Recovering Specular Surfaces Using Curved Line Images

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The Problem

• Existing reconstruction methods rely on robust correspondences, which is particularly difficult for cases where images contain large distortions.

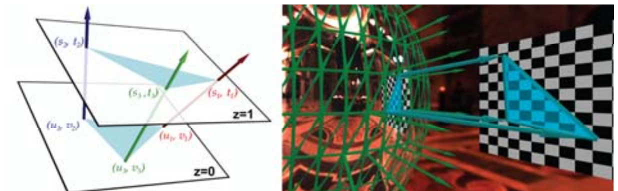
Key Contributions

• A new shape-from-distortion framework for recovering specular surfaces.

• A complete analysis and categorization of all possible curved line images (CLI) in all possible General Linear Cameras (GLC).

• An efficient algorithm to use multiple CLIs to recover the GLC camera parameters.

Background and Previous Work



A GLC is described by 3 generator rays parameterized under two parallel planes (2PP) (a). We decompose a reflection image of a curved mirror into piecewise GLCs (b).

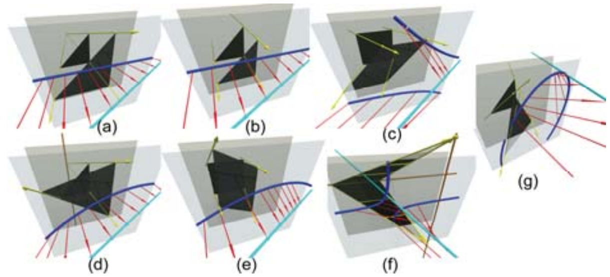
Characterizing Conic Types in GLCs

• **Lemma 1.** If a 3D line l is not parallel to 2PP, its CLI in the GLC is a line iff the GLC is a pinhole or orthographic camera.

• **Lemma 2.** The CLIs of all 3D lines that are not parallel to the image plane, their conic coefficients A, B, and C are identical (up to a scale) and their discriminant J have the same sign in a fixed GLC. They must correspond to the same conic type.

• **Corollary 1.** All CLIs are conics in a GLC. The conics are of the same type and the type can be determined by the GLC characteristic equation.

• **Corollary 2.** One conic CLI of a known 3D line is not sufficient to recover the GLC.



Each GLC image captures a unique curving pattern: lines project to lines in pinhole (a) and orthographic cameras (b), to hyperbolas in pushbroom (c) and cross-slit (f) cameras, to parabolas in pencil (d) and twisted orthographic cameras (e), and to ellipses in bilinear (g) cameras.

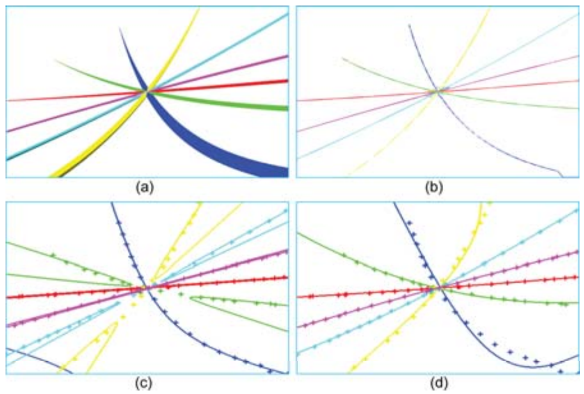
Table 1. Conic Types Observed in General Linear Cameras

GLC Type	Pinhole	Ortho.	XSlit	Pushbroom	Pencil	Twisted	Bilinear
Conic Type Determinant	Line $\Delta = 0$	Line $\Delta = 0$	Hyperbolae $\Delta > 0$	Hyperbolae $\Delta > 0$	Parabola $\Delta = 0$	Parabola $\Delta = 0$	Ellipse $\Delta < 0$

Conics Group Fitting

• Chamfer Distance Transform (CDT) and Laplacian operator to find the skeleton

• Simultaneously recovering the conic coefficients for all curves, enforcing them to have the same quadratic coefficients.



Conic fitting results. (a) shows the 6 CLIs in a cross-slit camera. (b) shows the recovered skeletons of the conic images. (c) shows the conic fitting results if we separately fit the curves. (d) shows the conic fitting results using our group fitting algorithm.

Recovering the GLC Parameters and Surface Curvatures

• Intersect every 3D line with *uv*-plane to get $[\sigma_{0i}, \tau_{0i}, u_{0i}, v_{0i}]$

• Every line projection satisfies GLC projection Equation:

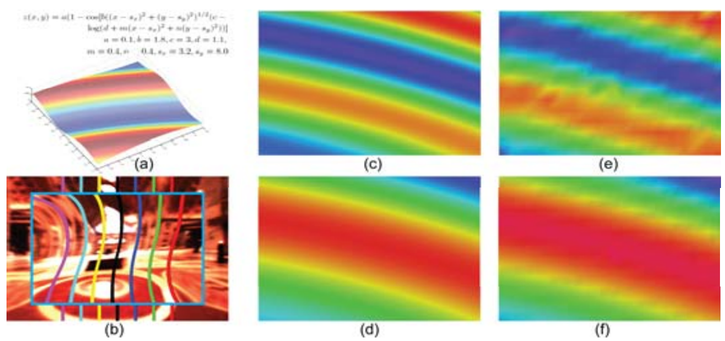
$$(u-u_0)((1-u-v)\tau_1 + u\tau_2 + v\tau_3 - \tau_0) \\ -(v-v_0)((1-u-v)\sigma_1 + u\sigma_2 + v\sigma_3 - \sigma_0) = 0$$

• Use SVD to solve the linear system below formed by projection equations.

$$\begin{pmatrix} 0 & 0 & 0 & 1 & -1 & 0 & A \\ -1 & 1 & 0 & 1 & 0 & -1 & B \\ -1 & 0 & 1 & 0 & 0 & 0 & C \\ v_{01} & -v_{01} & 0 & -u_{01}-1 & u_{01} & 0 & D_1 \\ 1+v_{01} & 0 & -v_{0i} & -u_{0i} & 0 & u_{0i} & E_1 \\ -v_{01} & 0 & 0 & u_{01} & 0 & 0 & F_1 \\ v_{02} & -v_{02} & 0 & -u_{02}-1 & u_{02} & 0 & D_2 \\ \vdots & & & \cdots & & & \vdots \\ -v_{0n} & 0 & 0 & u_{0n} & 0 & 0 & F_n \end{pmatrix} \begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_1 \\ \tau_2 \\ \tau_3 \\ \xi \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ -\tau_{01} \\ \sigma_{01} \\ \phi_{01} \\ -\tau_{02} \\ \vdots \\ \phi_{0n} \end{pmatrix}$$

• Finally, we use the Ray-Curvature theory in [1] to compute the surface curvature.

Results



(a) shows the surface height field map, (b) shows a ray-traced CLI image, (c) and (d) show the ground truth Gaussian and mean curvature, (e) and (f) show the Gaussian and mean curvature recovered using our algorithm.

References

• Y. Ding and J. Yu. Recovering Shape Characteristics on Near-flat Specular Surfaces. CVPR 2008.

• J. Yu and L. McMillan: General Linear Cameras. Proceedings of 8th European Conference on Computer Vision (2004), Volume 2, pp. 14-27.