

# Super-Resolution from Corneal Images

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The cornea of the human eye reflects the light from a person’s environment. Modeling corneal reflections from an image of the eye enables a number of applications, including the computation of scene panorama and 3D model, together with the person’s field of view and point of gaze [4]. The obtained environment map enables general applications in vision and graphics, such as face reconstruction, relighting [3] and recognition [5]. In reality, however, even if we use a carefully-adjusted high-resolution camera in front of the eye, the quality of corneal reflections is limited due to low resolution and contrast, iris texture and geometric distortion.

This paper introduces an approach to overcome these issues through a super-resolution (SR) [6] strategy for corneal imaging that reconstructs a high-resolution (HR) scene image from a series of lower resolution (LR) corneal images such as occurring in surveillance or personal videos. The process comprises (1) single image environment map recovery, (2) multiple image registration, and (3) HR image reconstruction. This is also the first non-central catadioptric approach for multiple image SR.

**Corneal reflection modeling.** We apply a common geometric eye model, where eyeball and cornea (Figure 1 (a)) are approximated as two overlapping spherical surfaces. A simple strategy assuming weak perspective projection recovers the pose of the model by reconstructing the pose of the circular iris from its elliptical projected contour (Figure 1 (b)).

A corneal image is transformed into a spherical environment map by calculating the intersection and reflection at the corneal surface. Since the eye model only approximates the true corneal geometry, it is not possible to obtain an accurate registration for the whole environment map. Instead, we assume spherical curvature for a user-defined region of interest, where we project the environment map to a local tangent plane (Figure 1 (c)).

Registration further requires the forward projection from the tangent plane into the image. As common iterative methods are not feasible to handle the large number of re-projections, we apply a recent analytic method that requires solving a 4th-order polynomial equation (for the case of a spherical mirror), that is calculated in closed form [1].

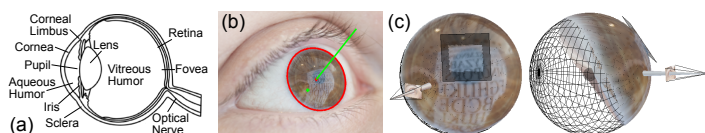


Figure 1: Modeling. (a) Cross-section of the eye. (b) Cropped eye image with iris contour, center (red), cornea center and gaze direction (green). (c) Environment map and local tangent plane at region of interest.

**Registration.** Regarding the small change of corneal sphere locations in continuous video frames, it is feasible to assume the cornea to be centered at the world origin, where the task of alignment amounts to finding the pose of the camera w.r.t. the world frame. This is achieved through a multiple-step iterative process: (1) Coarse alignment is carried out using at least two feature correspondences for each LR image (Figure 2 (b)-(d)). The transformation between the environment maps is a rotation around the origin that we estimate by minimizing the deviation of backprojected feature directions. To compensate for the error in eye pose estimation we continue adjusting corneal sphere locations through a pairwise and bundle registration. (2) Fine alignment is carried out through image matching in the local tangent plane (Figure 3 (d)), by minimizing the sum of absolute differences (SAD) at uniform sampling points using forward projection lookup. Finally, the remaining misalignment is corrected through a 2D subpixel rigid registration in the plane.

**Super-resolution.** Using the registration parameters we back project the region of interest for all corneal images and apply the rigid alignment. The obtained (LR) points represent non-uniform samples (observations) of an unknown HR image. The image is estimated through a MAP (maximum a posteriori) based SR approach using gradient descent to minimize the error between the observed and synthesized LR images under a Gaus-

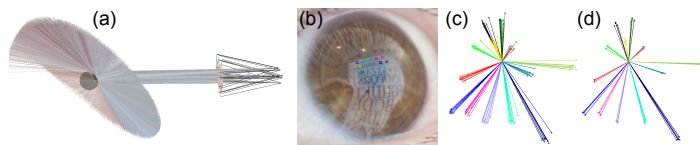


Figure 2: Alignment. (a) Cameras, image planes, corneal sphere (world origin), and limbus backprojection rays for 10 images. (b) Single corneal image with 13 feature correspondences. (c) Back-projected features for all images before alignment, and (d) after coarse alignment.

sian PSF assumption. As image priors, we evaluate the norm of the HR image filtered by either a Laplacian of Gaussian filter (LoG), a bilateral filter residual (BL) [7] or a bilateral total variation filter (BTV) [2].

**Experiments.** In a number of experiments for indoor and outdoor scenes we confirmed that the strategy using MAP-BL and -BTV performs best and recovers high-frequency textures (with a quality high enough to recognize small characters, human faces and fine structures) that are lost in the source images (Figure 3). We also confirmed this for a spherical mirror, suggesting applicability to other non-central catadioptric systems such as specular and liquid surfaces in everyday environments.

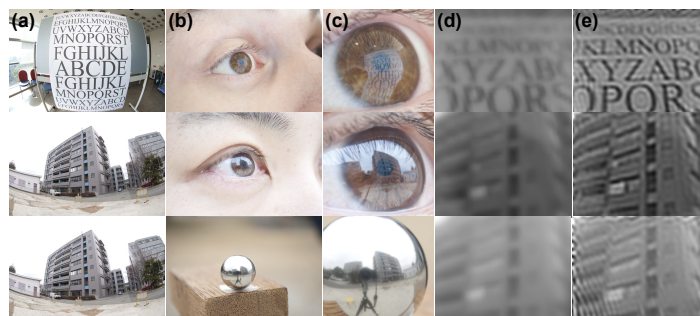


Figure 3: SR result for two scenes. (a) Fisheye scene image. (b) Single LR image. (c) Cropped eye/mirror region. (d) Local tangent plane projection. (e) Multiple image SR result using MAP with BTV prior.

Since this solves the quality degradation problem in corneal imaging techniques, we believe our contribution can become a foundation for future applications in this research category. The obtained information about a person and the environment has the potential to enable novel applications, e.g., for surveillance systems, personal video, human-computer interaction, and upcoming head-mounted cameras.

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