Rolling Shutter Bundle Adjustment

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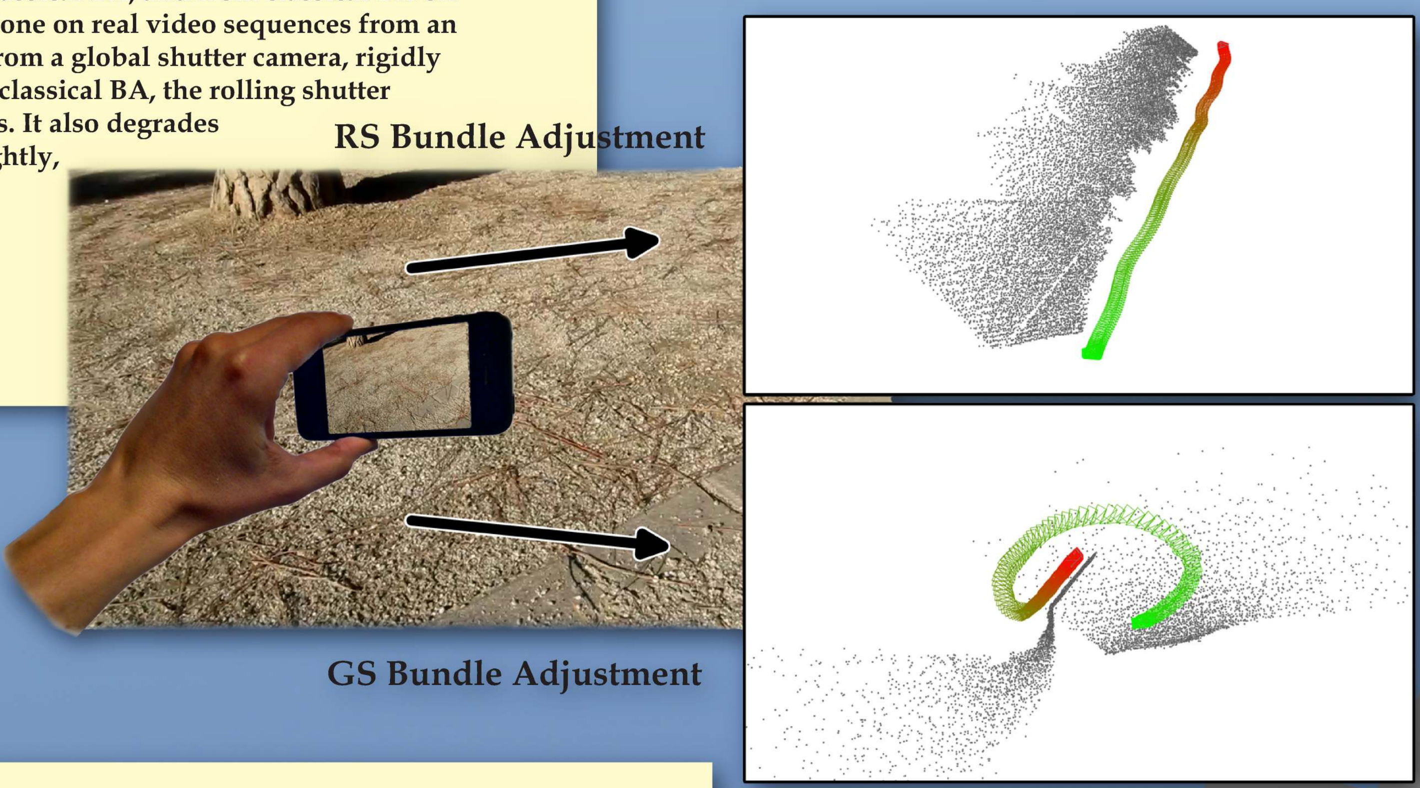
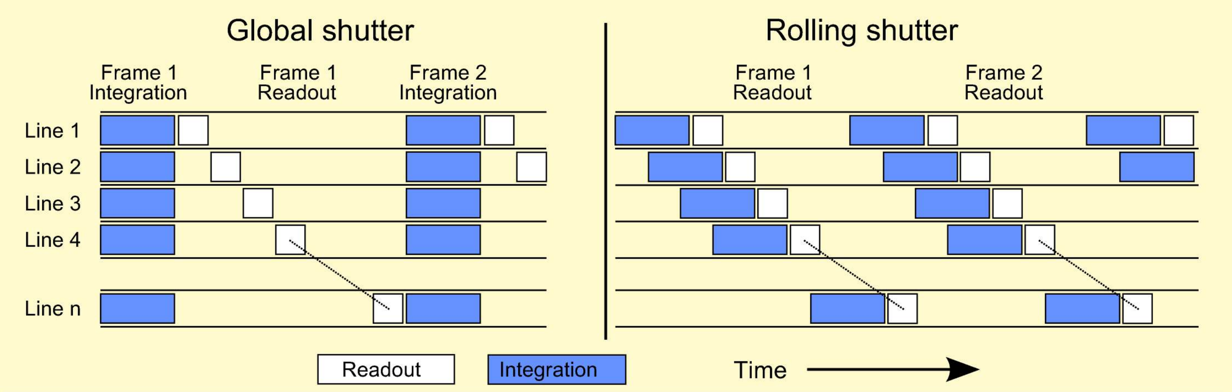
Introduction

This paper introduces a bundle adjustment (BA) method that obtains accurate structure and motion from rolling shutter (RS) video sequences: RSBA. When a classical BA algorithm processes a rolling shutter video, the resultant camera trajectory is brittle, and complete failures are not uncommon. We exploit the temporal continuity of the camera motion to define residuals of image point trajectories with respect to the camera trajectory. We compare the camera trajectories from RSBA to those from classical BA, and from classical BA on rectified videos. The comparisons are done on real video sequences from an iPhone 4, with ground truth obtained from a global shutter camera, rigidly mounted to the iPhone 4. Compared to classical BA, the rolling shutter model requires just six extra parameters. It also degrades the sparsity of the system Jacobian slightly, but as we demonstrate, the increase in computation time is moderate. Decisive advantages are that RSBA succeeds in cases where competing methods diverge, and consistently produce more accurate results.

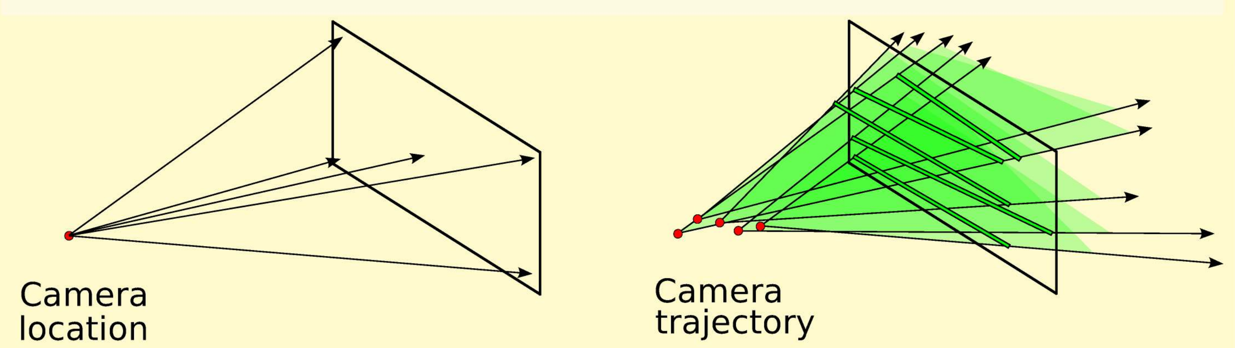
RS Bundle Adjustment



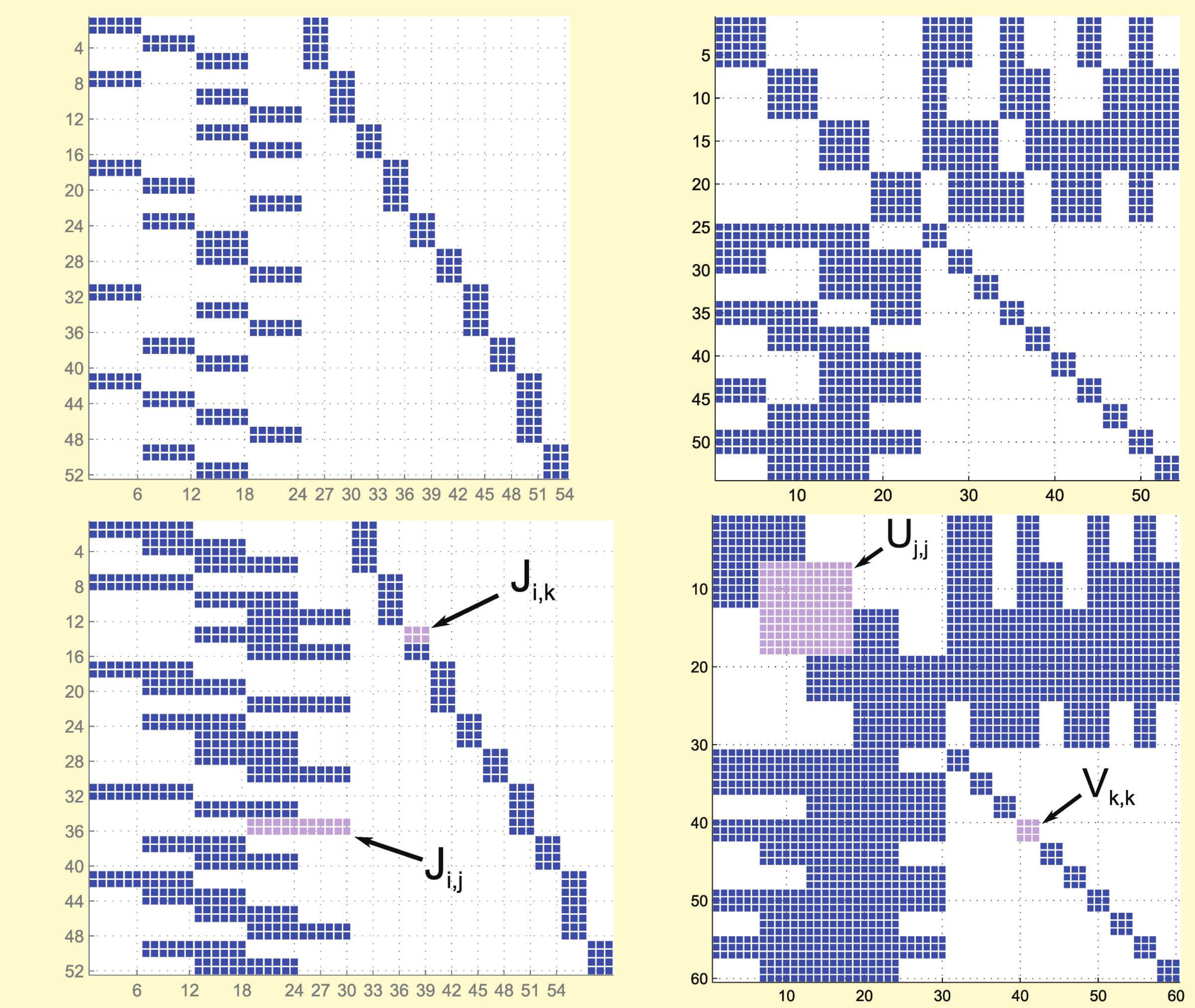
GS Bundle Adjustment



$\mathbf{C}_j = \mathbf{R}_j^T[\,\mathbf{I}\,|\,-\mathbf{t}_j]$ $\quad\quad$ $\mathbf{C}_j(y) = \mathbf{R}_{j,j+1}^T(y)[\,\mathbf{I}\,|\,-\mathbf{t}_{j,j+1}(y)]$



RS Bundle Adjustment



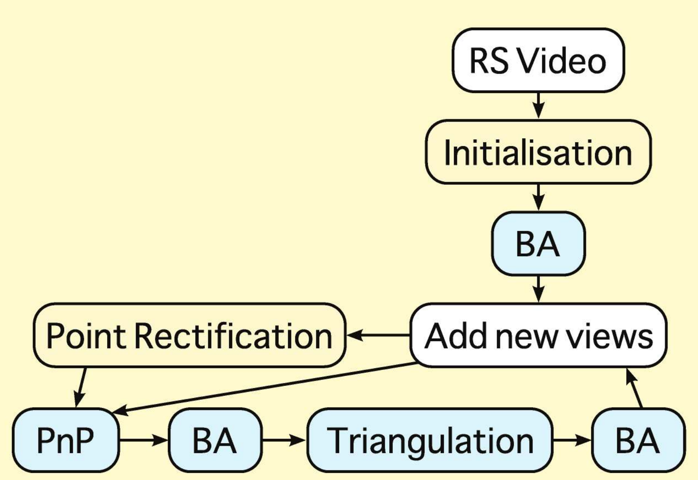
$$\begin{bmatrix} \mathbf{J}_c^T\mathbf{J}_c & \mathbf{J}_c^T\mathbf{J}_m \\ \mathbf{J}_m^T\mathbf{J}_c & \mathbf{J}_m^T\mathbf{J}_m \end{bmatrix} + \lambda\,\mathrm{diag}\begin{bmatrix} \mathbf{J}_c^T\mathbf{J}_c & 0 \\ 0 & \mathbf{J}_m^T\mathbf{J}_m \end{bmatrix} = \begin{bmatrix} \mathbf{U} & \mathbf{W} \\ \mathbf{W}^T & \mathbf{V} \end{bmatrix}. \tag{3}$$

$$\begin{bmatrix} \mathbf{U} & \mathbf{W} \\ \mathbf{W}^T & \mathbf{V} \end{bmatrix}\begin{bmatrix} \Delta\mathbf{c} \\ \Delta\mathbf{m} \end{bmatrix} = -\begin{bmatrix} \mathbf{J}_c^T \\ \mathbf{J}_m^T \end{bmatrix}\mathbf{r}. \tag{4}$$

$$(\mathbf{U} - \mathbf{W}\mathbf{V}^{-1}\mathbf{W}^T)\,\Delta\mathbf{c} = (\mathbf{W}\mathbf{V}^{-1}\mathbf{J}_m^T - \mathbf{J}_c^T)\,\mathbf{r}. \tag{5}$$

$$\Delta\mathbf{m} = -\mathbf{V}^{-1}(\mathbf{J}_m^T\mathbf{r} + \mathbf{W}^T\Delta\mathbf{c}). \tag{6}$$

SfM Pipeline



iPad

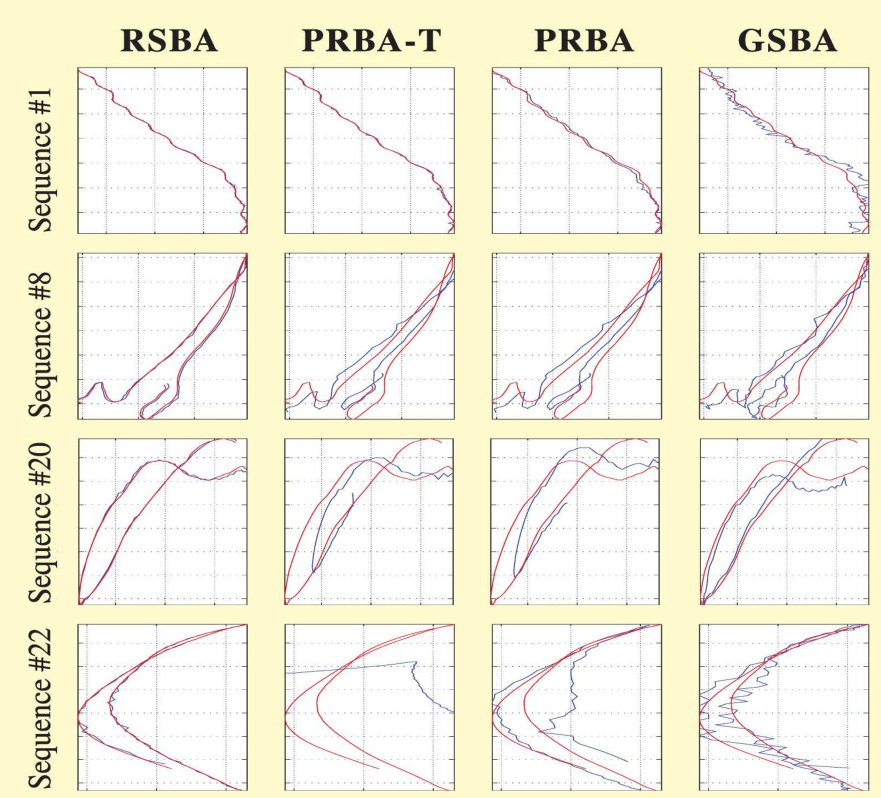
Evaluation

- "Ground truth" from a Canon S95, prosumer, large GS sensor, wide angle re-projection error ~0.2 pixel + Smooth trajectories without regularization
- Rolling Shutter Camera: iPhone 4, 720p ~30ms read-out time re-projection error ~0.6 pixel

- Evaluation on an extensive data set
- 36 Scenes, where a subset is shown here
- Varying camera motion (forward, sideways and rotation)

Result

- **RSBA**: Rolling Shutter Bundle Adjustment
- **PRBA-T**: Pre-rectification Bundle Adjustment Including outlier detection
- **PRBA**: Pre-rectification Bundle Adjustment (Hedborg et al. ICCV Workshop, 2011)
- **GSBA**: "Classical" Global Shutter Bundle Adjustment



seq#	1	2	3	4	5	6	7	8	9
RSBA	0.042	0.124	**0.096**	0.129	**0.088**	0.126	**0.019**	**0.500**	**0.154**
PRBA-T	**0.039**	**0.101**	0.125	**0.128**	0.968	0.247	0.033	2.600	0.154
GSBA	0.341	0.230	0.154	0.230	0.680	**0.122**	0.085	1.960	0.271
PRBA	0.182	1.150	0.127	2.860	0.988	0.247	0.033	2.590	0.154
seq#	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
RSBA	**0.534**	**0.032**	**0.091**	**0.116**	**0.029**	**0.066**	**0.179**	**0.055**	**0.591**
PRBA-T	1.110	0.068	0.192	0.240	0.286	0.092	0.208	0.060	3.280
GSBA	1.080	0.082	0.217	0.471	0.203	0.154	0.308	0.135	0.679
PRBA	1.360	0.066	0.194	0.242	0.344	0.093	0.208	0.060	3.280
seq#	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**
RSBA	4.590	**0.049**	**0.018**	**0.123**	**0.089**	**0.244**	**0.387**	**0.425**	**0.061**
PRBA-T	**2.370**	0.322	0.061	3.930	0.131	0.407	0.502	1.520	0.238
GSBA	135.0	0.235	0.123	0.374	0.170	0.785	0.886	0.585	0.129
PRBA	2.370	0.328	0.078	1.140	0.185	0.476	0.539	1.340	0.269
seq#	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
RSBA	**0.584**	**0.102**	**0.309**	0.701	**0.060**	**0.191**	**0.068**	**0.036**	**0.026**
PRBA-T	3.320	0.104	6.990	1.360	0.233	1.080	0.153	0.083	0.039
GSBA	0.952	0.235	0.714	**0.679**	0.180	0.798	0.204	0.110	0.071
PRBA	3.330	0.644	7.390	16.00	0.233	1.090	0.153	0.081	0.186