The 10th International Symposium on Virtual Reality, Archaeology and Cultural Heritage VAST (2009)
K. Debattista, C. Perlingieri, D. Pitzalis, and S. Spina (Editors)

Artifacts removal for color projection on 3D models using flash light

M. Dellepiane[1], M. Callieri[1], M. Corsini[1], P. Cignoni[1] and R. Scopigno[1]

[1]Visual Computing Lab, ISTI-CNR Pisa Italy

Abstract

Lighting artifacts are one of the main issues in digital photography: complex light setups are needed to attenuate or remove them. Flash light is a very easy way to illuminate an object or an environment, but it is rarely considered in most of the Computer Graphics and Computer Vision applications. This is due to the big amount of artifacts introduced by this lighting, and to the difficulty in modeling its behavior.

In this paper we present a simple method to use flash light in the context of color acquisition and mapping on 3D models. We propose a simple way to accurately estimate the flash position with respect to the camera, and we propose two automatic methods to detect and remove artifacts from a set of images which are registered to a 3D model. These methods are integrated in the context of a color mapping framework. The results show that it is possible to obtain high quality colored 3D models using flash light, which is the most simple illumination setup. This results are extremely important especially in the context of Cultural heritage, where the acquisition of color has often to be performed on site, without a specific lighting setup.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Color, shading, shadowing, and texture—

1. Introduction

3D scanning has become a widely used technology for the acquisition of highly accurate geometric data from real objects. The initial issues related to the management of the very dense sampling of geometric data have been mostly overcome in recent years, thanks to several new approaches to encode, process and render the sampled data. But shape acquisition is only one side of the problem. Many current applications require also an accurate sampling of surface reflection properties to perform a number of useful operations (high-quality rendering, relighting, color projection on copies [RWLB01]). Seminal works have proposed approaches to sample Bidirectional Radiance Distribution Functions (BRDF) [LKG*03, DHT*00] by means of sophisticated controlled lighting environments.

Unfortunately, there are applications where the objects of interest cannot be transferred to a reflection acquisition lab. Cultural Heritage is a fitting example: we need to sample many artifacts which usually cannot be moved from their location (e.g. museum); moreover, budget and sustainability considerations impose the use of low cost and easy to use procedures and technologies.

An alternative and easy solution to acquire a lot of information about the appearance of the target object is to use photographs. In a similar fashion to scanning campaign, an object can be entirely depicted in a very short time: moreover, due to the high resolution provided by digital cameras, a few tens of images can be enough to cover the whole surface of complex objects with a high sampling density.

However, the projection of a set of images on a 3D model presents several issues, like image registration and color projection and visualization. Additionally, the quality of the final colored 3D model is strongly related to the quality of the starting photo set. Most of the photographic artifacts (i.e. highlights and shadows) projected on the 3D model are generated by the specific illumination of the scene. These kind of artifacts can be removed by knowing exactly the lighting environment at the time of the shot. Unfortunately, it is usually quite hard to recover the position of the lights in the scene, without introducing specific techniques that uses probes [CCC08, Deb98]. On the other side, most of the con-

trolled light setup solutions are difficult to apply in the practical applications.
In this paper, we propose a method to automatically remove illumination artifacts from images by using a very simple controlled light setup: the camera flash light. In particular, a procedure to remove highlights and shadows is combined with a previous method which is able to correct the color values of the acquired images.
The main contributions of this work are:

- A simple procedure, needed only once in a camera lifetime, to estimate the flash position with respect to the camera lenses.
- An automatic method to remove highlights and shadows from images which are registered to a 3D model.
- The integration with the color correction space, which brings to a complete system to obtain high quality color models from a set of registered images.

2. Related Work

The work proposed in this paper is related to several topics in Computer Graphics and Computer Vision research: controlled light environments, light modeling, material properties acquisition, computational photography.
In the context of this Section, we will focus on two of the most relevant subjects: digital photography (with particular aim to illumination artifacts removal and use of flash light) and color information acquisition and mapping.
References to other related research fields (i.e. material properties or illumination estimation) can be found in the context of the other sections of the paper.

Artifacts removal and Flash/No-Flash use in Digital Photography. The removal of artifacts from images is an operation which can be valuable for several fields of application, hence it has been widely studied. There are a number of Highlights Removal techniques which have been proposed in the last few years. They can be roughly divided in two subgroups: the ones working on a single image [Wol89, TLQS03, OT06, SZSX08], which are mainly based on the analysis of the colors of the image, and the ones using a set of images [SI93, LYK*03], which take advantage of the redundancy of information between images. In general, these methods assume no prior information about the geometry of the scene.
More recently, the use of flash/no-flash pairs to enhance the appearance of photographs has been proposed in several interesting papers. The *continuous flash* [HT03] has been a seminal work, where flash and no-flash images are combined to create adjustable images. Two almost contemporaneous papers [ED04, PSA*04] proposed techniques to enhance details and reduce noise in ambient images, by using flash/no-flash pairs. These works, which mainly differ only in the treatment of flash shadows, provide features for detail transfer, color and noise correction, shadows and highlights removal. Results are very interesting, considering the lack of geometry information, but clearly the systems are not completely automatic. The goal of a more recent work [ARNL05] is to enhance flash photography: in addition to the techniques just mentioned, a flash imaging model is proposed, and a gradient projection scheme is used to reduce the visual effects of noise. Moreover, by taking several images at different exposures and flash intensities a HDR image is created and used to enhance the results. Flash/no-flash pairs are used by [LDF06] to detect and remove ambient shadows.

Mapping of color information on 3D models. The apparent color value, as sampled in digital photos, is mapped on the digital object surface by registering those photos w.r.t. the 3D model (computing the camera parameters) and then by applying inverse projection, transferring the color from the images to the 3D surface. Despite the simple approach, there are numerous difficulties in selecting the correct color to be applied (when multiple candidates are present among different images), dealing with discontinuities caused by color differences between photos that cover adjacent areas and reducing the illumination-related artifacts (shadows, highlights, peculiar BRDFs).

One of the main issues in the color mapping field is the color storage. However, in the framework of this paper we focus on the problems related to solving image discrepancies and to reduce illumination artifacts.

A first method to decide which color has to be applied to a particular area of the model is to select for each part of the surface an image following a particular criteria that, in most of cases [CCS02, BAF04, LHS00], is the orthogonality between the surface and the view direction. In this way, only the "best” parts of the images are chosen and processed. Artifacts caused by the discordance between overlapping images are then visible on the border between surface areas that receive color from different images. Between those adjacent images there is a common, redundant zone: this border can be used to obtain an adequate corrections in order to prevent sharp discontinuities. This approach was followed by [CCS02], who propagates the correction on the texture space, and by [BAF04], who used the redundancy to perform a matrix-based color correction on the original image. Other approaches, like the one proposed by [LHS00] do not work only on the frontier area, but blend on the 3d surface using the entire shared content to smooth out the discontinuities.

Instead of cutting and pasting parts of the original images, as the previous approach have done, it is possible to assign a weight to each input pixel (this value expresses the "quality" of its contribution), and to select the final color of the surface as the weighted mean of the input data, as in [PARD*98]. The weight is usually a combination of various quality metrics. This weight-blend strategy has been introduced, with many variants in terms of number and nature of assembled metrics, in various papers [BMR01, Bau02, RLE*05]. In particular, [CCCS08] presented a flexible weighting system, that could be extended in order to accommodate additional metrics.

Most of the analyzed methodologies present a common operation: the possibility to *discard* parts of the input images or to selectively *assign a weight* to contributing pixels. Since we will be able to precisely detect image artifacts produced by the flash, this detection would be a nice addition to the aforementioned methods, making them able to reduce the impact of such artifacts by eliminating or reducing the weight of unwanted parts.

3. Flash data collection

Flash light is generally a deprecated kind of illumination for non professional photographers for two main reasons: the production of undesirable artifacts and the variability of behavior between photos. These disadvantages can be partially solved using expensive type of flashes and more complex light settings.
Nevertheless, an extremely interesting aspect of the use of flash light is that the source of illumination is constrained to the camera, so that once the image is aligned to the corresponding 3D model, the position of the flash can be automatically found.
The main flash artifacts which must be corrected in order to obtain high quality color information are: uneven lighting, color deviation, highlights and sharp shadows. The aim is to be able to automatically correct them once that an image is registered to the 3D model.
In this Section, we will describe the operations needed to collect the basic calibration data which will be used to correct the artifacts. One of the main requirements is that these operations should be performed only once in a camera lifetime, in order to be able to perform corrections in a very easy way. In particular, the needed data are: a structure to correct the color values of the images, and a precise estimation of the flash light position with respect to the camera.

3.1. The color correction space

One of the most annoying artifacts produced by flash light is the uneven lighting between near and far objects. In order to be able to reconstruct the original color of the elements of the scene, we would need a mathematical model of the behavior of light. Unfortunately, due to the peculiar nature of flash light, this is very difficult to obtain it using simple models.
Hence, we will use the approach proposed by Dellepiane et al. [DCC*09], which builds a color correction space, called FLiSS, where a correction matrix is associated to each point in the camera space. Hence, once that an image is aligned to a 3D model, it is possible to associate a 3D position to each pixel in the image, and correct it appropriately.
The calculation of the correction space is made once in a camera lifetime, by taking several shots of a Mini MacBeth Color Checker using flash light. The shots are created to sample the camera space, and the correction matrices obtained from the shots are used to calculate the color correction space for any point in the view frustum (please refer to the cited paper for a detailed description of the method).
However, this correction alone cannot eliminate all the artifacts introduced by the flash illumination. In particular, it cannot detect and eliminate the errors that depend on the geometric characteristics of the flash light, like the hard shadows and the highlights. Since no information about the flash position is integrated in the correction space (to make it applicable to any kind of light which is bound to the camera) also the pixels which depict artifacts are considered part of the surface of the object, and corrected.

3.2. Flash position estimation

After having collected the data to correct the colors of the acquired images, we need to carefully estimate the relative position of the flash with respect to the optical sensor of the camera. These data will be critical to be able to eliminate the remaining artifacts introduced by flash light in an automatic way.
When working with built-in flash, the position has to be measured just once, making the process much simpler. Nevertheless, since the camera lens and the flash are very near, our estimation must be accurate to prevent errors in the calculation of reflections and shadows.

While the proximity of the flash and the sensor may suggest that direct physical measurement can produce good results, it is also true that the exact position of the CCD sensor is hidden inside the camera. Moreover, even using a caliper, measuring distances from the inside to the outside of the camera body can be tricky. For this reason we decided to perform an analytical estimation of the flash position. There are several approaches to estimate light positions based on either reflection or shadow tracing. We chose a very straightforward and easy-to-implement procedure, which uses one photo and a simple calibration device.

We built a calibration rig using LEGO blocks and modeled the same rig with a 3D modeler [leo]. We took some photos of the device using flash (one example is shown in Figure 1) in order to have shadows over the base plane. We registered the photos using the tool described in [FDG*05], so that the camera position in space can be computed with sufficient precision. Having the registered image and the 3D model, it was then possible to pick point couples that represented geometric features and their corresponding projected shadows. The picked point couples in 3D space generate a set of lines, whose intersection represents the geometric location of the flash center. The lines intersection point has been calculated as the closest point to all the lines in the set,

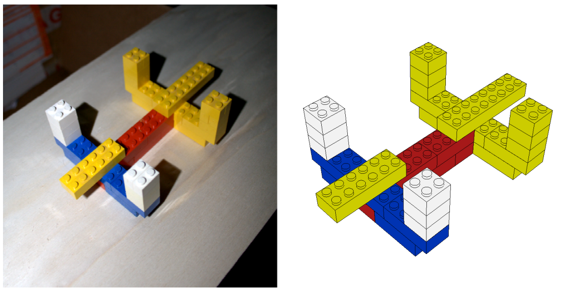

Figure 1: *Left: one of the images used for position estimation; Right, a rendering of the corresponding 3D modeled rig.*

Model	X shift	Y shift	Z shift
Casio Exilim Z50	-27 mm	31 mm	1 mm
Nikon D40x	0 mm	75.0 mm	37.0 mm
Canon EOS350D + Flash	0.6 mm	153.2 mm	17.5 mm

Table 1: *Results of the estimation of the flash position for the three selected camera models.*

using the method described in Appendix A. The relative positions of the flash for three cameras (shown in Figure 2), obtained with this method, are shown in Table 1; these locations are given in a coordinate space centered with the view point of each camera.

Figure 2: *Digital cameras used for light space sampling.*

The estimated positions proved to be accurate enough to be used for artifacts removal, as shown in Section 5. Direct measurement with a caliper, in the case where it was possible (Nikon SLR camera), gave very similar results, with a 1-2 mm divergence.

4. Artifacts removal

Once that the flash position and the color correction space have been reconstructed in the camera calibration phase, we can proceed by detecting and eliminating some of the macroscopic artifacts present in the flash images. As stated in the introduction, we start from the 3D model of the artifact and the set of flash photos which have been registered to the 3D model [FDG*05]. Provided that the estimation of the reconstructed flash position is correct, there are two artifacts we can recover: highlights and shadows. Moreover, color is corrected using the FLiSS approach.

4.1. Highlights detection

Highlights are present on the parts of the 3D surface where specular reflection can happen: specifically, where the ray from the light source would be reflected toward the camera viewpoint. Given the 3D model and the registered image, it is possible to find the highlight areas by using the same realtime technique used to display Phong specular highlights (the half vector technique). Unfortunately, geometric considerations alone are not enough to discriminate highlights in the images, due to local changes of the surface BRDF (that is unknown as well), minor discrepancies of the 3D model w.r.t. the real surface and other similar irregularities. For this reason, we prefer to use this geometric considerations just to select candidates for a possible highlight, and then we decide the actual highlight extent by performing a comparison with the corresponding regions of the other images.
The use of flash light also ensures that the areas of the object which are subject to highlights will be different from one image to the other. This is because the light ”follows" the camera in every shot. Hence, using the redundancy between different photos, it is possible to compare the luminance of the candidate point with the luminance of the corresponding area on other photos. The luminance value of the highlight candidate pixel is compared with the average luminance value of the corresponding pixels on the other images. If the difference in luminance is bigger than a fixed threshold, the pixel can be marked as an highlight. We used a two-level threshold: if the luminance value is between 150% and 180% of the average luminance, the pixel is on the border of the highlight; if it's bigger than 180%, the pixel is considered as completely saturated. This two-levels threshold also reflects the nature of the highlight in low dynamic range images: the border of the highlight (marked in our system with a blending ramp) presents a luminance shift that rises progressively towards the central area, which is composed entirely by over-saturated pixels (marked as completely useless and thus not used in subsequent weighted average computation of final mesh color).

An example of a highlights detection result is shown in Figure 3. The presented model is characterized by a very reflecting material. Most of the highlights are detected automatically (see upper row images). Lower row images present a detail view: given all the pixels mapping on mesh vertices which have been detected as geometric candidates for highlights (green pixels), only a subset is detected as real highlights, and marked as border (blue) or over-saturated (cyan). The green rectangles show two white zones which are small breaks on the real objects. The use of redundancy permits to the system to distinguish between highlights and white colored zones.

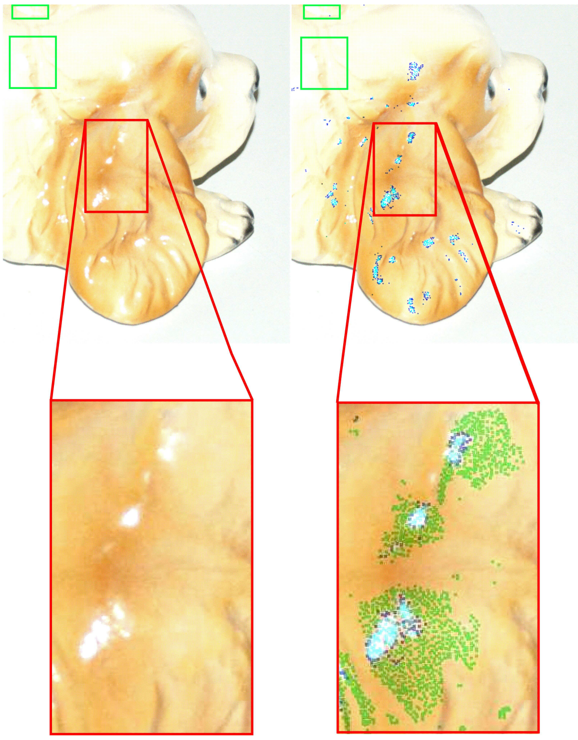

Figure 3: *An example of highlights detection. Upper row: an input flash image and the same image after detection of highlights (blue is the highlight border, cyan is the internal highlight region). Lower row: detail view of a group of highlights with corresponding geometric candidates (in green) and detected highlight pixels.*

4.2. Shadows detection

Since the flash light is very near to the camera lenses, the amount of shadows in the images is generally low. But due to the nature of this kind of light, the shadows are very marked and visible. Especially in the context of color projection applications, this results in visible artifacts.

Nevertheless, detecting the parts in the images that are in shadow is even simpler than detecting highlights. Using the camera associated to the specific flash image, it is possible to obtain a depth map for the image. Similarly, given the flash position offset, it is possible to generate the depth map for the light source; comparing the two depth maps, the parts of the flash image which are under shadow are detected. An example of the accurate results obtained for shadows detection is shown in Figure 4. The photo was taken using the Canon camera with external flash, which is positioned to a greater distance from the camera. The shadow position is detected with great accuracy at any distance from the viewpoint. The good results in shadow removal are also an indirect demonstration that the flash position was estimated in a sufficiently accurate way in the camera calibration phase.

Figure 4: *An example of shadows detection: left, the original image; right, the shadow detection map.*

5. Results

The methodologies for spatial color correction and artifact removal presented in the previous sections are quite general, and can be profitably used in different situations. To show the potentiality of this kind of processing, we show its impact in the framework of color mapping from photos. We followed the approach described in [CCCS08] where the color assigned to every vertex of the 3D model is a computed as weighted sum of the contributions of all the photos which project on that vertex. These weights are a kind of per-pixel masks that specify importance values that are automatically computed based on several metrics (e.g. distance from the sensor, camera orthogonality, focusness). The properties of these weights guarantee a smooth blending between photos, without loss of detail; however, the final results can suffer from the fact that the illumination is not known in advance. In particular, this mapping approach is fast, robust and easy to be implemented, but it cannot automatically deal with highlights, hard shadows and strong localized light (as the flash produces), as shown in the examples in Figure 5, where we have undesired lighting artifacts projected on the model. The purpose of the research described in this paper is to find a simple and versatile way to deal with those very artifacts.

We selected a test set of artifacts to assess the quality and the impact of the flash light approach. The test set is a group of objects of different heights (from 20 to 80 cm.), which are characterized by different colors and reflecting materials. We 3D scanned all the objects and acquired photos (from 13 to 32 photos for each object, depending on object size and complexity). The photos were taken turning off the lights in the room, thus having flash light as the principal light. The Nikon D40x was used for most of the test presented here, the other two cameras have also been used to test the accuracy and applicability of the method.

The color mapping approach [CCCS08] was easily extended

Figure 5: *Details of two colored models produced with [CCCS08] (no flash images), visualized without illumination and shading (only color values assigned to vertices): multiple highlights show up on the digital models (left); the presence of shadows and different illumination between photos generates a non completely continuous color (right).*

by applying the color correction space before the projection and adding another weighting mask that takes into account the result of artifact removal methods. In particular, the weight of pixels detected as shadows or saturated highlights were assigned to zero, while the pixels detected as borders of the highlights were assigned to a weight value progressively increasing, in order to provide a smooth mask transition.
While the color correction phase obtains good results as already shown in [DCC*09], some of the results of artifacts removal are shown in the next figures. Figure 6 shows two examples where the highlight removal produced considerable improvement in the final result. In the upper row, several spot-like highlights were removed (one of the images used for projection is the one shown in Figure 2). In the lower row, some more complex in shape highlights were completely removed from a 20 cm Nativity statue.

The effect of shadows removal in most cases appears more subtle with respect to the highlight processing, this because, after the blended mapping, the residual trace of shadows is just a darkening of areas that can often go unnoticed. However, when the hard shadow line is visible, the advantage of the removal process is significant, as shown in the example in Figure 7, which shows a detail of a model with and without shadows removal. It can be noted that the even very small shadows are detected, such as the shadows projected on the back of the leg and on the top of the foot (see framed regions in the image).

These results show that the estimation of the flash light position permits to automatically remove almost all the lighting artifacts from the 3D model. Obviously, like all the contexts where no information about the material is known in advance, some conditions could lead to unsatisfying results. This happens for example when there is not enough redundancy in the photo data set, or when the object material presents a peculiar BRDF behavior. One example of the latter is shown in Figure 8: the golden jug in the left-most image presents a metallic-flake paint with unusual reflectance. Both the standard 3D-mapped (center) and the flash-light enhanced (right) reconstructed color result in a not sufficiently realistic output when rendered. In this case, further inves-

Figure 6: *Details of two colored models, visualized with no illumination (only color values assigned to vertices): on left, the result without highlights removal, on right the model after applying highlights removal.*

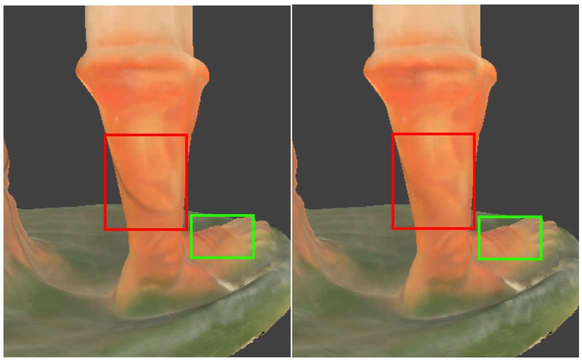

Figure 7: *Details of two colored models, visualized with no illumination (only color values assigned to vertices): on left, the result without shadows removal, on right the model with also shadows removal.*

tigation on the original data, or a user assisted intervention are needed to reconstruct the original color of the model. However, it must be stressed that materials with particular reflectance (e.g. gold patinas) often interfere also with active optical geometry acquisition, so they are rarely considered for 3D scanning using standard acquisition devices.

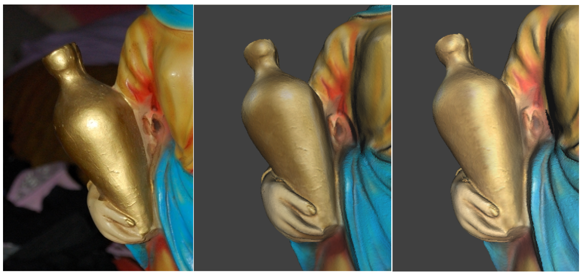

Figure 8: *Left: image of the detail of a Nativity statue (real photo). Center: rendering of the color reconstruction without flash artifacts removal. Right: rendering of the color reconstruction with artifacts removal*

6. Conclusions

We presented an automatic method to detect and remove artifacts in flash lighted images in the context of color projection on 3D models. An accurate estimation of the flash light position respect to the camera is obtained using a simple approach. Then, given a 3D model and a set of registered images, it is possible to automatically detect and remove the main lighting artifacts (highlights and shadows) from the images.

The use of this technique together with a color correction method brings to the creation of extremely realistic colored 3D models, where the peculiar artifacts introduced by flash light are corrected or removed in order to obtain a high quality color information.

Even though some information about the geometry of the scene is necessary, this method can be extended to other applications, like image enhancement. Current methods of 3D reconstruction from images (like the one proposed by [VG06]) can obtain a sufficiently accurate geometry of the scene, so that the use of our method in conjunction can easily lead to artifacts detection and removal.

Hence, flash can turn from a unreliable and not manageable light to a easy-to-use, reliable and fast way to acquire images even in the Cultural Heritage field.

Acknowledgements This work was partially funded by EU IST IP 3DCOFORM and Tuscany Regional Project STArT. We would like to thank Giuliano Kraft and Francesco Dellepiane for providing us the hardware for experimental studies.

Appendix A: How to find the closest point to N lines

With closest point to a given set of lines we intend the point having the minimum Euclidean distance with respect to those lines. Typically, this problem is formulated using Plücker coordinates. Instead, here we compute this point by solving the problem in a closed form, since the resulting matrices are not ill-conditioned in our case. More precisely, by indicating the set of n lines with

$$L = \left\{ l_i = \vec{O}_i + t\vec{d}_i | t \in \mathbb{R} \right\} \quad i = 1 \dots n \tag{1}$$

where O_i is the origin of the i-th line and d_i is the corresponding direction (normalized), we found the closest point by minimizing:

$$p = \arg\min_{\vec{x}} \sum_{i=1}^{n} d(\vec{x}, l_i) \tag{2}$$

The distance $d(\vec{x}, l_i)$ can be written as

$$d(\vec{x}, l_i)^2 = (\vec{x} - \vec{O}_i) \left[\mathbf{I} - \vec{d}_i \vec{d}_i^{\,T} \right] (\vec{x} - \vec{O}_i) \tag{3}$$

The minimization is obtained by substituting (3) in (2), and imposing the derivative to zero. After some simple algebra we obtain the final formulation:

$$p = \left[n\mathbf{I} - \sum_{i=1}^{n} \vec{d}_i \vec{d}_i^{\,T} \right]^{-1} \sum_{i=1}^{n} \left[\mathbf{I} - \vec{d}_i \vec{d}_i^{\,T} \right] O_i \tag{4}$$

References

[ARNL05] AGRAWAL A., RASKAR R., NAYAR S. K., LI Y.: Removing photography artifacts using gradient projection and flash-exposure sampling. *ACM Transactions on Graphics 24*, 3 (Aug. 2005), 828–835.

[BAF04] BANNAI N., AGATHOS A., FISHER R.: Fusing multiple color images for texturing models. In *3DPVT04* (2004), pp. 558–565.

[Bau02] BAUMBERG A.: Blending images for texturing 3d models. In *BMVC 2002* (2002), Canon Research Center Europe.

[BMR01] BERNARDINI F., MARTIN I., RUSHMEIER H.: High-quality texture reconstruction from multiple scans. *IEEE Transactions on Visualization and Computer Graphics 7*, 4 (2001), 318–332.

[CCC08] CORSINI M., CALLIERI M., CIGNONI P.: Stereo light probe. *Computer Graphics Forum 27*, 2 (2008), 291–300.

[CCCS08] CALLIERI M., CIGNONI P., CORSINI M., SCOPIGNO R.: Masked photo blending: mapping dense photographic dataset on high-resolution 3d models. *Computer & Graphics 32*, 4 (Aug 2008), 464–473. for the online version: http://dx.doi.org/10.1016/j.cag.2008.05.004.

[CCS02] CALLIERI M., CIGNONI P., SCOPIGNO R.: Reconstructing textured meshes from multiple range rgb maps. In *7th Int.l Fall Workshop on Vision, Modeling, and Visualization 2002* (Erlangen (D), Nov. 20 - 22 2002), IOS Press, pp. 419–426.

[DCC*09] DELLEPIANE M., CALLIERI M., CORSINI M., CIGNONI P., SCOPIGNO R.: Flash lighting space sampling. *Lecture Notes in Computer Science 5496* (may 2009), 217–229.

[Deb98] DEBEVEC P.: Rendering synthetic objects into real scenes: bridging traditional and image-based graphics with global illumination and high dynamic range photography. In *SIGGRAPH '98: Proceedings of the 25th annual conference on Computer graphics and interactive techniques* (New York, NY, USA, 1998), ACM Press, pp. 189–198.

[DHT*00] DEBEVEC P., HAWKINS T., TCHOU C., DUIKER H.-P., SAROKIN W., SAGAR M.: Acquiring the reflectance field of a human face. In *SIGGRAPH '00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques* (New York, NY, USA, 2000), ACM Press/Addison-Wesley Publishing Co., pp. 145–156.

[ED04] EISEMANN E., DURAND F.: Flash photography enhancement via intrinsic relighting. In *ACM Transactions on Graphics (Proceedings of Siggraph Conference)* (2004), vol. 23, ACM Press.

[FDG*05] FRANKEN T., DELLEPIANE M., GANOVELLI F., CIGNONI P., MONTANI C., SCOPIGNO R.: Minimizing user intervention in registering 2d images to 3d models. *The Visual Computer 21*, 8-10 (sep 2005), 619–628. Special Issues for Pacific Graphics 2005.

[HT03] HOPPE H., TOYAMA K.: *Continuous Flash*. Tech. Rep. MSR-TR-2003-63, Microsoft Research, 2003.

[LDF06] LU C., DREW M. S., FINLAYSON G. D.: Shadow removal via flash/noflash illumination. *Multimedia Signal Processing, 2006 IEEE 8th Workshop on* (Oct. 2006), 198–201.

[leo] BT Software. http://www.leocad.org/.

[LHS00] LENSCH H., HEIDRICH W., SEIDEL H.: Automated texture registration and stitching for real world models. In *Proc. 8th Pacific Graphics 2000 Conf. on Computer Graphics and Application* (Los Alamitos, CA, 2000), IEEE, pp. 317–327.

[LKG*03] LENSCH H. P. A., KAUTZ J., GOESELE M., HEIDRICH W., SEIDEL H.-P.: Image-based reconstruction of spatial appearance and geometric detail. *ACM Trans. Graph. 22*, 2 (2003), 234–257.

[LYK*03] LIN S., YUANZHEN S. L., KANG S. B., TONG X., YEUNG SHUM H.: Diffuse-specular separation and depth recovery from image sequences. In *In Proceedings of European Conference on Computer Vision (ECCV* (2003), pp. 210–224.

[OT06] ORTIZ F., TORRES F.: Automatic detection and elimination of specular reflectance in color images by means of ms diagram and vector connected filters. *Systems, Man, and Cybernetics, Part C: Applications and Reviews, IEEE Transactions on 36*, 5 (Sept. 2006), 681–687.

[PARD*98] PULLI K., ABI-RACHED H., DUCHAMP T., SHAPIRO L., STUETZLE W.: Acquisition and visualization of colored 3d objects. In *Proceedings of ICPR 98* (1998), pp. 11,15.

[PSA*04] PETSCHNIGG G., SZELISKI R., AGRAWALA M., COHEN M., HOPPE H., TOYAMA K.: Digital photography with flash and no-flash image pairs. *ACM Trans. Graph. 23*, 3 (2004), 664–672.

[RLE*05] RANKOV V., LOCKE R., EDENS R., BARBER P., VOJNOVIC B.: An algorithm for image stitching and blending. In *Proceedings of SPIE. Three-Dimensional and Multidimensional Microscopy: Image Acquisition and Processing XII* (March 2005), vol. 5701, pp. 190–199.

[RWLB01] RASKAR R., WELCH G., LOW K., BANDYOPADHYAY B.: Shader lamps: Animating real objects with image-based illumination. In *Rendering Techniques 2001, The Eurographics Workshop on Rendering* (2001), Springer-Verlag, pp. 89–102.

[SI93] SATO Y., IKEUCHI K.: Temporal-color space analysis of reflection. In *Computer Vision and Pattern Recognition* (Jun 1993), pp. 570–576.

[SZSX08] SHEN H.-L., ZHANG H.-G., SHAO S.-J., XIN J. H.: Chromaticity-based separation of reflection components in a single image. *Pattern Recogn. 41*, 8 (2008), 2461–2469.

[TLQS03] TAN P., LIN S., QUAN L., SHUM H.-Y.: Highlight removal by illumination-constrained inpainting. In *ICCV '03: Proceedings of the Ninth IEEE International Conference on Computer Vision* (Washington, DC, USA, 2003), IEEE Computer Society, p. 164.

[VG06] VERGAUWEN M., GOOL L. V.: Web-based 3d reconstruction service. *Mach. Vision Appl. 17*, 6 (2006), 411–426.

[Wol89] WOLFF L.: Using polarization to separate reflection components. In *Computer Vision and Pattern Recognition, 1989* (Jun 1989), pp. 363–369.