

# Revealing Pentimenti Through Raking Angle Photography

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## Abstract

*Discovering hidden details in historical paintings, such as pentimenti, can help reveal historical influences and changing intentions of an artist. Top-down photographs of visible light historical paintings do not capture much of the finer surface detail on the object being photographed. We present a technique using only visible light photography with a specially constructed octagonal reflector to aid the discovery of hidden details in historical paintings, by measuring Fresnel reflectance effects through raking angle photography. We exploit the significantly higher reflectance of dielectric surfaces at low angles to reveal hidden details that are otherwise not visible through ordinary photography. We also present a way to explore the details both statically and interactively.*

Categories and Subject Descriptors (according to ACM CCS): I.3.6 [Computer Graphics]: Methodology and Techniques

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## 1. Introduction

Since the Middle Ages, the art community has used the term *pentimenti* - Italian for “regrets” or “repentance” - to refer to the changes made by an artist by overpainting and later revealed when the top layer thins by wear, or by becoming transparent. Revealing pentimenti is important to art conservators, because it can reveal the artistic process, decisions and historical influences that culminate in historically important paintings [GT07]. To aid the discovery of such hidden details, art historians and conservation scientists utilize many techniques, such as infrared photography, ultraviolet photography and x-ray photography to reveal layers underneath the surface of the painting [BP05].

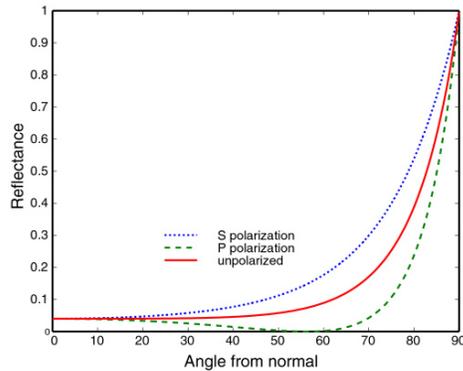
Our goal is to develop a technique that allows museum personnel to capture and explore the surface of a painting by *raking angle photography* - illuminating and capturing images at low angles to the object of interest simply and inexpensively. The technique should be expandable for use on paintings of any size and repeatable, so that each part of the painting can be illuminated and viewed from the same set of directions. We present techniques to explore this data set interactively, and demonstrate that low angle visible light reveals pentimenti and other hidden details to offer some assistance to the art conservation community.

## 2. Background

Specular reflection occurs when the angle of incidence and the angle of reflection relative to the normal of a surface point are the same. Therefore, surface variations on the painting will cause a corresponding variation in the presence of specular highlights, and may help capture surface variations caused by overpainted features or pentimenti. Surprisingly, color photographs taken with the camera perpendicular to the surface of the painting do not capture much of this surface information, because most are taken with broad, soft lighting and contain almost no shape-revealing surface highlights. Even low-angle *raking-light* is not enough; it reveals self-shadowing, but specular highlights are weak for most oil paintings because they are dominated by angle-dependent Fresnel reflectance. A dielectric with an index of reflection of 1.5 will only reflect about 4% of the incoming rays that strikes the surface perpendicularly, as shown in Figure 1 [Wes07].

On the other hand, dielectric materials exhibit strong reflectance at angles of incidence near grazing, meaning that at low angles of incidence ( $\theta_i \geq 60^\circ$  from normal), a dielectric surface will reflect almost all of the incoming light. By placing a camera at a low angle to the painting, we can capture most of the light reflected specularly by the painting, which is otherwise invisible.

Debevec *et al.* pioneered the concept of the “light stage”



**Figure 1:** *Fresnel reflectance for dielectric materials (e.g. oil paint) falls rapidly as viewing and lighting directions rise above raking angles. Seeing strong specular reflectances requires raking angle cameras and lights. [Wes07]*

[DHT\*00], in which subjects are photographed at the center of a spherical dome surrounded by many fixed light sources. However, creating large scale light stages is extremely expensive, and requires a lot of dedicated space, which might not be available in some smaller museums.

Malzbender *et al.*'s groundbreaking work, Polynomial Texture Maps, used a hemisphere-shaped apparatus with 50 light sources distributed evenly in the dome to capture specular highlights. By assuming a specular highlight indicates that the light source and the camera are at the same angle to the normal at a particular point on a surface, they estimated surface normals to create computationally relightable PTMs [MGW01].

Mohan *et al.* used the idea of a computer-steerable light source, coupled with a matte-white reflector to simulate a light source from any direction [MTB\*05]. Our device uses the same idea. Using a reflector allows the elimination of all but one of the light sources required to light an object from any direction, making such a setup more economical. The scheme also allows the illumination to be repeatable, allowing the calculations of 4D light fields using the collected data, and allows further data to be collected at a later date, ensuring the consistency of the data.

Our system does not depend on fixed lighting, but instead uses computer-controllable and adjustable light sources that can be repositioned freely. Our device, including host computer, costs less than \$5000. In addition, as our device uses an octagonal reflector to reflect light, so that the light arrive at the painting from a specific location, our rig can be scaled according to the size of the object photographed. Using a computer-steerable light source also means that we can capture images lit from an unlimited number of light positions. This allows the user to concentrate on illuminating a painting from directions that the user deems most important or interesting.

### 3. Method

How can we capture specular highlights visible only at low angles? As the surface of a painting is non-metallic, it exhibits Fresnel reflectance, meaning that if we place the camera and the light source close to perpendicular of the painting surface, we will only be able to capture a small portion of the reflected light from the surface. Therefore, we devise a means to place both the light source and the camera close to the painting plane.

#### 3.1. Building the Reflector

We constructed an octagonal reflector,  $80'' \times 80'' \times 60''$  in dimensions, instead of a hemispheric cylinder because it is easy to construct and calibrate. We built the main reflector using wood veneer with a glossy white plastic coating, treated with a matte finish clear paint so that they would act as Lambertian reflective surfaces.

The American DJ Pocket Scan is equipped with a mirror reflector to control the direction of the light spot. It can pan  $170^\circ$  and tilt  $110^\circ$  and includes 16 colors, 14 gobos and other features. Computer control of the light sources by the DMX512 protocol is easy using the SoundLight USB DMX controller.

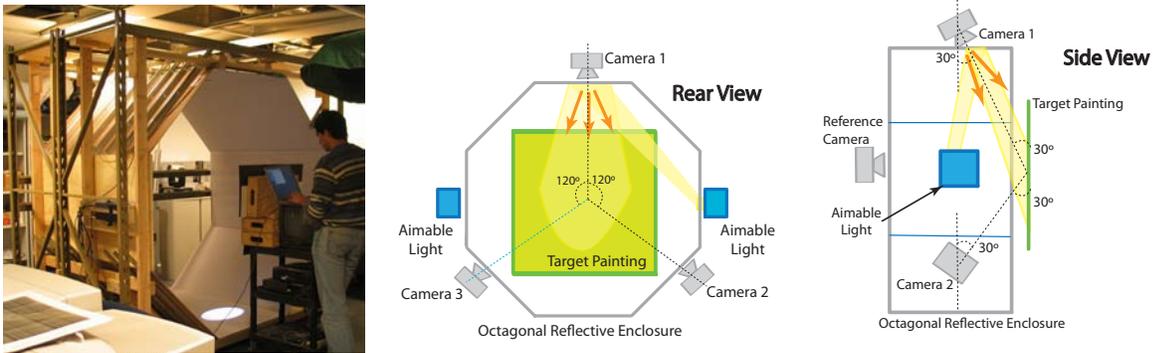
The Canon Powershot G6 cameras are capable of capturing high resolution, 7.1 megapixel images. We mounted three of them  $120^\circ$  apart from each other in a circle outside the rim of the octagonal reflector, so that surface information that may be occluded in one camera angle will be captured by one of the other raking angle cameras. These cameras view the painting from  $60^\circ$  away from the painting's overhead (normal) direction, as shown in Figure 2, enabling us to capture the specular light rays that reflect off the surface of the painting. We cut three holes in the reflector to let the cameras peek at the painting without occluding the reflector. We also mounted a single Canon Powershot G3 at the other end, lens aimed perpendicular to the painting plane, as the reference camera.

#### 3.2. Data Collection

We specified the starting and ending pan and tilt positions, and the number of light position intervals. The software moves the light spot to predetermined points on the reflector, and triggers each of the four cameras. We captured each area of the painting with 4 exposure times (2,4,8,16 seconds) to ensure we capture highlights and shadows without clipping. Obtaining the dataset in multiple exposures gives the additional benefit that these individual exposures can be combined into a single HDR data set.

#### 3.3. Data Processing

Due to the location of the raking angle cameras relative to the painting, the raw raking angle images suffer from



**Figure 2:** *Left:* Octagonal reflector - we place the large painting 3" from opening near standing man. *Middle, Right:* Two aimable lights illuminate at any desired spot. Three cameras view painting from low angles under reflected light illumination.

severe foreshortening, meaning directly comparing images captured from two different raking angle cameras is difficult without exact rectification, including correction for radial distortions from the lens. We used *Direct Linear Transform* [HZ00], or DLT, to calculate the homographies between the reference camera and the raking angle cameras using laser-generated correspondence points captured during the data collection phase. The resulting rectified images match the reference camera.

To help users interpret the raw data, which consists of images taken with over 200 low angle light positions, we used the *neighborhood averaging* algorithm to aggregate changes from every light position into a single composite image. For each raw image captured under the 200+ lighting positions, the algorithm calculates an image with averaged color channel values using the equation  $L_{(x,y)} = \frac{R_{(x,y)} + G_{(x,y)} + B_{(x,y)}}{3}$ , which produced results that can be distinguished adequately. We then convolve each resulting image with the  $5 \times 5$  box filter  $A$  with all weights 0.04. Next, we find the blurred image that has the highest pixel value for each location  $(x,y)$  in the image, and copy the RGB pixel from the corresponding source image to the output image. The result is an aggregate image that shows the combined specular highlights from all 200 lighting directions, and neatly summarizes large sets of individual photos, as shown in Figure 3. However, exploring these photos interactively also helps reveal pentimenti.

We created an interface to interactively explore changes in specular highlights using blink comparison [DHT\*00]. As long hard disk seek times meant that we were unable to load rectified full resolution images rapidly, we arranged our rectified dataset, depicting over 200 different light positions, into structures called pixel tunnels. To create a pixel tunnel, we take all pixels from location  $(x,y)$  from each rectified photo for each of the 200+ lighting directions. Grouping together  $200 \times 200$  pixels into one "brick slice" file allows us to retrieve them quickly for display as user browses the painting's dataset. The user can quickly "blink compare" a

part of the image between arbitrary lighting and viewing directions. We supply a light position selection circle similar to the one in the PTM viewer [MGW01]. This allows the user to explore the painting surface through the variations in those specular highlights, selecting cameras, lights and positions interactively.

#### 4. Results

Our results are visually impressive - while conventional high angle photography did not reveal much, if any, details of the painting surface, as shown in Figure 3, the raking angle photographs we captured and rectified showed faint outlines and surface variations that did not correspond with the features of the painting. With the help of the data we collected, the Art Institute of Chicago was able to find variations that may indicate the presence of pentimenti that was previously invisible. With blink comparison, these variations are made even more visible, though we had a lot of difficulty trying to combine the data collected by the three raking angle cameras into a single coherent dataset, as discussed below.

#### 5. Limitations and Future Work

Our technique has several advantages and limitations. As our interface loads an entire viewing area's worth of image data at once, while blink comparing light positions is in real time, navigating to different areas of the painting can take several seconds due to the long load time. While this does not impede the user's ability to spot hidden details through blink comparing light positions, the slow roaming to other parts of the painting makes free exploration more difficult. To solve this problem, we implemented a quick-loading previewing image that shows just one nominally lit view to explore. Ultimately, we want to be able to load only the portion of the image the user can see into memory, as implemented in VIPS [CM05].

Our technique currently does not let us estimate surface

normals well. Our attempts to adapt Malzbender's method for raking angle data were complicated by large surface normal changes and limited (raking) angle and lighting viewing. Camera lens radial distortions also prevented accurate merging of normal vector estimates from rectified raking angle images. To solve this problem, we can use Gray-coded projector patterns to find dense painting point correspondences between all cameras, rather than relying on simple homographies. Also, the Linear Light Source Reflectometry method proposed by Gardner *et al.* [GTHD03] may also be a viable technique for us to use to derive surface normals for PTM. We will evaluate these methods and find the most appropriate method for our project.

## 6. Conclusion

Our work shows that raking angle photographs and image processing, can reveal hidden details on the surface of the painting. Rectified datasets explored interactively through blink comparison also aids in exploring the painting, and allows comparison with other measurements such as X-ray, IR and UV images of the painting. Our system is relatively inexpensive, and can be built by any interested museum personnel using inexpensive materials, and provides a new technique to help in the search for elusive pentimenti.

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**Figure 3: Example Images: Top** Rectified, aggregated dataset of Picasso, 1913 “Man With Moustache...” [Pic15] shows over-painted region and rough inclusions (sand?) **Bottom** Overhead reference image shows these features are pentimenti.

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