Reflection Transformation Imaging on Larger Objects: an Alternative Method for Virtual Representations

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1. Introduction

The term *Reflection Transformation Imaging* has been originally used by Tom Malzbender of the HP Laboratories to describe an image-based method to acquire the reflectance properties of objects' surface. This technique, as other image-based relighting techniques, creates a "special" image of the object which encodes a reflectance function per-pixel. These images are called Polynomial Texture Maps (PTMs) (Malzbender et al. 2001). PTMs are generated starting from a set of photos of the object of interest taken under controlled illumination. Thanks to the reflectance functions encoded in the PTMs it is possible to generate new images of the object under different lighting conditions. Due to the easiness and effectiveness of this method PTMs have been used in several applications in the field of Cultural Heritage in recent years. One of the main motivation to use PTMs to represent artifacts is that this kind of visualization allows the user to change interactively the effects of the illumination on the object's surface, and hence the exploration of the object is performed in a new interesting way. In particular, the use of contrast enhancement mechanisms related to the PTM viewing technology (specular enhancement, diffuse gain) have proven to be very useful not only in term of documentation, but also in terms of analysis of the surface details hard to reveal under classical viewing systems. Another reason is that PTMs may be an interesting alternative to the other well-known 3D acquisition techniques, like 3D scanning, which are "expensive" in terms of equipment, acquisition time and post-processing. Moreover, visualization of detailed 3D models is problematic in online environment while PTMs can be a good representation to make data more accessible to the public. Finally, PTMs seem to be a better solution for the visualization of certain objects, like bas-relieves, where the information provided by re-illumination is more important than the one provided by geometry. Most of the existing work about PTMs acquisition regard small size objects. In this paper we present a new low-cost system for producing high quality PTMs of medium-large objects, from 60-70 cm of width by 50-60 cm of height up to 2m of width by 1m of height. During the description of our system we also underline some differences with respect to the classic 3D scanning pipeline. We also present an analysis of quality of the PTMs acquired by our system and a novel software to browse huge resolution PTMs.

After an overview of the application of PTMs in Cultural Heritage in Section 2, we analyze our method for PTMs acquisition in all its aspects in Section 3. In Section 4 we propose an analysis of quality of the PTMs obtained in comparison with 3D scanning, and a study on quality degradation relative to the number of shots used to calculate the reflectance function. This analysis is not limited to our system and it is a good starting point to optimize PTMs acquisition techniques. Some examples of Cultural Heritage objects acquired with our system are presented in Section 5. Conclusions and future work are outlined in Section 6.

2. PTMs and Cultural Heritage

The appearance of a surface could change significatively when lighting conditions change. Typically, global illumination rendering methods are used to render such appearance (Debevec et al. 2004) (Goesele 2004) . This kind of methods requires both the geometry and the properties of the material of the object and hence a lot of effort in the acquisition and modeling phase. Another way to reproduce global illumination rendering effects like sub-surface scattering, inter-reflections, shadowing and refractions that does not need the geometry of the model and an accurate reflectance estimation of the surface object are the so-called image-based relighting (IBRL) methods (Choudhury and Chandran 2006). These kind of methods start from a set of images to compute a new image with different lighting conditions. Polynomial Texture Maps are one of these methods. As stated in the Introduction PTMs are created starting from a set of photos under varying lighting conditions. For a static object and a fixed camera, per-pixel reflectance functions can easily be estimated. More specifically, the reflectance function is approximated by a biquadratic polynomial in the following way:

$$\begin{aligned} L(u,v,l_u,l_v) &= a_0(u,v)l_u^2 + a_1(u,v)l_v^2 + \\ &+ a_2(u,v)l_u l_v + a_3(u,v)l_u + \\ &+ a_4(u,v)l_v + a_5(u,v) \end{aligned} \quad (1)$$

where (l_u, l_v) is the direction of the incident light and (u,v) are the pixel coordinates. Hence, each pixel of a PTM is composed by the RGB values and the six coefficients of the reflectance function. In order to estimate the coefficients $(a_0, \ldots, a_5)$ the light positions have to be known.

Several Cultural Heritage projects have been using PTMs for the inspection of artifacts. One of the first work in this field was the representation of cuneiform epigraphy (Malzbender et al. 2000). The PTM viewer of HP Laboratories (Malzbender et al. 2001) was used to inspect clay cuneiform tablets under different (optimal) light conditions. Reflection transformation tools were used also in Paleontology, to provide noticeable improvement in imaging of low color contrast, high relief fossils (Hammer et al. 2002). The application of PTM technology on ancient stone tools revealed fine details of conchoidal knapping fractures, use scarring and stone grain (Mudge 2004). A joint work done by National Gallery and Tate Gallery of London showed that PTMs under specular enhancement provided additional information about the surface textures of oil paintings (Padfield et al. 2005). Cuneiform tablets were analyzed using both 2D (PTM) and 3D (structured light scanner) information. The PTMs were texture mapped on the model, and a special 3D viewer was created (Mudge 2004). Recently, the application of PTMs and scanning techniques on a large numismatic collection permitted the creation of a ”virtual exhibition” (Mudge et al. 2005). Moreover, the use of specular enhancement and diffuse gain produced an improvement in data discernment.

3. Acquisition and Visualization

Standard PTM acquisition devices work by positioning the object of interest inside a light dome of fixed size. In this way the photos under controlled illumination can be easily acquired in a completely automatic fashion. Instead, PTM acquisition for objects of medium to large size has several specific issues and the overall pipeline have to be re-designed. Since the size of our objects is too big to create a fixed dome, we deal with a “virtual” light dome as explained in the next sections. In particular, the acquisition process is subdivided in three steps. First of all we consider the physical acquisition planning. The size of the objects, and the fact that in most cases they cannot be moved from their place led us to the necessity to plan carefully the acquisition phase in order to make it faster. After the acquisition planning the effective acquisition is performed using a simple system described in the following. The third step consist of a post-processing of the acquired data in order to improve the estimation of the per-pixel reflectance function. These three steps are described in details in the following.

3.1 Acquisition planning

Selecting the correct lighting point is an important step in the PTM acquisition of large objects; given the size and position (in the majority of cases, on a wall) of an object, in general we do not have the possibility to use a physical dome to illuminate the object. Instead, we will have to manually place the light in different positions, forming a “virtual” illumination dome. The size of this illumination dome and its light distribution will depend on the size of the target object and on the number of light directions we want to use to sample the reflectance function of the object. To simplify the light placements we developed a software tool, called *PTM Planner*. With this tool it is possible to define the properties of the lighting dome, to visually check its correctness and to automatically generate the coordinates for the light placements. The tool usage is quite simple; the scene setup is generated as the user inputs the size of the object to be acquired, its height from the ground and the distance of the camera. Objects in the scene are scaled according to user specifications; camera is pointed towards the center of the object. Next step is the definition of the acquisition pattern. The array of light can be generated by choosing the light distance and two angles (vertical and horizontal step). The tool can automatically exclude the light positions that are near to the "wall" (there can be problems in positioning the light source in such position) and that are aligned with the camera axis (light will be shadowed by camera or will occlude the camera).

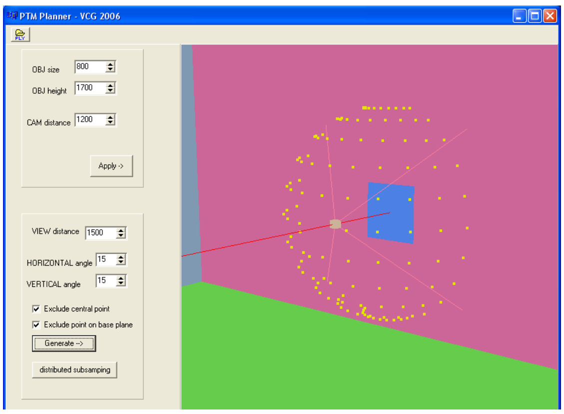
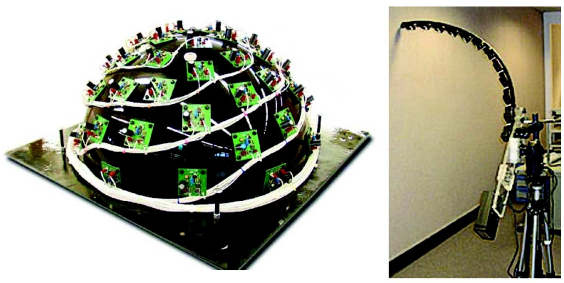


Fig. 1. PTM Planner tool.

The points are generated using a parallel-meridian grid as showed in Figure 1. This method does not guarantee a uniform distribution over the sphere but, as we will show describing the acquisition procedure (Section 3.2), having a series of light position at the same height will result in a much faster acquisition. The user can also manually *turn off* (by clicking on the 3D view) the light positions that will probably be impossible to be used due to occlusions. Finally, given a complete dome, the program can perform a light pruning following the *distributed scheme* described in Section 4. This scheme, by generating a more uniform distribution, greatly reduces the number of required light positions without influencing excessively the PTM quality. When the light setup has been completed, the PTM Planner tool can save a written description of all the points where the light should be positioned. This information are saved also in the format required by the transformation tool that creates the PTM starting from the input photos and light positions. Even though this tool is a quite simple software, it greatly helped us in speeding up the acquisition process both during planning, by giving visual feedback and instant parameters editing, and during acquisition, by providing step-by-step instructions on light placement.

3.2 Acquisition

Several experimental devices has been created to acquire PTMs. Two of them are shown in Figure 2.



(a) (b)

Fig. 2. (a) PTM acquisition dome; (b) PTM acquisition arc (Photos: HP Labs)

The object in Figure 2(a) is suitable for sampling small objects (nearly 15 cm). It is a 90 cm diameter black plastic hemisphere, with fifty evenly distributed strobe lights mounted such that they illuminate the hemispheric dome's interior. The digital camera is positioned at the top of the hemisphere and photographs the PTM subject through a view port cut in the dome. In Figure 2(b) a device designed for larger objects is shown. A 90 degree arc 1.50m in diameter is mounted with 12 strobe lights facing towards the center of the arc. One end of the arc is connected to a circular bearing race in the shape of a doughnut. This allows the arc to spin in a 360 degree circle around the bearing race.

These two experimental devices work very well but they are not suitable for our target. Various reasons support this statement:

- The diameter of the "hemisphere" formed by all the light positions depends on the size of the object, since for each photo the light must completely cover the target. For the object shown in the results Section, the minimum diameter for the "virtual" dome was 3 m.
- To completely illuminate a large size object we need powerful lights.
- In most cases, the target object cannot be moved from its place, so we have to deal with the fact that it is not always possible to exploit all the light positions, due for example to the height from the ground.

Fig. 3. Our acquisition setup.

We have designed the system following these remarks. Our solution is shown in Figure 3. Since it is not feasible to use a big number of lights, we decide to use only one, and to change its position for every photo of the set. The time needed to position the light is minimized thanks to the acquisition planning and by using some references placed on the floor. We make the acquisition faster using a printed scheme of the angle directions (it helps in placing the references on the floor very quickly), and a plumb line attached to the light in order to facilitate the positioning. Our acquisition equipment is composed of an 8MPixel Canon Digital Camera, a 1000W halogen floodlight, a tripod and a boom stand. The fact that we use only one light explains also the parallel-meridian placement of lights: with these configuration we need to set the height and direction of the light only once for each level of height. The acquisition can be summarized in this way:

- Take the measures of the object, find the center of it and its height from the ground.
- Using these data, generate the "virtual dome" and choose the positions of all the lights.
- Position the digital camera on the tripod. Measure aperture and shutter speed under the illumination of the central light. Keep these values fixed for all the photos, in order to have a constant exposure.
- With the help of the output of PTM planner, put the reference marks related to each light.
- For each level of height, set the height and the direction of the light, then put it on each reference mark related to the level, and take the photo.

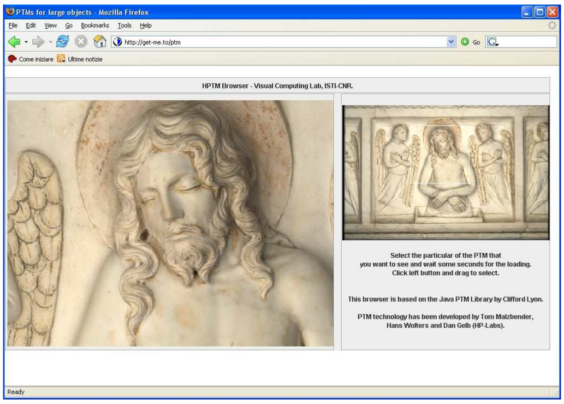


Fig. 4. A screenshot of the HPTM Browser in action.

Following this approach we are able to acquire several PTMs of an object in relative short time (see Section 5). Other big advantages of this equipment are that it is quite cheap (nearly 1000 Euros in total) and easily transportable.

3.3 Data processing

In order to calculate an accurate reflection function, a critical factor is that the digital camera must not move from one photo to the other. In fact, for our experience even a misalignment of a few pixel (corresponding to a millimetric misalignment) can produce visible aliasing. In our experimental acquisition set it is almost impossible to avoid small movements of the camera. This led to the necessity of aligning the set of photos before building the PTM. To account for this problem we align automatically the photos before the reflectance function estimation using a freeware tool for panoramic images. This is the only data processing we need, in fact there are no need of any image to image calibration, since all the photos have the same exposure. This step is very different with respect to the usual post-processing required by 3D scanning data. We can state that one of the main advantage of PTM technology comparing with 3D scanning is that PTMs require trivial post-processing. In fact in the 3D scanning the most time-consuming phase is the post-processing step, when the range images acquired have to be aligned and merged together in order to build the final 3D model. Additionally, after the alignment and merging phase also the complex task of color mapping using the photos have to be performed. After this post-processing the PTM is generated with the *PTMfitter* tool developed by the HP Laboratories and public available.

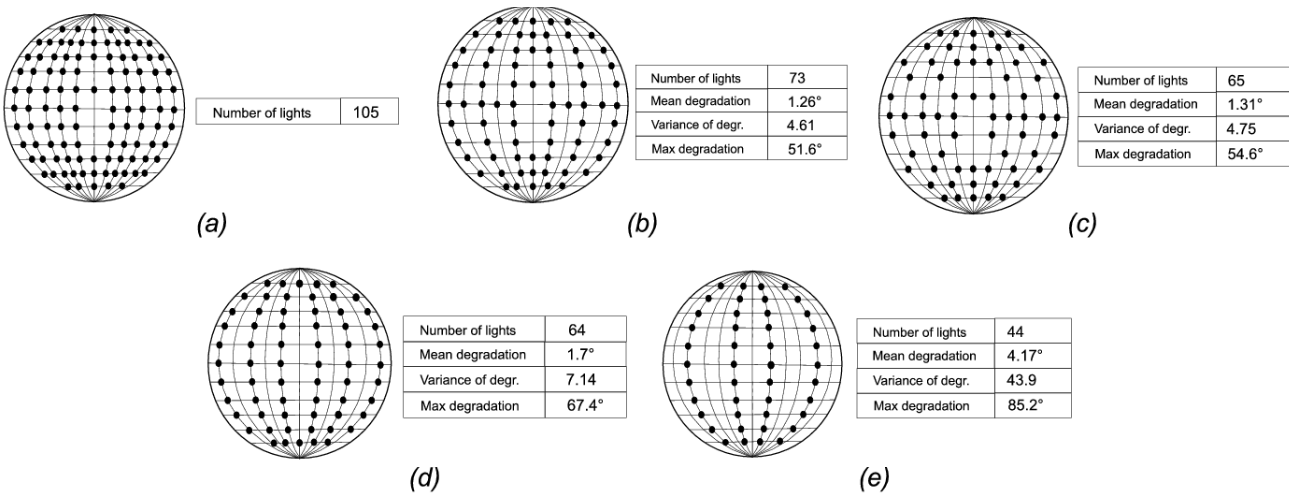
3.4 Visualization

The remote fruition of the virtual representation of the objects obtained is an important aspect, especially in Cultural Heritage applications. In fact, it is desirable that the virtual representation can be inspected by a large number of users through the Internet. For this purpose we developed a Java Applet capable to browse PTMs with huge resolution efficiently. We call this browser *HPTM Browser*. The PTM is first decomposed in a set of sub-ptms by another tool that works in conjunction with the browser. The browser retrieves efficiently such sub-ptms in a multi-resolution fashion in order to visualize quickly the huge PTM in the case of a zoom operation. Figure 4 shows a screenshot of the HPTM Browser. This software is now part of the *ptmviewer* Java open source project regarding PTM visualization originally created and developed by Clifford Lyon (`http://ptmviewer.dev.java.net`).

Fig. 5. Comparison between the normal maps of the 3D scanning and the PTM: full model and particular.

4. Quality assessment

In this section we discuss and analyze some issues regarding the quality evaluation of the acquired PTM. As a case study we consider a 70 by 80 cm section of the XIVth Century Tomb of Archbishop Giovanni Masotti. We performed a very accurate PTM acquisition, using a big number of lights (105 light positions, 11 angles and 11 height levels) and we acquired the same object also with a triangulation Scanner (Minolta 910i). We used the 3D scanned model as a reference for our quality evaluation. In fact, for larger objects 3D scanning is a very reliable technique, in terms of accuracy (Bernardini and Rushmeier 2002). The output 3D model is composed by nearly 2.4 millions of faces, the accuracy is about $\frac{1}{3}$ of millimeter. Our first comparison concerns the quality of the normals calculated from the PTM data. To do this, we aligned the 3D scan model to the PTM (Franken et al. 2005) and we calculated the normals of both the model and the PTM. In Figure 5 a comparison of the normal maps is shown. The variation of the normals in the PTM is smoother than in the corresponding 3D scan, but their values are coherent. This test demonstrates that, even though PTM provides an approximation of the objects' geometry, estimated by analyzing the per-pixel reflectance functions, the obtained data are reliable.



(a)

Number of lights	105

(b)

Number of lights	73
Mean degradation	1.26°
Variance of degr.	4.61
Max degradation	51.6°

(c)

Number of lights	65
Mean degradation	1.31°
Variance of degr.	4.75
Max degradation	54.6°

(d)

Number of lights	64
Mean degradation	1.7°
Variance of degr.	7.14
Max degradation	67.4°

(e)

Number of lights	44
Mean degradation	4.17°
Variance of degr.	43.9
Max degradation	85.2°

Fig. 6. Quality degradation: (a) Best quality PTM (b-e) Differences in dihedral angle of normals. The sphere shows the lights placement.

It also demonstrates that our setup does not introduce significative errors in the PTM acquisition. The second analysis is related to the degradation of the PTM quality with respect to the number and position of lights. For this purpose, we compute four PTMs starting from subsets of the original lights. Then we compare between the normal maps of the "best" PTM (the one with 105 lights) and the "subsampled" ones. This comparison was made calculating the difference in dihedral angle between the normals of each pixel. In Figure 6 we show the analysis of the difference between the best PTM and four possible subsets. In terms of number of lights, we can observe that we can considerably reduce the number of lights without having an excessive degradation of quality. In particular, concerning the lights placement, we can notice (Figure 6(c) and 6(d)) that a more "distributed" position of the lights brings to lower mean degradation and peak error. Considering these facts, we can conclude that a set of 60-70 properly distributed photos can be used to produce high-quality PTMs.

5. Experimental Results

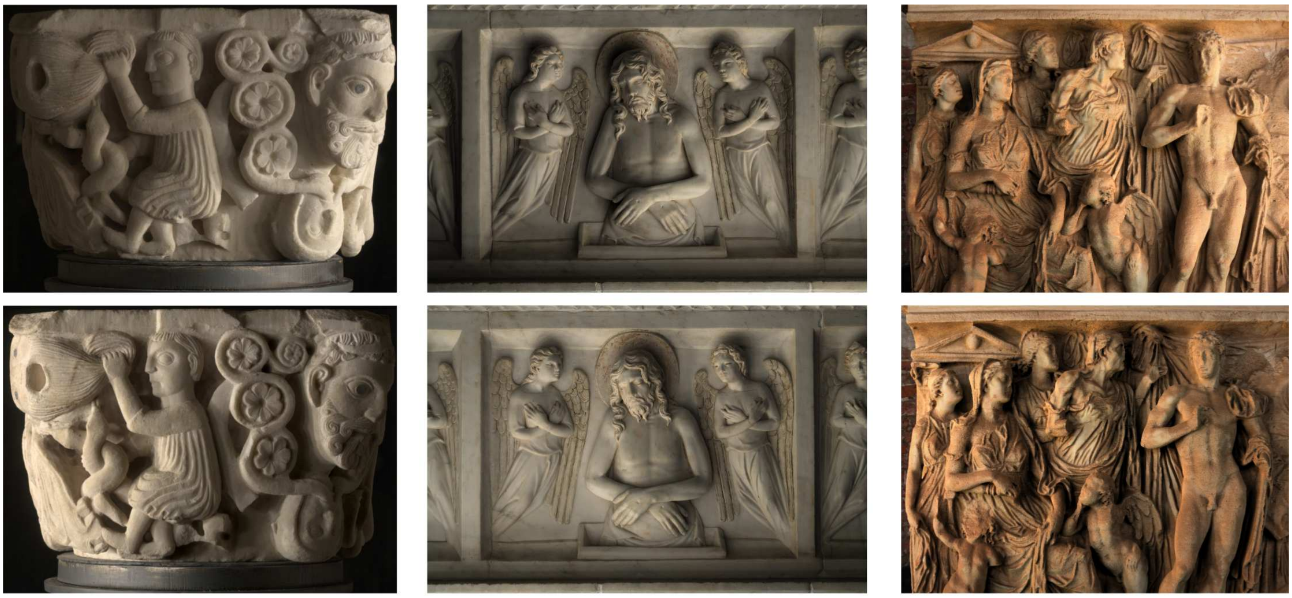
Several objects have been acquired with the developed system. In this Section we present three examples; all these PTMs are available for real-time exploration at `http://get-me.to/ptm`. The first example is one face of a small (30 $\times$ 30 $\times$ 20 cm.) Medieval Capital from the Museum of S. Matteo in Pisa. With the help of a professional photographer, we created a set of 36 high resolution (5440 $\times$ 4080) photos. In this case, we did not use the equipment described in Section 3.2, but a 20 MPixel Monorail View Camera and a professional flash light.

We produced a very detailed horizontal PTM of the Capital: some snapshot are shown in Figure 7(a). The acquisition time for this object was nearly 1 hour. The second example has been already shown in Section 5: it is a part (70 $\times$ 80 cm.) of the XIVth Century Tomb of the Archbishop Giovanni Scherlatti, by Nino Pisano (Museum of the Opera Primaziale in Pisa). We performed a very detailed acquisition (105 light positions, image resolution 3496 $\times$ 2280), which lasted about 3.5 hours. In this case we used the acquisition system described in Section 3. In Figure 7(b) we show a snapshot of the acquired PTM.

The third object is a II Century A.D. Roman Sarcophagus in Camposanto Monumentale of Pisa, representing the Phedra and Hyppolitus Myth. We chose this particular example since the Sarcophagus is situated outdoors. In this way we tested if the proposed system could produce good results even when the ambient light is considerable high with respect to the light equipment we used. In this acquisition we also used the considerations made in the quality assessment in order to perform the acquisition with a lower number of lights (and consequently a shorter acquisition time). The acquisition time was about 2.5 hours. The size of the portion is 90 $\times$ 60 cm (66 photos, resolution 3496 $\times$ 2280, see Fig. 7(c)). In this time we acquired also two horizontal PTMs (10 photos each) of the two halves of the Sarcophagus The obtained PTMs are more than satisfying, considering the non ideal condition of lighting.

6. Conclusions and Future Work

In this article we presented a new low-cost system to acquire Polynomial Texture Maps of large objects. Due to the impossibility to utilize the usual fixed acquisition dome, we have to rethink the usual PTM acquisition pipeline. The comparison and the differences with respect to the 3D scanning acquisition pipeline are also analyzed and described. In order to preserve the high detail and the interactivity of exploration, we developed new software to progressively browse PTMs. Finally, we presented novel studies about the quality assessment of polynomial texture maps. This studies could be very useful to design



(a) (b) (c)

Fig. 7. Acquired PTMs. The images are generated from different lighting conditions. (a) The Museum of San Matteo Capital. (b) Placed Christ from the Museum of Opera. (c) Roman Sarcophagus from Camposanto Monumentale.

more efficient acquisition scheme without compromising quality in the final result. The examples produced with our system gave satisfying results, showing that PTMs can be an alternative method for documenting and communicating Cultural Heritage information also for large size objects. In particular, PTMs can be a technology particularly suitable to analyze and represent bas-relieves and paintings.

Currently we are working in order to estimate the light direction starting from the photo set in order to eliminate the needed of manual positioning and making the system more automatic and accurate. Another desirable feature that is now missing is the possibility to remove the ambient lighting contribution, which lowers the quality of the results, especially for outdoors objects.

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