3D with Rolling Shutter

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What is the Rolling Shutter Effect?

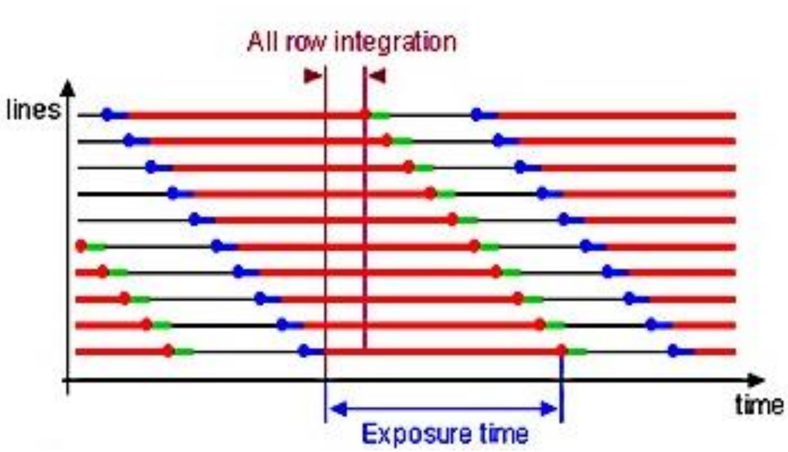
GS - Global shutter

RS - Rolling shutter (most cameras)

youtu.be/7TGKFdrY9aw

How does the Rolling Shutter work?

- **Images scanned line by line**



- **The effect**

The good

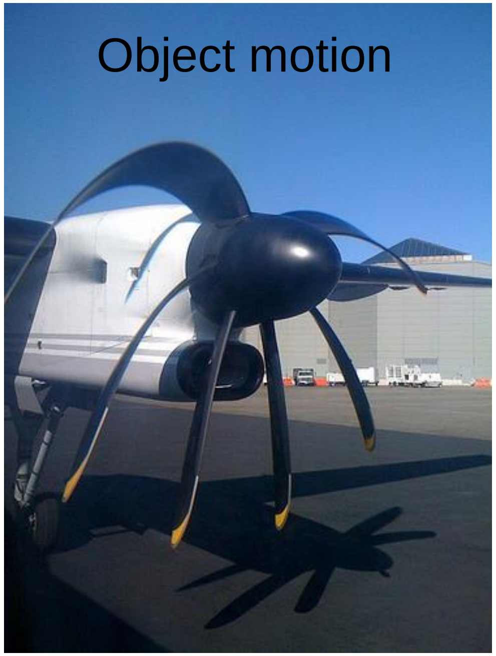
- Higher frame rate
- Longer exposure time
- Cheaper and easier to manufacture

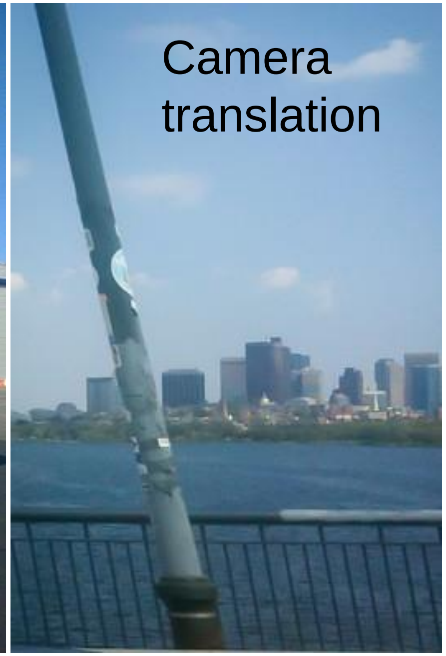
The bad

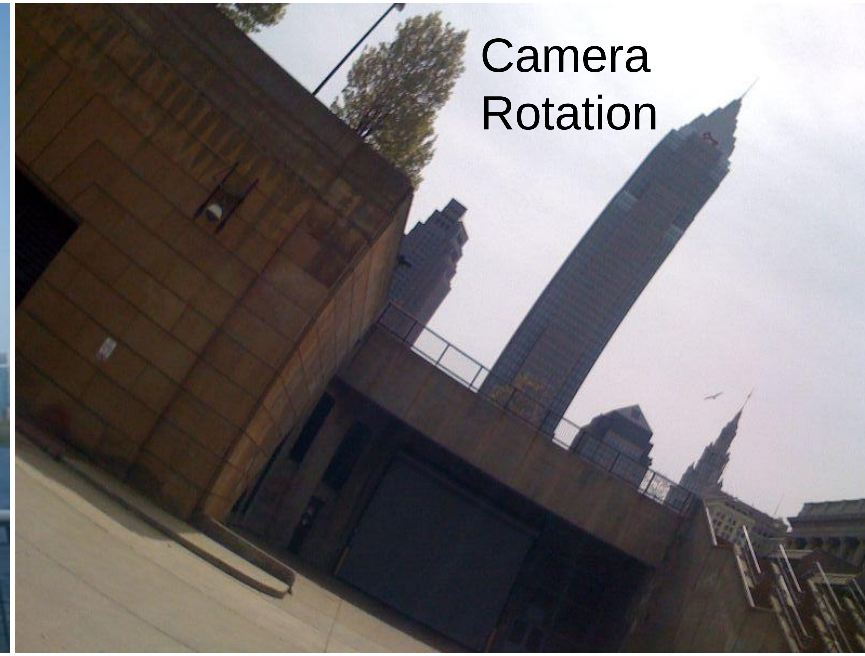
- Image distortions
- Non-perspective projections

How does the Rolling Shutter look?

And the ugly...







String
oscillations

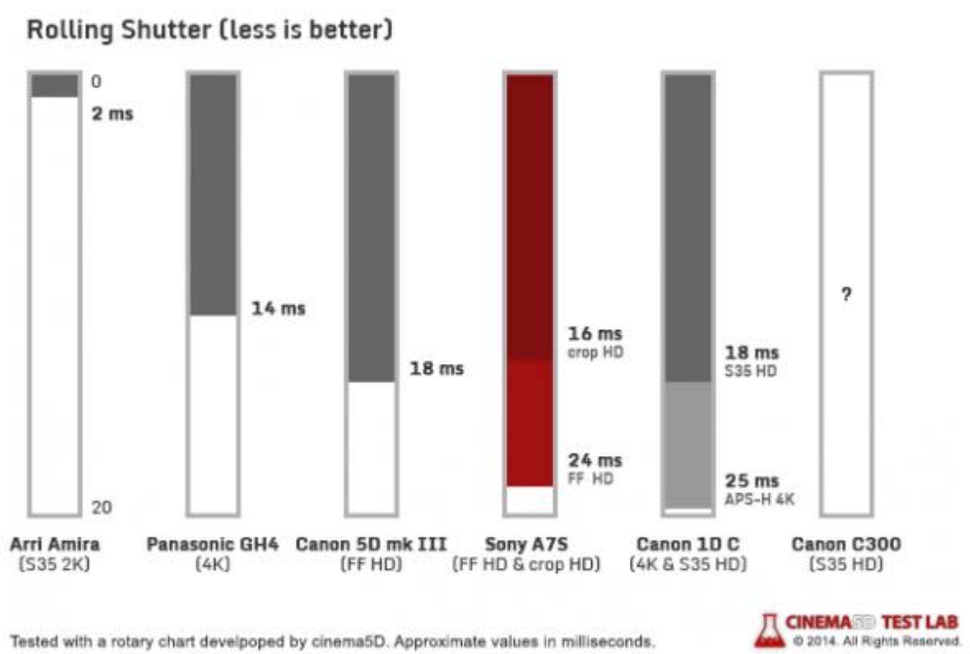
http://www.red.com/learn/red-101/global-rolling-shutter

Rolling shutter is ubiquitous

- It is in majority of cameras today ranging from cellphones, industrial cameras to professional DSLR



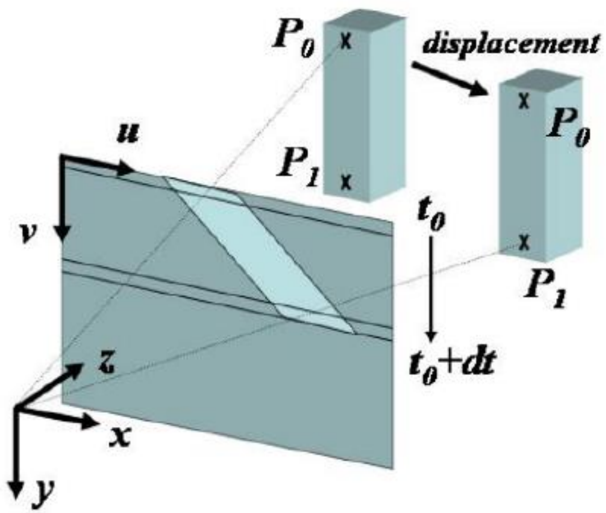

- Affects both videos AND single images
  - Difference between top and bottom can be ~1/30s



Can we take advantage of Rolling shutter?

Object pose and velocity estimation

- O. Ait-Aider et al., ECCV'06
- Shape of the object known
- Image distortion -> object motion

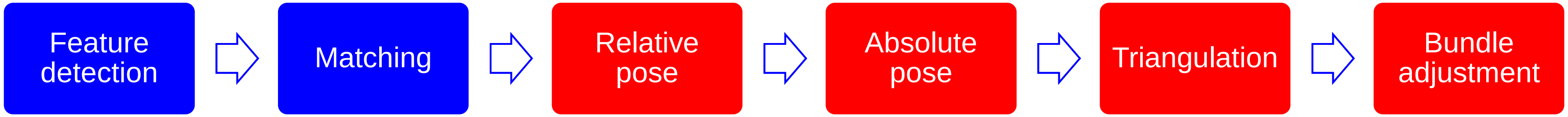


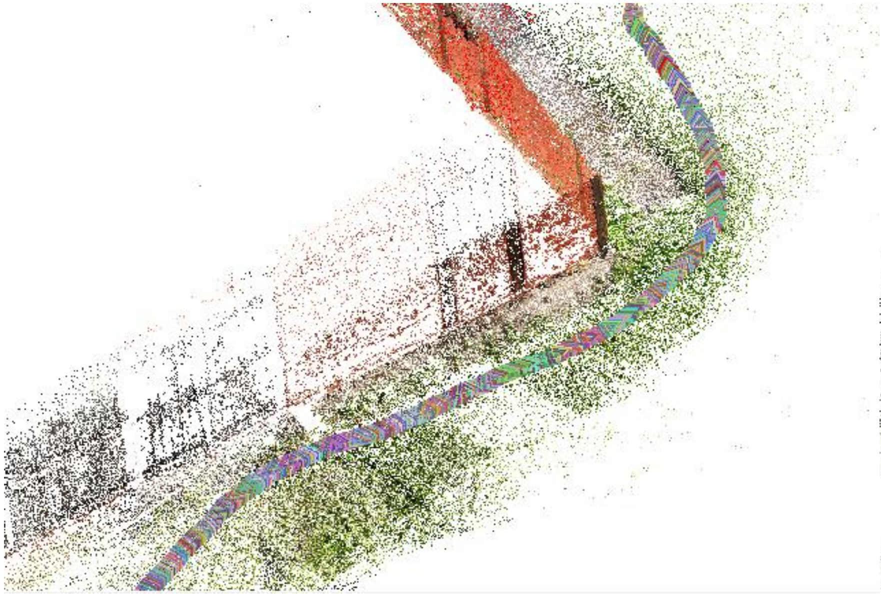
Multi-camera synchronization from flashes

- Smid et al., VISAPP'17
- Frames captured at different times -> different lines illuminated

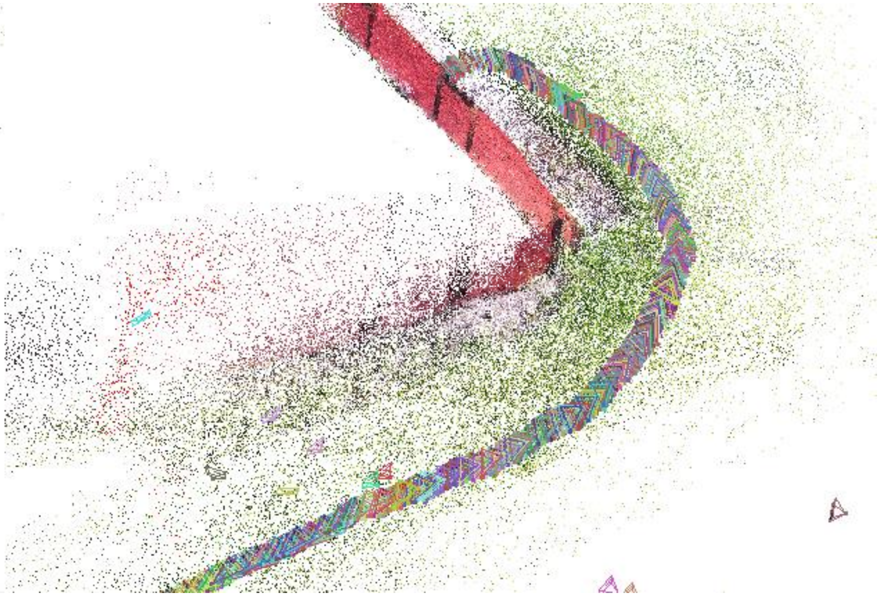
3D Reconstruction with Rolling Shutter

3D reconstruction from RS images ... degraded if ignored

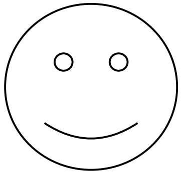


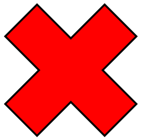


Global shutter (Canon)



Rolling shutter (iPhone 4)

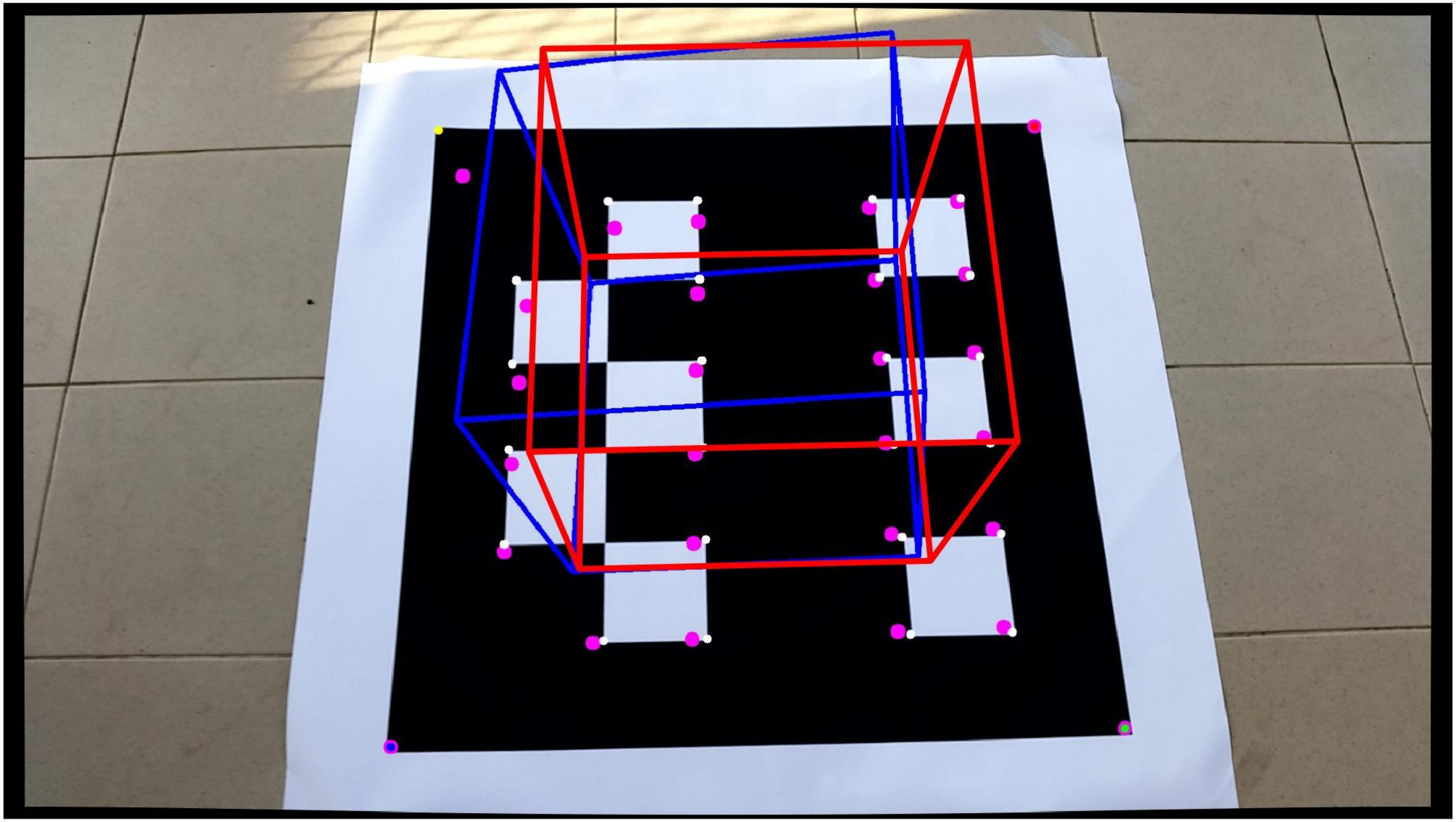




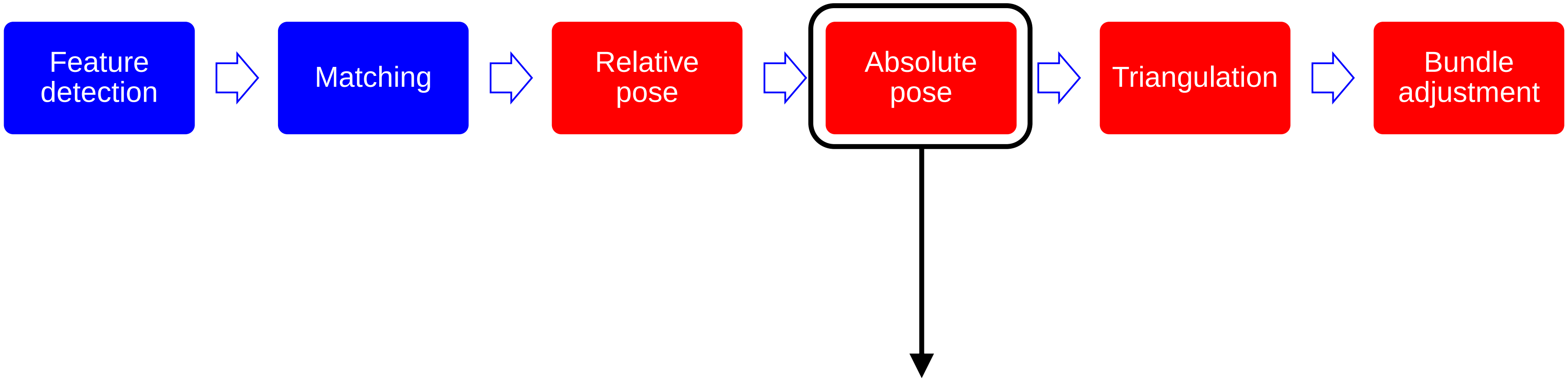
Augmented reality, localization with RS

- **Determining the camera pose**
- **Placing objects in the image**

Perspective camera model
Rolling shutter camera model



Absolute Camera Pose with Rolling Shutter



Absolute camera pose with RS

1. ***R6P - Rolling Shutter Absolute Camera Pose.***
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2. ***Rolling Shutter Absolute Camera Pose Problem with known Vertical Direction.***
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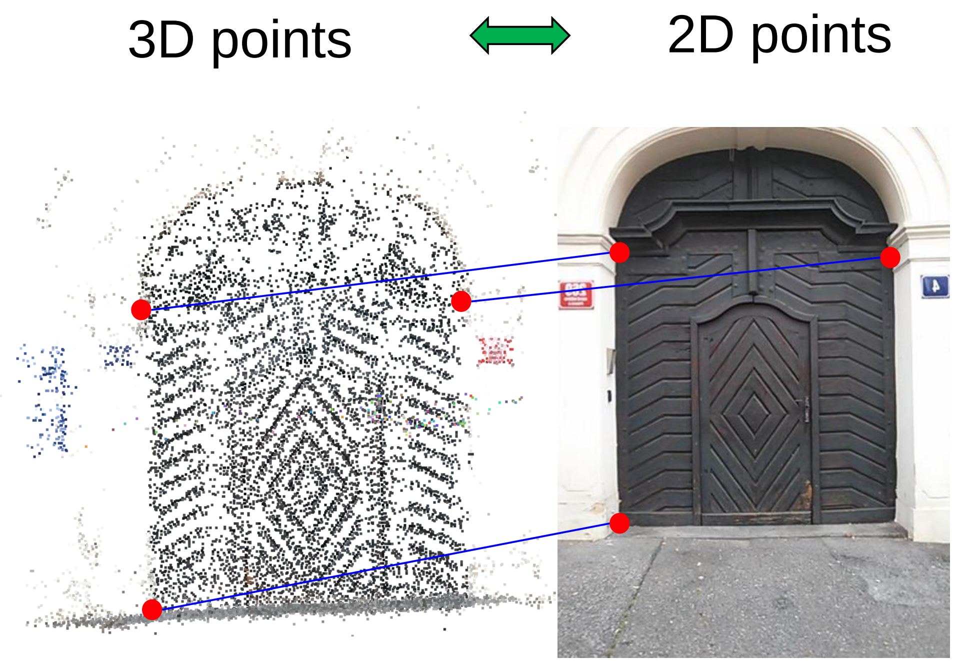
Previous Work

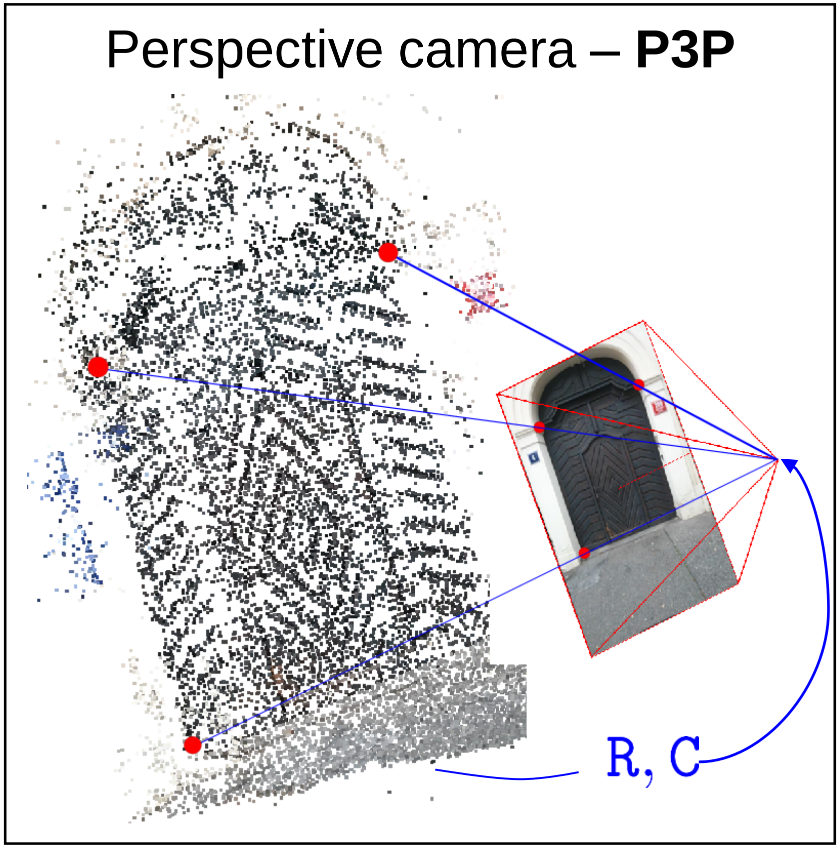
- Klein et al. ISMAR'09, Hedborg et al. CVPR'12

Video sequences only

- Ait-aider et al. ECCV'06
  - Non-linear optimization
  - Initial guess – 8,5 points + planar scene
- Magerand et al. ECCV'12
  - Globally optimal
  - 7 points
  - Sensitive to outliers
  - Slow for RANSAC

Absolute Camera Pose with Rolling Shutter



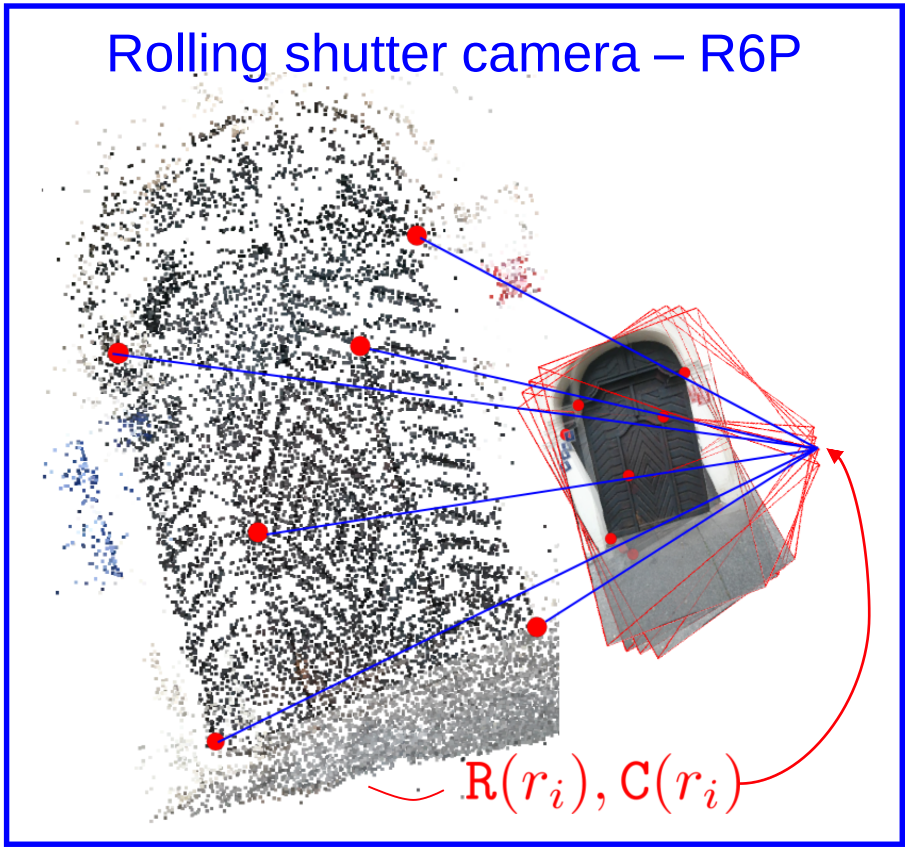


3 correspondences

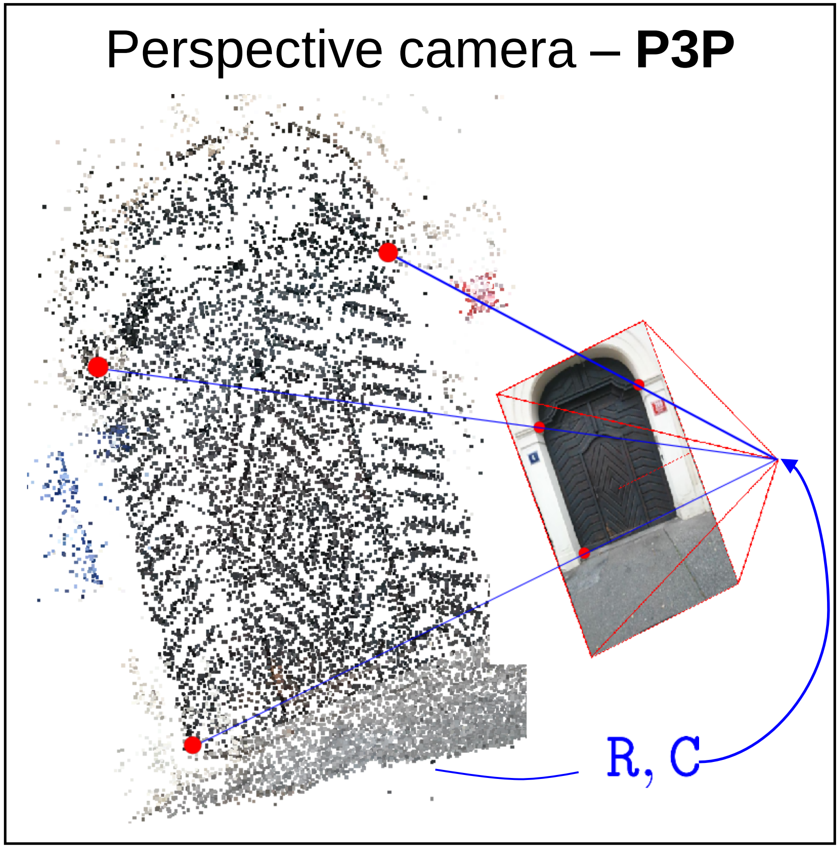
[Haralick CVPR 1991][Quan PAMI 1999]
[Triggs IJCV 1999][Wut JMIV 2006]
[Zhi MMRC 2002][Lepetit IJCV 2009]

Absolute Camera Pose with Rolling Shutter

This work = R6P



6 correspondences



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Rolling Shutter Camera Projection

Standard (calibrated) perspective projection

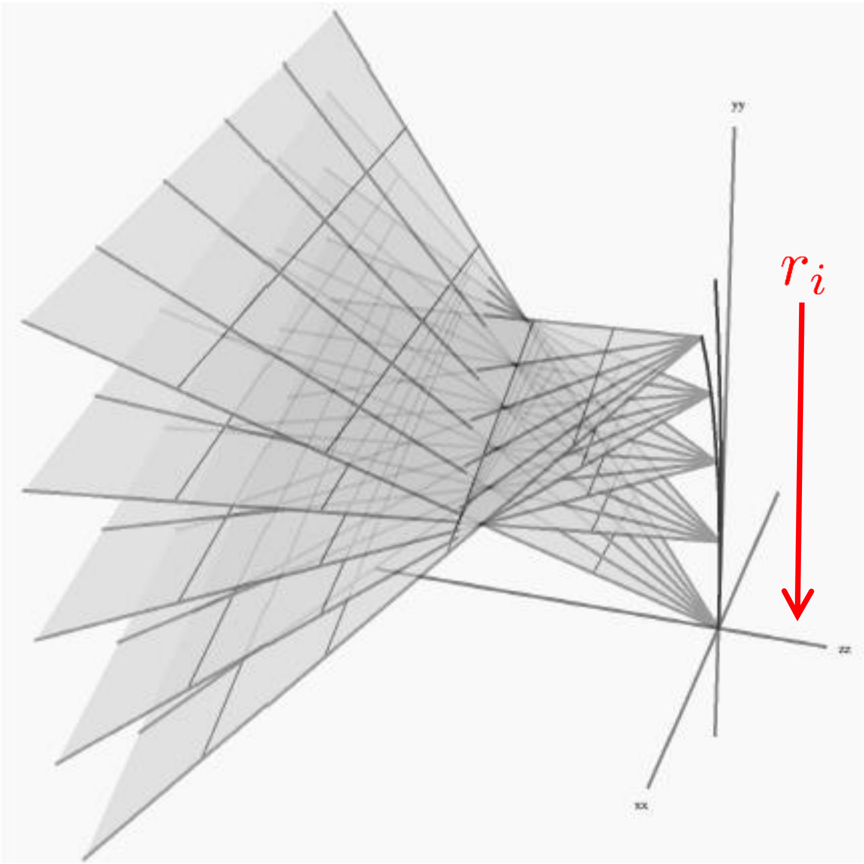
$$\lambda_i \mathbf{x}_i = \mathtt{R}\mathtt{X}_i + \mathtt{C}$$

RS camera undergoing motion

$$\lambda_i \mathbf{x}_i = \begin{bmatrix} r_i \\ c_i \\ 1 \end{bmatrix} = \mathtt{R}(r_i)\mathtt{X}_i + \mathtt{C}(r_i)$$

Camera pose changes for every row

How to model $\mathtt{R}(r_i)$ and $\mathtt{C}(r_i)$?



Picture from Meingast et al.

Rolling Shutter Camera Projection

$$\lambda_i \mathbf{x}_i = \begin{bmatrix} r_i \\ c_i \\ 1 \end{bmatrix} = \mathtt{R}(r_i)\mathbf{X}_i + \mathtt{C}(r_i)$$

Camera initial pose

$$\lambda_i \mathbf{x}_i = \begin{bmatrix} r_i \\ c_i \\ 1 \end{bmatrix} = \mathtt{R}_m(r_i)\mathtt{R}_0\mathbf{X}_i + \mathtt{C} + \mathtt{C}_m(r_i)$$

Motion during capture

Solving in general leads to complicated polynomials

We analyzed several models

- SLERP
- Cayley parameterization
- Linearized
- …
- **Double linear model**

$$\mathtt{C}_m(r_i) = (r_i - r_0)\mathtt{t}$$

[Hedborg CVPR-2012]

Rolling Shutter Double-Linearized Projection

Full projection model

$$\lambda_i \mathbf{x}_i = \begin{bmatrix} r_i \\ c_i \\ 1 \end{bmatrix} = \mathtt{R}_m(r_i)\mathtt{R}_0\mathtt{X}_i + \mathtt{C} + \mathtt{C}_m(r_i)$$

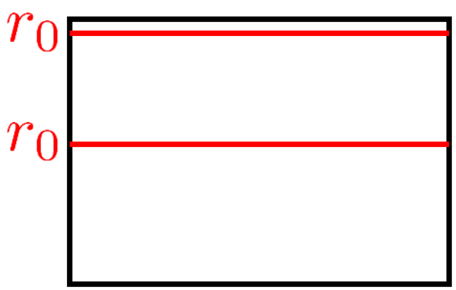
Double-linearized projection model

Camera initial pose

$$\lambda_i \boxed{\begin{bmatrix} r_i \\ c_i \\ 1 \end{bmatrix}} = (\mathtt{I} + (r_i - r_0)[\mathtt{w}]_x)(\mathtt{I} + [\mathtt{v}]_x)\boxed{\mathtt{X}_i} + \mathtt{C} + (r_i - r_0)\mathtt{t}$$

Motion during capture

known



R6P Minimal Solver

$$\lambda_i \begin{bmatrix} r_i \\ c_i \\ 1 \end{bmatrix} = (\mathtt{I} + (r_i - r_0)[\mathtt{w}]_x)(\mathtt{I} + [\mathtt{v}]_x)\mathtt{X}_i + \mathtt{C} + (r_i - r_0)\mathtt{t}$$

Camera initial pose

Motion during capture

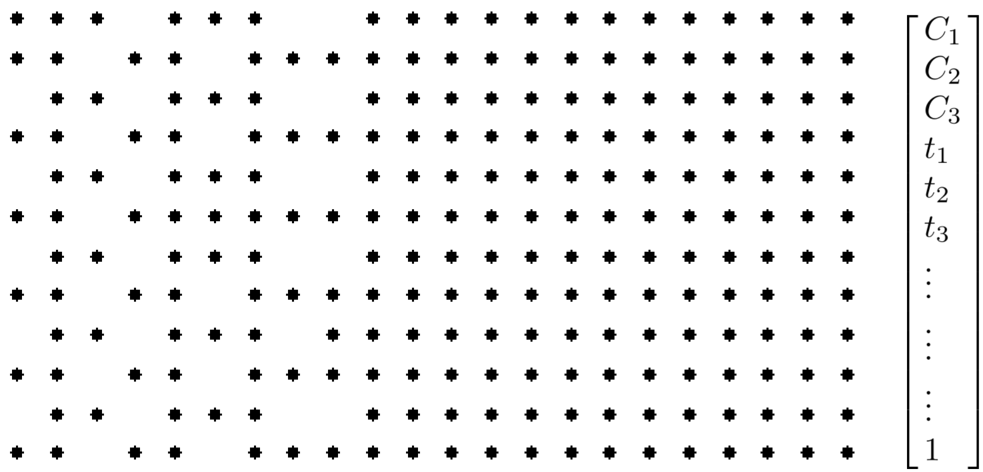
known

- 12 unknowns → 6 3D-2D correspondences
- A system of 12 equations in 12 unknowns and 22 monomials
- Automatic generator of Gröbner basis solvers [Kukelova ECCV 2008]
- Can we do better?

Constructing R6P Solver

12 linearly independent equations (12x22 matrix … 22 monomials)

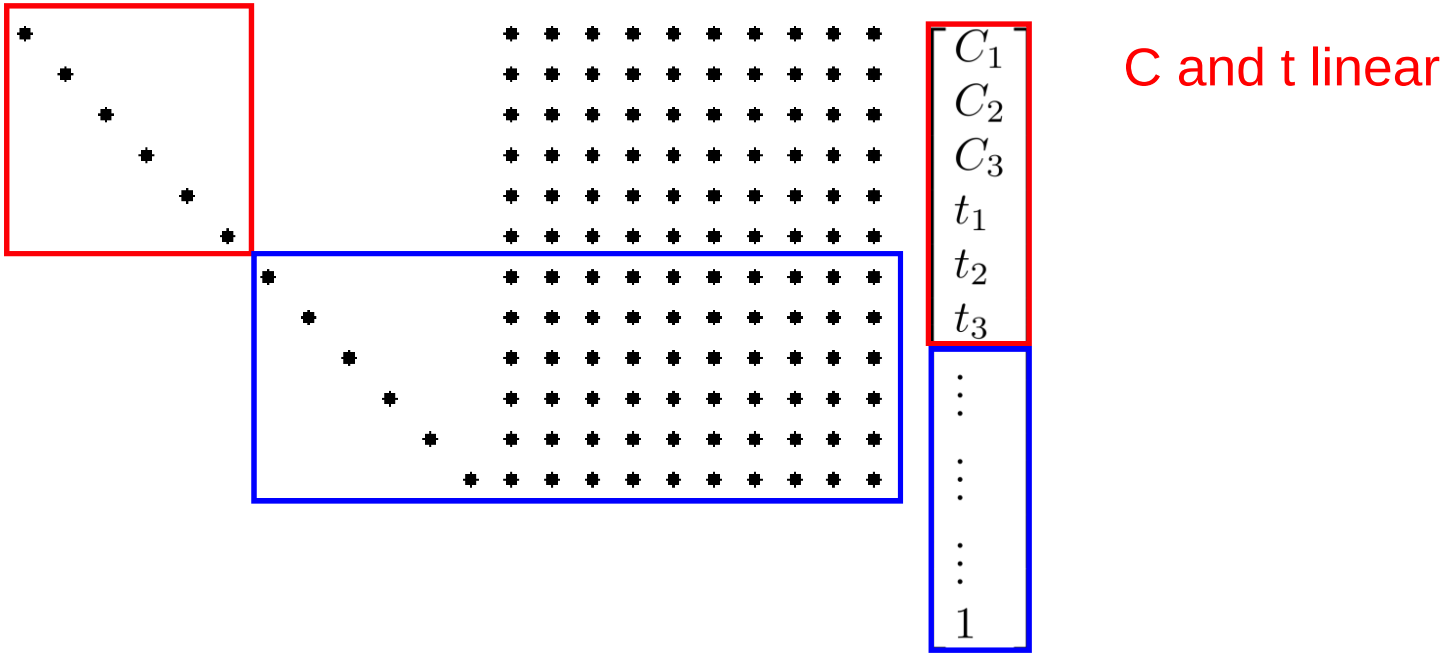
Matrix form



= 0

Constructing R6P Solver

Simplify by Gauss-Jordan elimination



6 equations, 6 unknowns v & w (16 monomials)

Solve for v & w → back-substitution → C & t

Can we do even better?

Constructing R6P Solver

The remaining 16 monomials are bilinear in v and w

$$v_1, v_2, v_3, w_1, w_2, w_3, v_1w_1, v_1w_2, v_2w_1, v_1w_3, v_2w_2, v_3w_1, v_2w_3, v_3w_2, v_3w_3$$

We can write $\mathtt{M}(v)\begin{bmatrix} w_1 \\ w_2 \\ w_3 \\ 1 \end{bmatrix} = 0$, where $\mathtt{M}(v)$ is a 6x4 matrix

4x4 subdeterminants of $\mathtt{M}(v)$ must be zero

↓

15 equations in 3 variables and 35 monomials

Use automatic generator of Gröbner basis solvers [Kukelova ECCV 2008] to solve for v

0.3ms in C++ (Eigen)

Double linearization … Initialization need

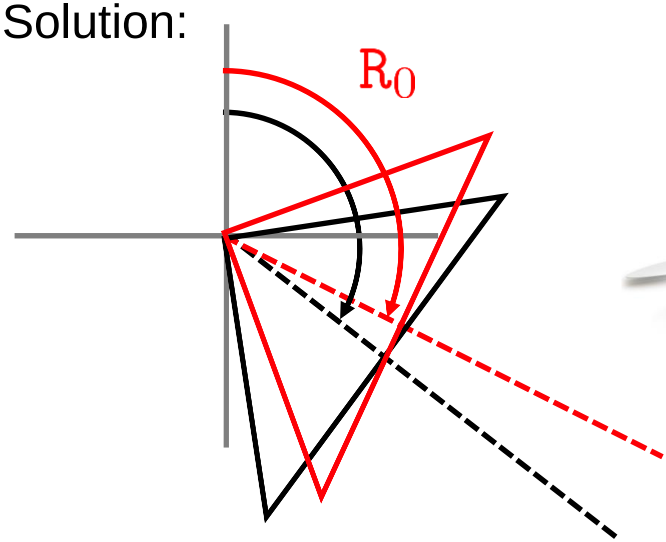
Linearization of rotation

$$\lambda_i \begin{bmatrix} r_i \\ c_i \\ 1 \end{bmatrix} = (\mathtt{I} + (r_i - r_0)[\mathtt{w}]_x)(\mathtt{I} + [\mathtt{v}]_x)\mathtt{X}_i + \mathtt{C} + (r_i - r_0)\mathtt{t}$$

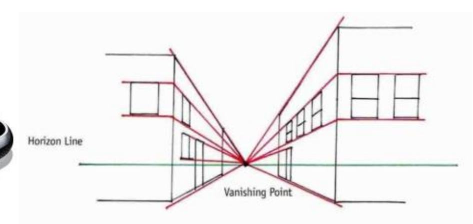
OK – small rotation during the capture

NOT OK – rotation can be arbitrary

Solution:



P3P → R6P



IMU → R6P

Synthetic Experiments

Synthetic data

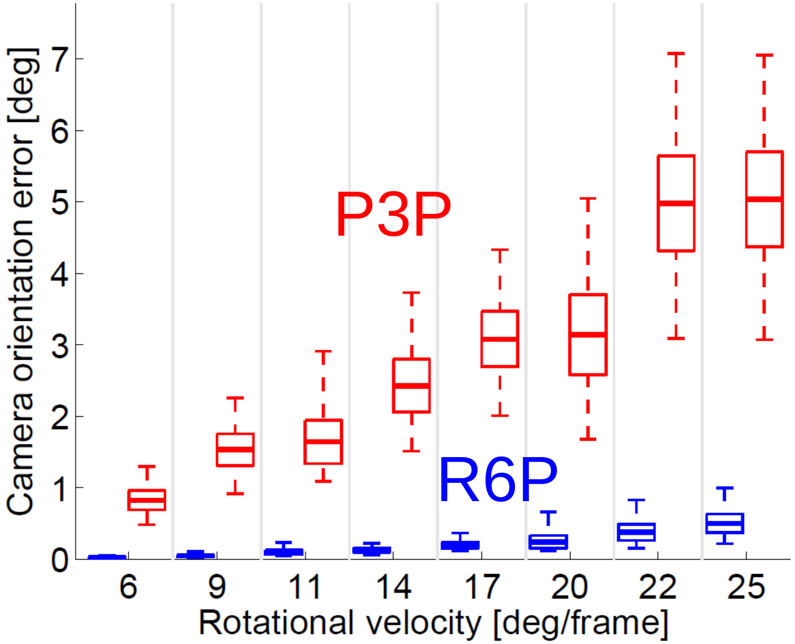
- Compared $\mathtt{R}(\mathtt{v}), \mathtt{R}(\mathtt{w}), \mathtt{C}, \mathtt{t}$ to GT
- Camera pose accuracy

Camera pose accuracy

- Orientation < 0.5°
- Position < 2%

Significant improvement over P3P

Increasing RS effect



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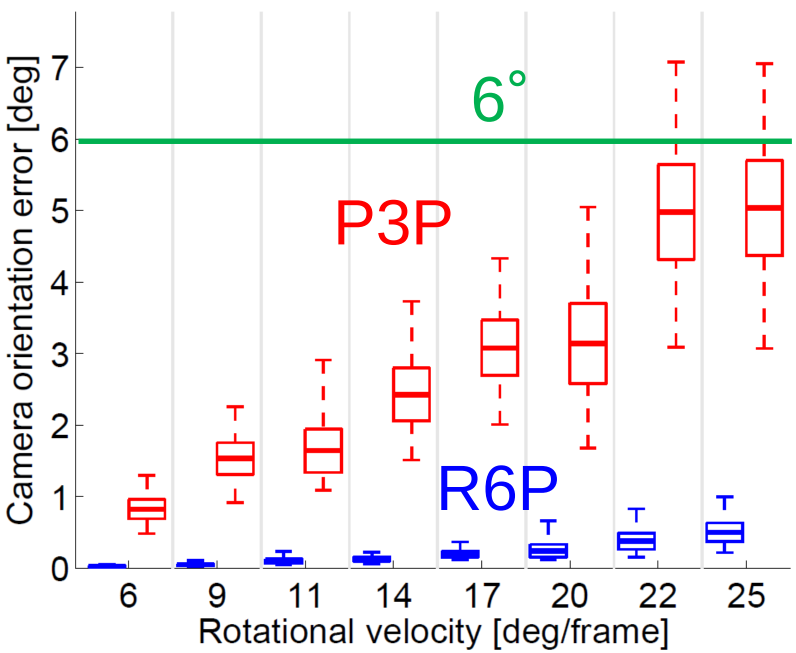
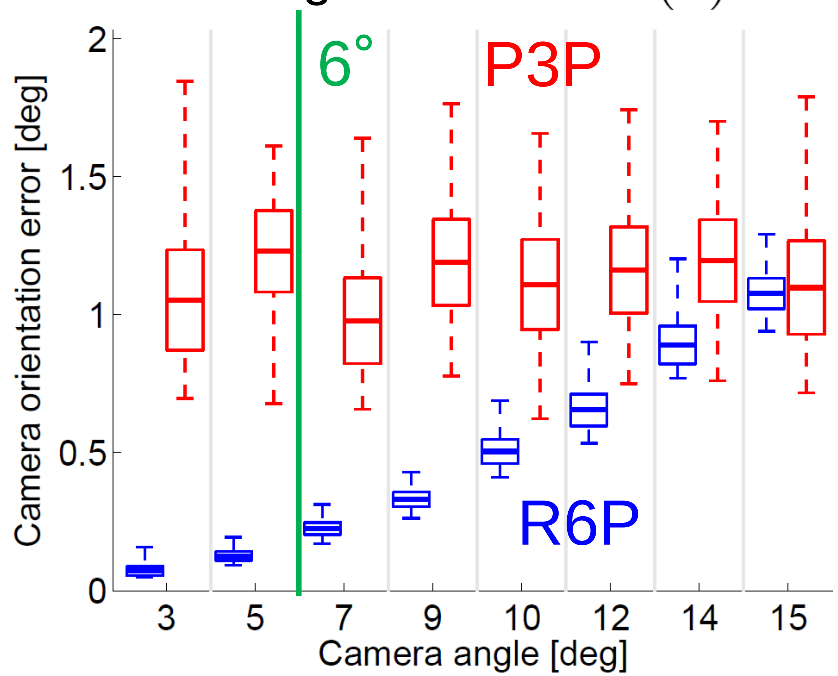


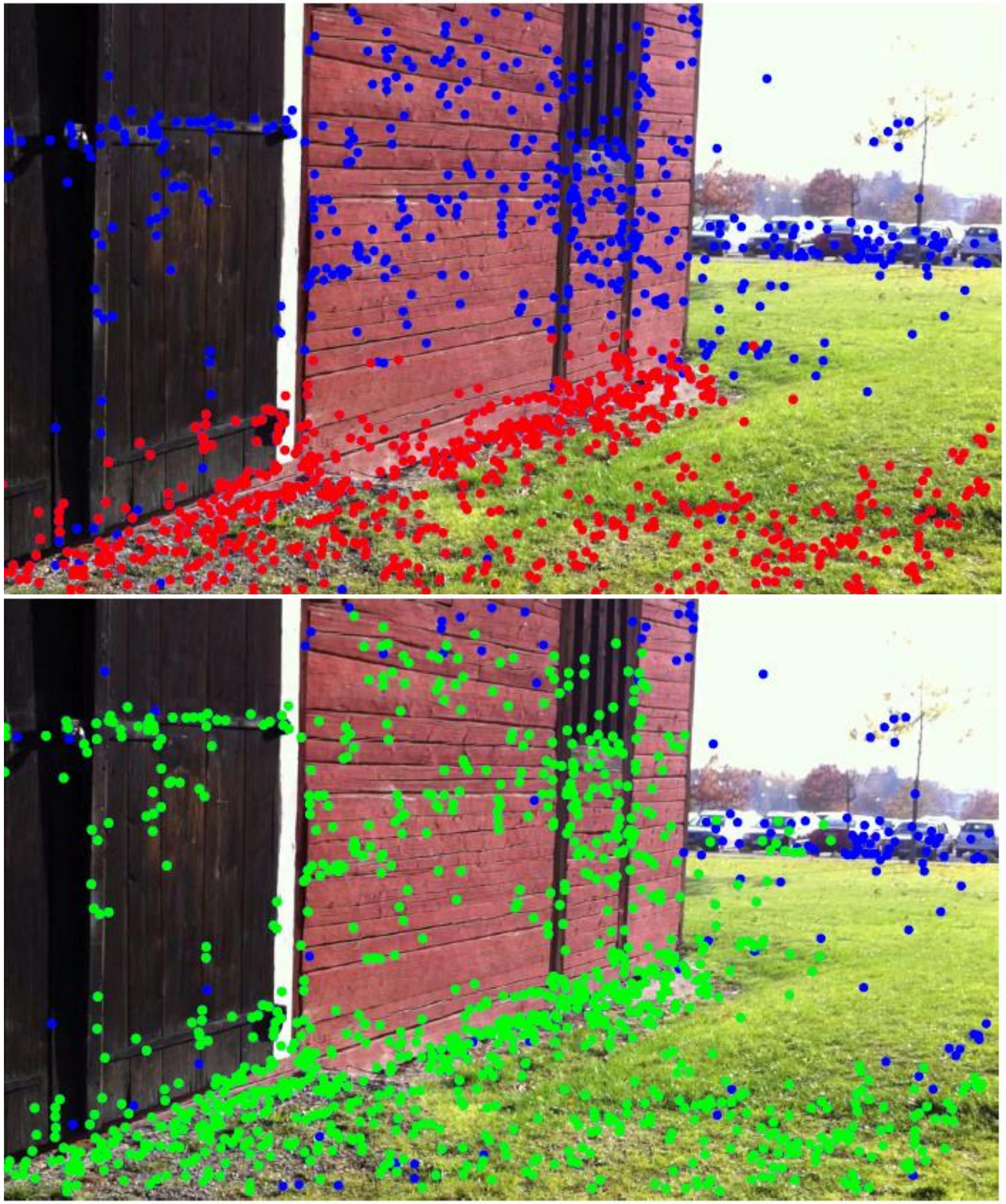
Increasing distance of $\mathtt{R}(\mathtt{v})$ from $\mathtt{I}$



Real Experiments

P3P inliers
788

R6P inliers
1152

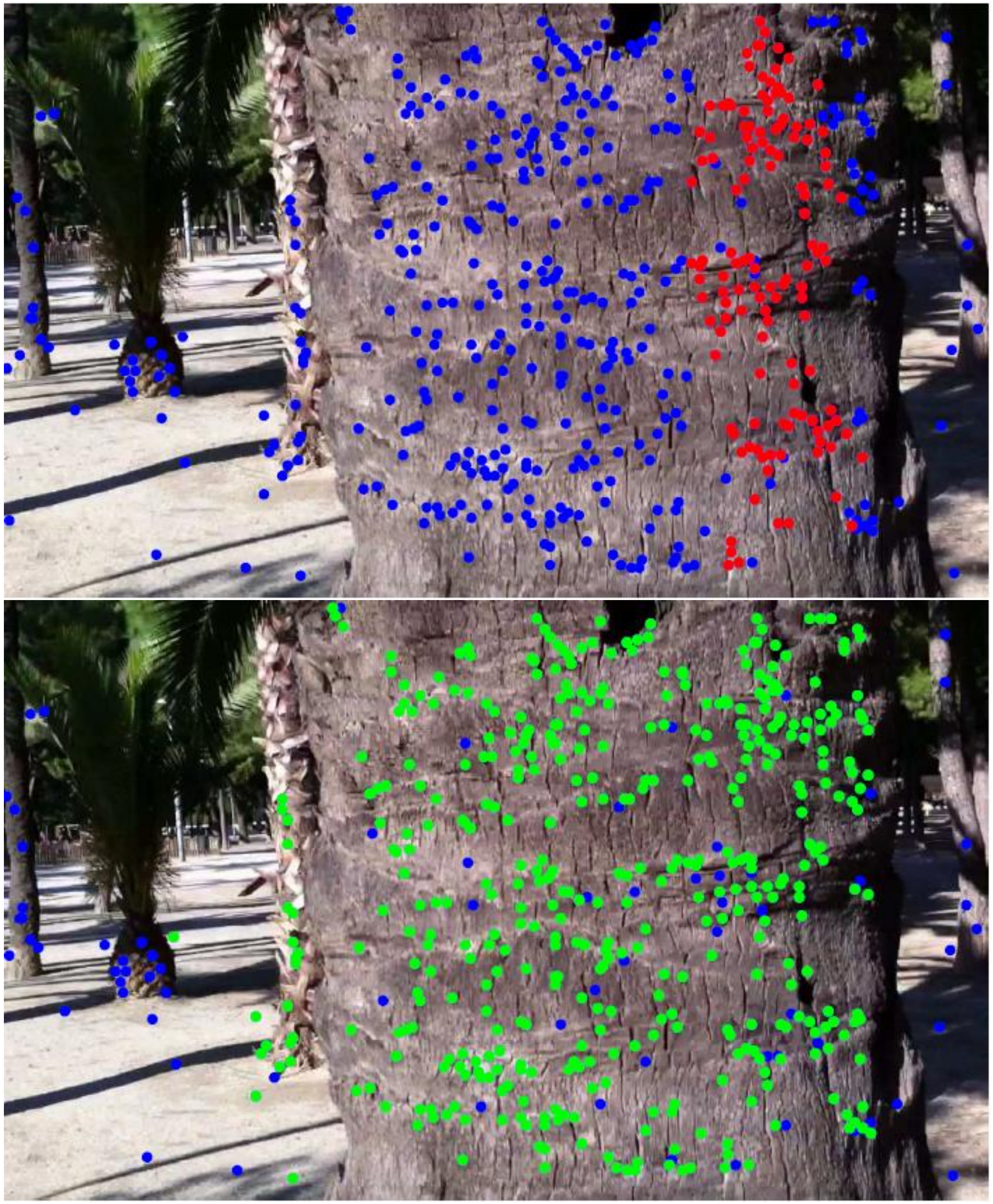


Data from
Hedborg et.al,
CVPR12

Real Experiments

P3P inliers
139

R6P inliers
465

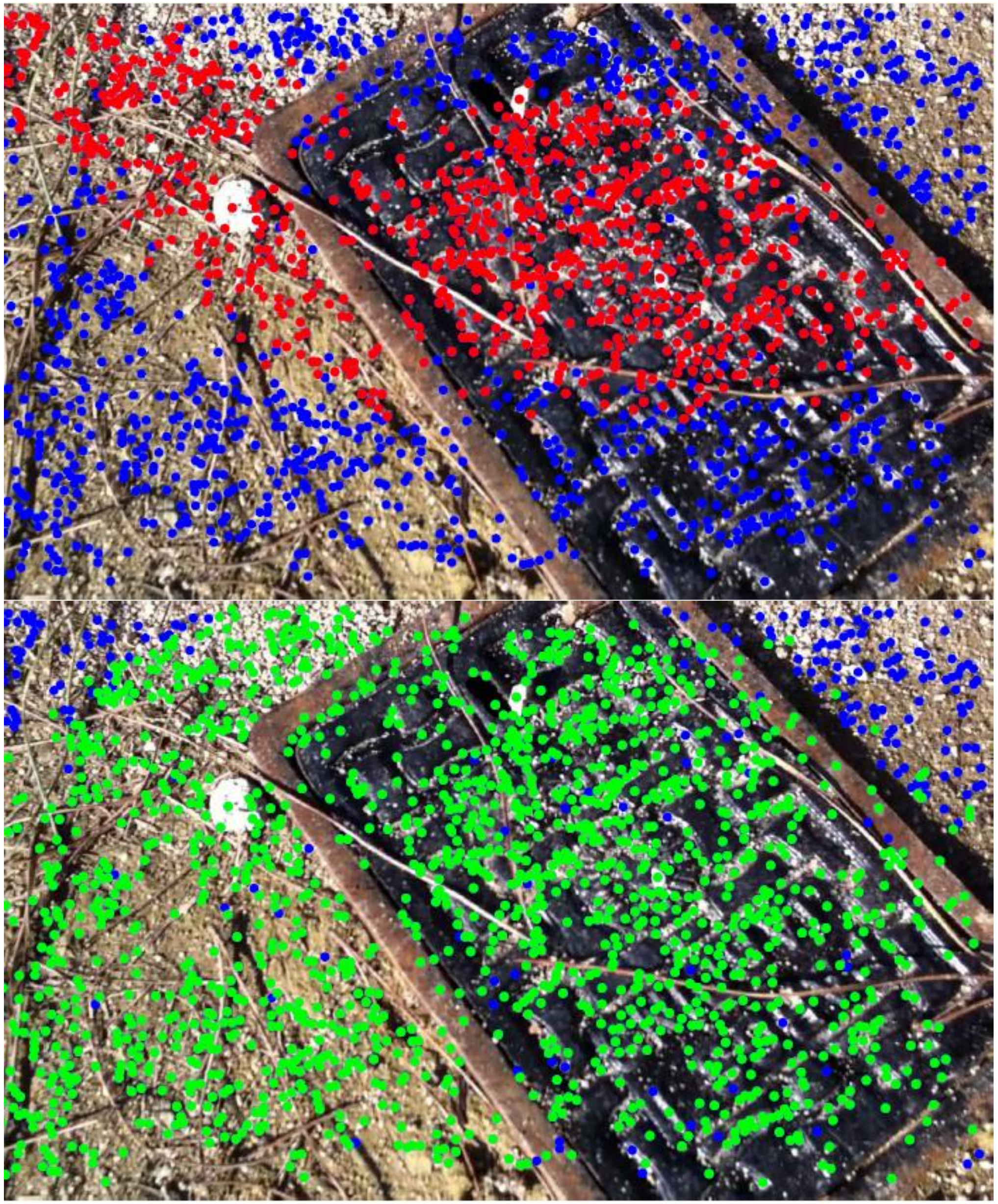


Data from
Hedborg et.al,
CVPR12

Real Experiments

P3P inliers
937

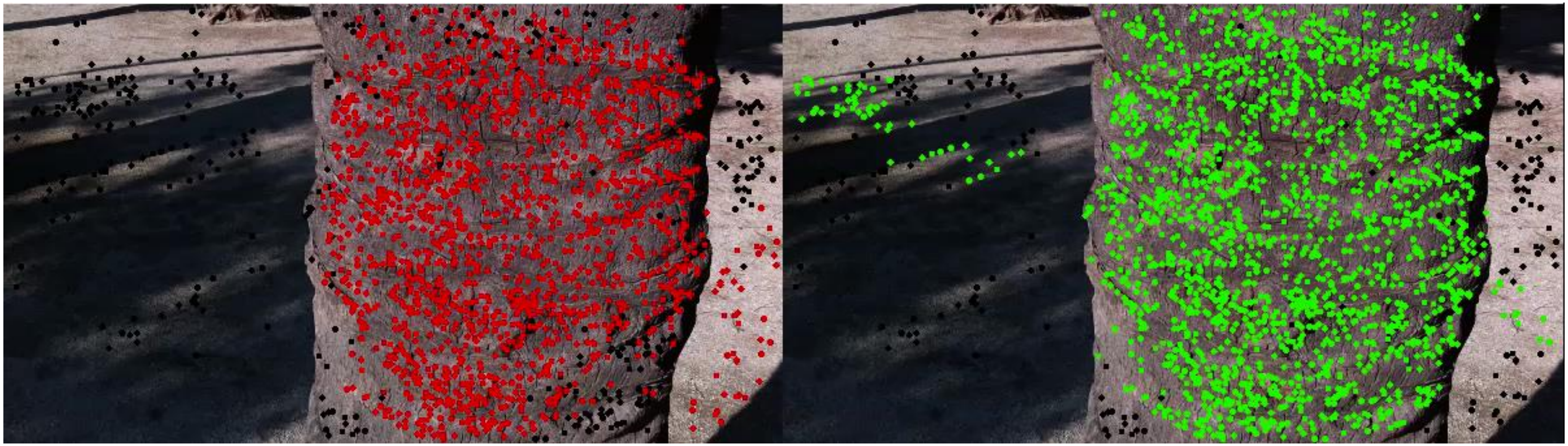
R6P inliers
1742



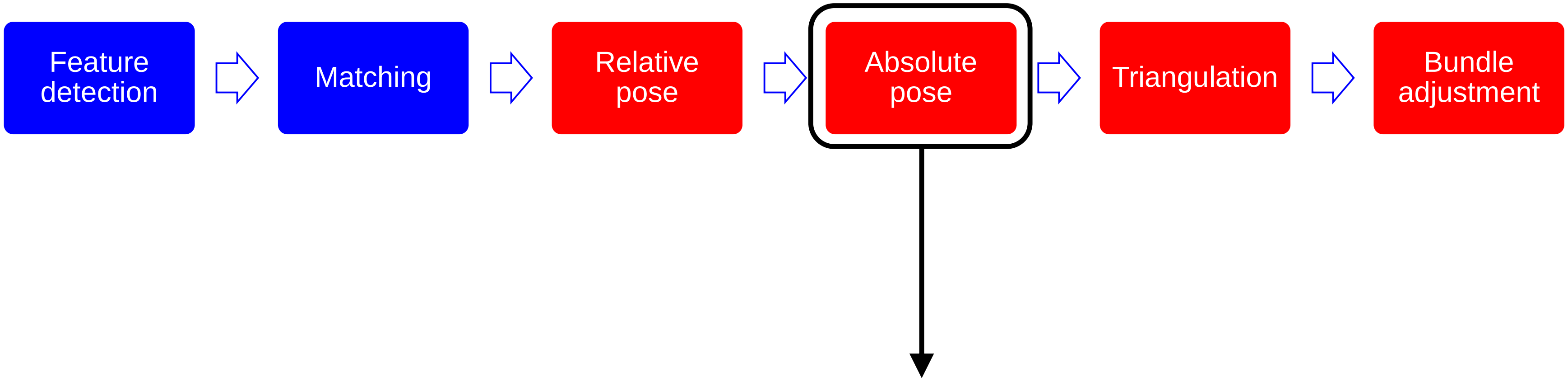
Data from Hedborg et.al, CVPR12

Real experiments

P3P (inliers in red) R6P (inliers in green)



Absolute Camera Pose with Rolling Shutter



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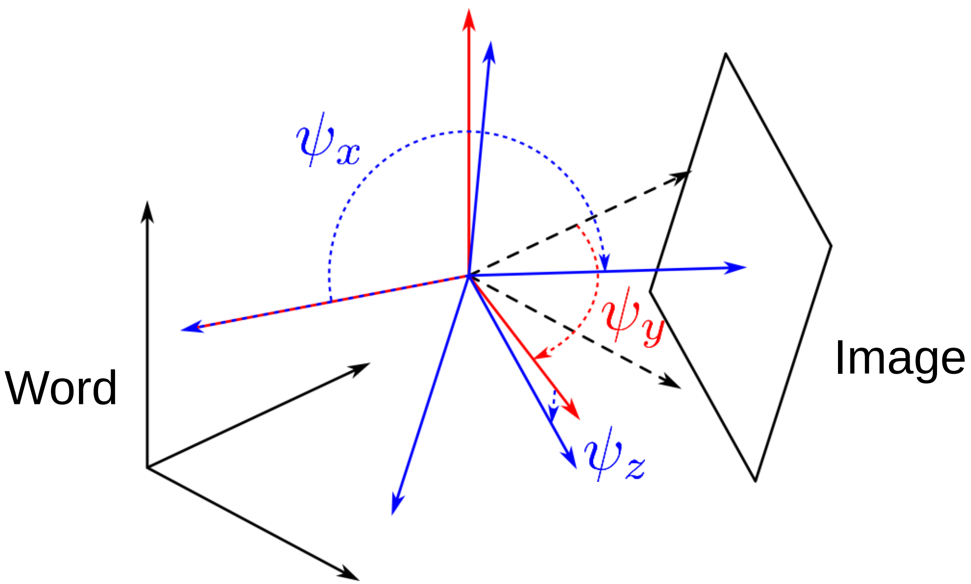
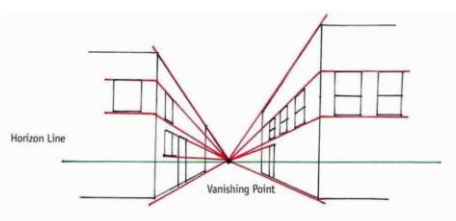
R5P – Rolling Shutter Absolute Pose (with UP Vector)

- UP-vector known (IMU, vanishing points, …)
- Needs only 5 correspondences
- Solved by hidden variable resultant method
- Faster – 0.1 ms

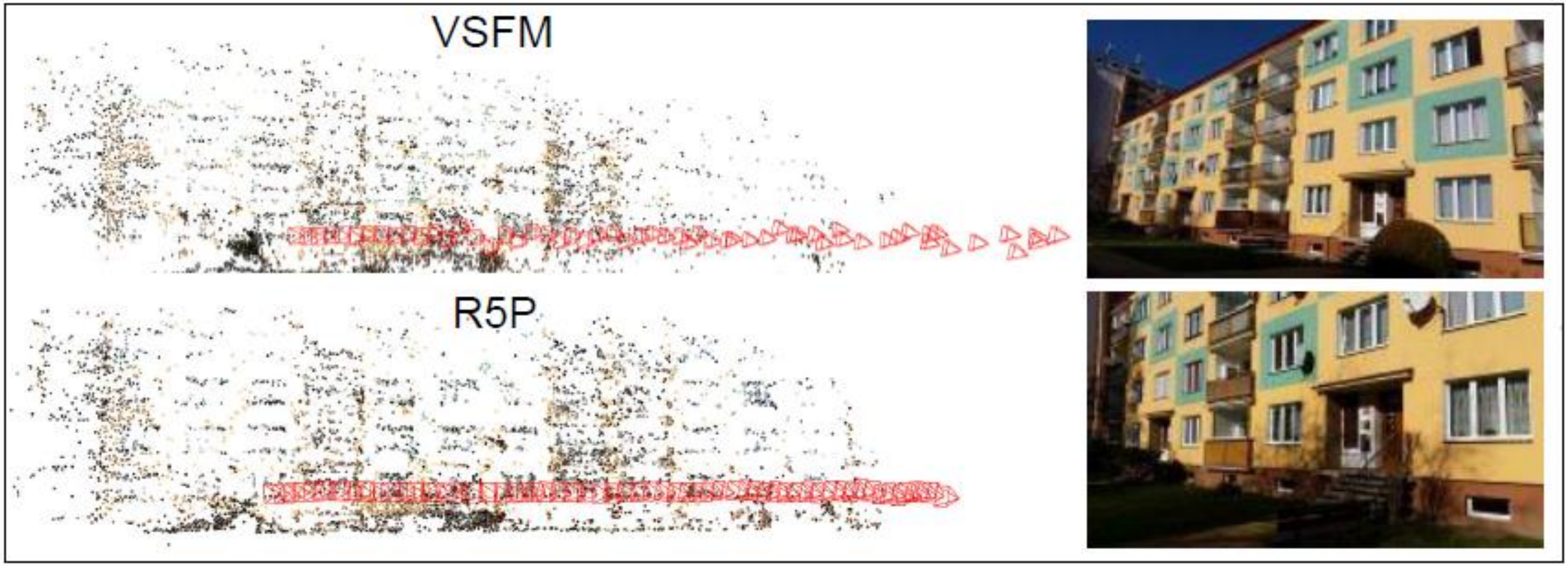
Unkown Known (IMU, vanishing points, …)





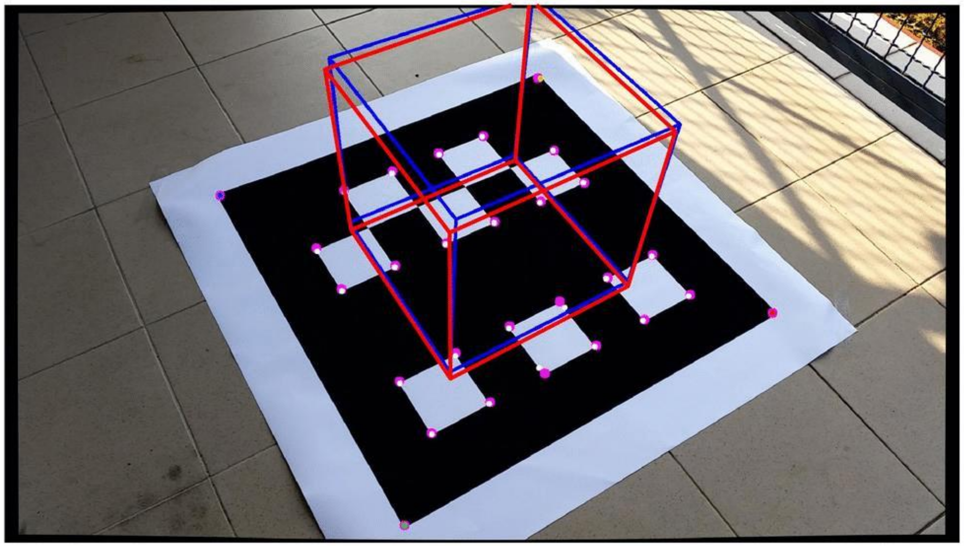
Rolling Shutter Absolute Camera Pose Problem with known Vertical Direction.
C. Albl, Z. Kukelova, T Pajdla. ICCV 2015.

R5P – RS Absolute Pose with UP Vector – SFM & VR

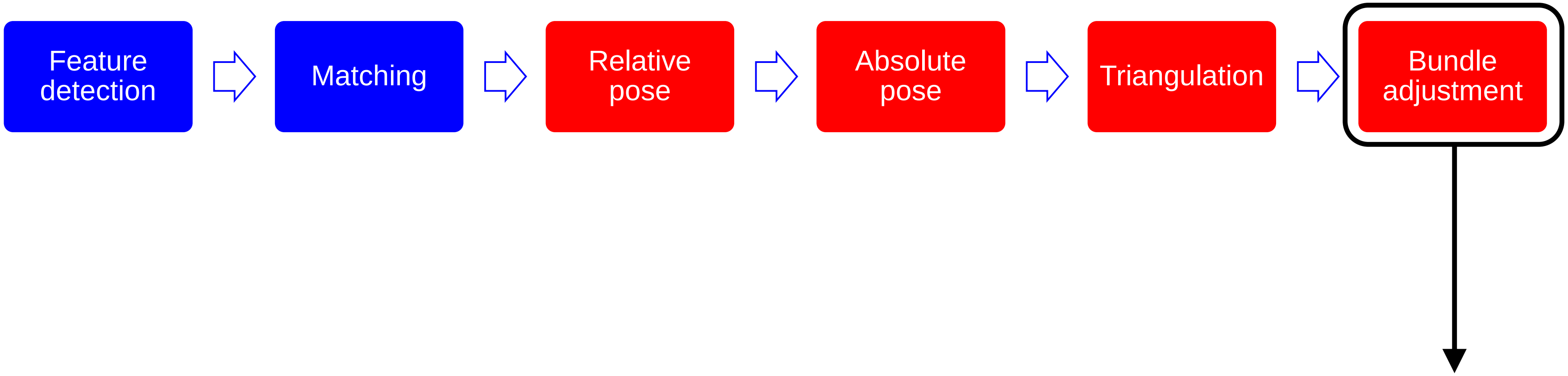


P3P

R5Pup



Rolling Shutter Bundle Adjustment



RS Bundle Adjustment

Degeneracies in Rolling Shutter SfM
C. Albl, A. Sugimoto, T Pajdla. ECCV 2016.

RS BA on RS Images helps for videos

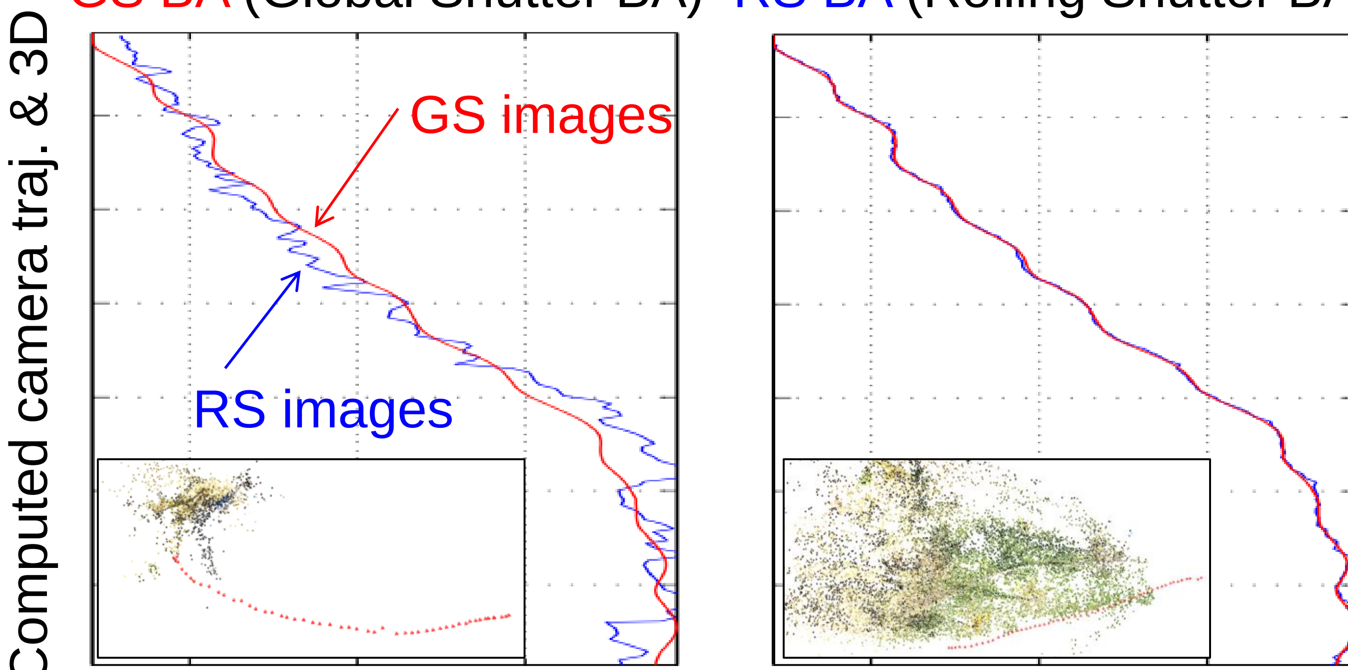
Global shutter camera

moves together with

Rolling shutter camera

RS BA improves over GS BA
on videos
when
motion during capture constrained
motion between captures

GS BA (Global Shutter BA) RS BA (Rolling Shutter BA)



Rolling shutter bundle adjustment. J. Hedborg, P. E. Forssen, M. Felsberg, E. Ringaby. CVPR 2012.

Rolling Shutter BA - Motivation

- Can we reconstruct general unordered sets of images?
  - motions during and between image capture are independent
- Why would we do that?
  - Rolling shutter is present even in still images
  - Computing entire video is expensive
- We need Rolling Shutter Bundle Adjustment for unordered image sets

Bundle Adjustment with RS Model

Projection model (full, linearized, …)

Motion between captures

$$\alpha_i \mathbf{u}_i = \alpha_i \left[c_i, r_i, 1\right]^\top = \mathrm{R}_r(r_i)\mathrm{R}_0\mathbf{X}_i + \mathbf{C}_0 + r_i\mathbf{t}$$

Motion during captures

Image reprojection error

$$\mathbf{e}_i^j = \tilde{\mathbf{u}}_i^j - \mu(\pi(\mathrm{P}^j(\tilde{r}_i), \mathbf{X}_i)) \qquad \mu([x, y, z]^\top) = [x/z, y/z]^\top$$

Image measurement

Projection model

Perspective projection

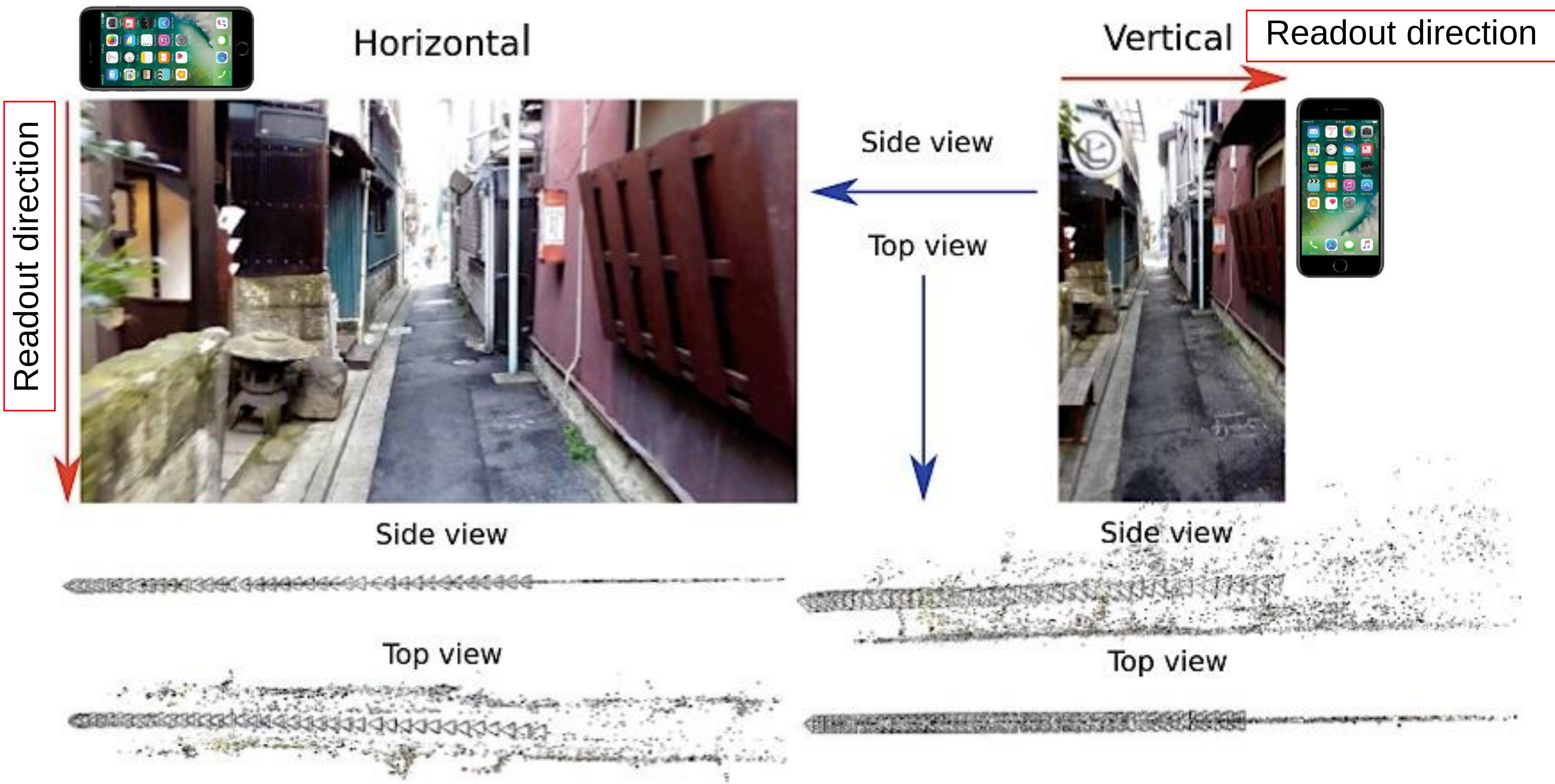
Bundle adjustment (minimizes the SOS of reprojection errors)

$$(\mathrm{P}^{j*}, \mathbf{X}_i^*) = \arg\min \sum_{(i,j)} \|\mathbf{e}_i^j\|^2 \qquad \mathrm{P}(r) = [\mathrm{R}_r(r), \mathrm{R}_0, \mathbf{C}_0, \mathbf{t}]$$

Many parameters per camera

RS BA Fails for Unstructured Images

- Rolling Shutter BA flattens 3D in the readout direction



- for RS & GS cameras … problem with the RS model
- RS model has more freedom … more degenerate situations

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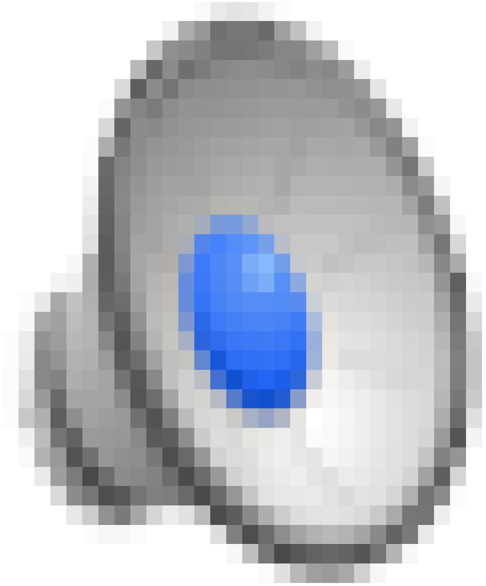

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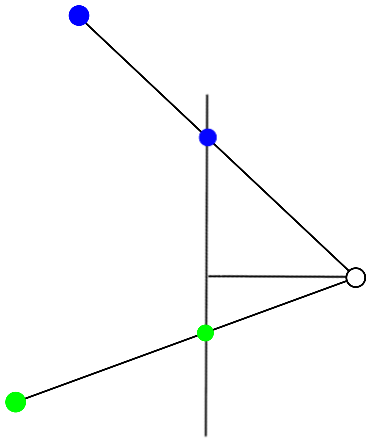
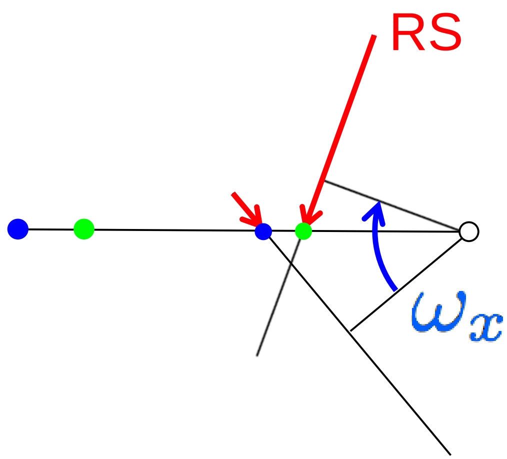
1 image – Degenerate – 3D explained by 2D

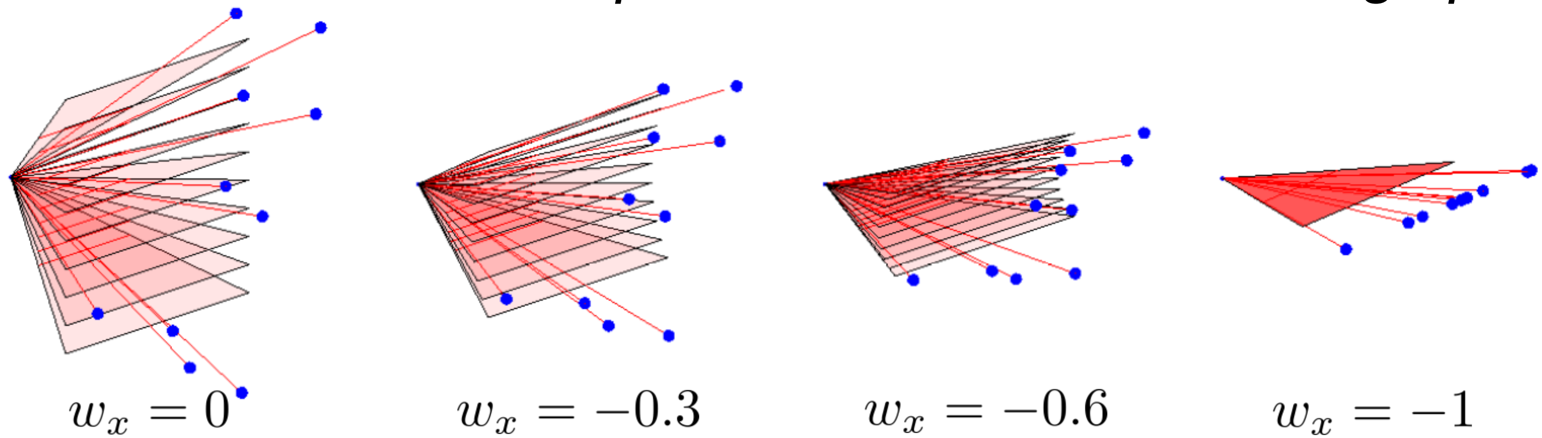
Camera rotation compensates RS scanning to explain 3D by 2D





Global Shutter & 3D *explained by* Rolling Shutter & 2D

when camera motion speed matches RS scanning speed

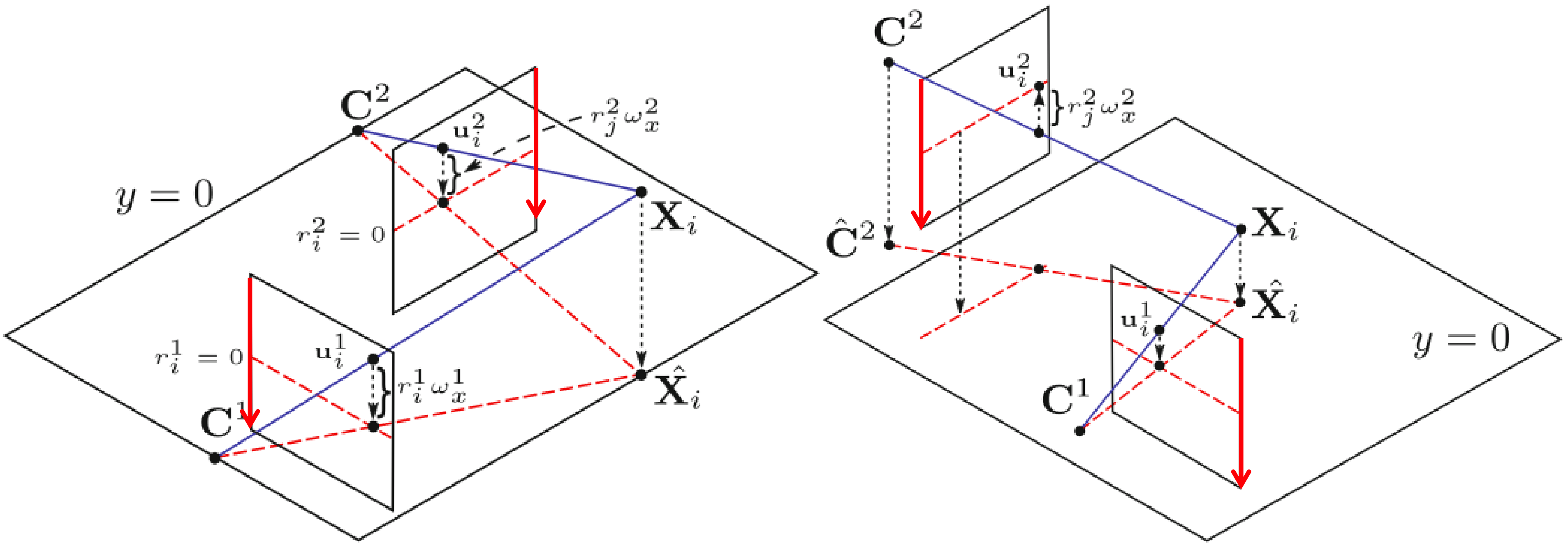


N images – Degenerate – 3D explained by 2D

N images with aligned (parallel) readout directions

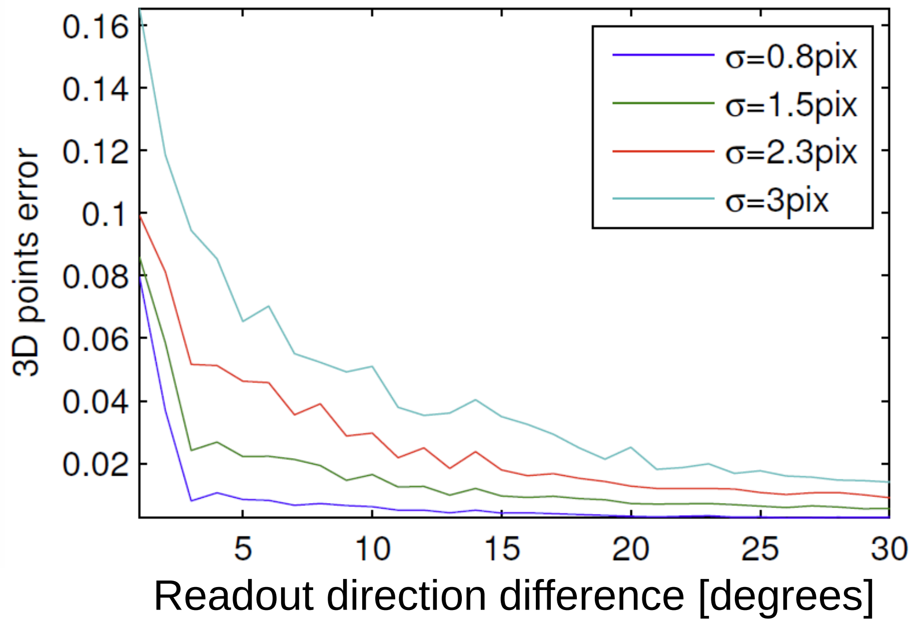
⇓

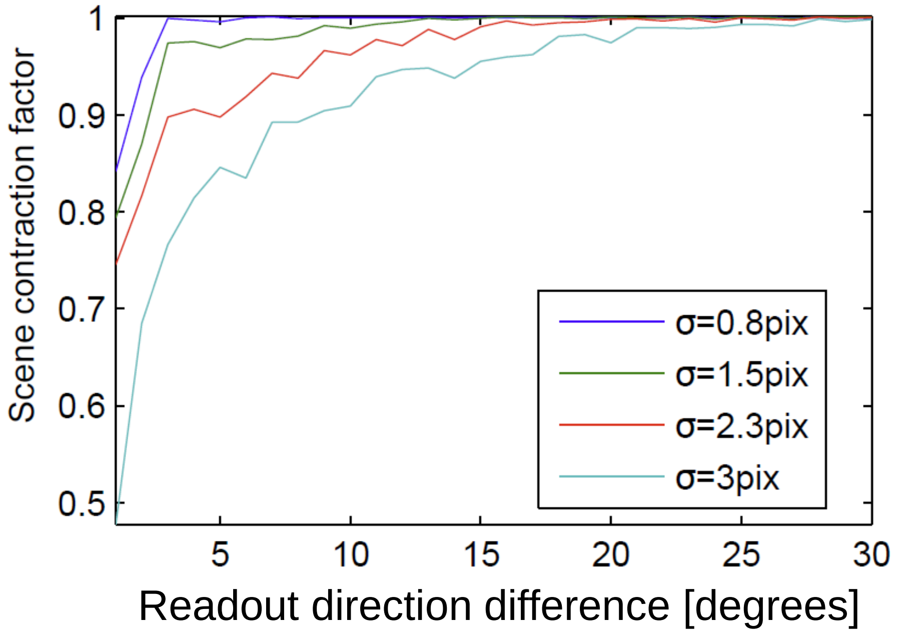
Images can be explained by a 2D scene



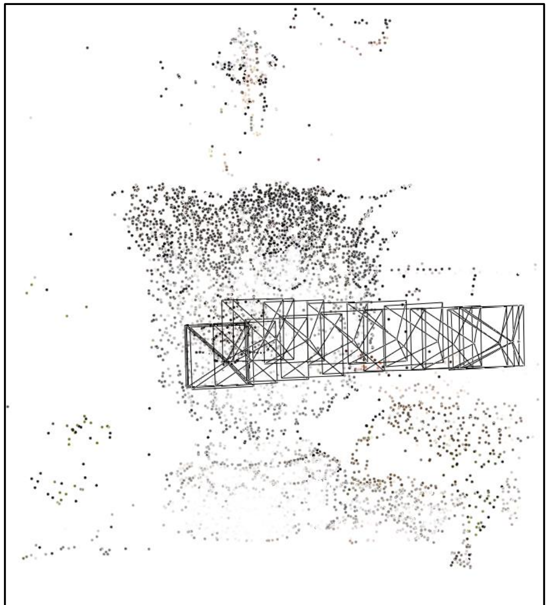
All images explained by a planar scene
in the plane perpendicular to the scanning directions

Practice: Similar readout directions are BAD

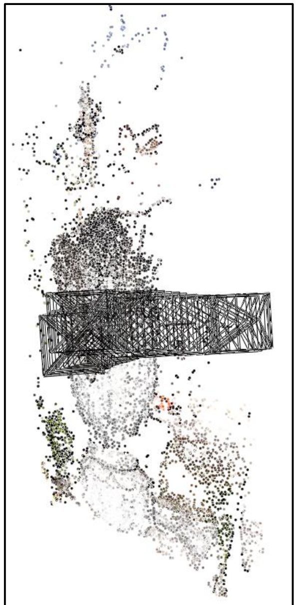




“Ciorrect” reconstruction



“Distorted” reconstruction



Why does BA do that?

Degenerate solution has usually lower re-projection error

Might increase

$$\mathbf{e}_i^j = \begin{bmatrix} e_{ix}^j \\ e_{iy}^j \end{bmatrix} = \tilde{\mathtt{u}}_i^j - \mu \left(\mathtt{R}_r^j(\tilde{r}_i^j)\mathtt{R}_0^j\mathtt{X}_i + \mathtt{C}^j + \tilde{r}_i^j\mathtt{t}^j \right) = \begin{bmatrix} \tilde{c}_i^j - \frac{C_x^j + x\cos(\phi^j) + z\sin(\phi^j)}{C_z^j + z\cos(\phi^j) - x\sin(\phi^j)} \\ 0 \end{bmatrix}$$

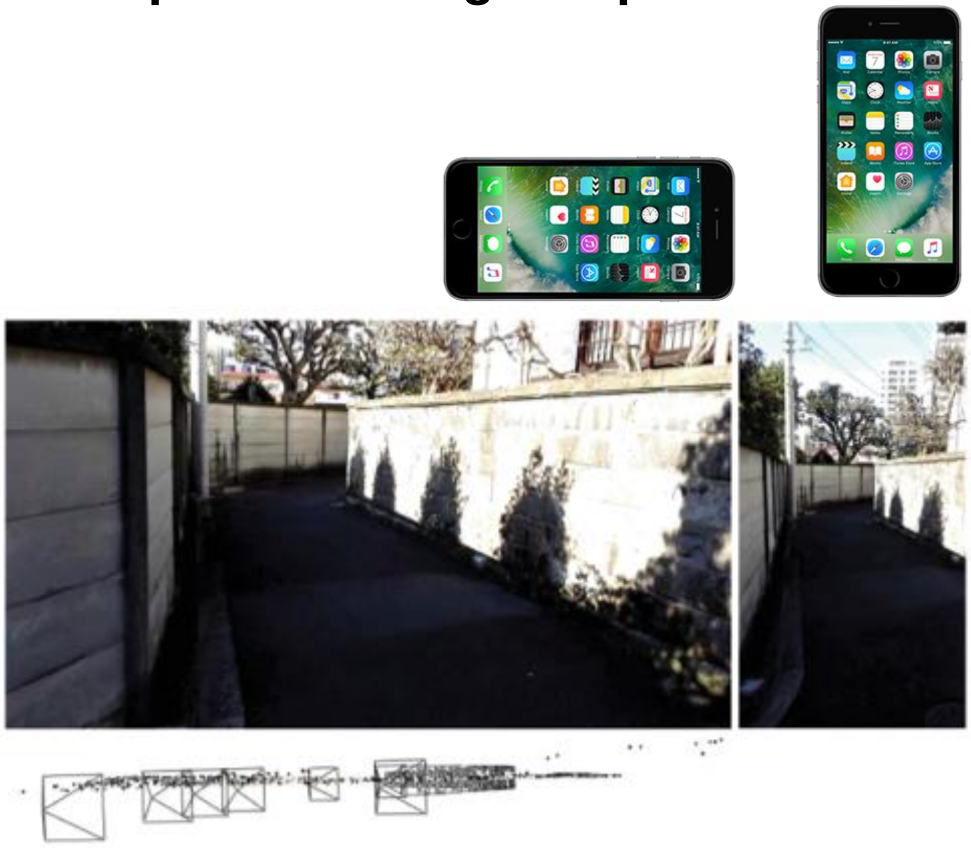
Gone

More similar readout directions – less increase in e_{ix}^j

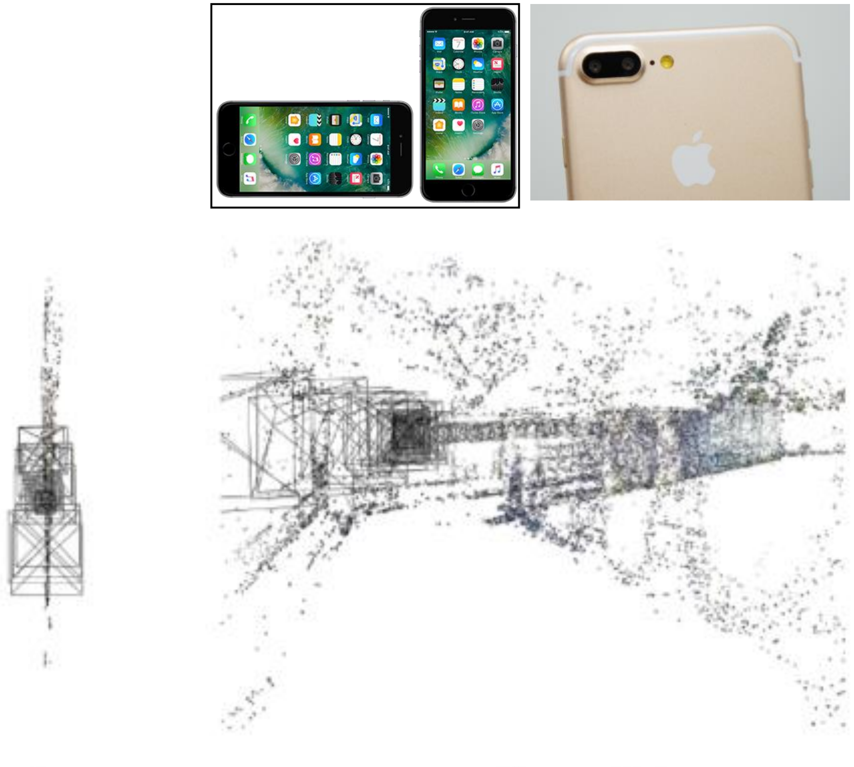
A Practical Solution

1. Use images with many different readout directions
2. Use a camera pair with orthogonal readout directions.

Independent image sequences

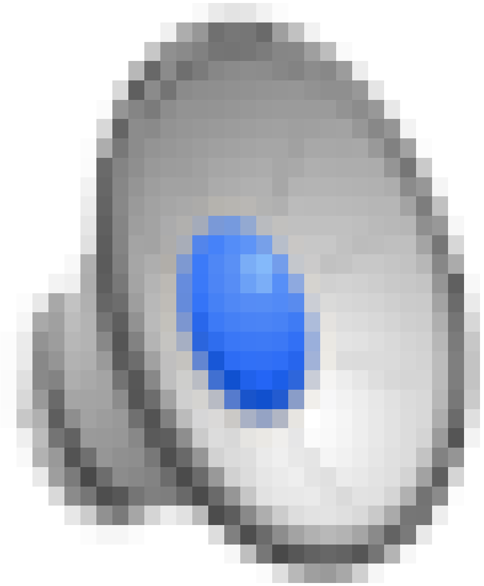


2 coupled cameras with perpendicular readouts

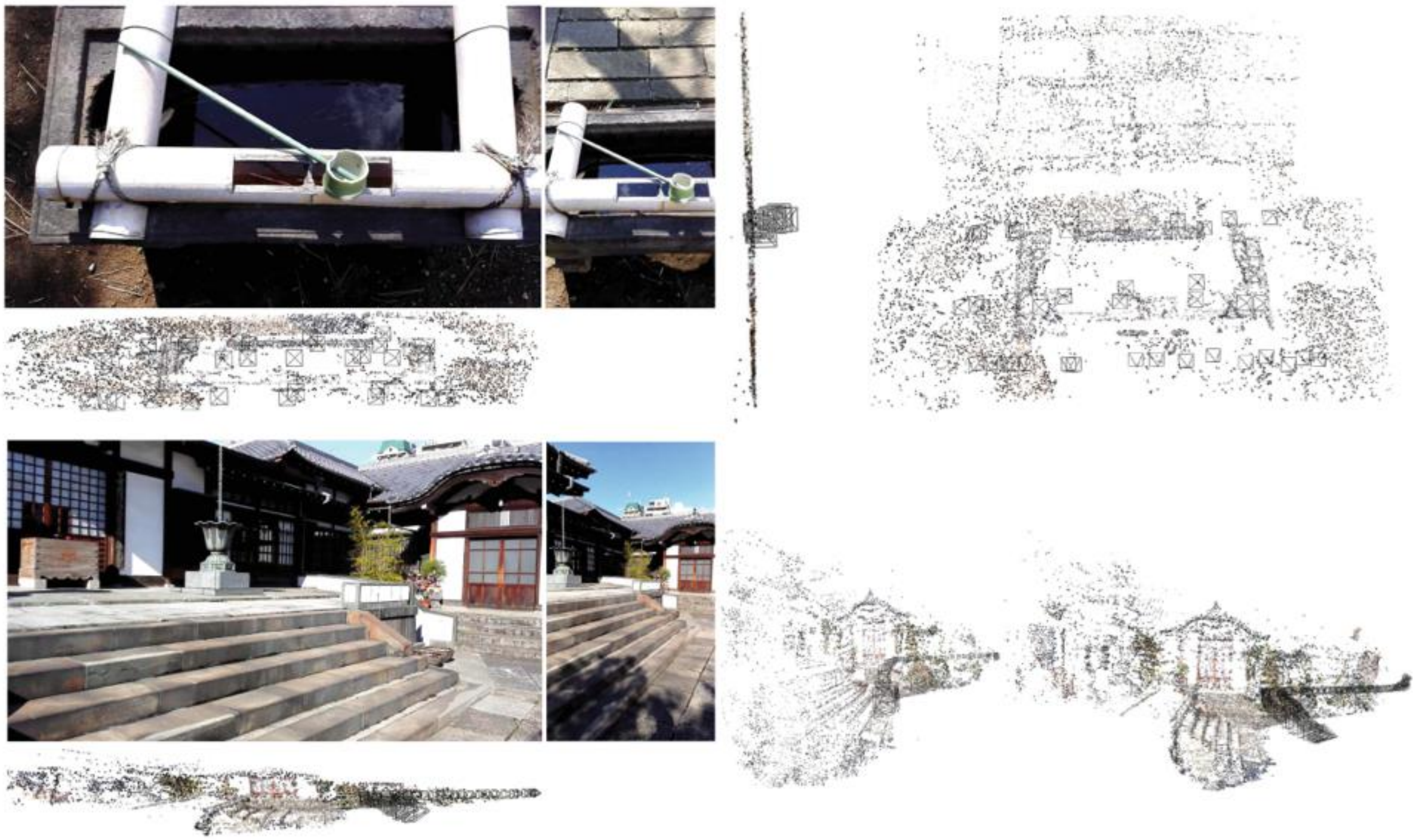


A Practical Solution

1. Use images with many different readout directions
2. Use a camera pair with orthogonal readout directions.



A Practical Solution



A Practical Solution

3D with Rolling Shutter

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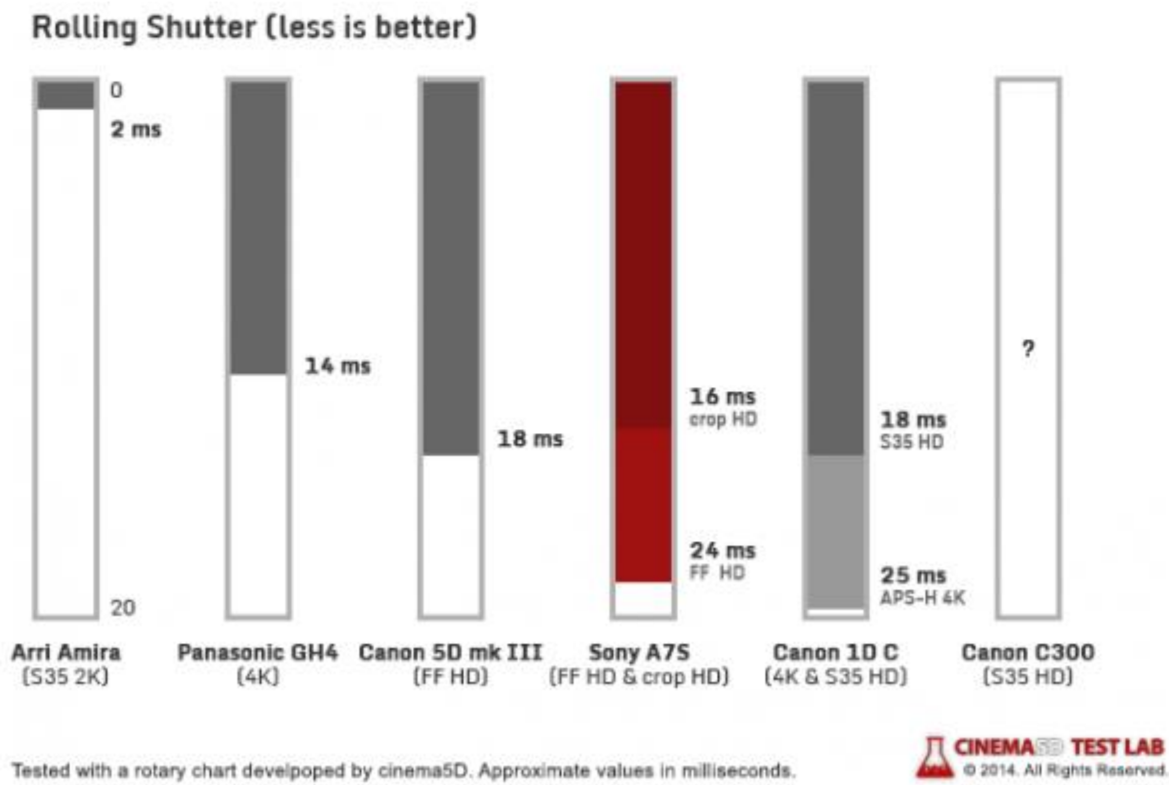
Rolling Shutter (less is better)
0
2 ms
20
14 ms
18 ms
16 ms
crop HD
24 ms
FF HD
18 ms
S35 HD
25 ms
APS-H 4K
?
Arri Amira
(S35 2K)
Panasonic GH4
(4K)
Canon 5D mk III
(FF HD)
Sony A7S
(FF HD & crop HD)
Canon 1D C
(4K & S35 HD)
Canon C300
(S35 HD)
Tested with a rotary chart develpoped by cinema5D. Approximate values in milliseconds.
CINEMA5D TEST LAB
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