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Removal of Dust Artifacts in Focal Stack Image Sequences

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Abstract

We propose a technique for removing the appearance of sensor dust in a focal stack image sequence captured with multiple focus settings. Our method is based on the key observation that sensor dust artifacts shift in image position with respect to focus setting, which allows scene information occluded by dust in one image to be inferred from other images in the focal stack. To deal with complications arising from differences in local defocus blur among the images, we analyze the relative blur among corresponding image regions in detecting and removing dust artifacts. Our results show improvements over the state-of-art technique for automatic removal of sensor dust.

1. Introduction

Dust on a camera's sensor is a common and bothersome problem in digital photography. As seen in Fig. 2(b), dust particles can block or attenuate light that enters the camera, leading to unwanted dark spots in an image. The artifacts caused by sensor dust not only degrade the quality of photographs, but also can mislead computer vision algorithms by distorting local image features and measurements of scene radiance.

In this paper, we address the problem of sensor dust in the context of focal stack image sequences, in which a set of photos is taken of a scene at different focus settings. Focal stack imaging provides various benefits for artistic and scientific photography, such as in expanding the depth of field, increasing light throughput, and reducing diffraction blur [4]. Such imaging is of particular importance when using lenses with a long focal length or when capturing close subjects, as the depth of field becomes shallow in these cases.

Some previous works have addressed visibility problems caused by occluders in the optical path, but mostly deal with occluders that lie beyond the lens rather than on the sensor. In [8], Willson et al. modeled the appearance of dust affixed to a protective lens cover, but did not present a method for detecting and removing them from images. McCloskey et al. [5] examined large occlusions nearby the lens and proposed a user-assisted technique based on geometric flow for removing their effects. The method of Gu et al. [2] is similar to ours in that it takes a set of images captured with different focus settings as input. Their approach, however, is inapplicable to sensor dust since it requires occluders to be far enough away from the sensor such that changes in focus setting lead to differences in light attenuation.

The most closely related work to ours is the method of Zhou and Lin [9] for removing sensor dust in a single input image. Their technique jointly utilizes partial light transmission through dust particles and texture repetitions in the scene to remove dust artifacts. Though applicable to our scenario, their approach is not well suited to focal stacks for two main reasons. The first is that in many instances where focal stacks are needed (e.g., long focal length lenses) there is little or no light transmission through dust particles, as exemplified in Fig. 2(b). Secondly, their technique is not designed to take advantage of the additional images in a focal stack.

To effectively remove dust in such image sequences, we make a key observation about focal stacks – that sensor dust artifacts shift in image position with changes in focus setting. We give a physical explanation for this behavior in Section 2. Because of these shifts, it is possible to gain information from other focal stack images about scene areas occluded by sensor dust, and use them for dust removal[1]. However, taking advantage of this observation is not straightforward, since differences in local defocus blur among the focal stack images complicate both dust detection and removal. We address this issue through an analysis of relative blur among corresponding areas in the focal stack images.

[1]We note that dust that lies on the lens is typically not visible in images, as explained in [9].

Our results validate the proposed technique for dust removal in focal stacks, and demonstrate improvements over [9] in this scenario. Because of its effectiveness, our method is currently being employed by the Dunhuang Academy in China for high-quality photography of cave drawings and carvings located in the Gobi desert, where sensor dust is a particularly serious issue.

2. Focal Stack Images

In focal stack imaging, a sequence of images is acquired from a stationary camera at a sampled set of focus settings, defined as the distance of the lens from the sensor plane. As illustrated in Fig. 1(a), when the lens moves farther away from the sensor plane, the in-focus plane at which scene objects come into perfect focus moves closer to the camera. This property is modeled by the thin lens equation [3]:

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{F} \tag{1}$$

where u is the distance between the lens and sensor plane, v is the distance between the in-focus plane and lens, and F is the focal length of the lens.

Another result of the thin lens equation is that changes in the focus setting, u, lead to changes in defocus blur for a given scene point. Shown in Fig. 1(b), at a certain focus setting the light from a scene point may be focused onto a point on the sensor plane. But as the lens moves away from this position, the light will be focused at points increasingly farther away from the sensor plane. The projection of this light onto the sensor plane consequently grows larger, resulting in greater defocus blur of the scene point. It can be geometrically derived that the radius of the blur is

$$b = \frac{Du}{4} \left| \frac{1}{F} - \frac{1}{u} - \frac{1}{d} \right|. \tag{2}$$

where D is the lens diameter and d is the depth of the scene point. We note that for different focus settings there generally will be slight magnification variations of the recorded scene due to non-telecentricity, as well as minor brightness variations due to differences in the sensor plane area over which light is distributed [6].

Changes in the focus setting additionally cause shifts of sensor dust in images. This effect is illustrated in Fig. 1(c) and Fig. 2(b). Typically, there exists a lowpass filter directly in front of the sensor to prevent Móire patterns from appearing in photographs. As a result, sensor dust does not lie directly on the sensor, but rather it lies on the filter and is slightly displaced from the sensor [9]. As the distance between the lens and sensor is changed, the angle of light focused by

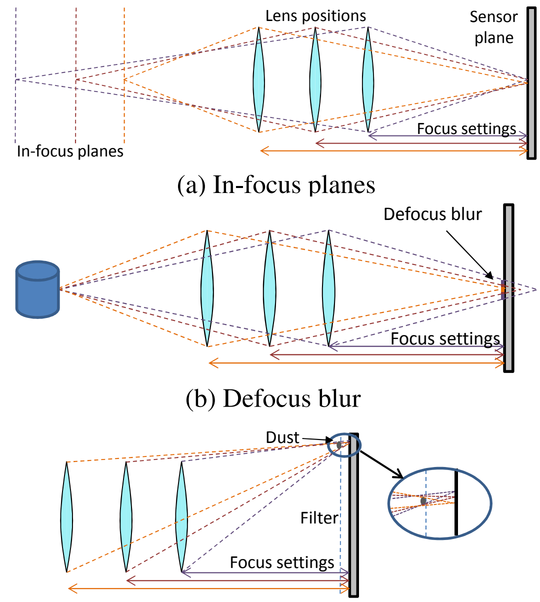


Figure 1. Effects of focus settings.

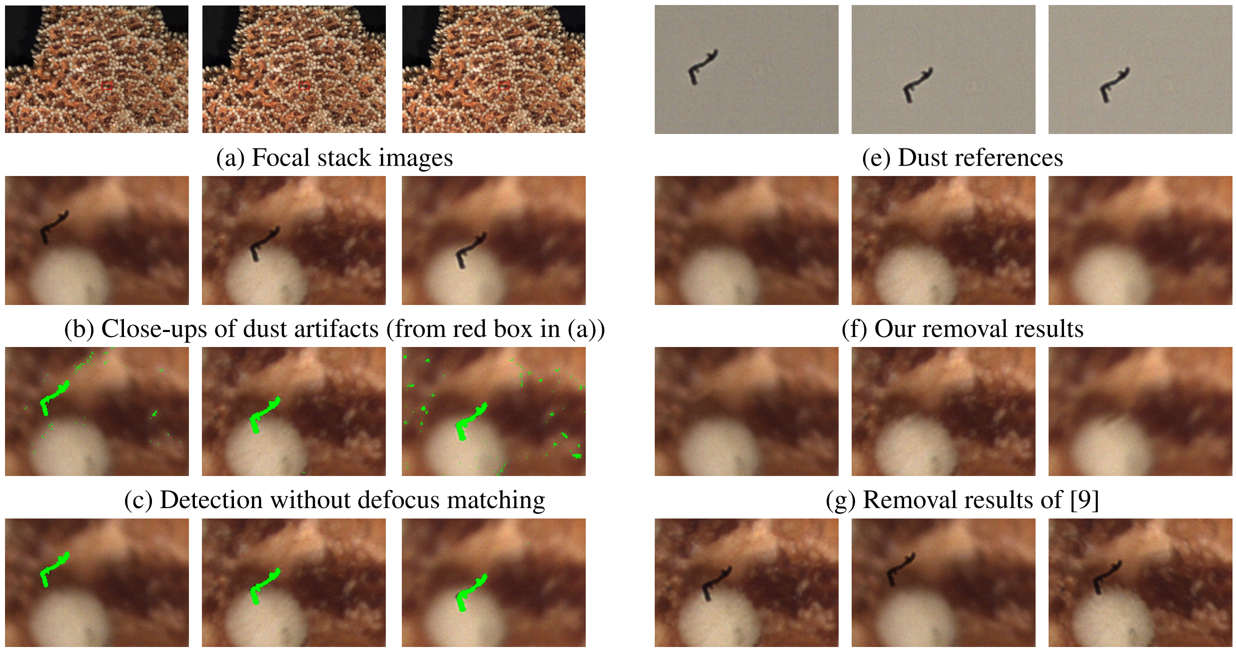
the lens changes as well, causing the dust "shadow" to shift in position. We capitalize on these shifts to detect and remove dust artifacts in focal stack images. We note though that dust that lies along or near the optical axis may have little change in lighting angle under different focus settings, and thus may undergo little or no shift within the focal stack. Our experiments have nevertheless shown sufficient shifting to exist in a vast majority of the image (approximately 85% of pixels for the smallest focus setting in our imaging system), and those pixels close to the optical axis may instead be processed by algorithms such as [9].

3. Dust Detection

Our algorithm first identifies dust artifacts in the images before removing their effects. In this detection stage, we take advantage of dust displacements in the focal stack to distinguish dust artifacts from features in the scene.

Because of the aforementioned magnification and brightness variations among focal stack images, we begin with intensity normalization of the images and alignment using Microsoft Research's Image Composite Editor (ICE) [1].

With the alignment of images and the displacement of dust among them, dust artifacts could potentially be detected as intensity outliers among corresponding pixels. However, significant intensity variation may exist among corresponding pixels due to differences in defo-



(a) Focal stack images
(b) Close-ups of dust artifacts (from red box in (a))
(c) Detection without defocus matching
(d) Detection with defocus matching (before filtering/dilation)
(e) Dust references
(f) Our removal results
(g) Removal results of [9]
(h) Removal references

Figure 2. Dust detection and removal. Please zoom in to pdf for a closer view.

cus blur. To accurately identify dust outliers, we therefore determine the relative defocus levels among corresponding image patches and then match their levels of defocus blur prior to outlier detection.

To obtain the relative defocus levels, we first estimate the scene depth of the surface patch with a depth-from-focus (DFF) method [6], in which Eq. (1) is used to compute depth from the focal length of the lens and the focus setting for the patch with maximum sharpness. From this depth d, the defocus blur radius b of each corresponding patch is solved from its focus setting according to Eq. (2).

Let $h(\sigma_b^2)$ be a Gaussian point spread function, or blur kernel, of variance σ_b^2 that corresponds to a blur radius of b. Supposing that we have corresponding patches P_0, P_1 with blur radius b_0, b_1 and $b_0 \geq b_1$, the two patches can be matched in blur level through the following convolution on P_1:

$$P_1' = P_1 \star h(\sigma_{b_0}^2 - \sigma_{b_1}^2). \quad (3)$$

Using Eq. (3), we match the set of corresponding patches to the blur level of the most defocused patch.

Matching of defocus levels allows dust artifacts to be reliably identified through outlier detection among corresponding pixels. A pixel p in image I_k with intensity $I_k(p)$ is marked as dust if

$$I_k(p) < \hat{I}(p) - t \quad (4)$$

where $\hat{I}(p)$ is the median intensity of p within the focal stack, and t is an outlier threshold. In principle, t should be set as a function of the image noise level after applying the relative blur for defocus matching. However, in practice we have found a fixed value of $t = 15$ to be effective in our implementation. To reduce the influence of image noise, we apply a size filter to exclude single-pixel regions from the dust detection results. The remaining dust regions are dilated by two pixels to promote fuller coverage of each dust.

An example result of this dust detection technique is exhibited in Fig. 2 for three images of a focal stack. Close-ups are shown for better visibility of dust artifacts. Rows (c) and (d) display detection results without and with defocus matching, respectively, which supports the need for relative defocus analysis in the detection process. The references in (e) captured with a white scene provide only an approximation of ground truth dust, since ICE cannot perform accurate image alignment for solid backgrounds.

4. Dust Removal

In the dust removal stage, we also take advantage of dust shifts, which reveal in other focal stack images the scene areas occluded by dust. Since other images may exhibit different levels of defocus, defocus matching is again applied before using the unoccluded scene areas for dust removal purposes.

(a) Focal stack images

(b) Close-ups of dust artifacts

(c) Our removal results

(d) Removal results of [9]

(e) References from other focal stack images

Figure 3. Results for Dunhuang Caves.

For a detected dust region in one of the focal stack images, we collect the corresponding regions which do not contain dust from the other images. Among these regions we select an *exemplar* that is less defocused and closest in focus setting to the dust region. The defocus level of the exemplar is then matched to the dust region according to their relative defocus using Eq. (3), similarly to the detection process. In the relative defocus estimation, the influence of sharp dust regions are avoided by excluding them from the evaluated local patch. If none of the corresponding regions is less defocused than the dust region, then the least defocused among them is taken as the exemplar, and is iteratively sharpened by increasing amounts of unsharp masking until it matches the defocus level of the dust region.

The defocus-matched exemplar is then inserted into the dust region by Poisson image blending [7] to remove the appearance of dust. Results of this process are exhibited in Fig. 2(f). As a reference, we show in (h) the corresponding region in another focal stack image with the dust in a different position. Though the references have different defocus levels from the removal results in (f), they provide an indication of the actual scene content behind the removed dust.

Results from the state-of-the-art method of [9] are shown in Fig. 2(g). For opaque dust regions such as those produced from a long focal length lens, their method becomes equivalent to texture synthesis to fill in the dust region. Though texture synthesis is capable of generating a *plausible* result, this result does not necessarily match the true scene content blocked by the dust. This problem is demonstrated in this example, where their results are not as consistent as ours to the references shown in (h). Specifically, in the first image a line is artificially extended from the light pink region, while in the other two images the edge of the white element becomes distorted under the influence of the complex surrounding texture.

Additional removal results for carvings in the Dunhuang caves (courtesy of the Dunhuang Academy) are shown in Fig. 3. Though artifact removal by [9] produces reasonable looking results, they do not agree with the references from different focal stack images (with different defocus levels and shifted dust positions) as closely as ours.

5. Conclusion

We presented a dust removal technique for focal stack images that takes advantage of dust shifts caused by changes in optical geometry when the focus setting is adjusted. For effective utilization of the image data, an analysis of relative defocus among corresponding focal stack areas is performed. By design, our method produces results that are consistent with the actual scene content occluded by sensor dust.

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