlighting shape and surface detail. These last enhancement methods are not, however, usually applied in the classical RTI pipelines used in the CH domain, where the analysis is typically based on PTM/HSH based relighting with related enhancements.

3. RTI visualization: direct relighting, feature maps and appearance profiles

The analysis of RTI stacks through relighting of PTM or HSH fitting provides useful insights on the objects, but presents several limitations due to the fact that it relies on a quite rough approximation of the material reflectance functions. This results in a detail lost or even false detections of non-existing drawings, as shown in Figure 6. This motivated us to develop a novel framework to analyze the multi-light image stack.

Rather than just using the stack for PS/PTM/HSH coefficient estimation, and subsequently using a visualization tool, our idea is to allow for a direct analysis of the stack through the creation of relighted images and novel multi-light enhancements directly from the raw data, avoiding a-priori analytical models for fitting. This enables a better visualization of those material and shape details that are often missed by the classical, too simple approximation, and cannot be recovered by the standard RTI visualization tools.

3.1. RBF-based interpolation

The first visualization method we implemented is the estimation of a relighted image with an arbitrarily chosen directional illumination. This is obtained with a Radial Basis Function (RBF) interpolation [Buh03] in the (l_x, l_y) space of light direction.

This method has been chosen due to the fact that it is a classical solution for approximating sparse data. It is based on an interpolation function that is the sum of N radial functions, in this particular case Gaussians, centered in the sampled light directions and with standard deviation equal to R:

$$I(\vec{l}) = \sum_{i=1}^{N} \alpha_i e^{\frac{||\vec{l}-\vec{l}_i||^2}{R^2}} \tag{1}$$

In our implementation, light directions are first sorted according to distance from the query one, and then the closest five lights are used for the fitting. We use compact (Gaussian) basis functions, where the radius has been chosen reasonably according to the light sampling of our RTI acquisitions. The radius can be adapted to the acquisition sampling. In the experiments shown in this paper, the sampling covers the hemisphere with about 50 uniformly distributed light directions, as shown in Section 4, in order to have the chance of reasonably capturing the main specular properties of the material. With this choice, a value or the radius of 0.3 was considered a reasonable tradeoff between local information preserving and smoothing, as shown in Fig. 1. A possible improvement could consist in the adaptation of the interpolation to the local content in order to have a better behavior on highlights and shadows.

3.2. Appearance profile visualization

Given the RBF-based interpolation presented above, we can also visualize the entire local Appearance Profile (or Reflectance Map), i.e., the value of the interpolated intensity in (l_x, l_y) space. Given a pixel in the visualized image, we sample the light direction space in a regular grid, and we create the 2D image representing the interpolated Appearance Profile. We can also do it for a local region by averaging interpolated pixels for each light direction. By selecting two points or two regions on the image, it is thus possible to compare the reflectance fingerprints of the corresponding position, and to reveal the local properties of the surface (depending on local normals and material). This visualization can be used, for instance, to have an idea of spatially varying surface specularity, or to compare the behavior of neighbor surface regions with similar normals in order to appreciate their differences in material properties. Also in this case the value of R is critical for getting a reasonable map, as shown in the examples of Fig. 1. and can be chosen differently according to the density of the light sampling.

3.3. Enhancement of non-Lambertian behavior

Another key observation of our work is that important information on the shape and material variations across the object surface can be found by also analyzing the deviation between the RBF interpolated signal and the fitting using analytical models, e.g., Lambertian or PTM. Given a light direction (virtual or sampled), if this difference is higher than a variance around the local interpolated signal, we can consider those values as complex peculiar pixels (outliers). Those outliers come from different types of physical phenomena, such as geometric and material properties like casted shadows or inter-reflections, and it is difficult to separate the contributions of these effects from other shading signals. Visualizing those higher "non-Lambertian" appearance behavior without trying to use further reflectance modeling (such as in Drew et al. [DHOMH12]) do not increase framework complexity and do not force additional a-priori assumptions on material. Moreover, it provides valuable insights on the objects under study.

One simple way to estimate the deviation due to those outliers is simply to map the sum of the squared differences between the original intensity and the fitted Photometric Stereo or PTM values (Lambertian Outlier, LO map). We give the possibility to visualize this signal in our tool. However, LO map looses information about the distribution of light di-

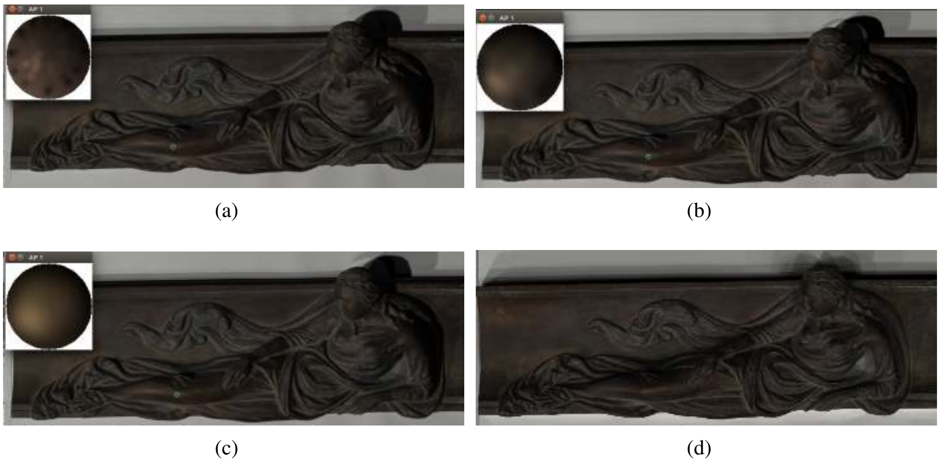


Figure 1: *(a),(b),(c) examples of RBF relighted images (with $l_x = 0.3, l_y = 0.45$) estimated with different values of R (0.1,0.3,0.6). Top left windows show the dense reflectance maps obtained with the corresponding values of R in the circled location. Small radii result in weighting mainly the closest image, large radii result in smoothed details and worst shadows definition. Small radii creates sparse reflectance maps, too large create oversmoothed maps. (d) PTM relighting from the same light direction. Here shadows and light direction related information tend to disappear.*

rections generating the non-matte reflections. Moreover, although it would be ideally possible to separate effects of casted shadows ("dark" outliers) from effects of specularities and inter-reflections ("bright" outliers), we have found that, due to the bad quality of PTM fitting, this distinction works poorly in the case of relevant number of outliers.

For all these reasons, we estimate another map, called Outlier Direction map (OD-map) by first fitting a Lambertian model (classical Photometric Stereo) over the data, possibly with trimming to avoid a strong outlier effect, and by counting then the number of light directions with values that deviates from the fitted value more than a threshold.

4. Results

The proposed investigation framework has been implemented in a dedicated software tool and tested to represent, visualize and analyze CH objects, namely two works of art with different characteristics and material appearance behaviors, i.e., a glossy painting surface and a dark, bronze statue.

4.1. Implementation

The processing and visualization tool has been implemented as a C++ application on a Linux platform exploiting Qt and OpenCV libraries. For the RBF-based interpolation we used the open-source ALGLIB library [BB]. All the results are produced on a PC with a Intel Core i7-4720HQ CPU 16GB RAM.

In the presented tests, the analysis starts from the output of the improved RTI acquisition and processing pipeline suggested by Ciortan et al. [CPM*16], which use multiple reflective spheres and planar light calibration targets in order to get a per pixel interpolated value of the light direction, a light intensity correction that accounts for light beam inhomogeneity and inaccurate pointing in manual acquisition, and a vignetting removal. The pre-processed stack is then stored in a raw file as a stream of multiple RGB or Luminance (LRGB) values for each pixel location. In the LRGB format, chromaticity is considered constant across the light direction and stored in a separate image.

Nevertheless, the proposed tool is general enough not to need all the preprocessing steps; in fact, it can work as well on non-corrected image stacks or collimated light directions. It will just convert any type of RTI stack to our custom input format, where data are structured so that all the information for a single pixel will be stored sequentially. Moreoever, processing or fitting can be done on the fly while loading the data, without the necessity of storing all the information in the in-core memory. It should be noted, in addition, that we can process 16 bit images (and in perspective directly floating point data coming out of elaborated HDR acquisitions), and the pipeline should thus be able to preserve good quality details even in shadows and hilights. However, a good analysis would require tone mapping to adequately present the results on LDR (or limited gamut) displays. This is beyond the scope of this paper and will be addressed as future work.

The developed RTI/Appearance Profile Array analysis tool, shown in Fig. 2, does not only allow for the creation of RBF-based interpolated images, but it is also designed to estimate and store photometric stereo or PTM fitting coefficients using full or trimmed set of pixel values. It is also possible to visualize other types of image derived from the original stack, such as median/average image, normals/albedo maps, and specific enhancements (e.g., outlier maps described below). Furthermore, it allows for the plot and the comparison of the full reflectance map sampled in specific points or ROIs.

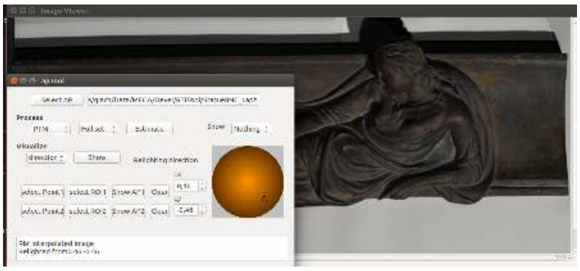


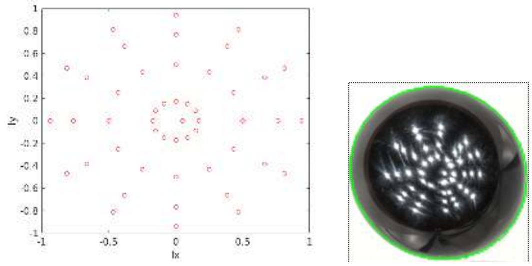
Figure 2: *User interface of the RTI/Appearance Profile Array analysis tool, which allows the user to select relighting direction and visualization/fitting options.*

4.2. Case studies

We have applied our method for the acquisition, visualization and analysis of a number of artworks. In this paper, we present the results obtained on two very different specimen (a painting and a shiny dark metal sculpture), which have been selected to cover very different test cases.

The first artwork analyzed is signed by Giovanni Fattori (Livorno 1825 - Firenze 1908), even though no authenticity test on authorship has been officially validated. It is a wooden substrate of small dimensions (10x15 cm) painted with oil colors and with a varnish layer applied. It belongs to the Macchiaioli art movement (the Italian precursor of the French Impressionism [FBVV10, BCC*03]), so that it is interesting to visually analyze not just the 2D shape of painted subjects but also the 2.5D/3D nature of the brush strokes, in order to better understand the artist technique, and to convey a more objective evidence of the making process. Oil and varnish make the painting surface a mix of diffuse and specular materials, which are a good testbed for the proposed investigation approach.

The second case study takes into consideration a bronze panel representing a female figure. It is a copy of one of the bronze panels of the Lorenzo Ghiberti's Paradise Door made for the Baptistery of Florence. The item was cast with a Cu90-Sn10 alloy, and an artificial patination was made on the surface, by using Iron (III) Chloride, to give the surface a brownish appearance. It has been also coated with a protective product and exposed outdoors in an urban environment, to test preservation strategies. Its dark and shiny surface is a very challenging surface for multi-light RTI data processing, and we will show how the presented approach is capable to deliver a better visualization of that material and its features.



(a) (b)

Figure 3: *(a) The protocol used for the 49 light direction sampling includes 4 zenith directions along 12 azimuth locations on a hemisphere. together with an additional light direction with high elevation. (b) Maximum of reflective sphere image showing the highlights created by the 49 light directions.*

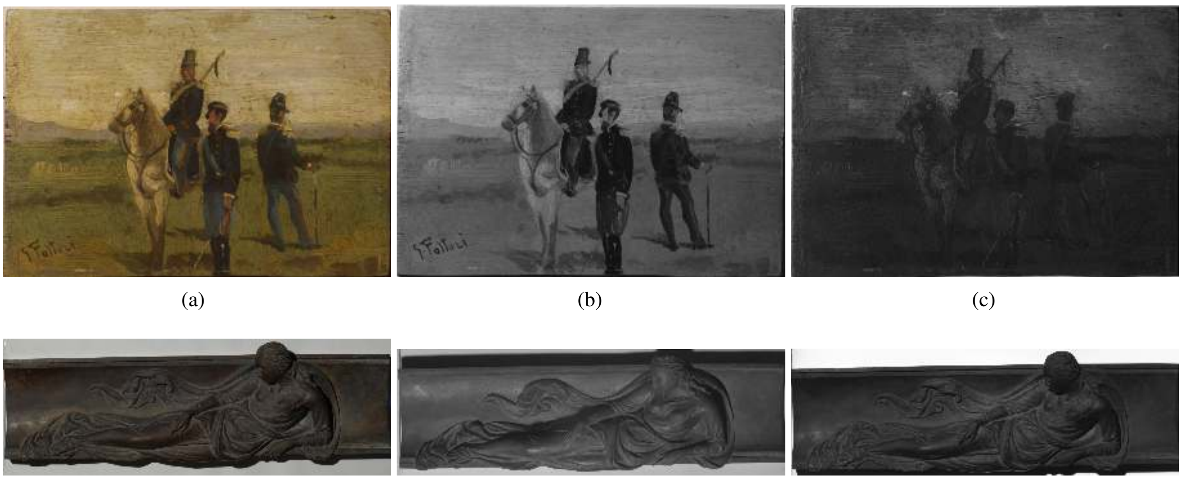
4.3. RTI stack acquisition setup

The artworks have been acquired with a hand-held light positioning protocol, using a custom Nikon D810 camera with removed IR-cut off filter and a NIKKOR 50mm lens. Three different light sources have been used to selectively emit signal in various parts of the electromagnetic spectrum: a white LED lamp for the visible signal, a halogen lamp together with a Hoya filter for selecting the NIR signal, and a 395 nm peaked UV LED lamp. Each light source has been freely positioned across a virtual hemisphere, sampling 4 zenith directions along 12 azimuth locations together with a central top direction, resulting in a total of 49 images per light source. Fig. 4 shows examples of acquired photos cropped in the region of interest. For each of those datasets, Fig. 4 shows one of the original images from the multi-light RTI stack acquired with the visible, near-infrared (NIR) and ultra-violet (UV) signal.

The 5 band analysis (near IR, RGB, near UV) is often used in practical acquisition campaign, since it is easy to perform with (approximately) off-the-shelf components, and it is known to be capable to reveal some interesting features of artworks. It is clear, however, that the low spectral sampling is a limitation of the case study analysis presented here, that could suggest the use of high definition spectral data as an obvious follow-up of this work. This would require also specific tools to handle spectral signal continuity and interpolation that should be carefully evaluated. This direction looks promising, since the RBF interpolation framework is easily scalable to a large number of bands.

4.4. Outcomes of the analysis

In Fig. 5 we relighted the painting from top $(lx = 0, ly = 0)$, and we show how the analytical PTM fitting and data-driven RBF interpolation give different outputs. Low-frequency fit-



(a) (b) (c)

(d) (e) (f)

Figure 4: ***Acquired images.*** *Top: Visible light, NIR and UV photos of the Fattori's painting. Bottom: Visible light, NIR and UV photos of the bronze statue.*

ting using PTM results in a signal that is quite similar to an albedo image, where all the information about depth cues caused by specular effects and micro-facets are completely lost. On the other hand, data-driven interpolation maintains the combination of diffuse and glossy signals and reproduces better the subtle details, giving a more reasonable relighting. This allows CH scholars to look and investigate micro details on the surface better than classical RTI approaches.

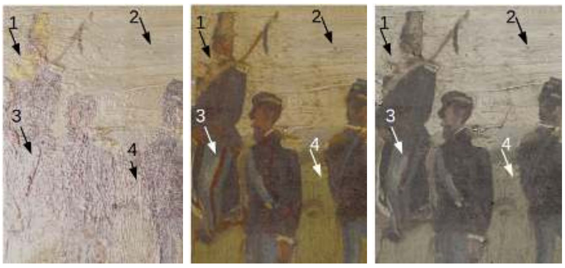
In [FBVV10], beside the wide range of pigments varying from traditional natural to novel synthetic ones, there was discovered that there were differences regarding the brush stroke technique that Fattori was adapting according to the paint media and subject. In particular, the artist was applying one or two overlapping strokes, without any priming when he was working on wood which complies with the fast execution required by on-site paintings. Fig. 6 shows how different techniques can contribute to this analysis, and how many details have been lost or misunderstood looking at the PTM fitted image. Arrow 1 indicates, in Fig. 6 (a), i.e., RBF-interpolation with light direction $(0,0)$, a location where it is possible to appreciate a peculiar material behavior not matched in other surface regions. This information is strongly lost in the PTM fitted image in the same location of (Fig. 6 (b)), due to the suppression of high-frequency components. Once the glossy effect has been cut away the specular enhancement cannot recover material differences as shown looking at Fig. 6 (c). Looking at the same images on the corresponding locations highlighted by arrows 2, it is possible to see that a bump in the surface clearly visible in (a), appears as a flat color spot in (b,c). Arrows 3 shows a location where a relevant depth edge from different paint layers is visible in (a), but not in (b,c). Finally, arrows 4 shows a region where both the PTM relighting and its specular enhancement (b,c) do not clearly show the texture of the brush stroke, that is, instead, visible in the RBF interpolated image (a).

Similar considerations can be done for the statue and for other types of analytical model fittings. Fig. 7 shows a detail demonstrating that the HSH-relighting looses the visibility of material differences across the surface, and that specular enhancements cannot compensate for the lost information. Moreover, the HSH-based 3D perception is strongly altered by the well-known inaccurate normal estimation in the case of non-Lambertian materials.

(a) (b)

Figure 5: *Relighted images of Fattori's painting from top* $(lx = 0, ly = 0)$ *using (a) RGB PTM. Image is quite similar to the simple albedo map and details related to differences in materials and micro-facets are lost. (b) RBF interpolation on RGB stack. User can get more information on relief and material differences.*

In order to visually analyze the material properties, the proposed tool is capable of plotting, for a selected point



(a) (b) (c)

Figure 6: *A detail of the painting relighted from top view* $(lx = 0, ly = 0)$ *using RBF interpolation (a), PTM fitting (b), PTM fitting viewed with specular enhancement (c). Arrows show regions where relevant information is lost in the PTM-based renderings.*

across the surface, the entire interpolated reflectance function. This will provide the user with a more local information about material behavior as a function of light direction (for a fixed view point). In our RTI visualization and analysis tool, whatever will be the signal displayed (e.g., median, average, relighted, enhanced, normals), the user can select points or regions to both compare their reflectance functions and infer interpretations on the artwork. For instance, in Fig. 8 two points that seem to be made of the same material, and might also share similar normals, actually present a clearly different specular behavior.

Beside the visible spectra, processing non-visible multi-light data can create clearer light independent maps of IR and UV albedo signals, and a better complementary information (Fig. 9). For instance, in the case of the painting, IR (Fig. 9(b)) exhibits a more contrasted signal due to the different absorbency of the pigments, while UV wavelength (Fig. 9(a)) highlights the regions with less varnish. As for visible light, however, both albedo and also PTM or HSH-fitted reflectance do not show all the information that can be seen on the original data. Looking at images relighted from top, it is possible to see that UV shows the relief pattern even better than visible light (Fig. 9(c)); further, in the IR images, the painted relief pattern almost disappears, but, conversely, this signal exhibits an enhanced perception of the wooden support's geometryt geometry, otherwise not distinguishable with other frequencies.

Another important tool to assist the work of CH scholars is the digital visual analysis of relighting signals that depict the spatially varying material behavior across the artwork surface. Here we prove that this task can be facilitated by the visualization of the proposed Lambertian Outliers and Outlier Direction maps estimated on the three different stacks. Fig. 10 shows how the appearance of the maps estimated on the visible or IR light images seems to provide useful information to discriminate some materials.

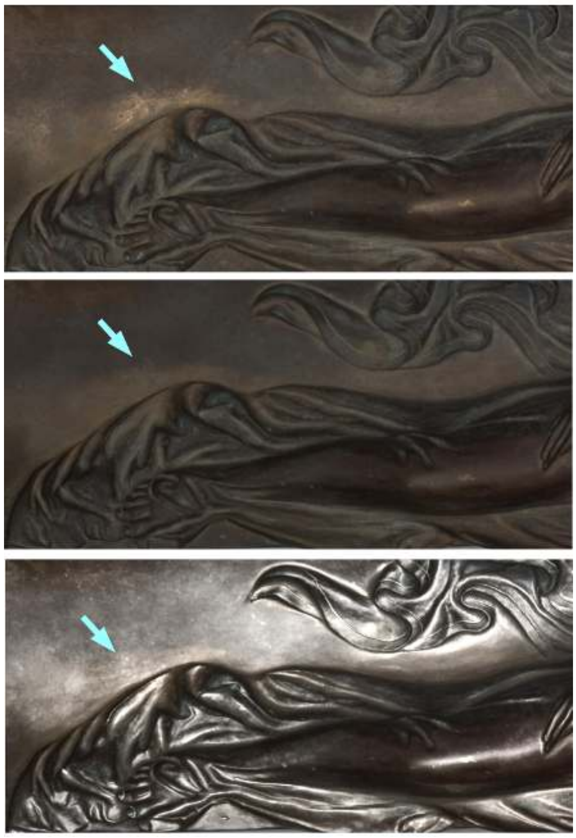
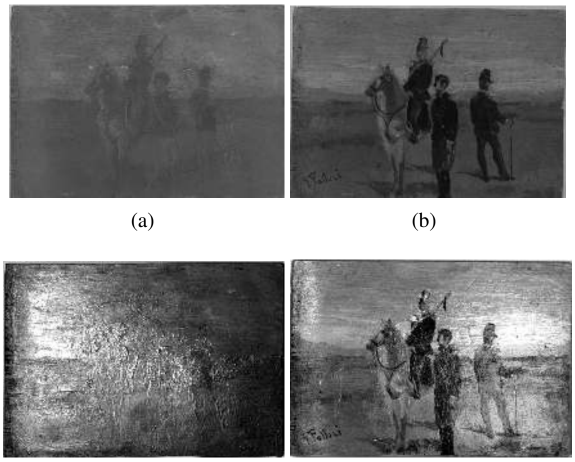


Figure 7: *A detail of the statue relighted from top view* $(lx = 0, ly = 0)$ *RBF interpolation (top), HSH interpolation (middle), and HSH with specular enhancement (bottom).*

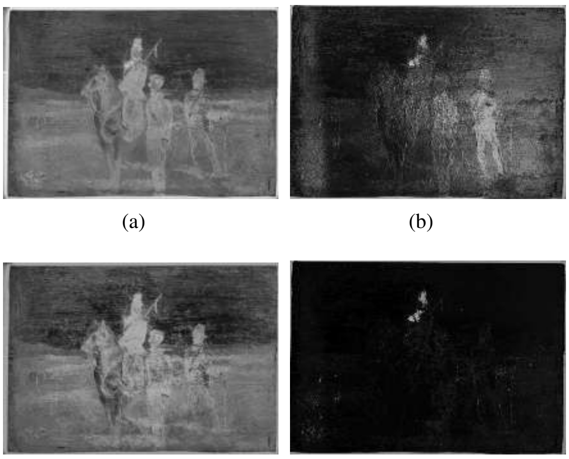
Figure 8: *The RTI analysis interface allows the display of a reflectance image related to single point or ROI, allowing an easy comparison of different material properties.*

In the task of analyzing paintings, it is clearly interesting to evaluate also brush patterns, that can be enhanced using the acquired RTI stack. This can be done on fitted PTM or HSH, for example using static Multi-Light enhancement [PCC*10] (Fig. 11 (a)) or trying to estimate edges with Di Zenzo gradient operator, as described in [Pan16]



(a) (b) (c) (d)

Figure 9: *(a,b) Albedos estimated from light-calibrated UV and IR stacks with trimmed Photometric Stereo. (c,d) UV and IR stacks relighted from top ($l_x = 0$, $l_y = 0$) using RBF interpolation. Specularities makes relieved structure clearly visible.*



(a) (b) (c) (d)

Figure 10: *Lambertian Outliers (a,b) and Outlier Directions (c,d) maps for the Visible and IR acquisitions. IR maps (b,d) seem useful to identify locations with particular pigments. Visible OD map (c) shows highlights as well brush strokes patterns.*

(Fig. 11 (b)). Due to the information loss, however, important edge lines are often missing. Normal visualization is probably the better option not using specular/shadow information. Fig. 11 (c) shows how the estimated and enhanced normal map is capable of discriminating line continuity. However, brush strokes are even more salient by looking at the OD map estimated on trimmed PS (Fig. 11 (d)). Here it is possible to see, simultaneously, strokes not visible with the other methods. In Fig. 12 we show the OD maps estimated on trimmed PS in the visible and IR signal for the statue. In this case, those visualizations convey more information on local differences in material behavior due to different level of patination or regions where Iron (III) Chloride is missing.

These simple examples show that it is possible to effectively use specularity and shadow information to improve the user understanding of both shape and reflectance features of the object. Clearly the proposed approach has several limitations, e.g. the RBF interpolation does not adapt locally to the reflectance map properties and therefore may present artifacts, for example due to shadow interpolation, the non-Lambertian enhancement does not distinguish highlights and shadows and is not based on measurement of physical properties of the surfaces. However it seems to show well which are the huge potentiality of a better characterization of visualization shape and reflectance measured in MLIC stacks. The proposed methods have been implemented in software tools supporting a complete MLIC pipeline and described in [GCD*17].

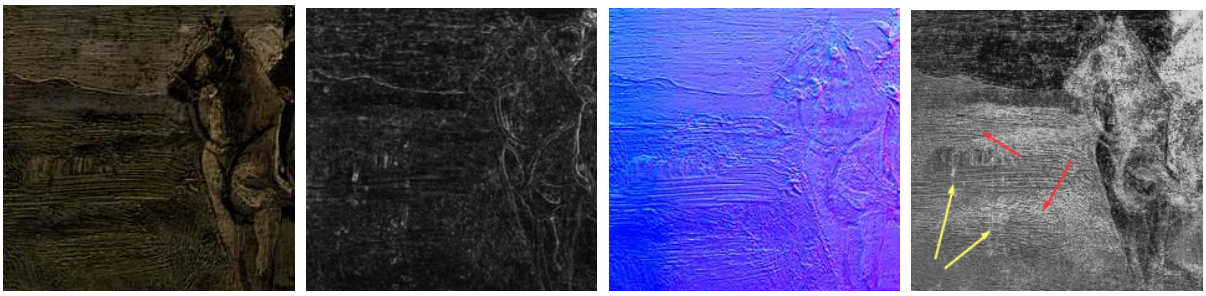
5. Conclusions

In this paper, we have proposed a practical approach for analyzing heterogeneous artworks. Departing from current approaches, just using the acquired images for PS/PTM/HSH estimation and subsequently using a visualization tool on the fitted representation, we allow for a direct analysis of the stack by enabling the creation of relighted images or novel multi-light enhancements directly from the raw data without fitting. This allows for a better visualization of material and shape details that are often removed by the drastic approximation and cannot be recovered by the standard RTI visualization tools. In comparison to hybrid methods that combine a low-frequency model with a high-frequency interpolation, our approach is more robust and repeatable, as it does not require the difficult extraction of separable models.

Furthermore, we estimate novel multi-light enhanced images based on the analysis of the global errors in model fitting or on the number of directions with non-matte reflectance behavior, allowing a better discrimination of material differences and depth edges, useful to analyze artworks' properties and allow the visual inspection of the full reflectance map at an image location.

We have tested the method in two very different scenarios, i.e., a shiny painting and a dark, glossy, bronze statue. We demonstrated how the proposed solution is capable of revealing or enhancing details such as brush strokes, amount of varnish, different materials, and we showed how it can assist scholars in investigating spatially variance of micro-geometry and material behavior across the artwork surface.

Our future work will first focus on improving our proof-



(a) (b) (c) (d)

Figure 11: *Image enhancements tested to show brush strokes features. (a) Static Multi-Light enhancement on PTM. (b) Di Zenzo Gradient map estimated on PTM coefficients. (c) Constast enhanced normal map. (d) Outlier Directions map. Red arrows show its ability to enhance relief patterns, while yellow ones show the detection of different material properties.*

Figure 12: *Top: OD map estimated on Visible RTI stack for the statue. Bottom: OD map estimated on IR RTI stack for the statue. While body contours are well shown due to the detection of shadow, in the region indicated with arrows, higher values show differences in local material reflectance due to different/missing patination.*

of-concept sequential implementation in order to speed-up computation of interpolated images, which is currently the bottleneck of our approach. Increased performance will be achieved by computing pixels in parallel, as well as by reducing computation by a careful data-reordering and trimming prior to RBF computation and evaluation. Moreover, we plan to employ more elaborate methods for interpolation, beyond pure RBF. Much of the work will be devoted, moreover, in extending the image-processing techniques to enhance and extract information from interpolated reflectance data.

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References

[AG*15] ACKERMANN J., GOESELE M., ET AL.: A survey of photometric stereo techniques. *Foundations and Trends® in Computer Graphics and Vision 9*, 3-4 (2015), 149–254. 2

[BB] BOCHKANOV S., BYSTRITSKY V.: Alglib. http://www.alglib.net/. 4

[BCC*03] BACCI M., CASINI A., CUCCI C., PICOLLO M., RADICATI B., VERVAT M.: Non-invasive spectroscopic measurements on the il ritratto della figliastra by giovanni fattori: identification of pigments and colourimetric analysis. *Journal of cultural heritage 4*, 4 (2003), 329–336. 5

[BCDG13] BROGNARA C., CORSINI M., DELLEPIANE M., GIACHETTI A.: Edge detection on polynomial texture maps. In *International Conference on Image Analysis and Processing* (2013), Springer, pp. 482–491. 2

[Buh03] BUHMANN M. D.: *Radial basis functions: theory and implementations*, vol. 12. Cambridge university press, 2003. 3

[CHI17] CHI: Cultural heritage imaging, 2017. URL: http://culturalheritageimaging.org. 1, 2

[CPM*16] CIORTAN I., PINTUS R., MARCHIORO G., DAFFARA C., GIACHETTI A., GOBBETTI E., ET AL.: A practical reflectance transformation imaging pipeline for surface characterization in cultural heritage. 2, 4

[DHOMH12] DREW M. S., HEL-OR Y., MALZBENDER T., HAJARI N.: Robust estimation of surface properties and interpolation of shadow/specularity components. *Image and Vision Computing 30*, 4 (2012), 317–331. 3

[DJB13] DUFFY S. M., JONES D., BACKHOUSE P.: *Multi-light imaging for heritage applications*. 2013. 1

[DRS10] DORSEY J., RUSHMEIER H., SILLION F.: *Digital modeling of material appearance*. Morgan Kaufmann, 2010. 2

[DWT*10] DONG Y., WANG J., TONG X., SNYDER J., LAN Y., BEN-EZRA M., GUO B.: Manifold bootstrapping for svbrdf capture. In *ACM Transactions on Graphics (TOG)* (2010), vol. 29, ACM, p. 98. 2

[EBB*11] EARL G., BASFORD P., BISCHOFF A., BOWMAN A., CROWTHER C., DAHL J., HODGSON M., MARTÍNEZ K., ISAKSEN L., PAGI H., ET AL.: Reflectance transformation imaging systems for ancient documentary artefacts. BCS. 1

[FAR07] FATTAL R., AGRAWALA M., RUSINKIEWICZ S.: Multiscale shape and detail enhancement from multi-light image collections. *ACM Trans. Graph. 26*, 3 (2007), 51. 3

[FBVV10] FAVARO M., BIANCHIN S., VIGATO P. A., VERVAT M.: The palette of the macchia italian artist giovanni fattori in the second half of the xixth century. *Journal of Cultural Heritage 11*, 3 (2010), 265–278. 5, 6

[FKIS02] FURUKAWA R., KAWASAKI H., IKEUCHI K., SAKAUCHI M.: Appearance based object modeling using texture database: Acquisition compression and rendering. In *Rendering Techniques* (2002), Citeseer, pp. 257–266. 2

[GCD*17] GIACHETTI A., CIORTAN I., DAFFARA C., MARCHIORO G., PINTUS R., GOBBETTI E.: A novel framework for highlight reflectance transformation imaging. *Computer Vision and Image Understanding* (2017). 8

[GDR*15] GIACHETTI A., DAFFARA C., REGHELIN C., GOBBETTI E., PINTUS R.: Light calibration and quality assessment methods for reflectance transformation imaging applied to artworks' analysis. In *SPIE Optical Metrology* (2015), International Society for Optics and Photonics, pp. 95270B–95270B. 2

[IA14] IKEHATA S., AIZAWA K.: Photometric stereo using constrained bivariate regression for general isotropic surfaces. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (2014), pp. 2179–2186. 2

[KK13] KOTOULA E., KYRANOUDI M.: Study of ancient greek and roman coins using reflectance transformation imaging. *E-Conservation Magazine 25* (2013), 74–88. 1

[LBAD*06] LAWRENCE J., BEN-ARTZI A., DECORO C., MATUSIK W., PFISTER H., RAMAMOORTHI R., RUSINKIEWICZ S.: Inverse shade trees for non-parametric material representation and editing. In *ACM Transactions on Graphics (TOG)* (2006), vol. 25, ACM, pp. 735–745. 2

[Mac15] MACDONALD L. W.: *Realistic visualisation of cultural heritage objects*. PhD thesis, UCL (University College London), 2015. 1, 2

[MBK] MÜLLER G., BENDELS G. H., KLEIN R.: Rapid synchronous acquisition of geometry and btf for cultural heritage artefacts. In *Proceedings of the International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage (VAST)*, pp. 13–20. 2

[MGW01] MALZBENDER T., GELB D., WOLTERS H.: Polynomial texture maps. In *Proceedings of the 28th annual conference on Computer graphics and interactive techniques* (2001), ACM, pp. 519–528. 2

[MMC*08] MUDGE M., MALZBENDER T., CHALMERS A., SCOPIGNO R., DAVIS J., WANG O., GUNAWARDANE P., ASHLEY M., DOERR M., PROENCA A., ET AL.: Image-based empirical information acquisition, scientific reliability, and long-term digital preservation for the natural sciences and cultural heritage. In *Eurographics (Tutorials)* (2008). 2

[MMSL06] MUDGE M., MALZBENDER T., SCHROER C., LUM M.: New reflection transformation imaging methods for rock art and multiple-viewpoint display. In *VAST* (2006), vol. 6, Citeseer, pp. 195–202. 1

[Pan16] PAN R.: Detection of edges from polynomial texture maps. *3D Research 7*, 1 (2016), 1–8. 2, 7

[PCC*10] PALMA G., CORSINI M., CIGNONI P., SCOPIGNO R., MUDGE M.: Dynamic shading enhancement for reflectance transformation imaging. *Journal on Computing and Cultural Heritage (JOCCH) 3*, 2 (2010), 6. 7

[PGG17] PINTUS R., GIACHETTI A., GOBBETTI E.: Guided robust matte-model fitting for accelerating multi-light reflectance processing techniques. In *Proc. British Machine Vision Conference* (September 2017). To appear. 2

[PLGF*15] PITARD G., LE GOÏC G., FAVRELIÈRE H., SAMPER S., DESAGE S.-F., PILLET M.: Discrete modal decomposition for surface appearance modelling and rendering. In *SPIE Optical Metrology* (2015), International Society for Optics and Photonics, pp. 952523–952523. 2

[PPY*16] PINTUS R., PAL K., YANG Y., WEYRICH T., GOBBETTI E., RUSHMEIER H.: A survey of geometric analysis in cultural heritage. In *Computer Graphics Forum* (2016), vol. 35, Wiley Online Library, pp. 4–31. 2

[RSK12] RUITERS R., SCHWARTZ C., KLEIN R.: Data driven surface reflectance from sparse and irregular samples. In *Computer Graphics Forum* (2012), vol. 31, Wiley Online Library, pp. 315–324. 2

[RTF*04] RASKAR R., TAN K.-H., FERIS R., YU J., TURK M.: Non-photorealistic camera: depth edge detection and stylized rendering using multi-flash imaging. In *ACM transactions on graphics (TOG)* (2004), vol. 23, ACM, pp. 679–688. 2

[SBG11] STANCO F., BATTIATO S., GALLO G.: *Digital imaging for cultural heritage preservation: Analysis, restoration, and reconstruction of ancient artworks*. CRC Press, 2011. 1

[STMI14] SHI B., TAN P., MATSUSHITA Y., IKEUCHI K.: Bi-polynomial modeling of low-frequency reflectances. *IEEE transactions on pattern analysis and machine intelligence 36*, 6 (2014), 1078–1091. 2

[SWM*16] SHI B., WU Z., MO Z., DUAN D., YEUNG S.-K., TAN P.: A benchmark dataset and evaluation for non-lambertian and uncalibrated photometric stereo. In *Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition* (2016), pp. 3707–3716. 1, 2

[SWRK11] SCHWARTZ C., WEINMANN M., RUITERS R., KLEIN R.: Integrated high-quality acquisition of geometry and appearance for cultural heritage. In *VAST* (2011), pp. 25–32. 2

[Sze10] SZELISKI R.: *Computer vision: algorithms and applications*. Springer Science & Business Media, 2010. 2

[WDR11] WU H., DORSEY J., RUSHMEIER H.: A sparse parametric mixture model for btf compression, editing and rendering. In *Computer Graphics Forum* (2011), vol. 30, Wiley Online Library, pp. 465–473. 2

[Woo80] WOODHAM R. J.: Photometric method for determining surface orientation from multiple images. *Optical engineering 19*, 1 (1980), 191139–191139. 2

[WWHL07] WEISTROFFER R. P., WALCOTT K. R., HUMPHREYS G., LAWRENCE J.: Efficient basis decomposition for scattered reflectance data. In *Proceedings of the 18th Eurographics conference on Rendering Techniques* (2007), Eurographics Association, pp. 207–218. 2

[ZD14] ZHANG M., DREW M. S.: Efficient robust image interpolation and surface properties using polynomial texture mapping. *EURASIP Journal on Image and Video Processing 2014*, 1 (2014), 1–19. 2

[ZERB05] ZICKLER T. E., ENRIQUE S., RAMAMOORTHI R., BELHUMEUR P. N.: Reflectance sharing: Image-based rendering from a sparse set of images. In *Rendering Techniques* (2005), pp. 253–264. 2