Reflection Removal using Ghosting Cues

YiChang Shih[1], Dilip Krishnan[2], Frédo Durand[1], William T. Freeman [1]
[1]MIT CSAIL, [2]Google Research

Taking photographs through windows or glass panes often results in reflections which reduce the picture quality. Such a situation is shown in Figure 1(a). Separating the transmission T and reflection R is a well-studied, but ill-posed problem, since both T and R are natural images with similar characteristics. Furthermore, traditional imaging models assume that T and R play symmetric roles when forming the observed image I, i.e. $T = I + R$. Most previous work tackles the ill-posedness through the use of multiple input images [2, 4] or through user input which marks regions of the observed image as belonging either to T or R (see [3]).

In this work, we present an algorithm that separates the two layers given only a single input image corrupted by reflections. To achieve this, we exploit "ghosting" effects – multiple attenuated and shifted copies of the reflected objects (see Figure 1). Ghosting phenomena occur often when capturing images through glass panes. Consider taking an image through a double-pane window which consists of two thin glass panes separated by some distance. The glass pane closer to the camera generates the first reflection, and the opposite side generates the second, which is a shifted and attenuated version of the first reflection. The distance between the two reflections depends on the space between the two panes. In single-pane windows of typical thickness 3-10mm, ghosting arises from multiple reflections by the near and far surfaces of the glass (see Figure 2).

To quantify the frequency of ghosting, we analyzed images returned by Google's Image Search, using the keywords "window reflection photography problems" and "reflections on windows." After removing irrelevant results such as cartoon images and reflections on water, we examined 197 randomly sampled images, and observed that 96 of them exhibit significant ghosting (49%).

Following the work in Diamant et al. [1], we model ghosting as the convolution of the reflection layer R with a two-pulse kernel k. Then the observed image I can be modeled as an additive mixture of the ghosted reflection and transmission layers by R and T respectively:

$$I = T + R \otimes k + n \tag{1}$$

where n is i.i.d Gaussian noise with standard deviation σ. The kernel k is parameterized by the distance and the relative intensity between the primary and secondary reflections (higher-order reflections are ignored as they contribute less than 1% of the energy of the image). These parameters may be estimated with a simple algorithm that relies on the auto-correlation of I. Then, given the observation I and kernel k, we recover T and R by using two forms of regularization: a patch prior proposed by Zoran et al. [5], and non-negativity constraints on T and R, which help in the regularization of low frequencies. We formulate the recovery problem as follows:

$$\min_{T,R} \frac{1}{\sigma^2}\|I - T - R \otimes k\|^2 - \sum_i \log(\mathrm{GMM}(P_i T)) - \sum_i \log(\mathrm{GMM}(P_i R))$$
$$\text{s.t. } T \geq 0, R \geq 0$$

where $\mathrm{GMM}(P_i I)$ refers to the Gaussian Mixture Model based patch prior [5], and $P_i I$ is a linear operator that extracts patch i from image I. We minimize the above function using alternating minimization with half-quadratic optimization and a constrained L-BFGS algorithm. In our experiments, we show that ghosting cues help in the recovery of high quality results from just a single input image. We demonstrate our method on synthetic data and real-world inputs.

(a) *Input* **(b)** *Close-up of ghosting*

(c) *Recovered Transmission* **(d)** *Recovered Reflection*

Figure 1: Our method removes undesired reflections in an image taken through a glass pane: (a) Input image with reflection artifacts; (b) Close-up shows ghosting on the reflection layer; (c) Recovered transmission layer using our algorithm; (d) Recovered reflection layer.

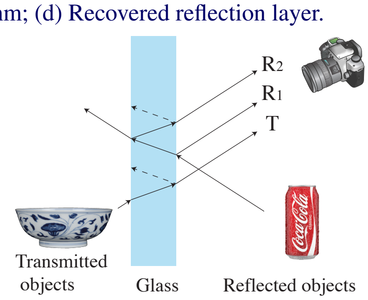

Figure 2: Ghosting image formation: (a) Light rays from an object on the same side of the glass as the camera (a soft-drink can) are partially reflected by the inner-side of the glass, generating the primal reflection R_1. The remainder is transmitted, and partially reflected by the far side of the glass, generating a secondary reflection R_2. R_2 is a shifted and attenuated version of R_1. The superposition of R_1 and R_2 leads to the observed ghosted image.

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This is an extended abstract. The full paper is available at the Computer Vision Foundation webpage.