Refining Single View Calibration With the Aid of Metric Scene Properties

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Single View Calibration

- Single View Calibration (SVC) is the process of estimating the intrinsic calibration parameters (i.e. interior orientation) of a camera using only one perspective image
- It is a fundamental problem that needs to be solved before any metric measurements can be made from an image
- It is a key ingredient for single view reconstruction (SVR), i.e. the task of creating 3D graphical models for scenes for which only a single image is available

SVR example

Single View Calibration (cont'd)

- In contrast to grid based calibration, SVC cannot rely on the knowledge of the 3D coordinates of certain points in a world reference frame; a self-calibration paradigm must be adopted
- SVC also cannot rely on geometric constraints that need multiple images to be computed (e.g., Kruppa equations, absolute quadric)
- SVC should rely on geometric properties of the imaged objects
- Those properties should be supplied via user interaction

Previous Work

- A pair of vanishing points corresponding to orthogonal directions provides one calibration constraint [Caprile and Torre 1990]
- Dual of the above: A pair of vanishing lines corresponding to orthogonal planes provides one calibration constraint
- A metric planar homography provides two calibration constraints [Liebowitz and Zisserman 1998]
- Multiple calibration constraints can be combined in a least squares manner [Liebowitz and Zisserman 1999]
- Calibration constraints can also arise from surfaces of revolution [Colombo et al 2005]

What this work is about

- The applicability of SVC methods depends on a minimum number of calibration constraints being available
- This boils down to certain geometric arrangements occurring in the imaged scene
- Such arrangements are not guaranteed to always be present, thus an insufficient number of constraints might be available
- Insufficient constraints force the use of approximate, simplified camera models
- This work concerns a method for refining an initial calibration estimate (possibly obtained using a simplified model) with the aid of a priori known metric measurements

Single View Geometry

- Camera calibration is specified by matrix $\mathbf{K}$ having 5 DOFs:

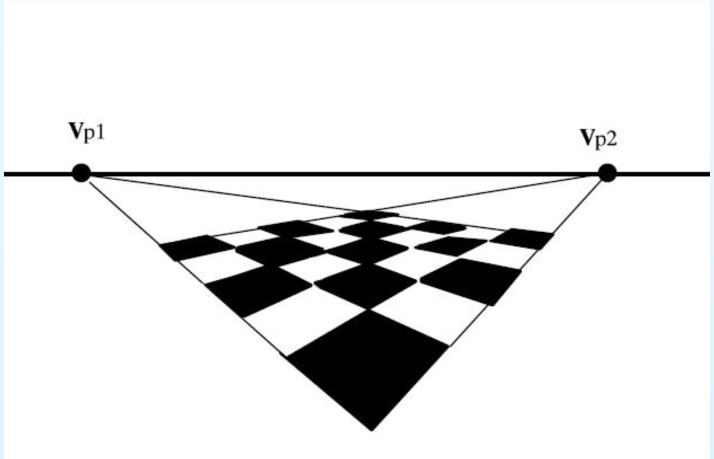
$$\mathbf{K} = \begin{bmatrix} f_u & s & u_0 \\ 0 & f_v & v_0 \\ 0 & 0 & 1 \end{bmatrix},$$

where f_u, f_v are the focal length in horizontal/vertical pixels, (u_0, v_0) the image principal point and s relates to the image axes angle. Usually cameras are *natural*: aspect ratio $r \equiv \frac{f_v}{f_u} = 1$, $s = 0$

- Calibration is performed with the aid of the *image of the absolute conic* (IAC)
- The IAC is the image of an imaginary conic that depends only on the intrinsic parameters and not on camera pose
- A point $\mathbf{x}$ on the IAC satisfies $\mathbf{x}^T \omega \mathbf{x} = 0$, where ω is a symmetric matrix ω defined as $\omega = (\mathbf{K}\mathbf{K}^T)^{-1}$

Single View Geometry (cont'd)

- Calibration through estimating the IAC is convenient since SVC constraints are linear in the elements of ω
- Given ω, $\mathbf{K}$ can be computed from its Cholesky decomposition
- The *vanishing point* (VP) of a 3D line is the point onto which infinitely far line points are imaged
- ω allows certain direct 3D measurements on images
- The VPs of non-parallel coplanar 3D lines lie on the same *vanishing line*



Metric Measurements Using the IAC

- Let $S(\mathbf{a}, \mathbf{b})$ denote the scalar $\mathbf{a}^T \omega \mathbf{b}$ for vectors $\mathbf{a}$ and $\mathbf{b}$
- If $\mathbf{v}_1$ and $\mathbf{v}_2$ are the vanishing points of two 3D lines, the acute angle θ between them can be computed from $\cos(\theta) = \frac{|S(\mathbf{v}_1, \mathbf{v}_2)|}{\sqrt{S(\mathbf{v}_1, \mathbf{v}_1)\, S(\mathbf{v}_2, \mathbf{v}_2)}}$
- Using the law of sines, the length ratio of four non collinear points A, B, C and D equals

$$\frac{AB}{CD} = \sqrt{\frac{S(\mathbf{v}_{ab}, \mathbf{v}_{ab})}{S(\mathbf{v}_{cd}, \mathbf{v}_{cd})} \cdot \frac{S(\mathbf{v}_{ac}, \mathbf{v}_{ac})\, S(\mathbf{v}_{bc}, \mathbf{v}_{bc}) - S(\mathbf{v}_{ac}, \mathbf{v}_{bc})^2}{S(\mathbf{v}_{ab}, \mathbf{v}_{ab})\, S(\mathbf{v}_{ac}, \mathbf{v}_{ac}) - S(\mathbf{v}_{ab}, \mathbf{v}_{ac})^2}} \cdot \sqrt{\frac{S(\mathbf{v}_{bd}, \mathbf{v}_{bd})\, S(\mathbf{v}_{cd}, \mathbf{v}_{cd}) - S(\mathbf{v}_{bd}, \mathbf{v}_{cd})^2}{S(\mathbf{v}_{bc}, \mathbf{v}_{bc})\, S(\mathbf{v}_{bd}, \mathbf{v}_{bd}) - S(\mathbf{v}_{bc}, \mathbf{v}_{bd})^2}},$$

where $\mathbf{v}_{ab}$, $\mathbf{v}_{ac}$, $\mathbf{v}_{bc}$, $\mathbf{v}_{bd}$, and $\mathbf{v}_{cd}$ are the VPs of segments AB, AC, BC, BD and CD

Refining an Intrinsic Calibration Estimate

- Known angles and length ratios impose high-order polynomial constraints on ω
- Such constraints are not usable for directly obtaining ω due to the problems associated with solving nonlinear polynomial equations
- Given an initial calibration estimate, known metric properties can be used for improving it. The idea is to refine the estimated ω in a nonlinear optimization framework so that metric measurements made with it are in close agreement with those a priori known

Refining an Intrinsic Calibration Estimate (cont'd)

- Let A be a set of line segment pairs with known 3D angles
- Let E be a set of line segment quadruples defining two unknown but equal 3D angles
- Let R be a set of line segment pairs with known 3D length ratios
- Let $\alpha(\mathbf{s}_i, \mathbf{r}_i; \omega)$ be the estimated cosine of the angle between segments $(\mathbf{s}_i, \mathbf{r}_i) \in$ A with a priori known angle ϕ_i
- Let $\rho(\mathbf{s}_i, \mathbf{r}_i; \omega)$ be the estimated length ratio for segments $(\mathbf{s}_i, \mathbf{r}_i) \in$ R with a priori known ratio λ_i

Refining an Intrinsic Calibration Estimate (cont'd)

- $\alpha(\mathbf{s}_i, \mathbf{r}_i; \omega) - \cos(\phi_i)$: cosine difference error, $(\mathbf{s}_i, \mathbf{r}_i) \in \mathsf{A}$
- $\alpha(\mathbf{s}_i, \mathbf{r}_i; \omega) - \alpha(\mathbf{p}_i, \mathbf{q}_i; \omega)$: cosine estimates difference error, $(\mathbf{s}_i, \mathbf{r}_i, \mathbf{p}_i, \mathbf{q}_i) \in \mathsf{E}$
- $\rho(\mathbf{s}_i, \mathbf{r}_i; \omega) - \lambda_i$: length ratio difference error, $(\mathbf{s}_i, \mathbf{r}_i) \in \mathsf{R}$
- A cumulative error term $\epsilon(\mathsf{A}, \mathsf{E}, \mathsf{R}; \omega)$ is defined by summing the squares of all cosine & length difference errors:

$$\epsilon(\mathsf{A}, \mathsf{E}, \mathsf{R}; \omega) = \sum_{(\mathbf{s}_i, \mathbf{r}_i) \in \mathsf{A}} \left[\alpha(\mathbf{s}_i, \mathbf{r}_i; \omega) - \cos(\phi_i)\right]^2 + \sum_{(\mathbf{s}_i, \mathbf{r}_i, \mathbf{p}_i, \mathbf{q}_i) \in \mathsf{E}} \left[\alpha(\mathbf{s}_i, \mathbf{r}_i; \omega) - \alpha(\mathbf{p}_i, \mathbf{q}_i; \omega)\right]^2 + \sum_{(\mathbf{s}_i, \mathbf{r}_i) \in \mathsf{R}} \left[(\rho(\mathbf{s}_i, \mathbf{r}_i; \omega) - \lambda_i\right]^2$$

Refining an Intrinsic Calibration Estimate (cont'd)

- Not all line segments involved in the definition of $\epsilon(\mathrm{A}, \mathrm{E}, \mathrm{R}; \omega)$ should be coplanar
- An arbitrary number of constraints can be accommodated
- The error term can be iteratively minimized over ω using a nonlinear least squares algorithm, e.g. Levenberg - Marquardt
- The starting point for the numerical minimization is the initial estimate of ω
- Details on the parametrization of ω are in the paper; 3 or 4 parameters suffice

Implementation Details

- Line segments were defined manually
- ML estimates of the VPs were estimated from groups of parallel line segments
- Initial calibration estimates were obtained from orthogonal VPs & metric rectification homographies
- Minimization of the error term was achieved by our free `levmar` library (`http://www.ics.forth.gr/~lourakis/levmar`)
- Objective function Jacobian was computed analytically with symbolic differentiation in MAPLE

Experiments: Calibration Grid

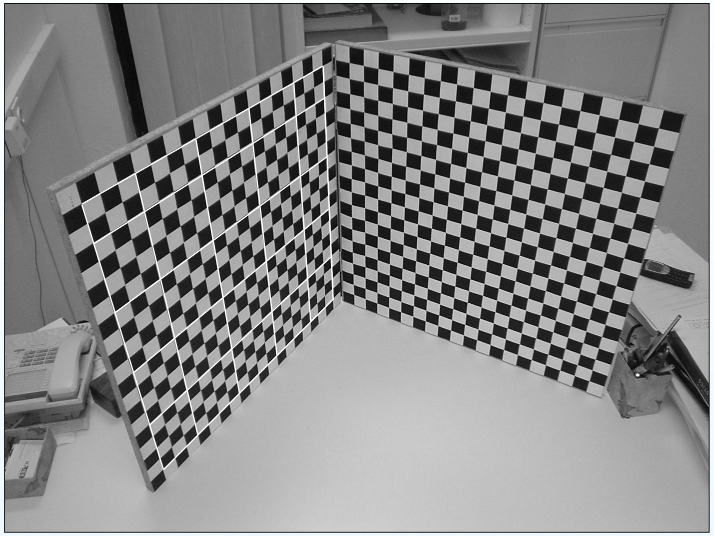
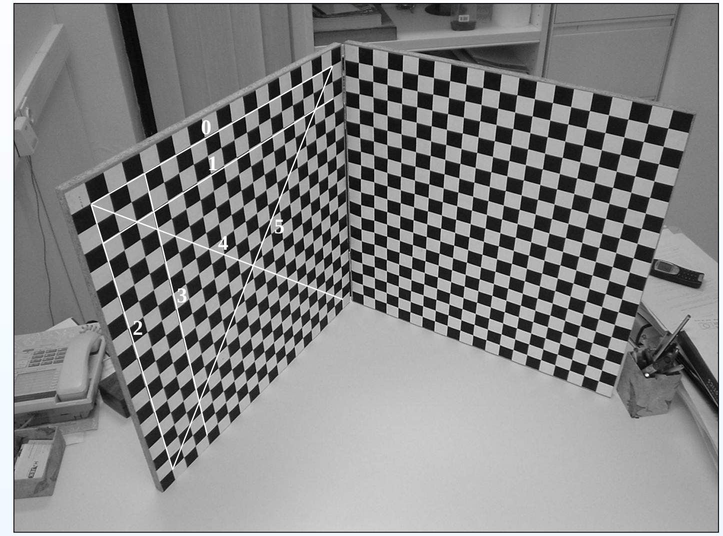
 

Image of a calibration object with the lines employed to detect orthogonal vanishing points (L) and line segments forming equal angles and known length ratios used for refining calibration (R)

$$\underset{Ground\ truth}{\begin{bmatrix} 1565.7 & 0 & 800.9 \\ 0 & 1565.5 & 642.44 \\ 0 & 0 & 1 \end{bmatrix}} \quad \underset{Initial\ estimate}{\begin{bmatrix} 1552.0 & 0 & 816 \\ 0 & 1552.0 & 612 \\ 0 & 0 & 1 \end{bmatrix}} \quad \underset{Refined\ estimate}{\begin{bmatrix} 1553.52 & 0 & 805.293 \\ 0 & 1553.52 & 638.787 \\ 0 & 0 & 1 \end{bmatrix}}$$

Experiments: Valbonne Church

A frame from the Valbonne church sequence with the lines employed to detect orthogonal vanishing points (L) and line segments defining known scene properties that are used for calibration refinement (R)

$$\begin{array}{ccc} \textit{Ground truth} & \textit{Initial estimate} & \textit{Refined estimate} \\ \begin{bmatrix} 682.84 & 0 & 256 \\ 0 & 682.84 & 384 \\ 0 & 0 & 1 \end{bmatrix} & \begin{bmatrix} 529.6 & 0 & 256 \\ 0 & 529.6 & 384 \\ 0 & 0 & 1 \end{bmatrix} & \begin{bmatrix} 672.0 & 0 & 256 \\ 0 & 672.0 & 384 \\ 0 & 0 & 1 \end{bmatrix} \end{array}$$

Experiments: Oxford Basement

An image from the “basement” sequence with the lines employed to detect orthogonal vanishing points (L) and the line segments of equal lengths that were used for refining single view calibration (R)

$$\underset{Ground\ truth}{\begin{bmatrix} 496.9 & 0 & 273.5 \\ 0 & 496.9 & 280.0 \\ 0 & 0 & 1 \end{bmatrix}} \quad \underset{Initial\ estimate}{\begin{bmatrix} 312.1 & 0.0 & 256.0 \\ 0.0 & 312.1 & 256.0 \\ 0.0 & 0.0 & 1.0 \end{bmatrix}} \quad \underset{Refined\ estimate}{\begin{bmatrix} 527.5 & 0 & 254.8 \\ 0 & 527.5 & 303.7 \\ 0 & 0 & 1 \end{bmatrix}}$$

Conclusions

- Presented a new nonlinear camera calibration refinement technique
- This technique exploits a priori knowledge of metric scene properties such as line segment angles and length ratios
- Has been experimentally demonstrated to significantly improve the accuracy of initial intrinsic calibration estimates
- Has little computational overhead

Any questions?