3D Reconstruction from Photographs
Principles & Applications

Tomas Pajdla

with contributions from

Z. Kukelova, M. Bujnak, A. Torii, T. Schilling, J. Heller,
C. Albl, …

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T O M A S P A J D L A

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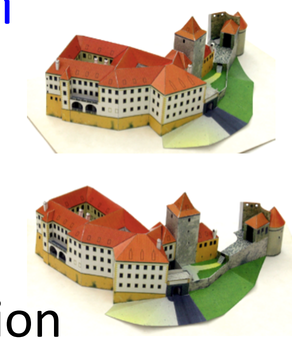
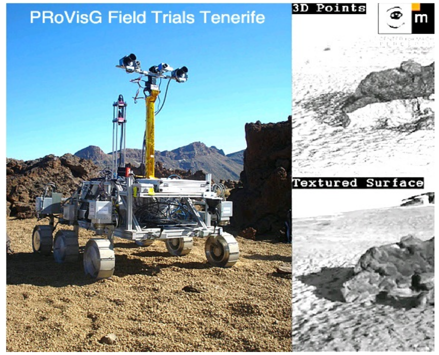
Research

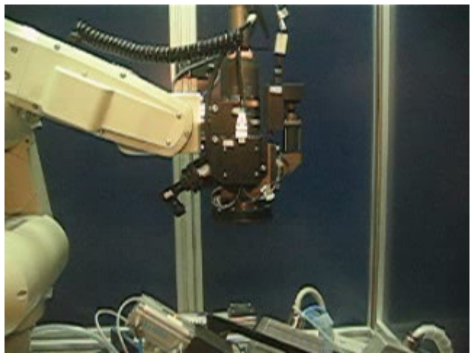
3D
Geometry
Algebra
Optimization

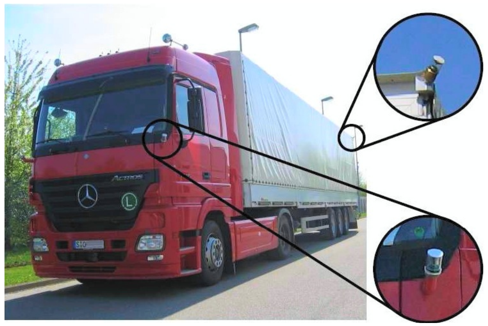


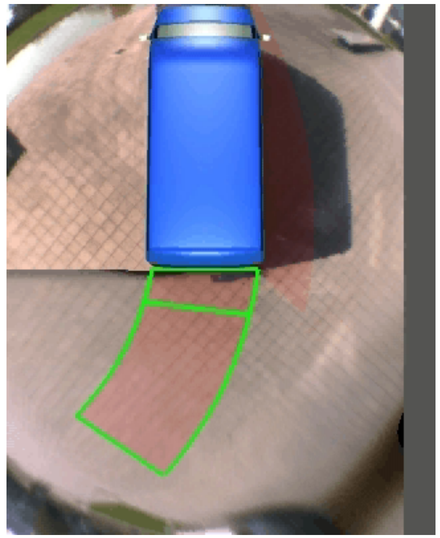


Applications

Neovision s.r.o., Daimler, Siemens, . . .







3D RECONSTRUCTION FROM PHOTOGRAPHS

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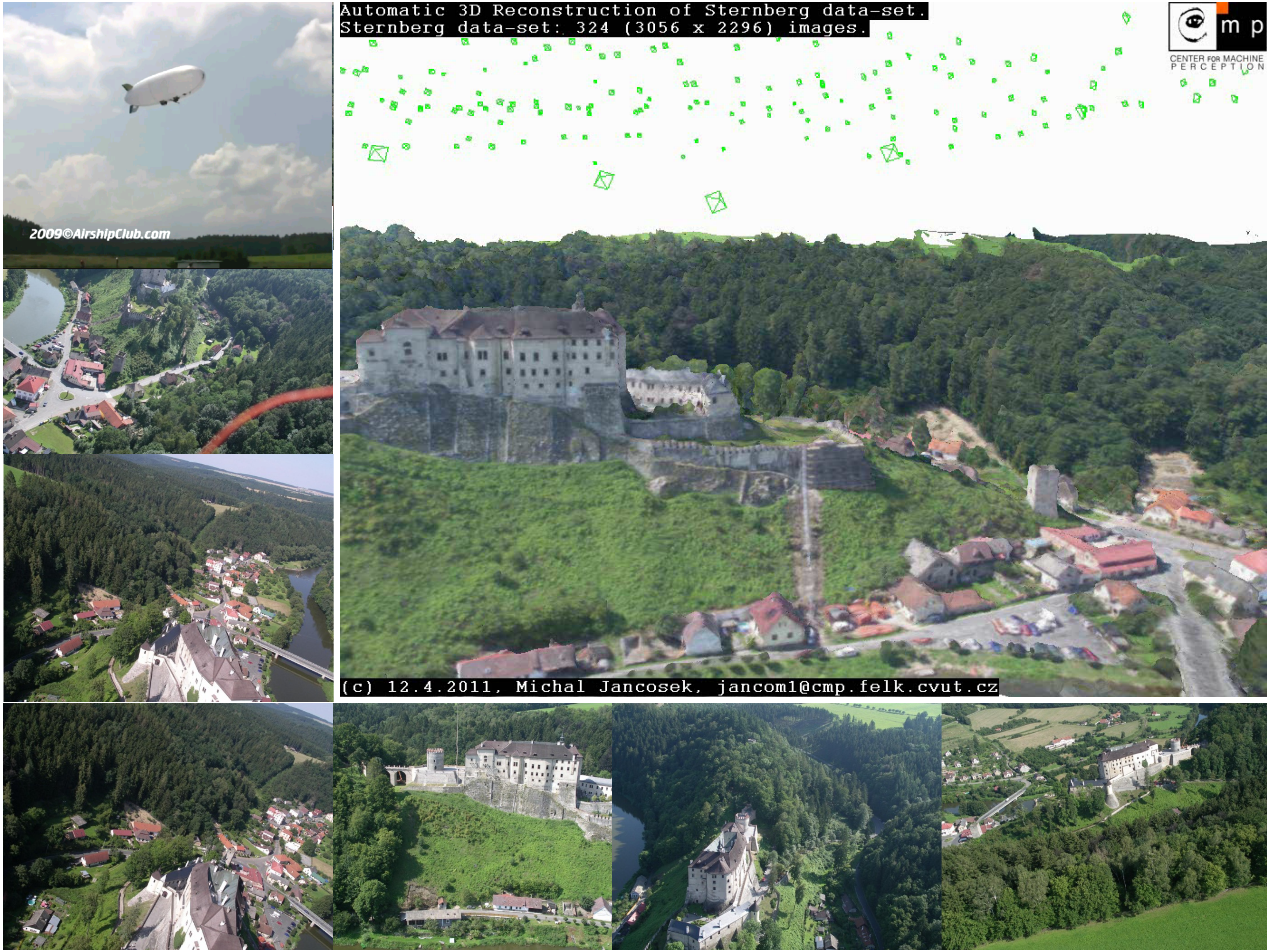
Original Image
3D Points
cmp
CENTER FOR MACHINE PERCEPTION
Shaded Surface
Textured Surface

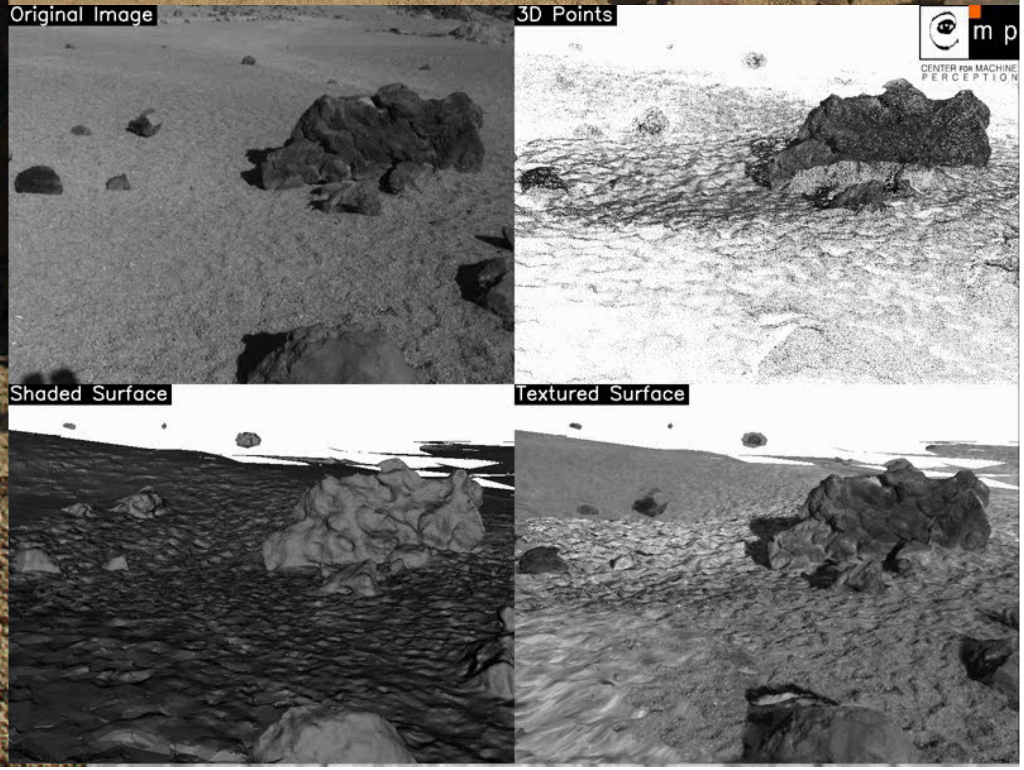

2009©AirshipClub.com
Automatic 3D Reconstruction of Sternberg data-set.
Sternberg data-set: 324 (3056 x 2296) images.
CENTER FOR MACHINE PERCEPTION
(c) 12.4.2011, Michal Jancosek, jancom1@cmp.felk.cvut.cz

ASTRIUM
AN EADS COMPANY

PRoViDE

m p

PRoVisG Field Trials Tenerife



3D reconstruction pipeline

300 users

2000 scenes

5000 rec's

See the proceedings ...

OUTLINE

1. Key elements of 3D reconstruction
    1. Camera relative pose computation
    2. From point clouds to surfaces

2. Applications

Key elements of

3D RECONSTRUCTION

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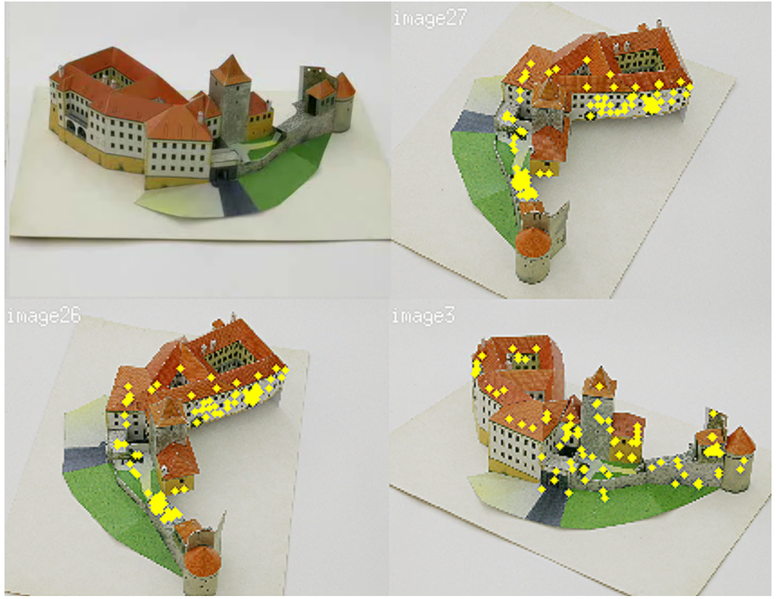
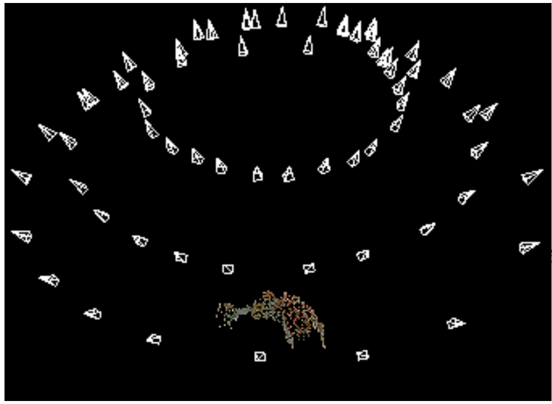
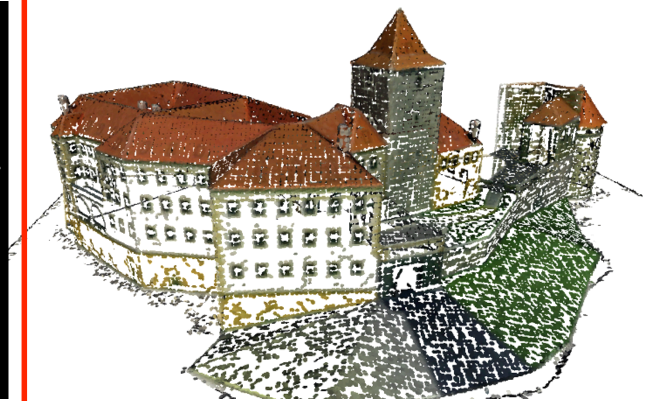
3D Reconstruction from Photographs

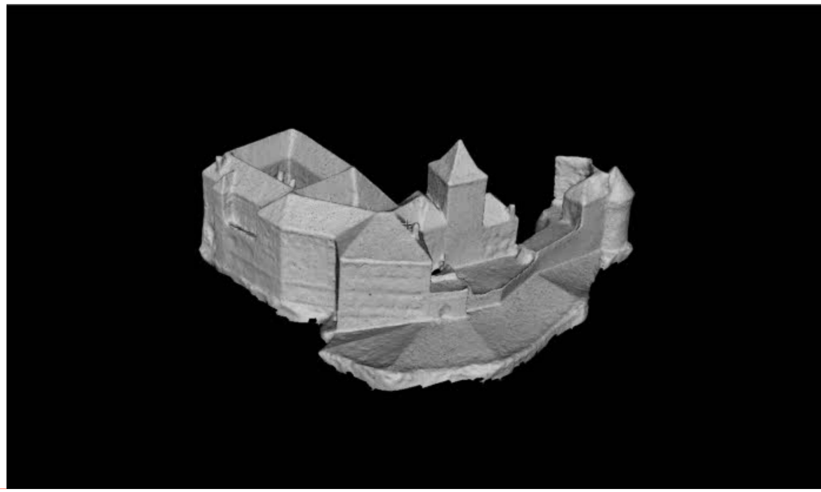
1. SFM: Images & EXIFs → Cameras poses → Sparse point cloud







2. MVS: → 3D Surface → Texture



RELATIVE CAMERA POSE PROBLEM

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SOLUTIONS 2004(6-12)

An old important problem (Grunnert 1841 …) with new solutions:

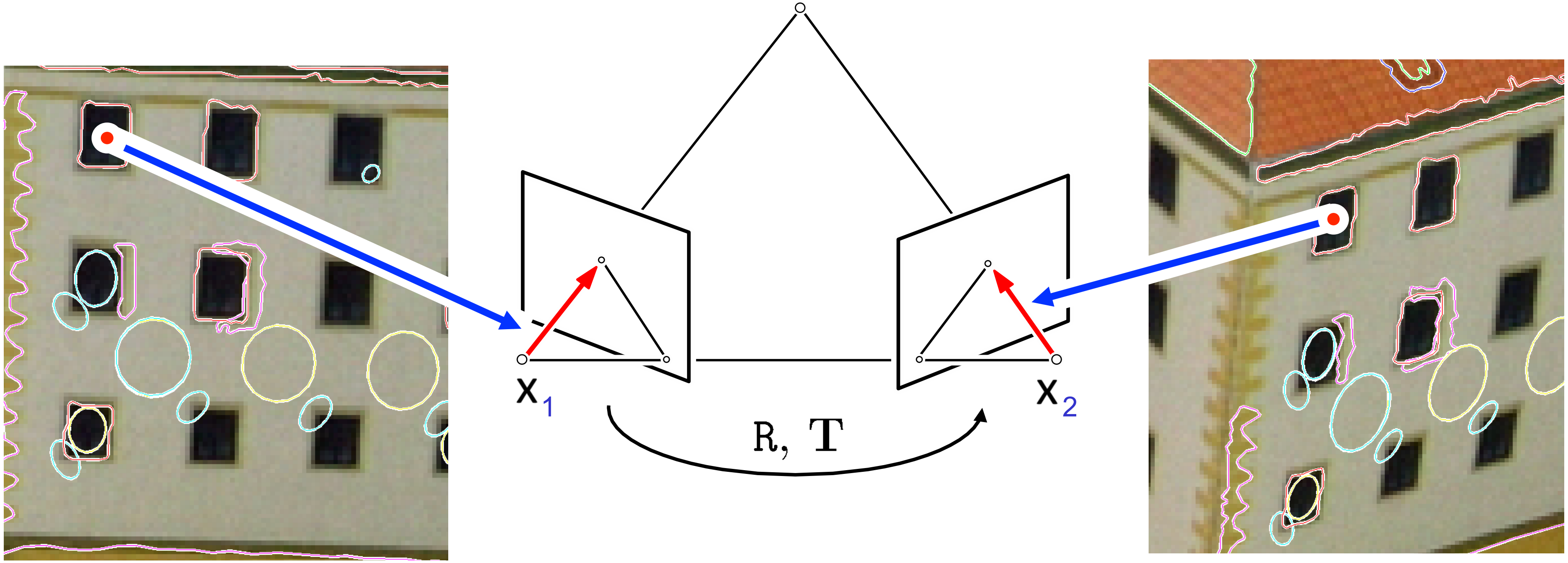
D. Nister. *An efficient solution to the five-point relative pose*
IEEE PAMI, 2004.

H. Stewenius, C. Engels, and D. Nister. *Recent developments on direct relative orientation*
ISPRS J. of Photogrammetry and Remote Sensing, 2006.

Z. Kukelova, M. Bujnak, T. Pajdla
Polynomial eigenvalue solution to the 5-pt and 6-pt relative pose problems
BMVC 2008

H. Li, R. Hartley. *An Efficient Hidden Variable Approach to Minimal-Case Camera Motion Estimation*
PAMI 2012

RELATIVE CAMERA POSE PROBLEM



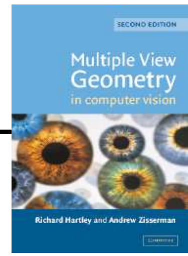
$$x_2^\top F x_1 = 0$$

$$\det F = 0$$

$$2 F F^\top F - \mathrm{trace}(F F^\top) F = 0$$

Algebraic equations

solve → F →



→ $R, \frac{T}{\|T\|}$

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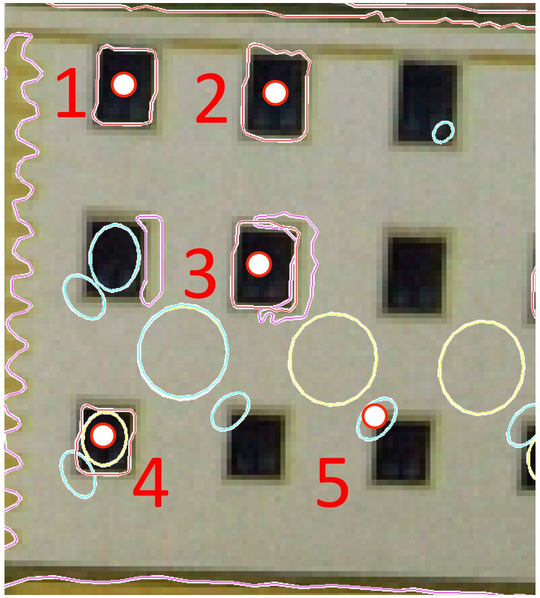
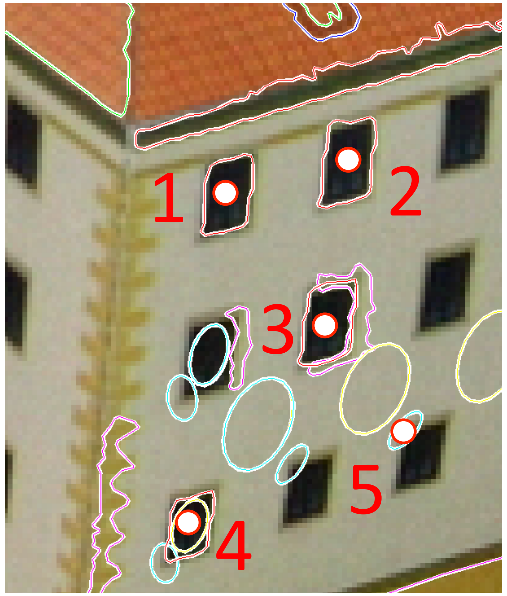
MINIMAL PROBLEMS & RANSAC



5 (correct) matches are sufficient to compute F

(but there are many incorrect tentative matches)



RANSAC (RANdom SAmpling Consensus)

1. Generate random 5-tuples of matches
2. Compute F by solving $\mathbf{x}_2^\top \mathrm{F}\, \mathbf{x}_1 = 0$ (not so trivial)
3. Count the number of good matches

Return the largest set of good matches

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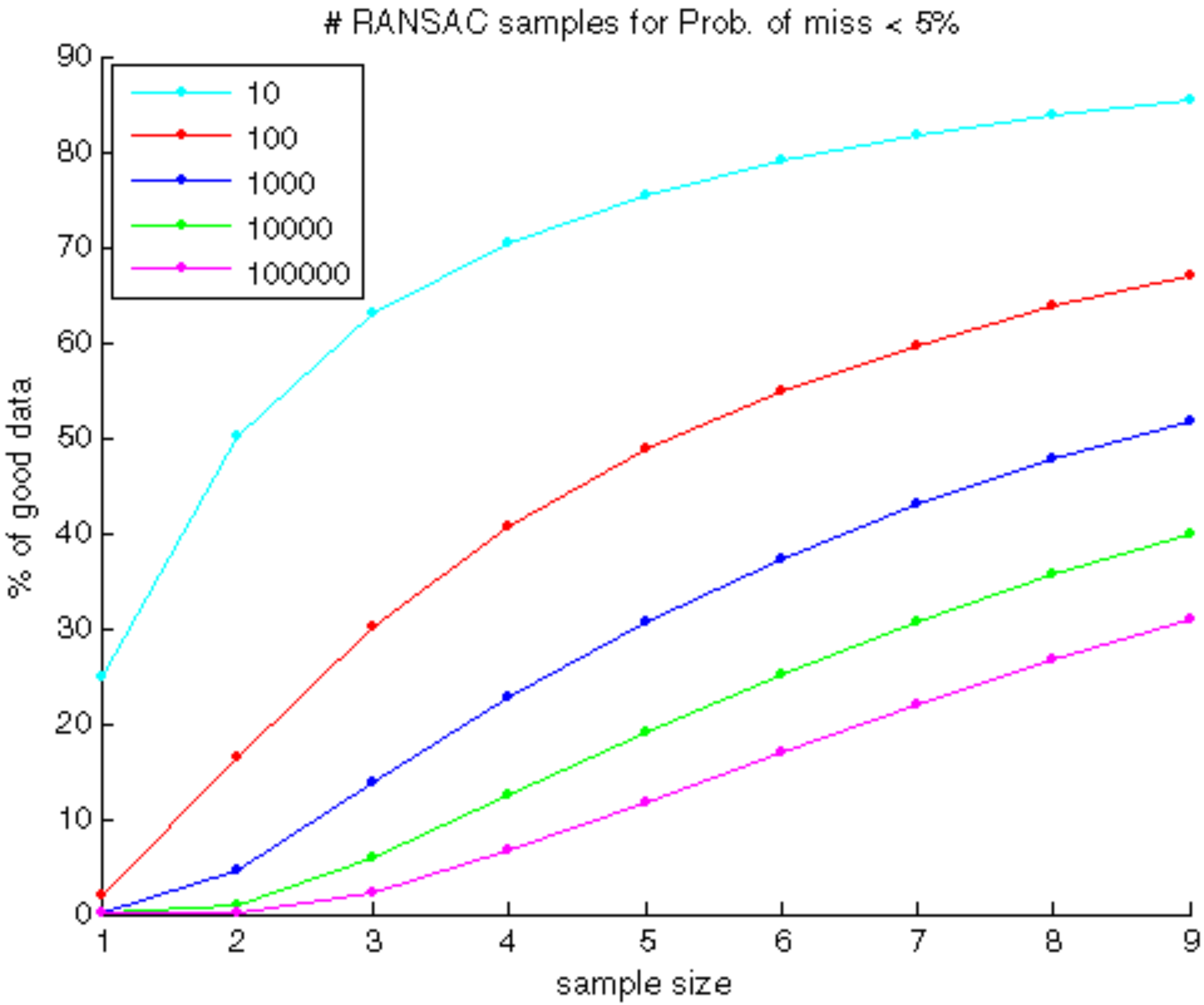
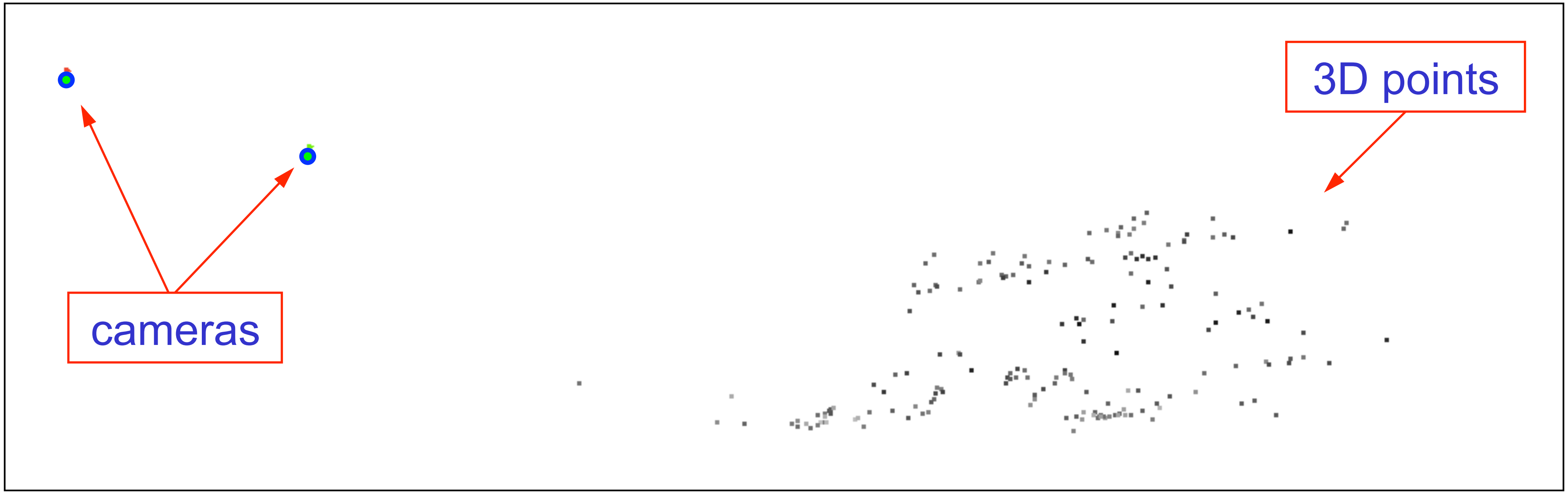
of R A N S A C SAMPLES for PROB. of MISS < 5%



SPARSE MATCHES between TWO VIEWS



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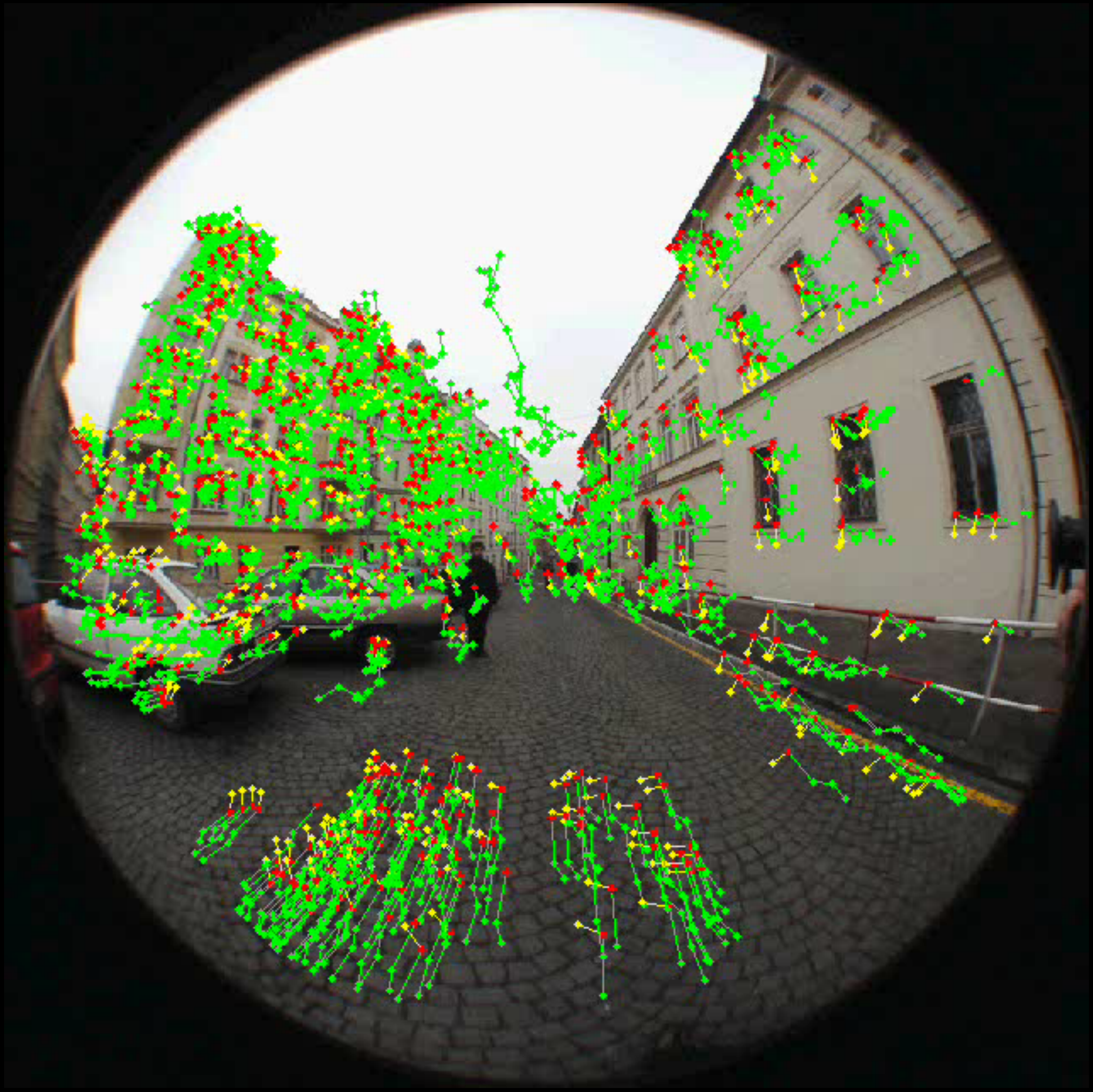
FISH–EY E IMAGE SEQUENCE



Features
Tracks
Matches

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RELATIVE CAMERA POSE

PROBLEM

ESSENTIAL (F) MATRIX COMPUTATION

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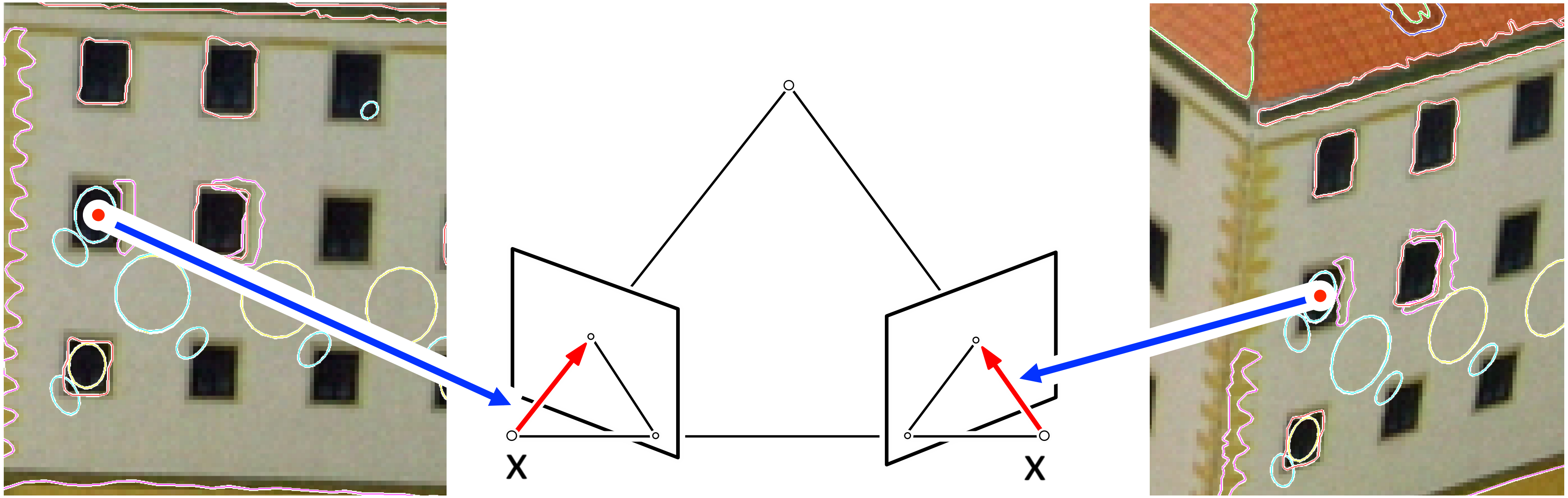
FORMULATION



$$x_2^\top F x_1 = 0$$

$$\det F = 0$$

$$2 F F^\top F - \mathrm{trace}(F F^\top) F = 0$$

Algebraic equations

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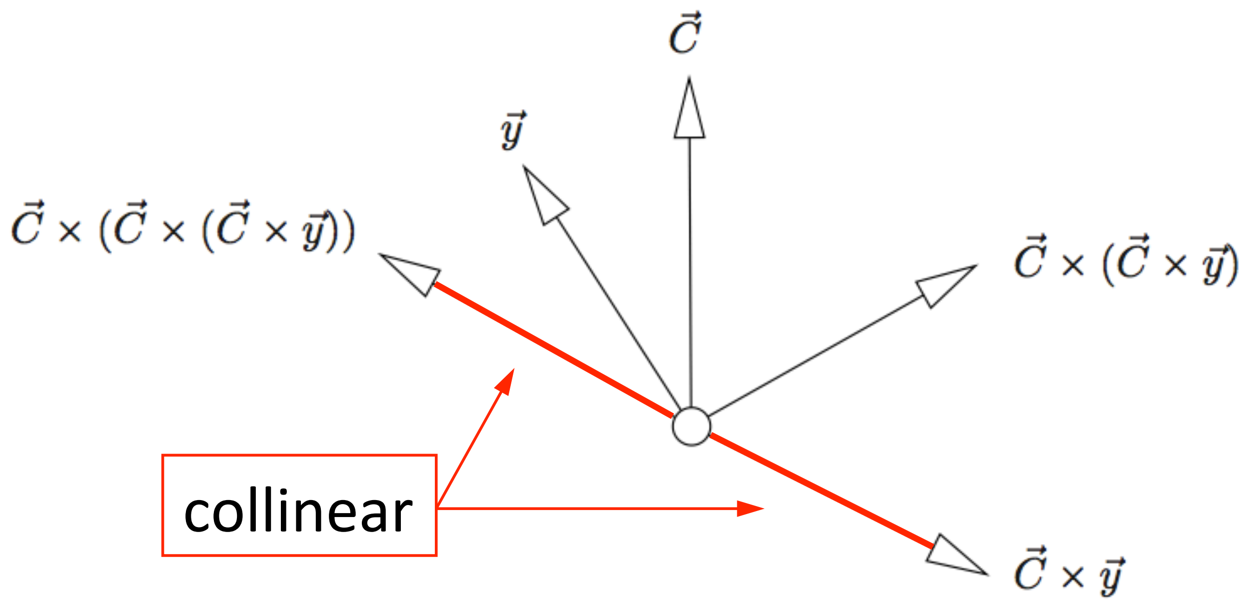
EQUATIONS

$$\mathrm{x}_2^\top \mathrm{F}\,\mathrm{x}_1 = 0$$ ... Epipolar constraint (1 eq per match)

$$\det \mathrm{F} = 0$$ ... Fundamental matrix (1 eq)

$$2\,\mathrm{F}\,\mathrm{F}^\top \mathrm{F} - \mathrm{trace}(\mathrm{F}\,\mathrm{F}^\top)\mathrm{F} = 0$$ ... Essential matrix (9 eqns)

$$\mathrm{F} = \mathrm{R}\left[\vec{C}_{\epsilon_1}\right]_\times$$



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U N K N O W N S

$$\mathtt{F} = \begin{bmatrix} f_{11} & f_{12} & f_{13} \\ f_{21} & f_{22} & f_{23} \\ f_{31} & f_{32} & f_{33} \end{bmatrix}$$

9 unknowns but only 8 have to be found (F up to scale)

$\rightarrow$ we need at least 8 independent equations

EQUATIONS

$$\det \mathtt{F} = 0$$

1 equation, degree 3

$$2\,\mathtt{F}\mathtt{F}^\top\mathtt{F} - \mathrm{trace}(\mathtt{F}\mathtt{F}^\top)\mathtt{F} = 0$$

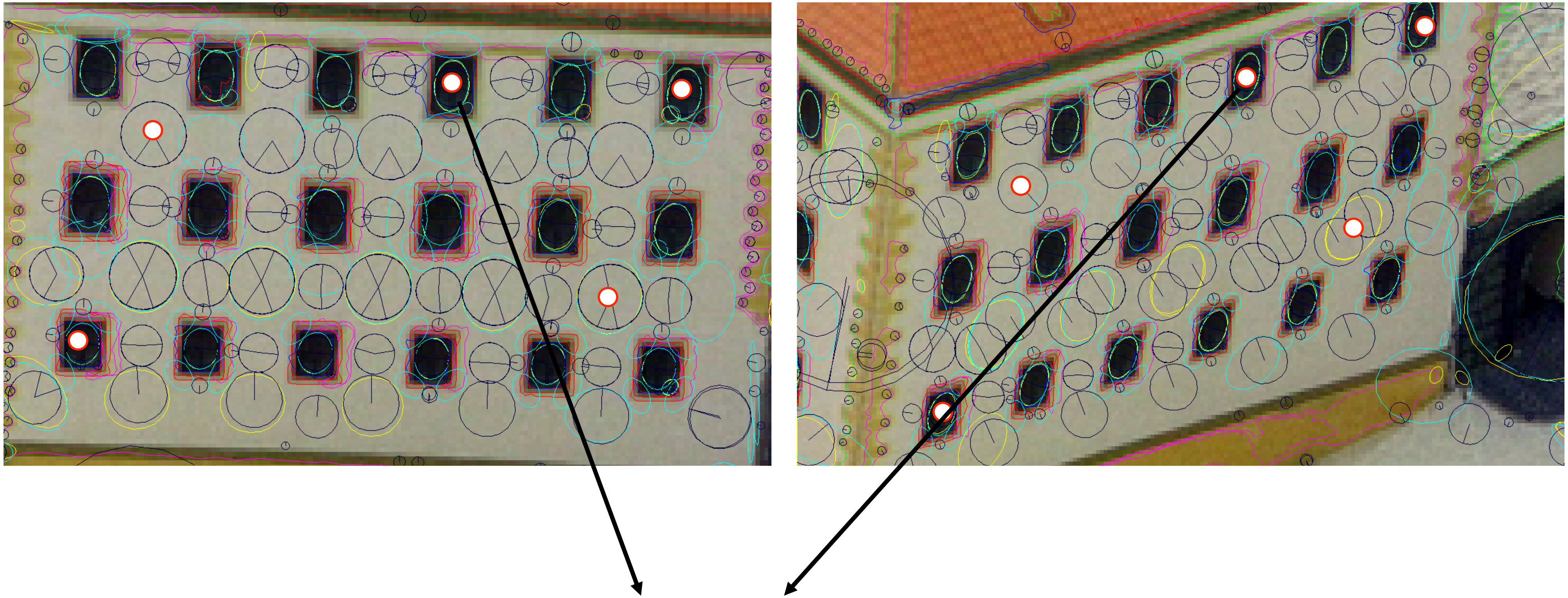
9 equations, degree 3

10 equations but only 3 “independent”

8 = 3 + 5

→ 5 more equations needed

5 EQUATIONS from image points



$$\mathbf{x}_2^\top \mathrm{F}\, \mathbf{x}_1 = 0$$

5 linear equations:

$$\bullet f_{11} + \bullet f_{12} + \bullet f_{13} + \bullet f_{21} + \bullet f_{22} + \bullet f_{23} + \bullet f_{13} + \bullet f_{23} + \bullet f_{31} + \bullet f_{32} + \bullet f_{33} \quad = \quad 0$$

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ELIMINATING UNKNOWNS

5 linear equations:

$$\bullet f_{11} + \bullet f_{12} + \bullet f_{13} + \bullet f_{21} + \bullet f_{22} + \bullet f_{23} + \bullet f_{13} + \bullet f_{23} + \bullet f_{31} + \bullet f_{32} + \bullet f_{33} \quad = \quad 0$$

can be written in a matrix form

$$\underbrace{\begin{bmatrix} \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \end{bmatrix}}_{\mathtt{A}} \begin{bmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ \vdots \\ f_{33} \end{bmatrix} = 0$$

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ELIMINATING UNKNOWNS

$$\underbrace{\begin{bmatrix} \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \\ \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet & \bullet \end{bmatrix}}_{\mathtt{A}} \begin{bmatrix} f_{11} \\ f_{12} \\ f_{13} \\ f_{21} \\ \vdots \\ f_{33} \end{bmatrix} = 0$$

5×9 matrix $\longrightarrow$ it has a 4 dimensional nullspace

$$\mathtt{A}\, N = 0$$

known

$$N = \boxed{x}\, N_1 + \boxed{y}\, N_2 + \boxed{z}\, N_3 + \boxed{w}\, N_4$$

new unknowns

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ELIMINATING UNKNOWNS

$$F \sim x\,N_1 + y\,N_2 + z\,N_3 + w\,N_4$$ ... 4 unknowns

F is up to scale → choose a representative by setting w = 1

$$F := \underbrace{x\,N_1 + y\,N_2 + z\,N_3 + N_4}_{\text{3 unknowns } x,\,y,\,z}$$

3 unknowns x, y, z

↓ substitute

$$\left.\begin{aligned} \det \mathtt{F} &= 0 \\ 2\,\mathtt{F}\,\mathtt{F}^\top\mathtt{F} - \mathrm{trace}(\mathtt{F}\,\mathtt{F}^\top)\mathtt{F} &= 0 \end{aligned}\right\}$$

10 3rd order equations in 3 unknowns x, y, z

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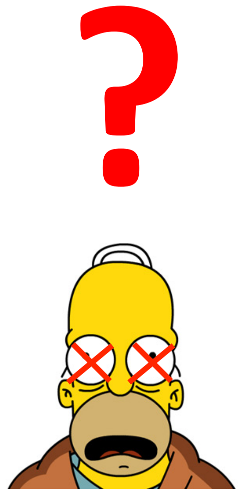
SOLVING IT

$$\left.\begin{aligned} \det F &= 0 \\ 2FF^\top F - \mathrm{trace}(FF^\top)F &= 0 \end{aligned}\right\}$$

10 3^{rd} order equations in 3 unknowns (x, y, z)



How?

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ESSENTIAL (F) MATRIX COMPUTATION

THE FASTEST (available) SOLUTION

Idea (1567 μs)
Z. Kukelova, M. Bujnak, T. Pajdla
Polynomial eigenvalue solution to the 5-pt and 6-pt relative pose problems
BMVC 2008

Efficient implementation (34 μs)
H. Li, R. Hartley.
An Efficient Hidden Variable Approach to Minimal-Case Camera Motion Estimation
PAMI 2012

1 UNKNOWN $\rightarrow$ EIGENVALUES

1 equation, 1 variable $\rightarrow$ companion matrix $\rightarrow$ eigenvalues

$$f(x) = x^3 + 4\,x^2 + x - 6 \;=\; -6 + 1\,x + 4\,x^2 + 1\,x^3$$

$$\mathtt{M}_x = \begin{bmatrix} 0 & 0 & 6 \\ 1 & 0 & -1 \\ 0 & 1 & -4 \end{bmatrix}$$

... a simple rule

```
>> e=eig(Mx)
```

$$\mathtt{e} = \begin{bmatrix} 1 \\ -2 \\ -3 \end{bmatrix} \qquad x_1 = 1,\; x_2 = -2,\; x_3 = -3$$

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EIGENVALUES SOLVE ALG EQNS

$$\texttt{>>}\ \lambda\ \texttt{= eig(}\begin{bmatrix}0 & 0 & 6\\ 1 & 0 & -1\\ 0 & 1 & -4\end{bmatrix}\texttt{)}$$

Numerical implementation

$$\begin{bmatrix}-\lambda & 0 & 6\\ 1 & -\lambda & -1\\ 0 & 1 & -4-\lambda\end{bmatrix}\begin{bmatrix}x_1\\ x_2\\ x_3\end{bmatrix} = 0$$

"Hide" λ

$$\begin{aligned}6\,x_3 - \lambda\,x_1 &= 0\\ x_1 - x_3 - \lambda\,x_2 &= 0\\ x_2 - 4\,x_3 - \lambda\,x_3 &= 0\end{aligned}$$

linear   bilinear (linear in λ)

Eigenvalues solve a special system of algebraic eqns via the hidden variable method

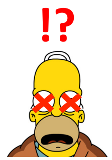
POLYNOMIAL EIGENVALUE SOLUTION

m equations, n variables

$$
\begin{aligned}
f_1(x,y) &= 25\,x\,y - 15\,x - 20\,y + 12 \\
f_2(x,y) &= x^2 + y^2 - 1
\end{aligned}
$$

"Hide" y (the "hidden variable method")

$$
\left(\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} y^2 + \begin{bmatrix} 0 & 25 & 20 \\ 0 & 0 & 0 \end{bmatrix} y + \begin{bmatrix} 0 & -15 & 12 \\ 1 & 0 & -1 \end{bmatrix} \right) \begin{bmatrix} x^2 \\ x \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
$$

2×3 matrix $\longrightarrow$ ∞ sols !!! $\longrightarrow$ 

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POLYNOMIAL EIGENVALUE SOLUTION

$$
\begin{aligned}
f_1(x,y) &= 25\,x\,y - 15\,x - 20\,y + 12 \\
f_2(x,y) &= x^2 + y^2 - 1
\end{aligned}
$$

"Hide" y (the "hidden variable method")

$$
\left(\begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix} y^2 + \begin{bmatrix} 0 & 25 & -20 \\ 0 & 0 & 0 \\ 25 & -20 & 0 \end{bmatrix} y + \begin{bmatrix} 0 & -15 & 12 \\ 1 & 0 & -1 \\ -15 & 12 & 0 \end{bmatrix} \right) \begin{bmatrix} x^2 \\ x \\ 1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}
$$

$\longrightarrow$ add $x f_1(x,y) = \boxed{25\,x^2\,y - 15\,x^2 - 20\,xy + 12x}$

$\underbrace{\quad}_{C_2}$ $\underbrace{\quad}_{C_1}$ $\underbrace{\quad}_{C_0}$

```
>> [v,y]=polyeig(C0,C1,C2)
```

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POLYNOMIAL EIGENVALUE PROBLEM

Quadratic eigenvalue problem

$$(\lambda^2 \mathtt{A} + \lambda \mathtt{B} + \mathtt{C})\,\mathbf{x} = 0$$

... generalization of

$$\mathtt{M}\,\mathbf{x} = \lambda\,\mathbf{x}$$

$$\Updownarrow$$

$$(\mathtt{M} - \lambda\,\mathtt{I})\,\mathbf{x} = 0$$

... can be rewritten as

$$\lambda^2 \mathtt{A}\,\mathbf{x} + \lambda \mathtt{B}\,\mathbf{x} + \mathtt{C}\,\mathbf{x} = 0$$

$$\lambda \mathtt{A}\,(\lambda\,\mathbf{x}) + \lambda \mathtt{B}\,\mathbf{x} + \mathtt{C}\,\mathbf{x} = 0$$

$$\mathbf{y} = \lambda\,\mathbf{x}$$

$$\lambda \mathtt{A}\,\mathbf{y} + \lambda \mathtt{B}\,\mathbf{x} + \mathtt{C}\,\mathbf{x} = 0$$

$$\left(\lambda \begin{bmatrix} \mathtt{A} & \mathtt{B} \\ 0 & \mathtt{I} \end{bmatrix} + \begin{bmatrix} 0 & \mathtt{C} \\ -\mathtt{I} & 0 \end{bmatrix}\right) \begin{bmatrix} \mathbf{y} \\ \mathbf{x} \end{bmatrix} = 0$$

Generalized eigenvalue problem

Higher order PolyEigs:
A. Wallack, I. Z. Emiris, D. Manocha.
MARS - A Maple-Matlab-C Resultant-based Solver.

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6-pt UNKNOWN f CAMERA RELATIVE POSE

Epipolar constraint $\mathbf{x}'^{\top}_j \mathtt{F}\, \mathbf{x}_j = 0,\ j = 1, \ldots, 6$

9 unknowns – 6 correspondences = 3 dimensional nullspace

$$\mathtt{F} = x\,\mathtt{F}_1 + y\,\mathtt{F}_2 + \mathtt{F}_3$$

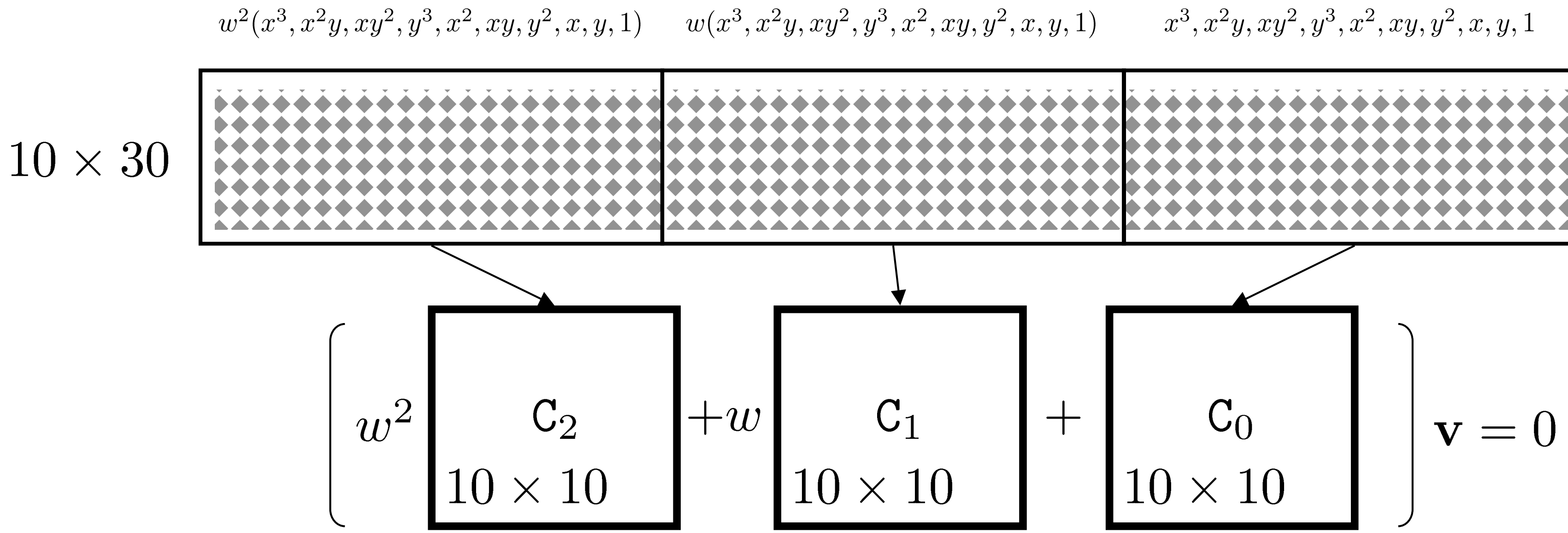
Fundamental matrix is singular $\det(\mathtt{F}) = 0$

Transfer F to the essential matrix $\mathbf{E} = \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix} \mathbf{F} \begin{pmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{pmatrix}$

Constraints on E $2\,\mathtt{E}\mathtt{E}^{\top}\mathtt{E} - trace(\mathtt{E}\mathtt{E}^{\top})\mathtt{E} = 0$

6-pt UNKNOWN f CAMERA RELATIVE POSE

- 10 x 3rd and 5th order polynomial equations in 3 variables x, y and $w = f^{-2}$ with 30 monomials



- Quadratic polynomial eigenvalue problem (in MATLAB)

$[v,w]=\mathtt{polyeig}(C_0, C_1, C_2)$

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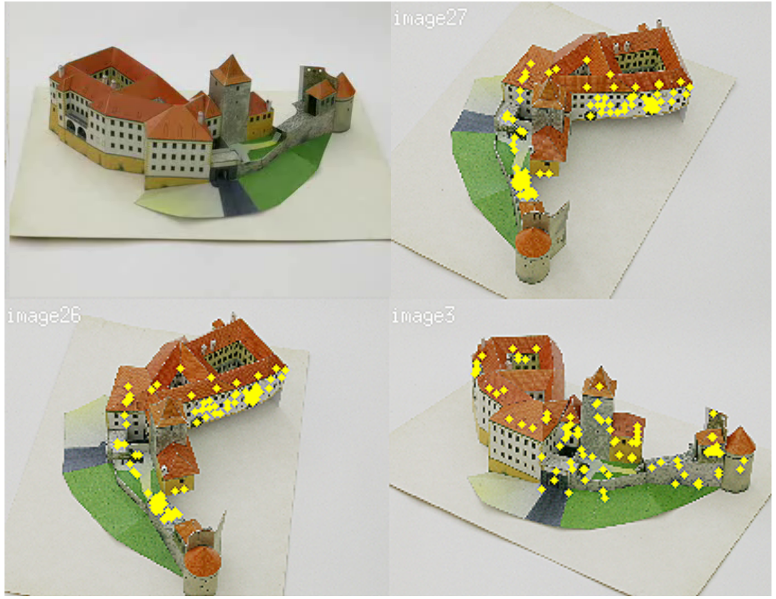
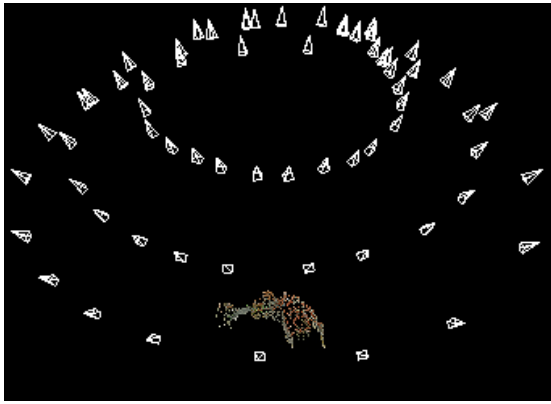
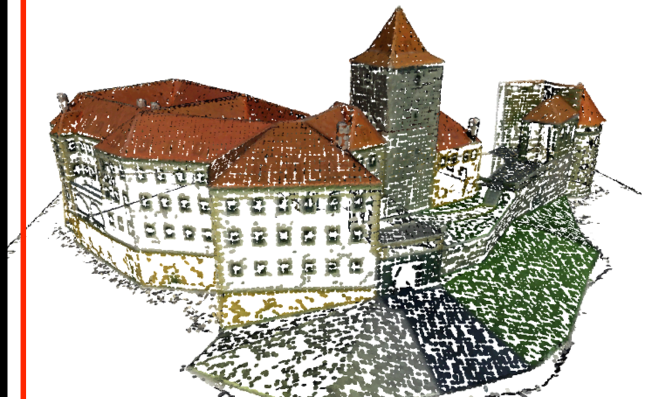
3D Reconstruction from Photographs

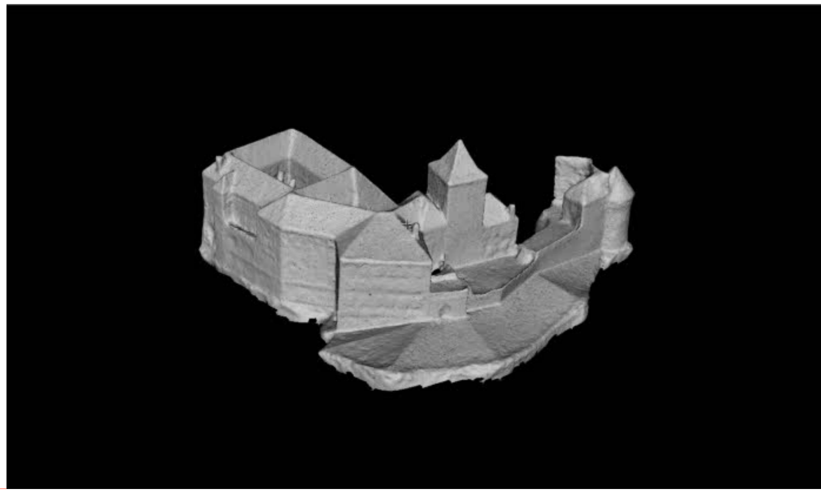
1. SFM: Images & EXIFs → Cameras poses → Sparse point cloud







2. MVS: → 3D Surface → Texture



FROM POINT CLOUDS TO SURFACES

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MVS – MULTIVIEW STEREO

1. Making a point cloud

Plane sweeping

- Known camera poses and calibration (from SFM)
- Corrected perspective images
- Camera neighborhood graph by intersecting view cones
- Sweeping planes with multiple orientations
- Cross correlation (GPU)

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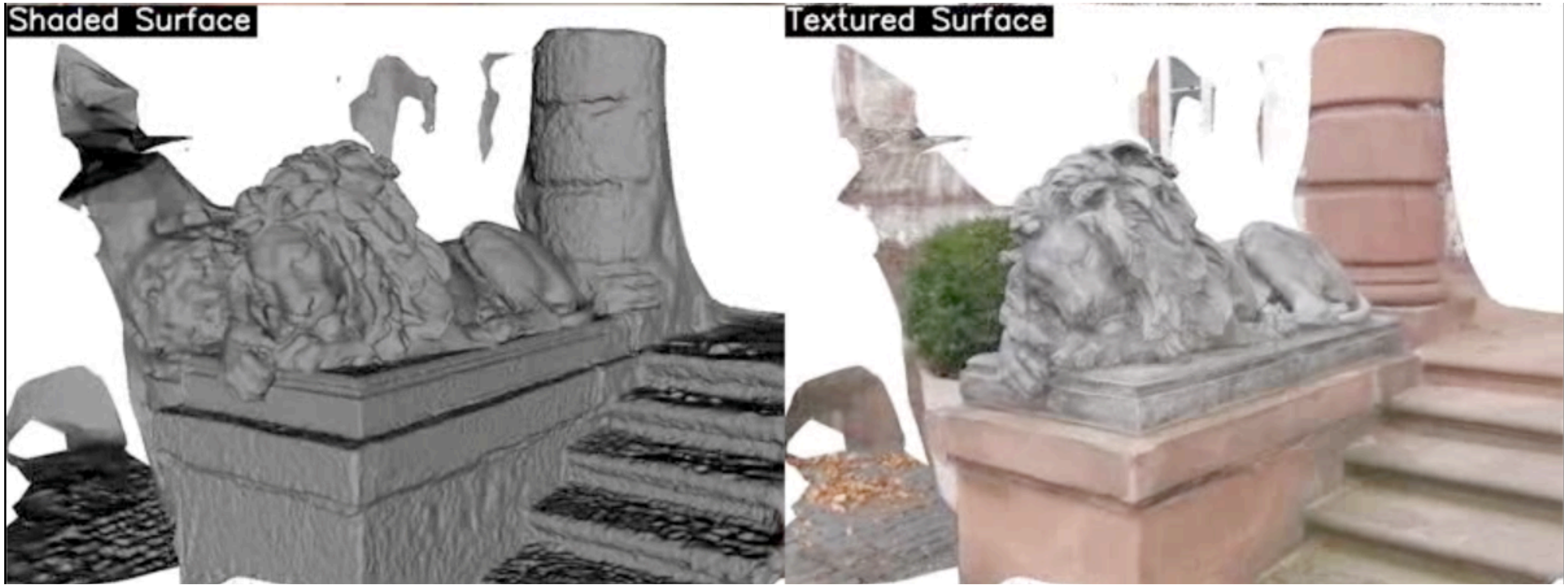
MVS – MULTIVIEW STEREO

2. Surface from a point cloud



Surface by st-cut of a graph

- Point clustering reduces the number of points
- Based on visibility, i.e. does not use images (which makes it faster)
- Semi-global = space partitioned into boxes, which are solved separately but visibility constraints are shared between the neighboring boxes
- can solve 1k (2-3 MPix) images in an hour (Capturing Reality impl.)

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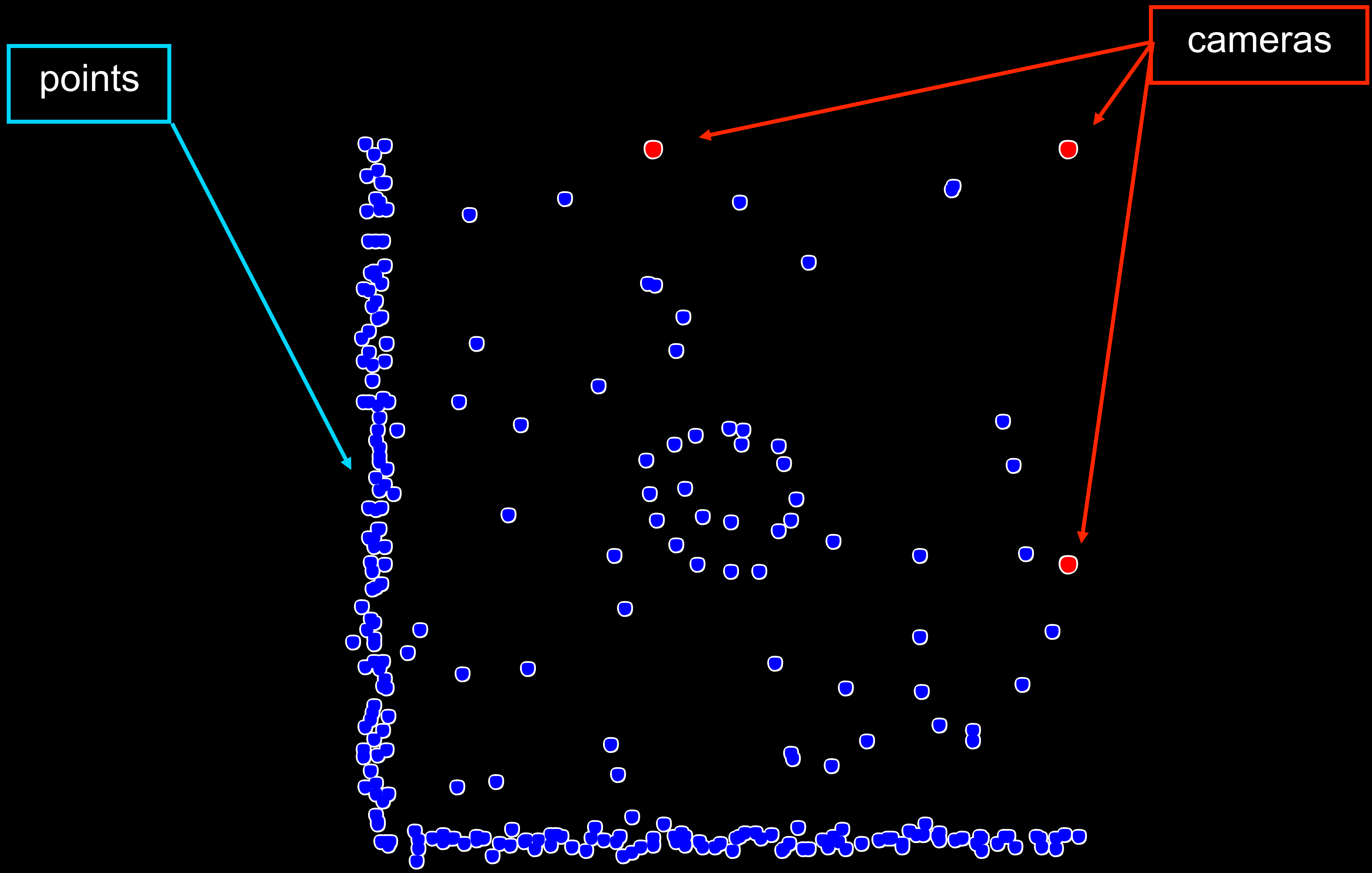
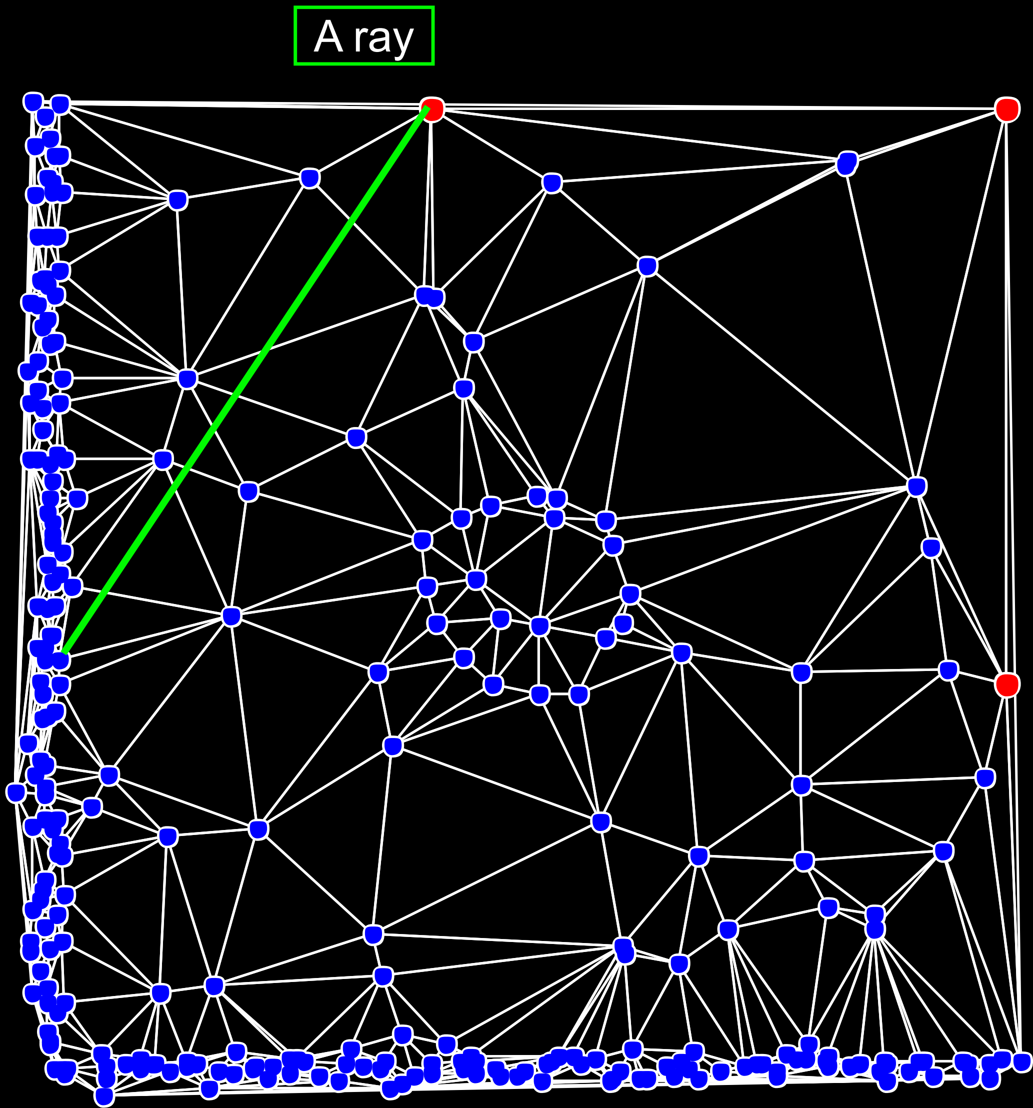
Cameras from SFM and points from plane sweeping



t.cz

Weighting the dual graph (Delaunay tatrahedralization)



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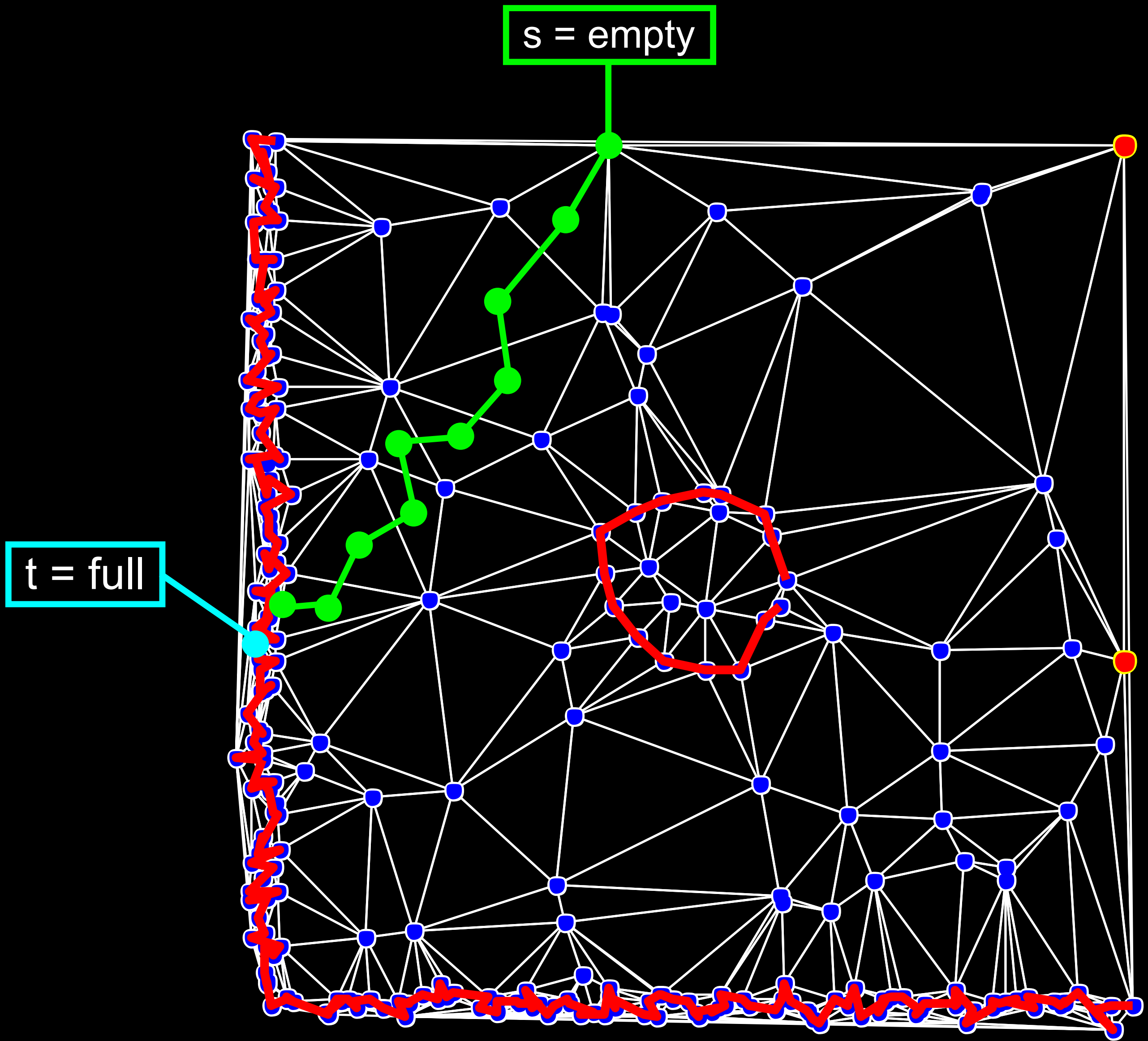
Surface = s-t cut through the dual graph



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M V S – M U L T I V I E W   S T E R E O

2. Surface from a point cloud

P. Labatut, J.-P. Pons, R. Keriven. (→ Accute3D)
Efficient Multi-View Reconstruction of Large-Scale Scenes using Interest Points, Delaunay Triangulation and Graph Cuts.
ICCV 2007

M. Jancosek, T. Pajdla. (CMPMVS → Capturing Reality)
Multi-View Reconstruction Preserving Weakly-Supported Surfaces.
CVPR 2011

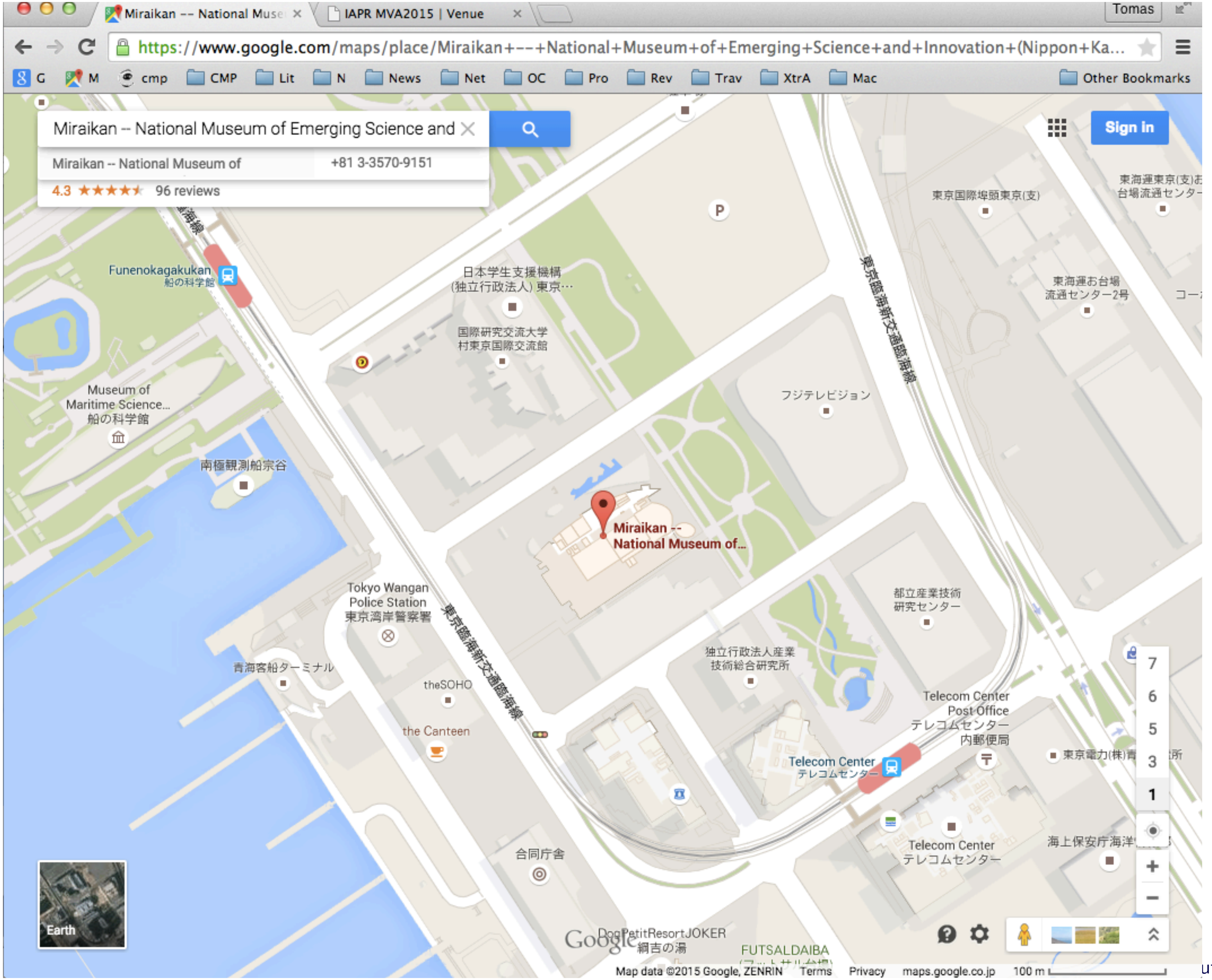
Binary available for CMPMVS

http://ptak.felk.cvut.cz/sfmservice/websfm.pl?menu=cmpmvs

Applications of

3D RECONSTRUCTION

pajdla@cmp.felk.cvut.cz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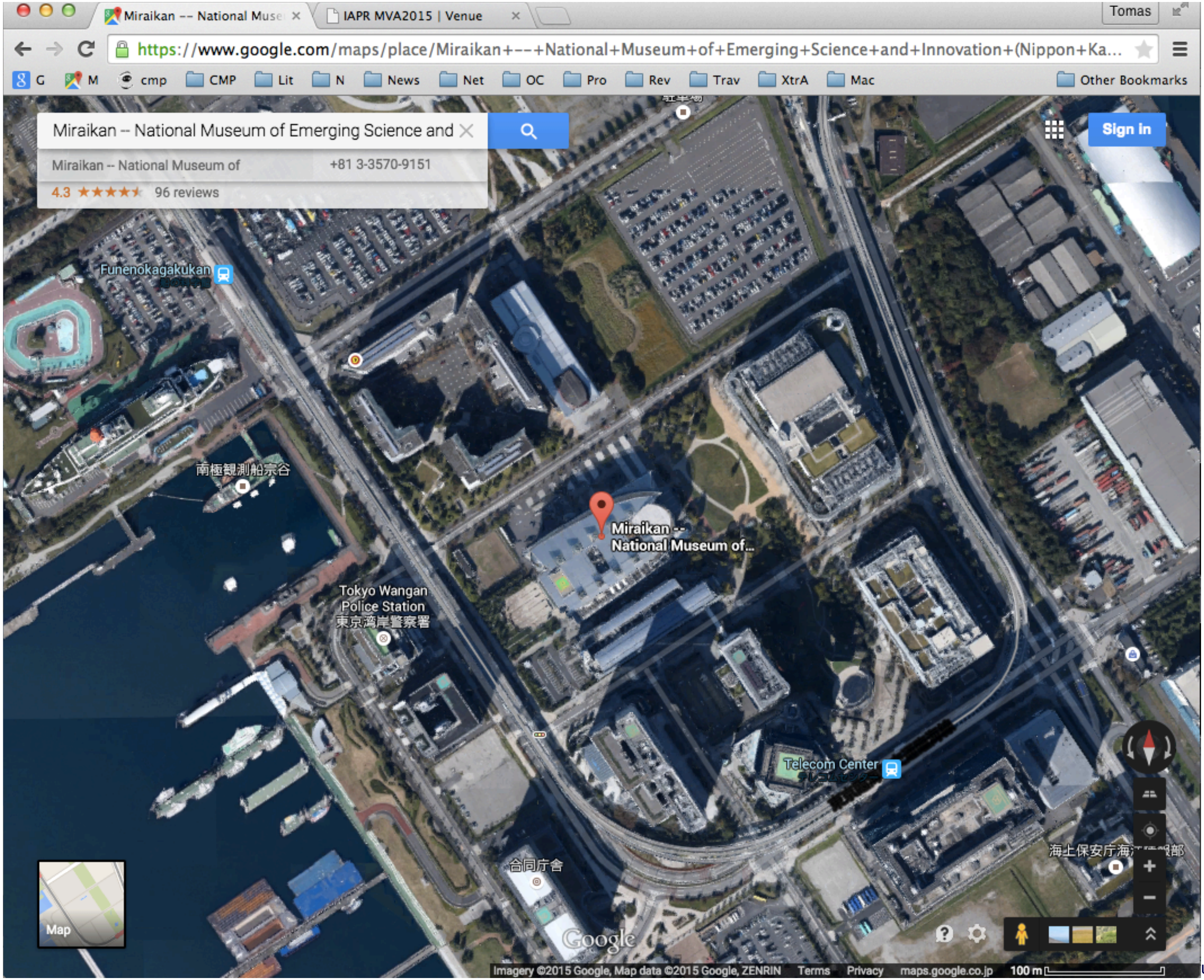
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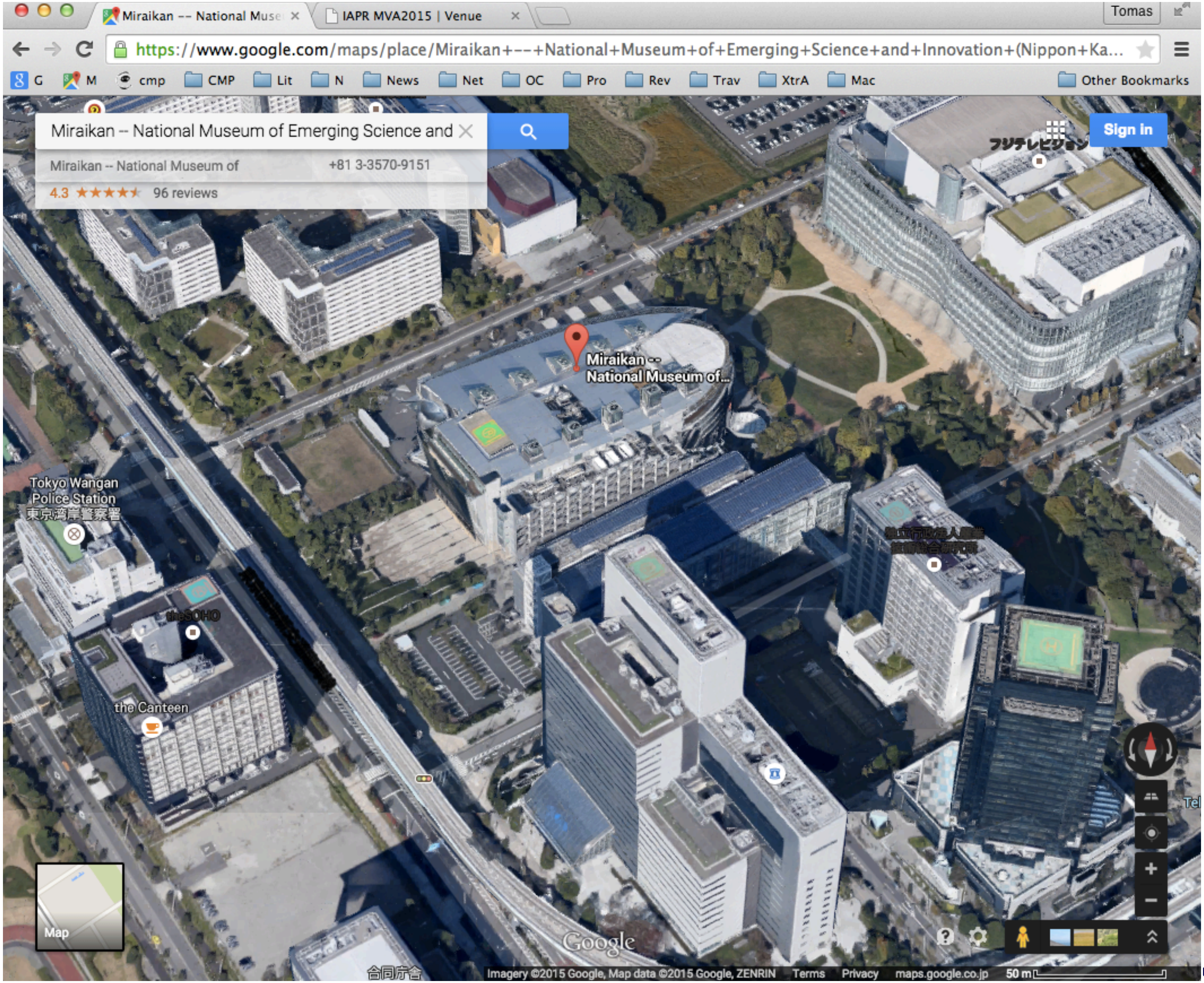

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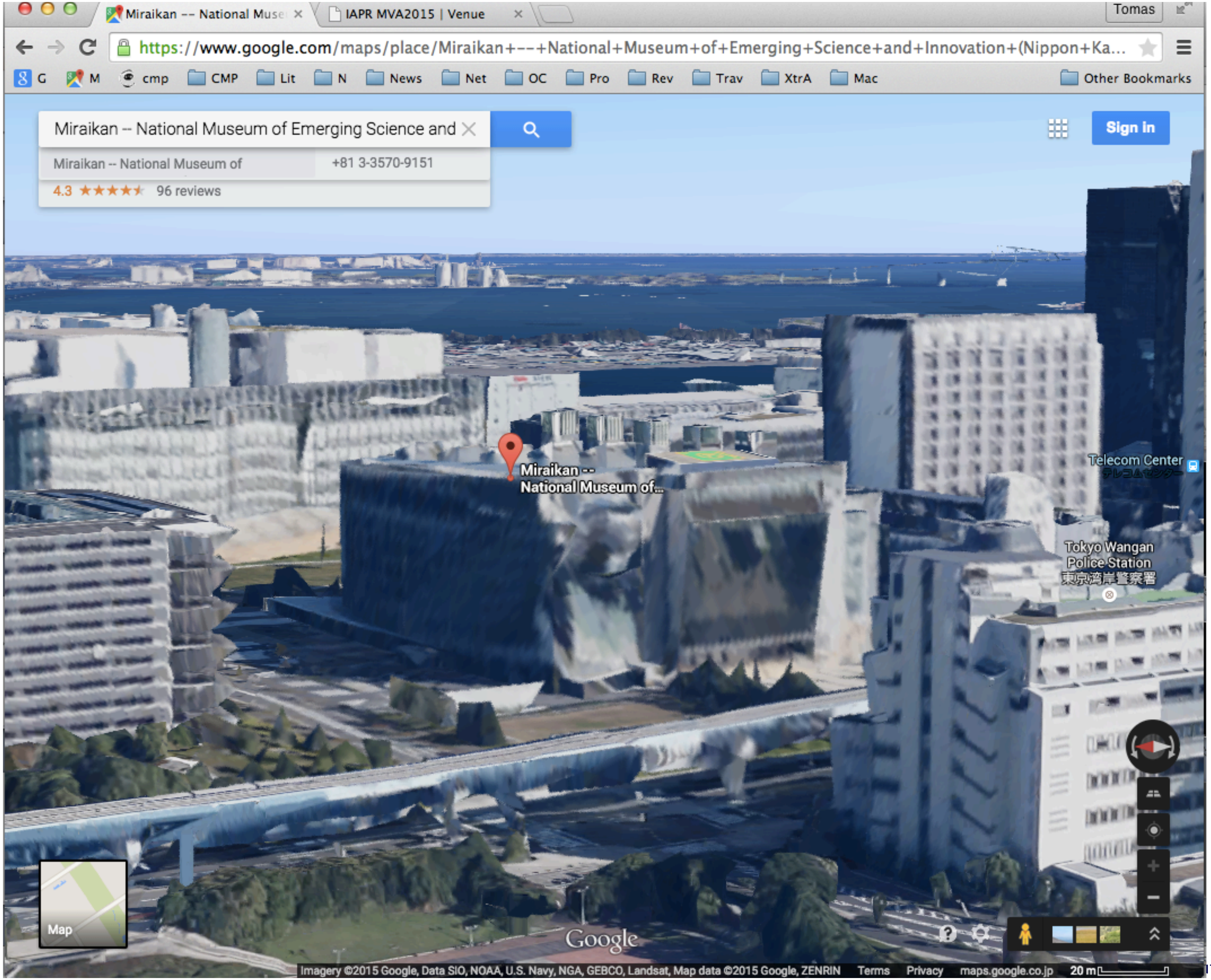
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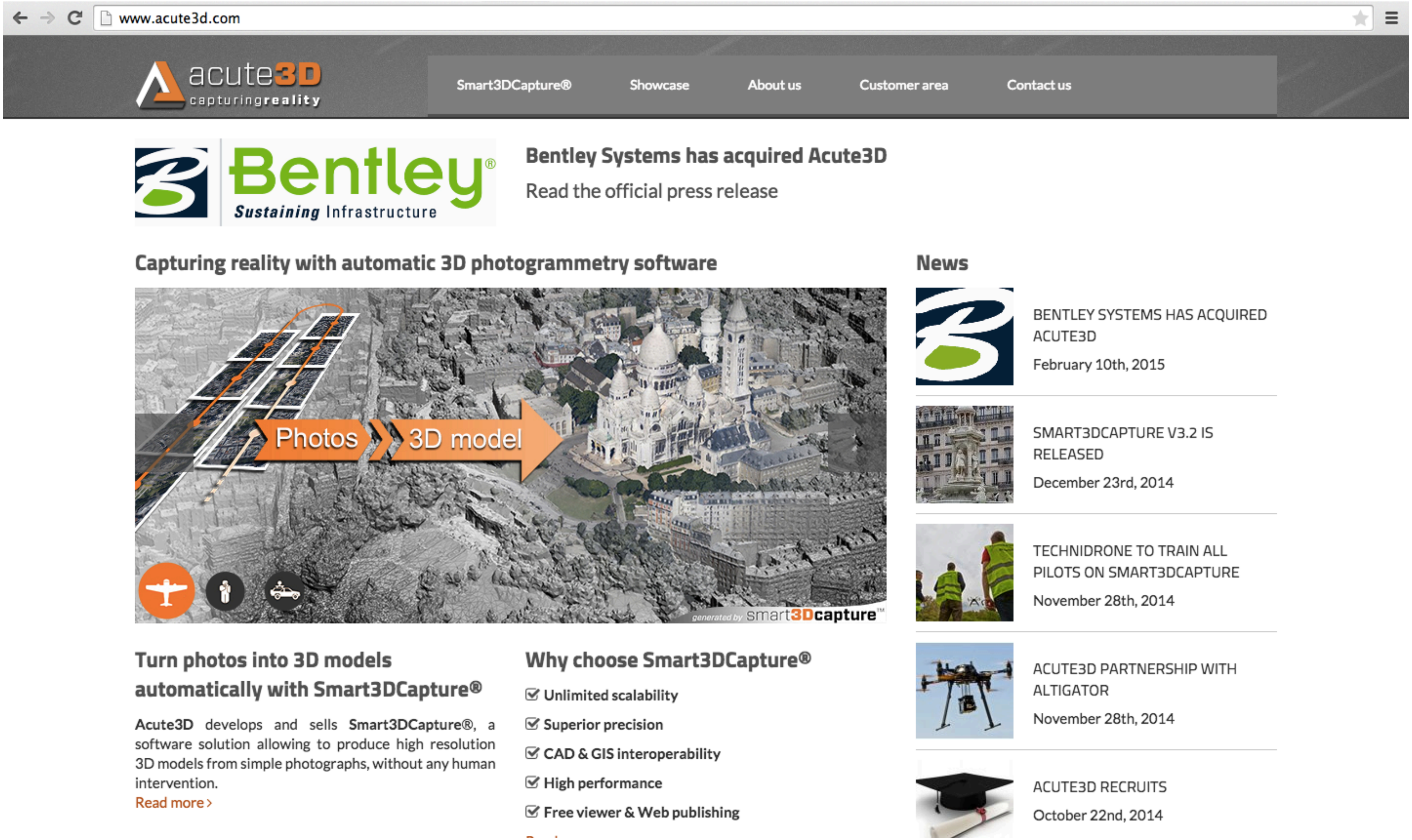
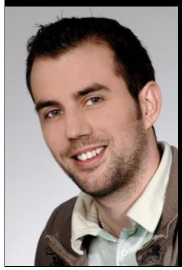


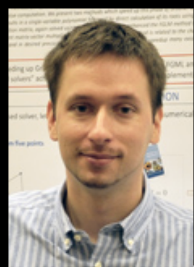
Founded 2011
Renaud Keriven (co-founder)
Formerly at IMAGINE Lab
École des Ponts ParisTech

Jean-Philippe Pons (co-founder)
Formerly at Centre Sci. et Tech. du Bâtiment in Sophia Antipolis

Founded 2011, Spin-off of EPFL Lausanne
Christph Strecha (CEO, co-founder)
Formerly EPFL Lausanne

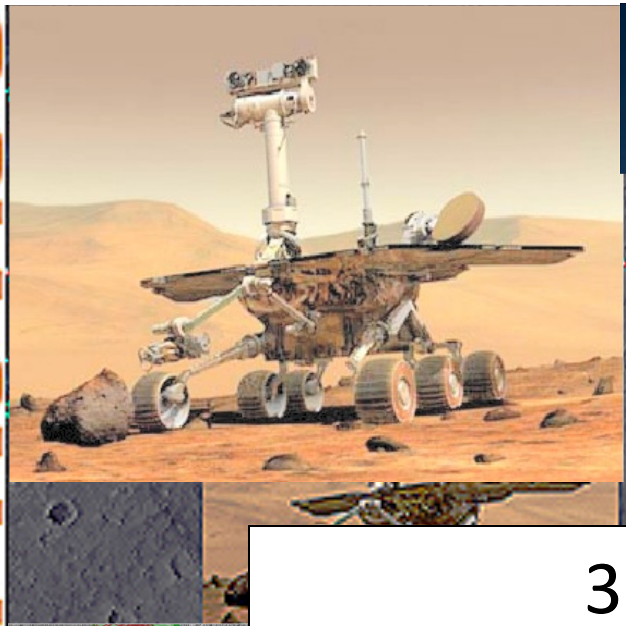


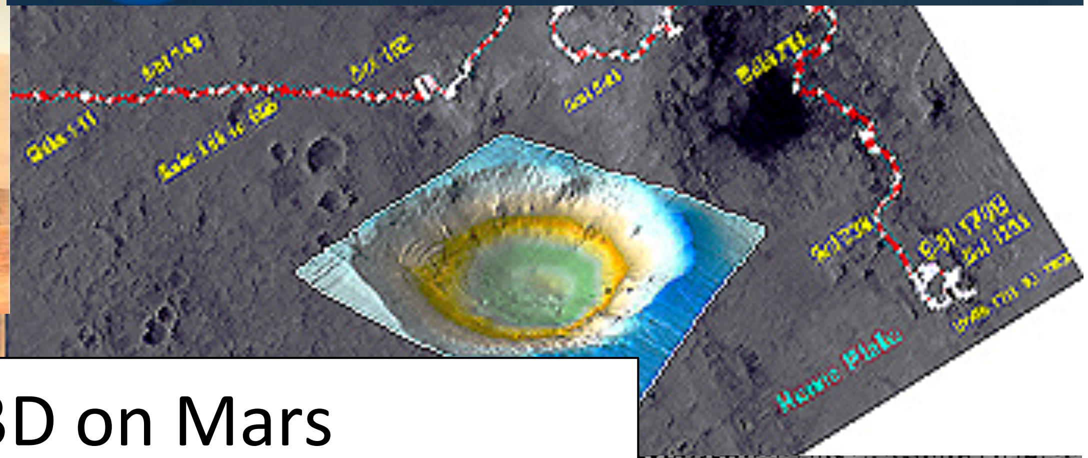
Founded 2014
Michal Jancosek (co-founder)
Formerly at CTU in Prague
PhD student of T. Pajdla



Martin Bujnak (co-founder)
Formerly at CTU in Prague
PhD student of T. Pajdla

Jet Propulsion Laboratory
California Institute of Technology





3D on Mars
CVVT Workshop @ CVPR 2015

SEVENTH FRAMEWORK PROGRAMME