



3D Computer Vision II

Introduction

Nassir Navab

based on a course given at UNC by Marc Pollefeys & the book "Multiple View Geometry" by Hartley & Zisserman

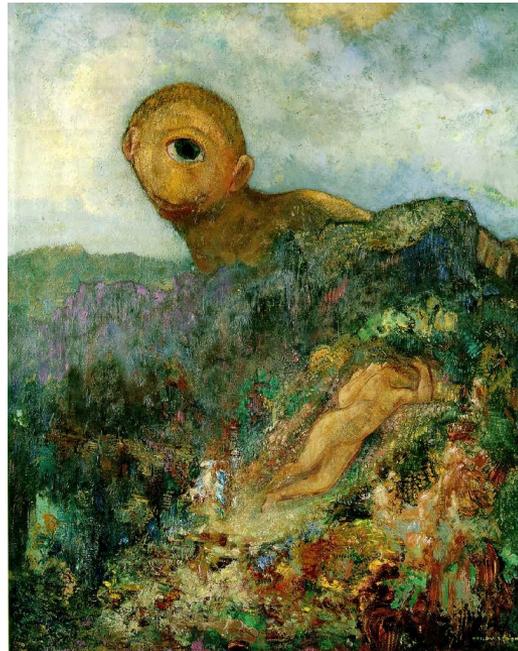
October 18, 2011

Course Objectives

- To understand the geometric relations between multiple views of scenes.
- To understand the general principles of parameter estimation (and error propagation).
- To be able to compute scene and camera properties from real world images using state-of-the-art algorithms.
- To have the basis to start working on a Computer Vision project.

3D Computer Vision I (Summer Term)

Lecture (Theoretische Informatik) 2+2 SWS, 5 Credits



Projective and Single-View Geometry
The Cyclops, c. 1914, Odilon Redon

3D Computer Vision II (Winter Term)

Lecture (Theoretische Informatik) 2+2 SWS, 5 Credits



Two-View Geometry



Three-View Geometry



Multiple View Geometry

The Birth of Venus (detail), c. 1485, Sandro Botticelli

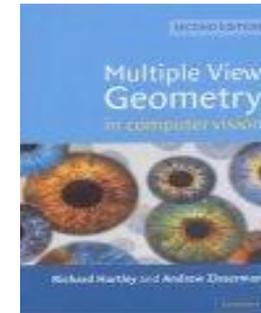
Material

Text book:

Multiple View Geometry in Computer Vision

by Richard Hartley and Andrew Zisserman

Cambridge University Press

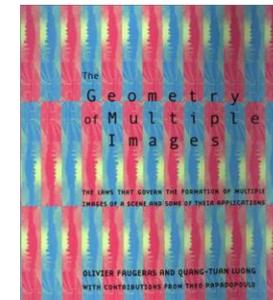


Alternative book:

The Geometry from Multiple Images

by Olivier Faugeras and Quan-Tuan Luong

MIT Press



On-line tutorial:

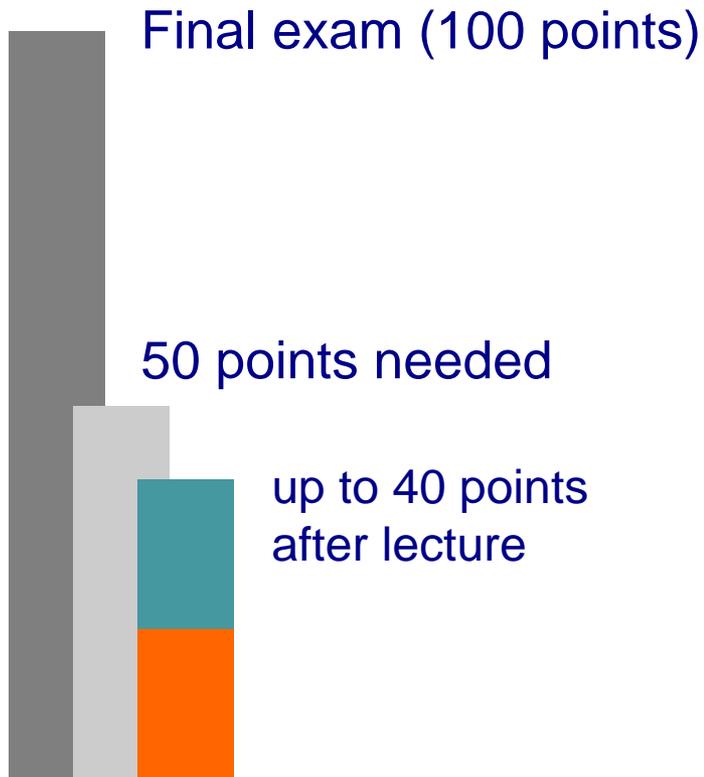
<http://www.cs.unc.edu/~marc/tutorial.pdf>

<http://www.cs.unc.edu/~marc/tutorial/>

Learning Approach

- Read the relevant chapters of the books before the course.
- In the course, the material will then be covered in detail and motivated with real-world examples.
- Hands-on assignments will be provided to give students a "feel" of the practical aspects.
- Students will be familiarized with and encouraged to use MATLAB.

Requirements



You can collect points already during the semester (not obligatory):



Midterm Exam

(20 points, 60 minutes)

Homework

(20 points, in groups of maximum 2 students)

You can have up to 40 points before the actual exam.

Applications

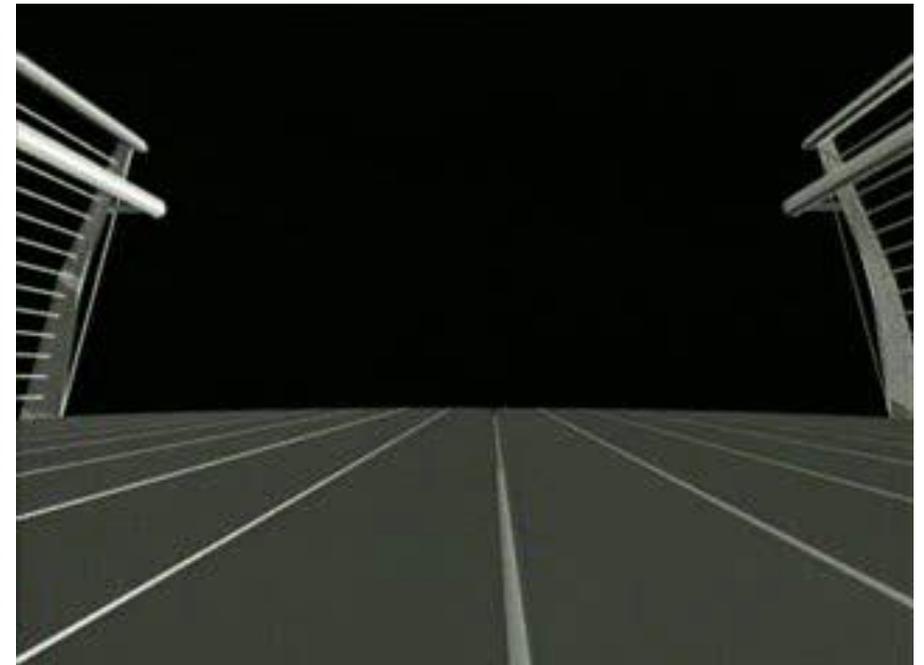
Augmented Reality (Marker-Based)



Video demonstrations: 1999

Applications

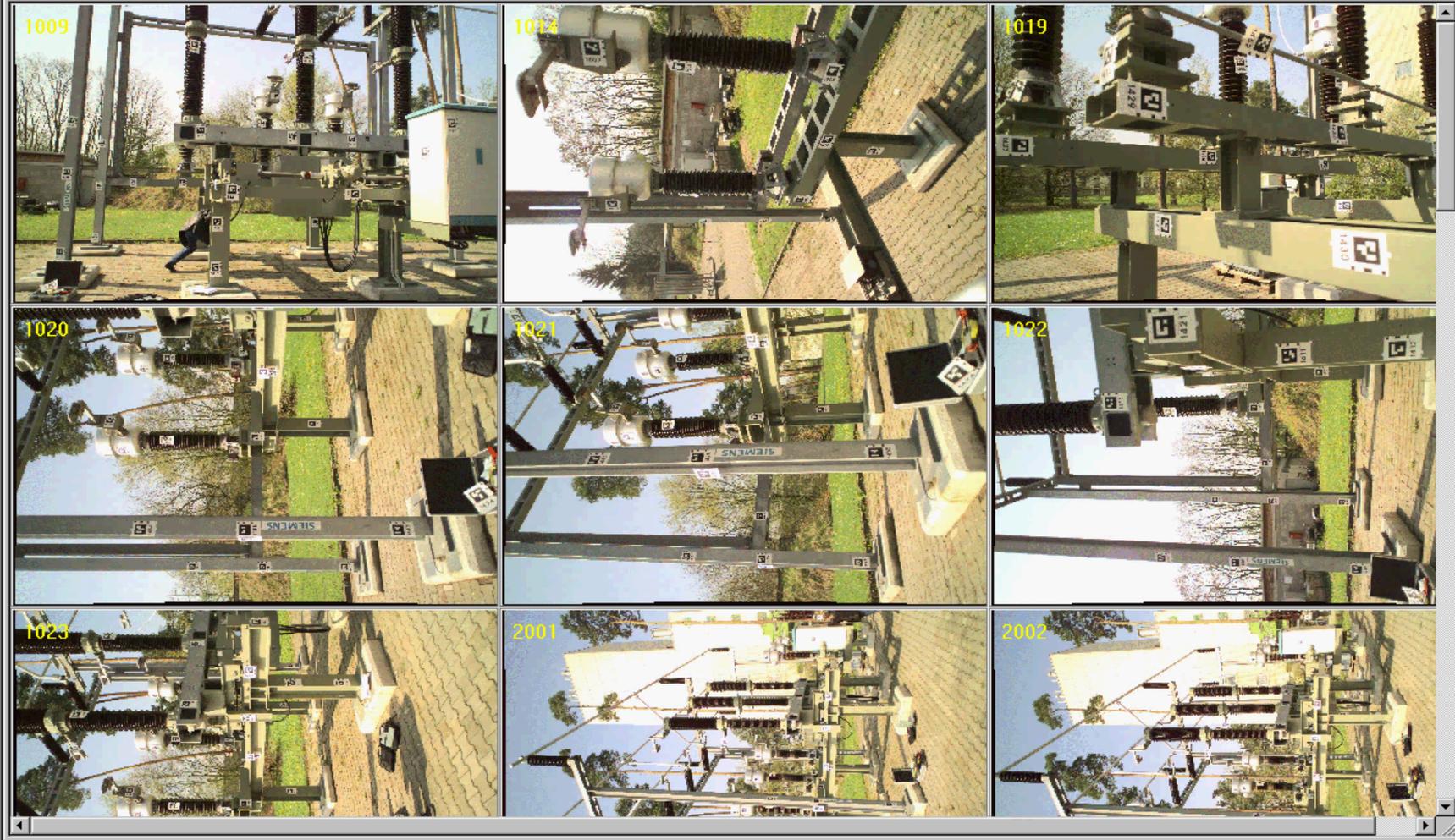
Augmented Reality
(Feature-based)



1998 - 2001

Applications – Advanced Visualization

Image Browser



Applications – 3D Modeling (Marker-Based)

New Add Edit Point Home Delete Info CanCel Find Zoom AR VR



Applications – Object Class Recognition



Object Class Recognition at a Glance

John Winn and Antonio Criminisi

Microsoft Research Ltd., Cambridge, UK

Applications – Cinema, Special Effects

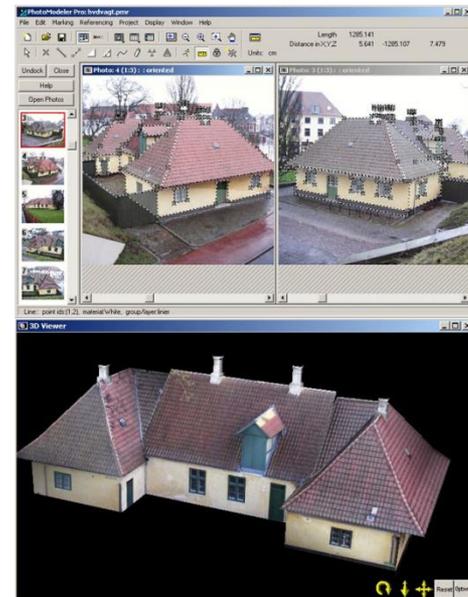
Andreas Weis
Philipp Kemmeter

3D Computer Vision Lab Course
CAMP – TU Muenchen

Applications – 3D Modeling (Model-Based)



Courtesy:Paul Debevec



Applications – 3D Modeling (Feature-Based)

Applications – 3D Modeling (Feature-Based)



Content

- **Transformations**
Projective Geometry (2D, 3D)
- **Parameter estimation**
Estimation, Error Analysis, Algorithm Evaluation
- **Single View**
Camera Models, Camera Calibration, Single View Geometry
- **Two Views**
Epipolar Geometry, 3D Reconstruction, Computing the Fundamental Matrix, Rectification and Disparity, Matching
- **Three Views**
Trifocal Tensor, Computing the Trifocal Tensor
- **More Views**
Multiple view reconstruction, Bundle Adjustment, Structure from Motion, Simultaneous Localization and Mapping

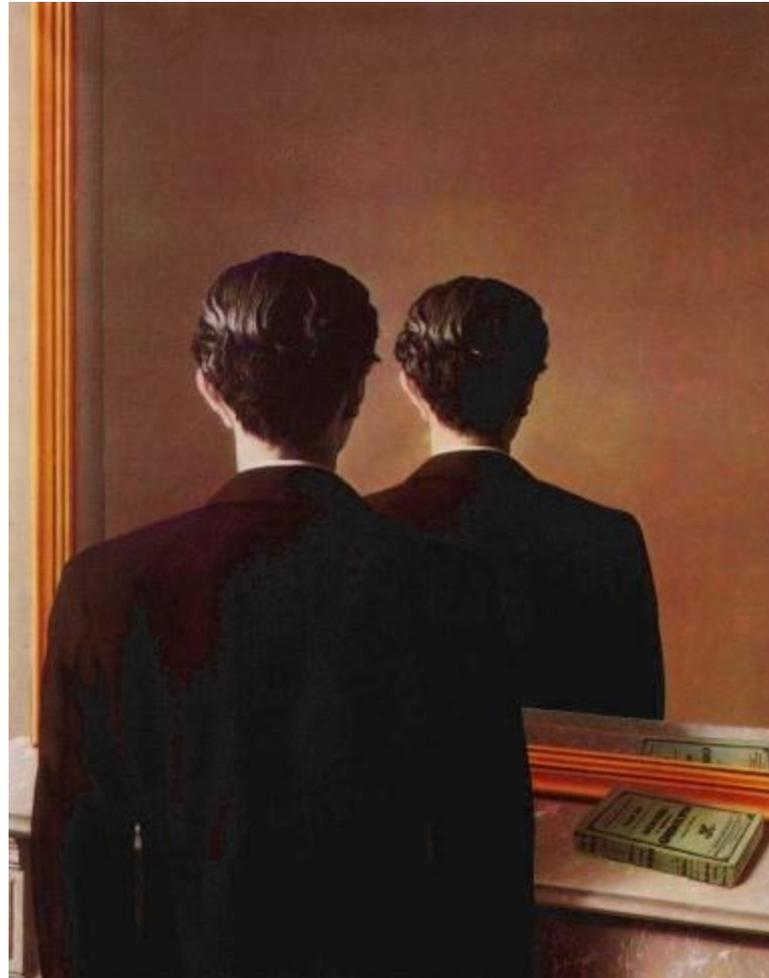
Fast Forward!

- Quick overview of the 3D Computer Vision lectures (I and II)...

3DCV I (Summer Term)

Background

3DCV I (ST)

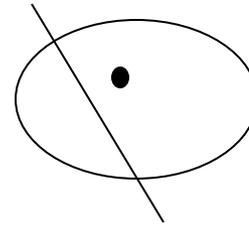


La reproduction interdite (Reproduction Prohibited), 1937, René Magritte.

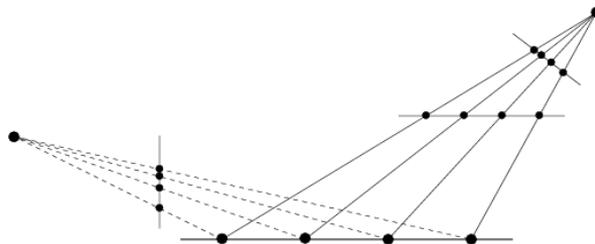
Projective 2D Geometry

3DCV I (ST)

- Points, lines & conics
- Transformations



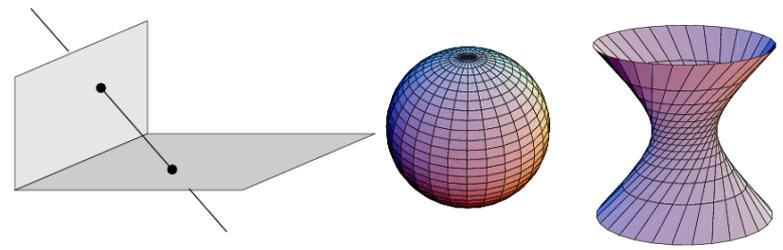
- Cross-ratio and invariants



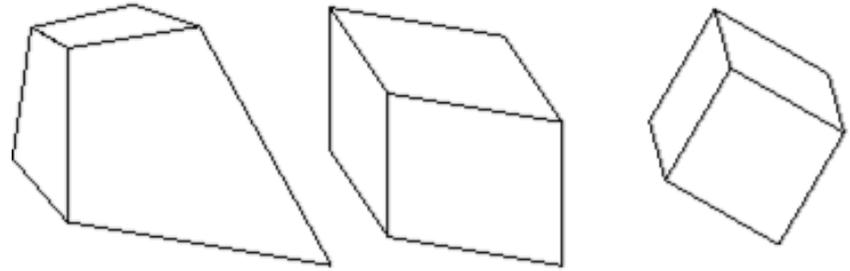
Projective 3D Geometry

3DCV I (ST)

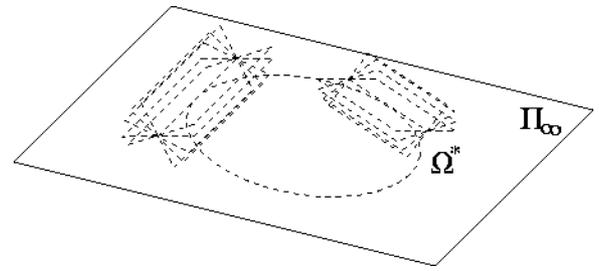
- Points, lines, planes and quadrics



- Transformations



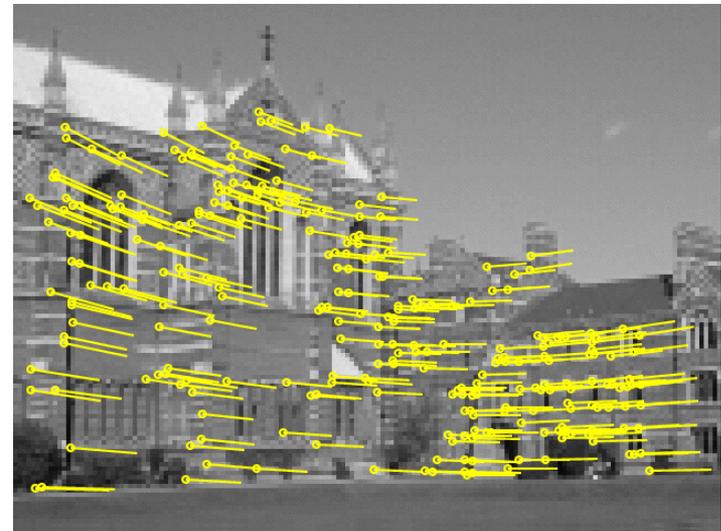
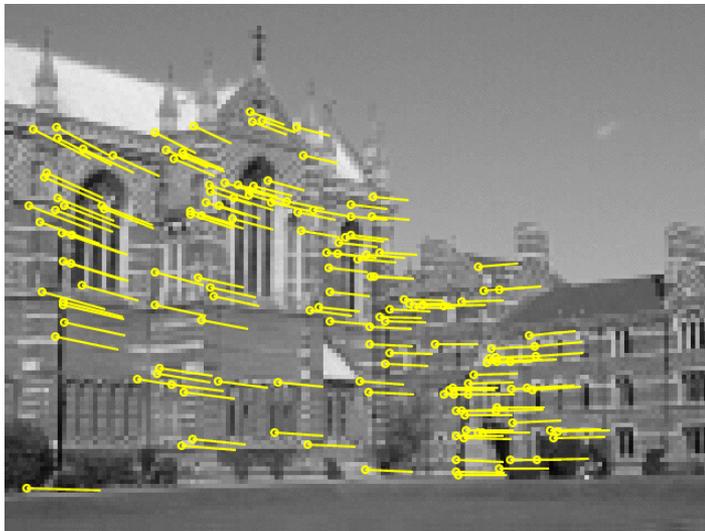
- Π_∞ , ω_∞ and Ω_∞



Estimation

3DCV I (ST)

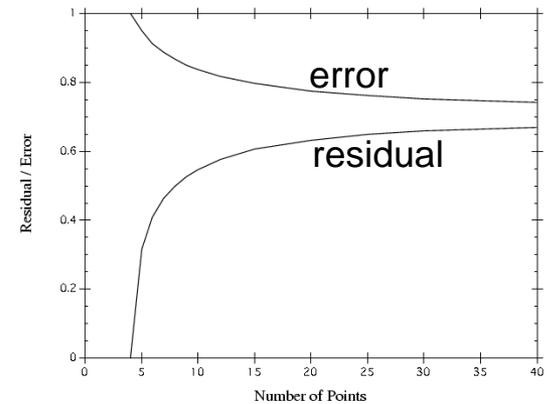
- How to compute a geometric relation from correspondences
- Linear (normalized), non-linear and Maximum Likelihood Estimation
- Robust (RANSAC)



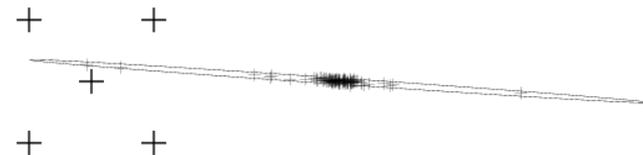
Evaluation and Error Analysis

3DCV I (ST)

- How good are the results we get
- Bounds on performance
- Covariance propagation
& Monte-Carlo estimation

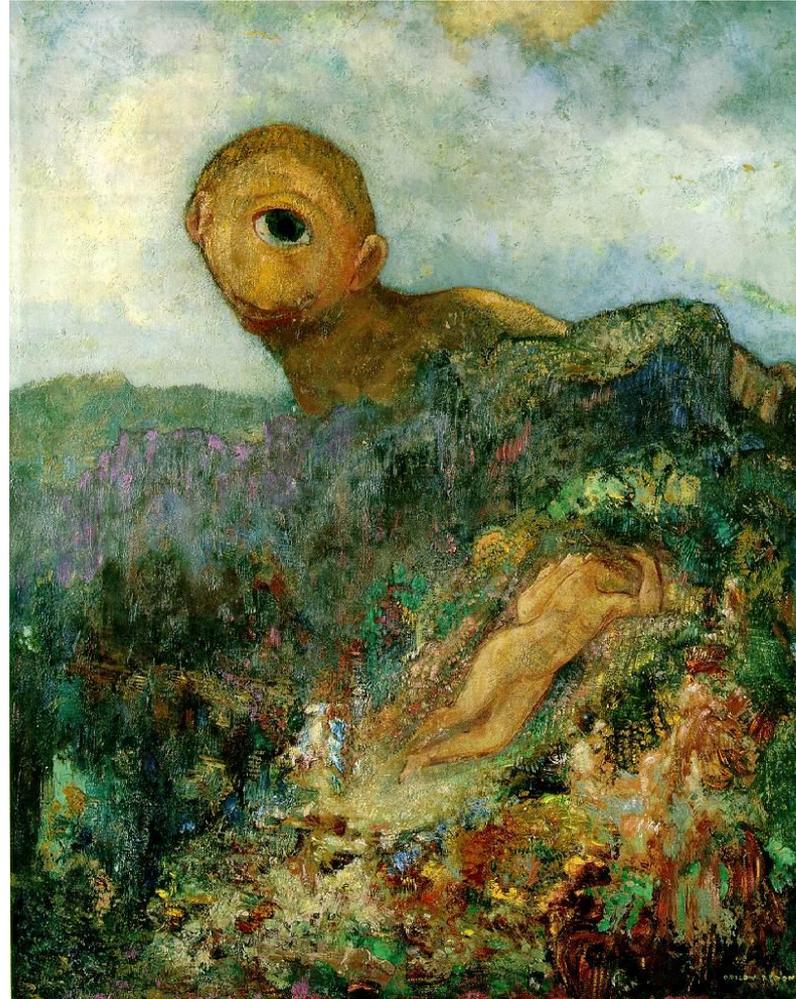


$$\Sigma_P = (\mathbf{J}^T \Sigma_X^{-1} \mathbf{J})^+$$



Single-View Geometry

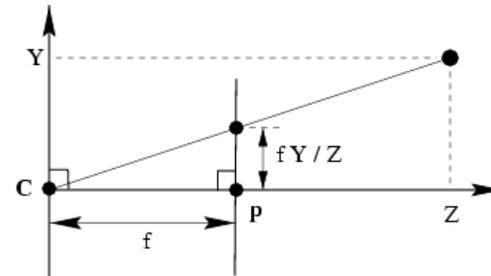
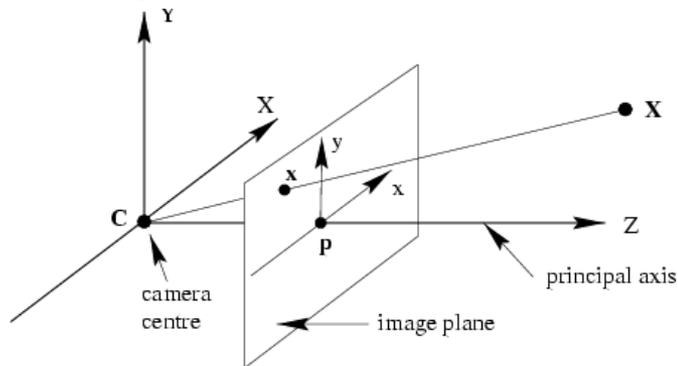
3DCV I (ST)



Camera Models

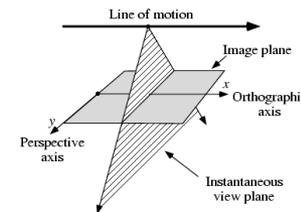
3DCV I (ST)

Mostly pinhole camera model



$$\lambda \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} f & p_x \\ & f & p_y \\ & & 1 \end{bmatrix} \begin{bmatrix} 1 \\ & & 1 \\ & & & 1 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}_3^T & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \quad \text{or} \quad \lambda \mathbf{x} = \mathbf{P} \cdot \mathbf{X}$$

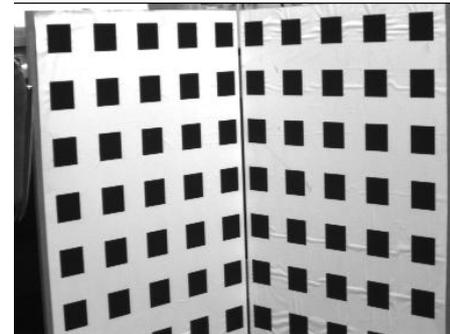
but also affine cameras, pushbroom camera, ...



Camera Calibration

3DCV I (ST)

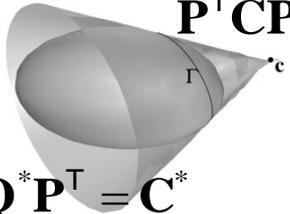
- Compute projection matrices given 2D-3D point correspondences
 - (normalized) linear, MLE,...
- Radial distortion



More Single-View Geometry

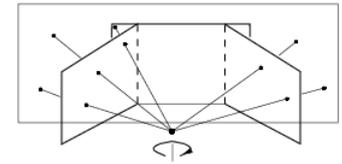
3DCV I (ST)

- Projective cameras and
- planes, lines, conics and quadrics.
- Camera center and camera rotation

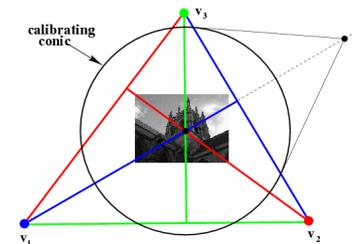
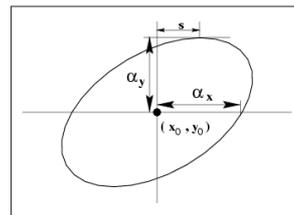


$$\mathbf{P}^T \mathbf{C} \mathbf{P} = \mathbf{Q}_{cone}$$

$$\mathbf{P} \mathbf{Q}^* \mathbf{P}^T = \mathbf{C}^*$$



- Camera calibration and vanishing points, calibrating conic and the IAC



3DCV II (Winter Term)

Two-View Geometry

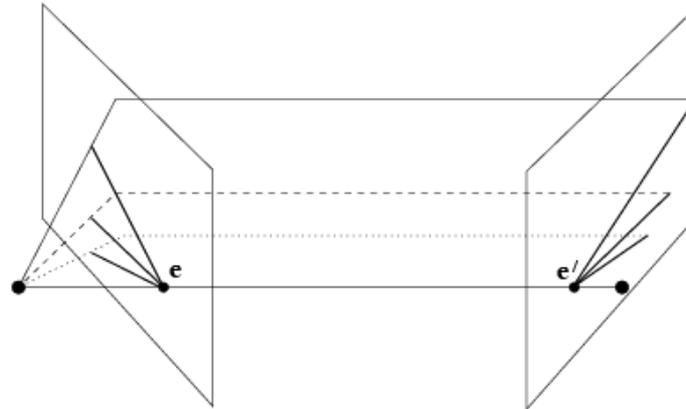
3DCV II (WT)



The Birth of Venus (detail), c. 1485, Sandro Botticelli

Epipolar Geometry

3DCV II (WT)



Fundamental matrix Essential matrix

$$\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0$$

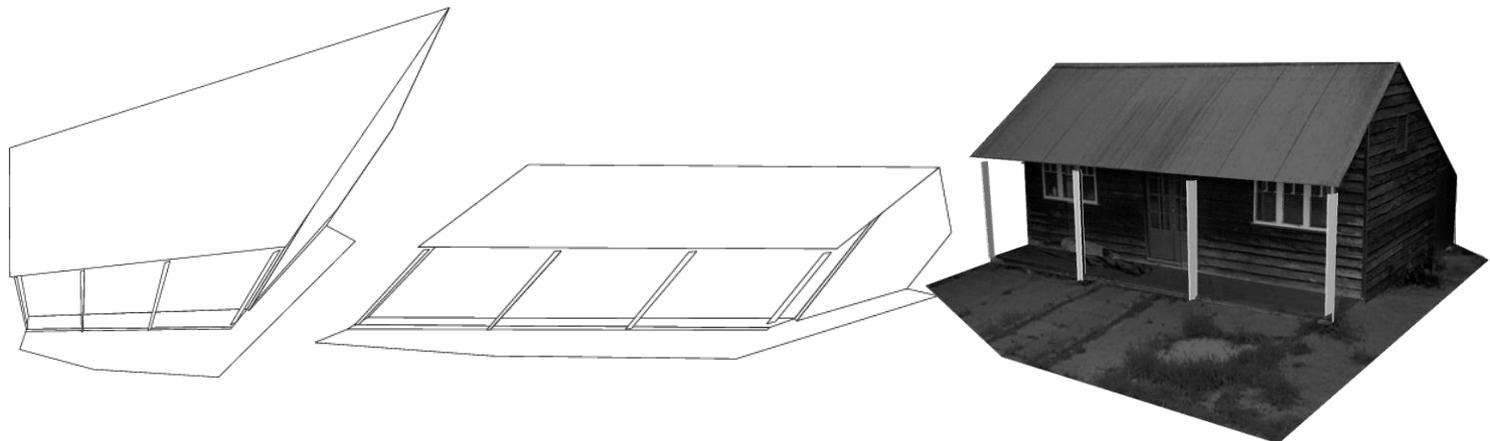
$$\mathbf{F} \rightarrow \mathbf{P}, \mathbf{P}'$$

$$\hat{\mathbf{x}}'^T \left([t]_{\times} \mathbf{R} \right) \hat{\mathbf{x}} = 0$$

$$\mathbf{E} \rightarrow \mathbf{P}, \mathbf{P}'$$

Two-View Reconstruction

3DCV II (WT)



Epipolar Geometry Computation

$$\mathbf{x}'^T \mathbf{F} \mathbf{x} = 0$$

- (normalized) linear estimation:

$$(x'x, x'y, x', y'x, y'y, y', x, y, 1) \cdot \mathbf{f} = 0$$

- minimal:

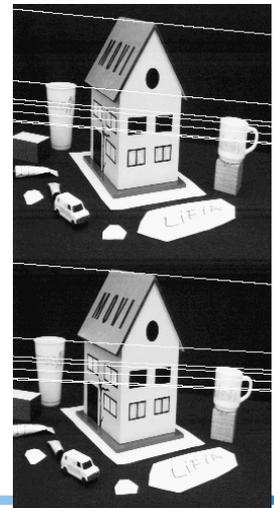
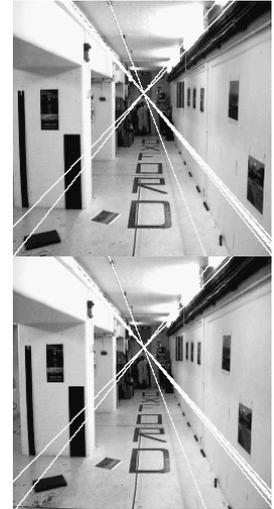
$$\det(\mathbf{F}_1 + \lambda \mathbf{F}_2) = 0$$

- Maximum Likelihood Estimation:

$$\min_i \sum d(\mathbf{x}_i, \hat{\mathbf{x}}_i)^2 + d(\mathbf{x}'_i, \hat{\mathbf{x}}'_i)^2$$

$$\text{for which } \hat{\mathbf{x}}_i'^T \mathbf{F} \hat{\mathbf{x}}_i = 0$$

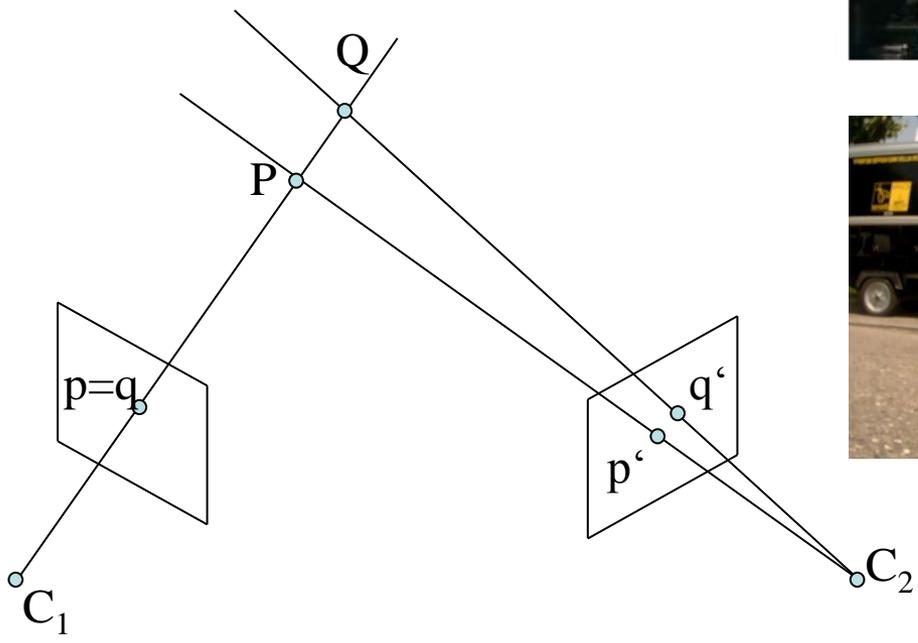
- RANSAC
- ... and automated two view matching



Reconstruction and Disparity, Stereo Matching

3DCV II (WT)

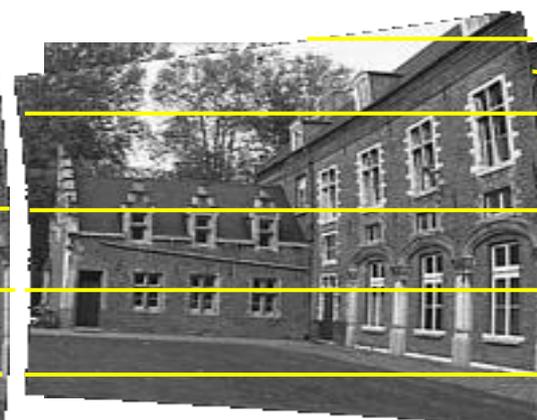
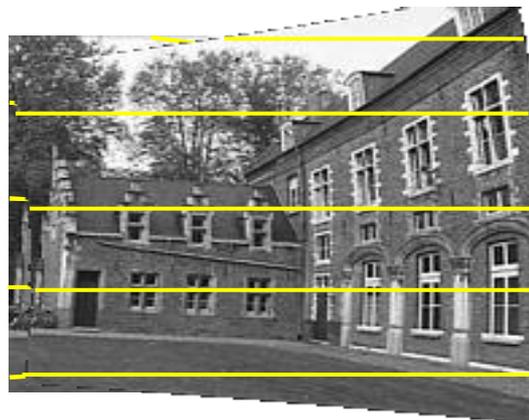
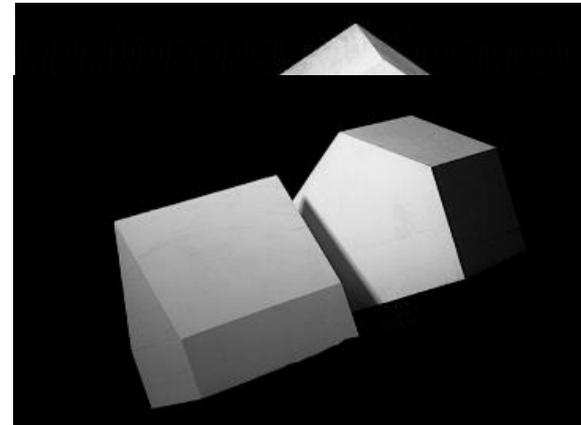
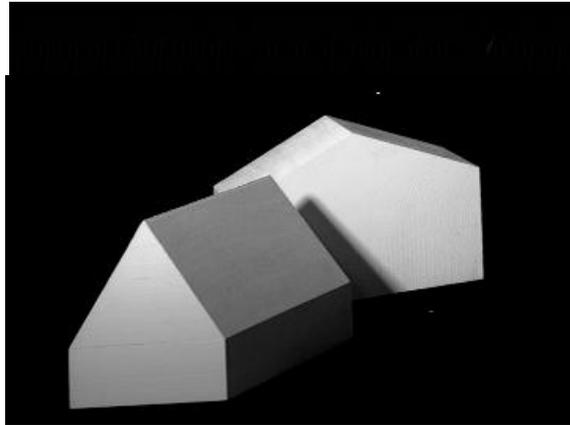
With two (or more) cameras we can infer depth from correspondences using triangulation.



Rectification

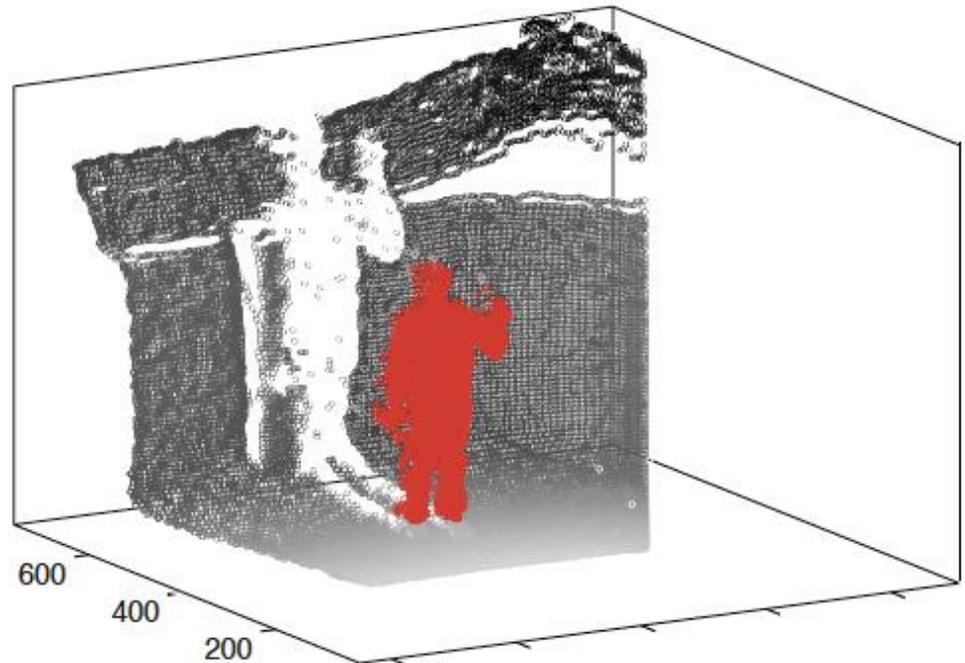
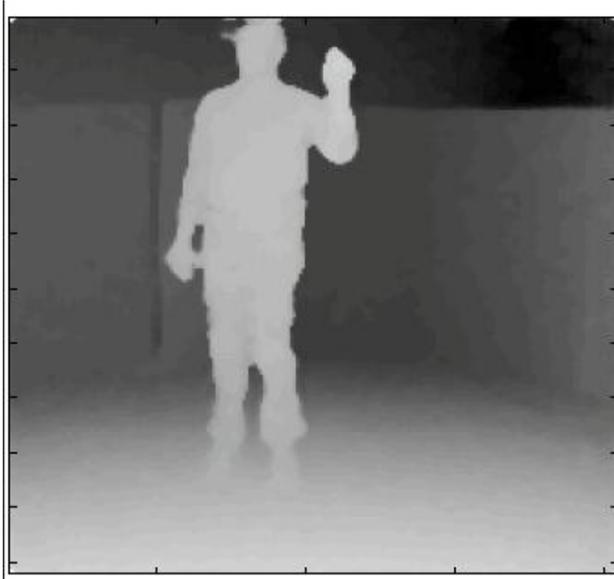
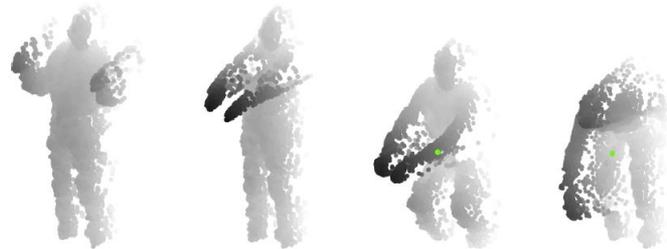
3DCV II (WT)

Warp images to simplify epipolar geometry

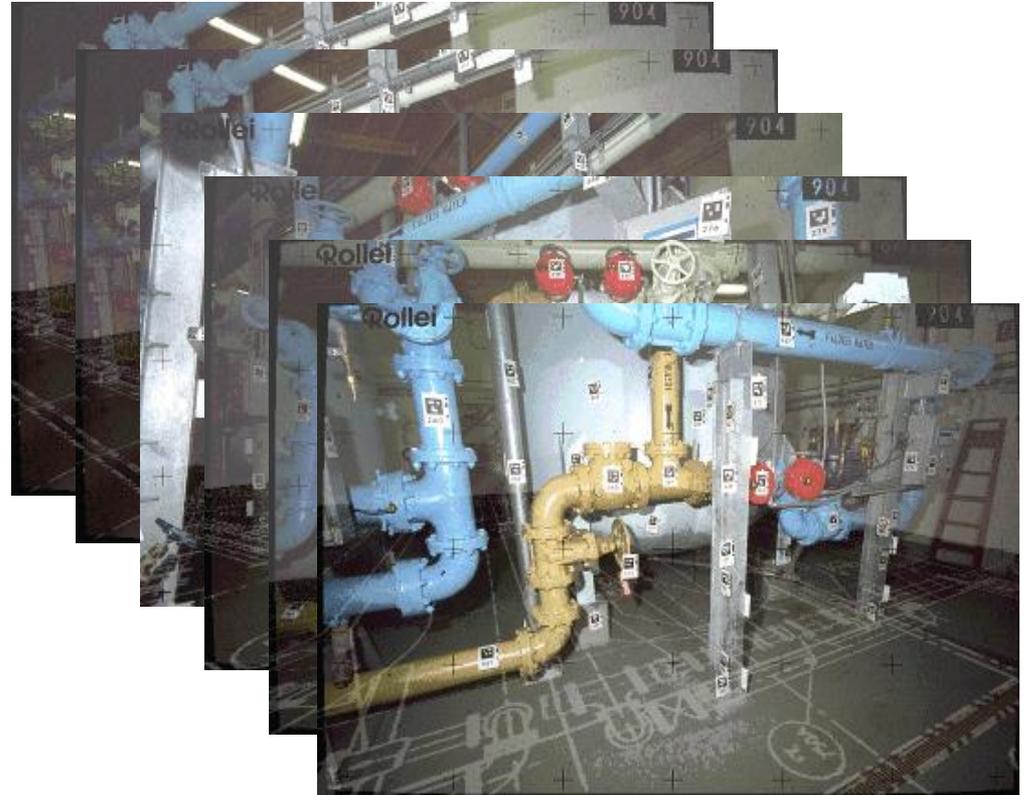
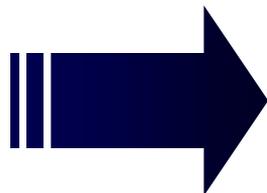
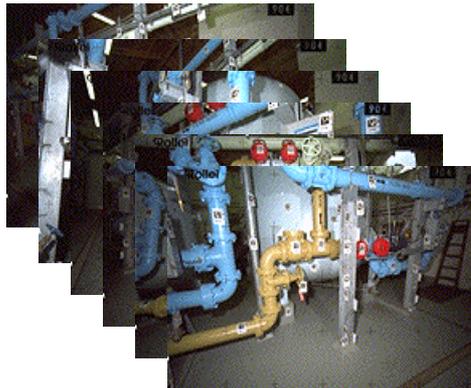
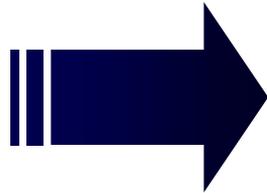
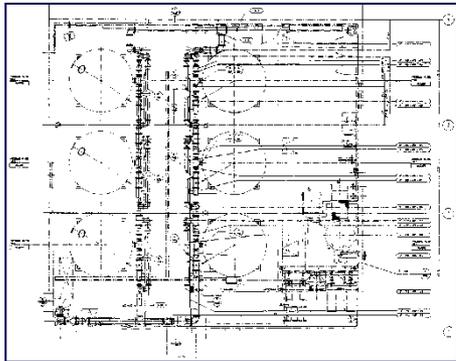


Time-of-Flight Imaging

3DCV II (WT)

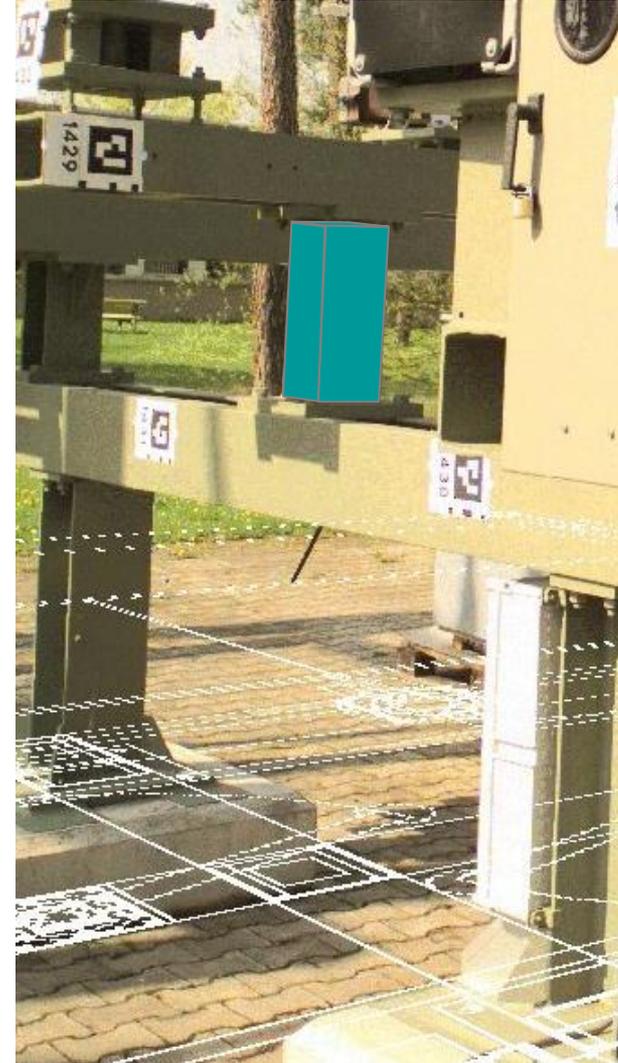
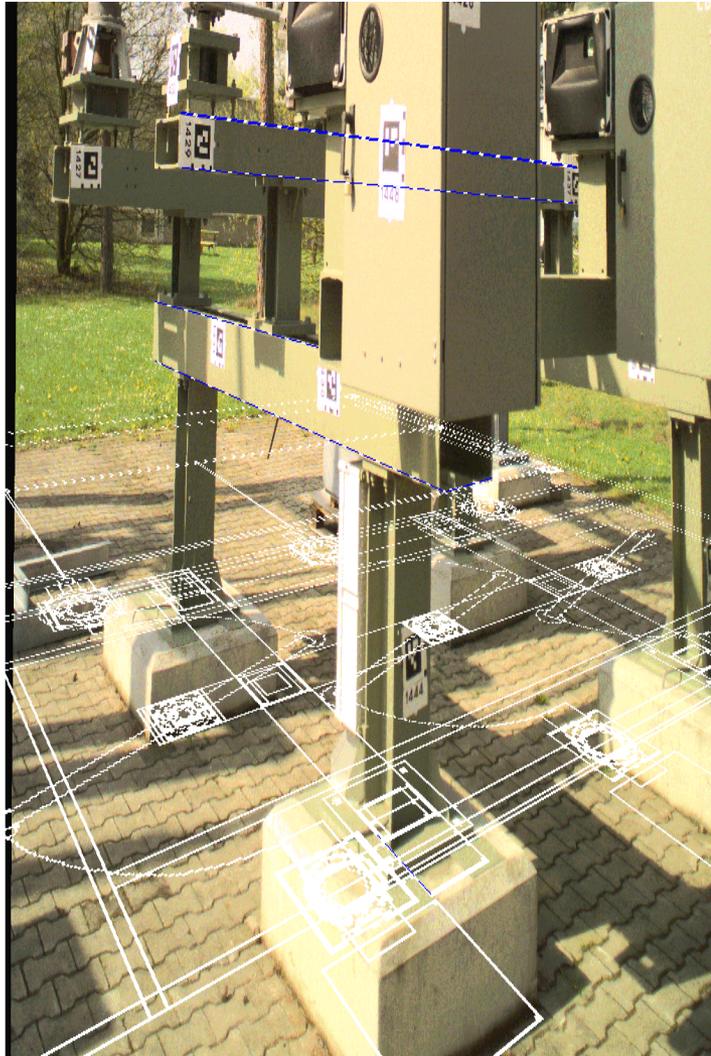


Combined Orthographic and Perspective (COP) Images

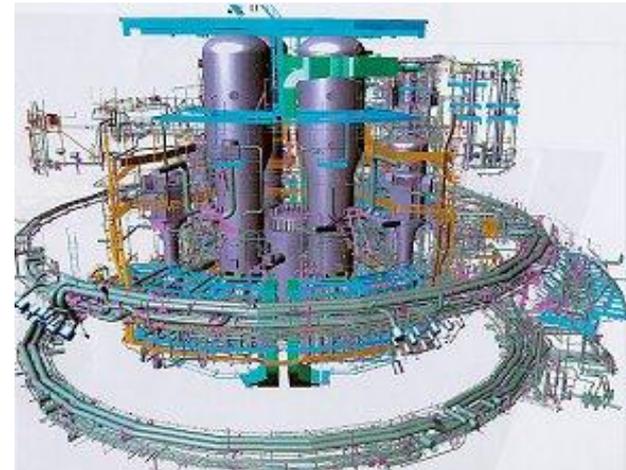


Calibration/Reconstruction from COP Images

3DCV II (WT)



Motion of Lines & Cylinders



$$\begin{bmatrix} \mathbf{I}_0 \\ \mathbf{N}_0 \\ r_0 \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{0}_{3 \times 3} & \mathbf{0}_{3 \times 1} \\ \mathbf{E} & \mathbf{R} & \mathbf{0}_{3 \times 1} \\ \mathbf{0}_{1 \times 3} & \mathbf{0}_{1 \times 3} & 1 \end{bmatrix} \begin{bmatrix} \mathbf{I}_1 \\ \mathbf{N}_1 \\ r_1 \end{bmatrix}$$

Where $\mathbf{E} = \tilde{\mathbf{T}}\mathbf{R}$ is the essential matrix.

Multiple-View Geometry

3DCV II (WT)



The Birth of Venus (detail), c. 1485, Sandro Botticelli

Multiple View Reconstruction

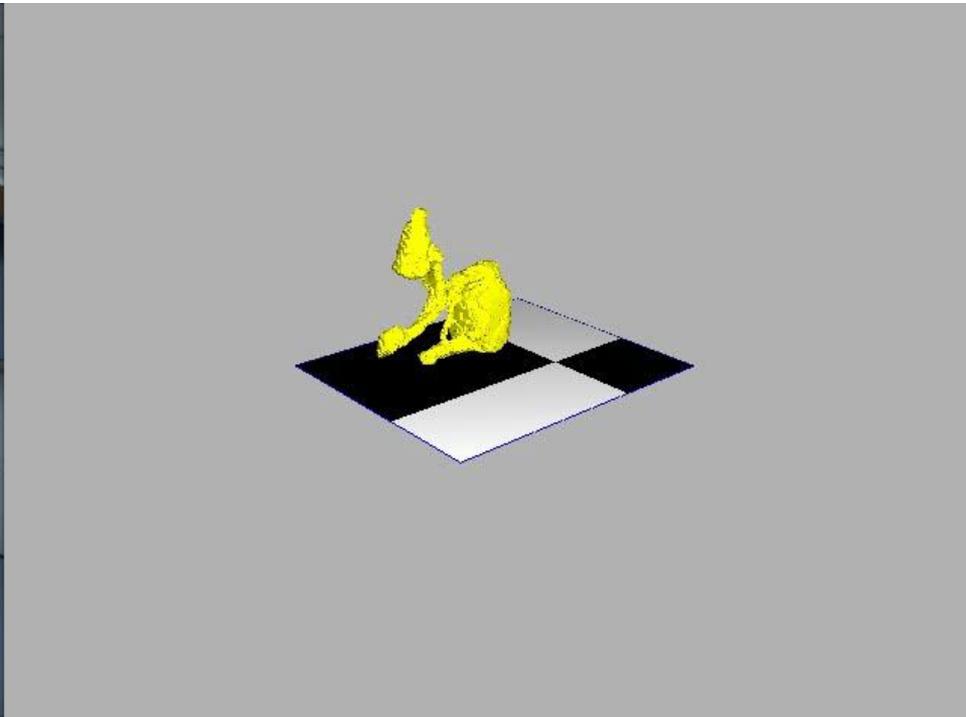
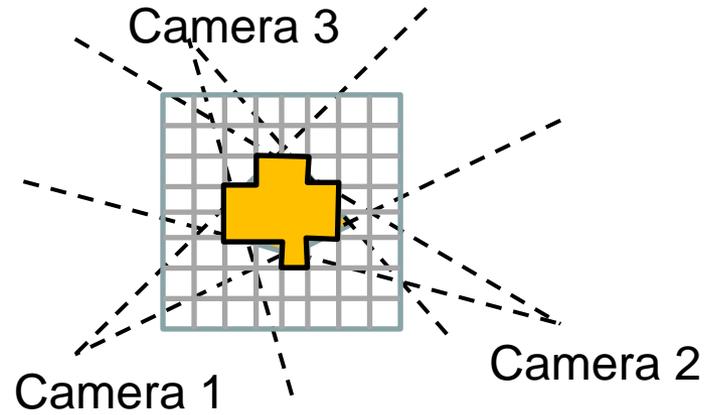
3DCV II (WT)

- Affine factorization
- Projective factorization

$$\begin{bmatrix} \mathbf{X}_1^1 & \mathbf{X}_2^1 & \cdots & \mathbf{X}_n^1 \\ \mathbf{X}_1^2 & \mathbf{X}_2^2 & \cdots & \mathbf{X}_n^2 \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{X}_1^m & \mathbf{X}_2^m & \cdots & \mathbf{X}_n^m \end{bmatrix} = \begin{bmatrix} \mathbf{P}^1 \\ \mathbf{P}^2 \\ \vdots \\ \mathbf{P}^m \end{bmatrix} [\mathbf{X}_1 \quad \mathbf{X}_2 \quad \cdots \quad \mathbf{X}_n]$$

Shape from Silhouettes

3DCV II (WT)



Structure from Motion

3DCV II (WT)



<http://phototour.cs.washington.edu/bundler/>

3D Computer Vision II

Time: Tuesday (10:30am - 12:00am) & Thursday (1pm – 2:30pm)
Location: MI 03.13.010
Lecturer: Prof. Nassir Navab
Exercises: Stefan Hinterstoißer, Loren Schwarz
Office Hours: Thursday, 2:30pm – 3:30pm

Lectures and Exercises can be both on Tuesday AND on Thursday! Please have a look on our Lecture Website at: <http://campar.in.tum.de/Chair/TeachingWs11Cv2> .

Latest News and lecture relevant stuff are also found on our Website

You need 100 points to pass the lecture with the best grade (1.0).

In total you can get 140 points (100 points from final exam,
20 bonus points from midterm exam,
20 bonus points from homework).

You need to register in TUMONLINE to take part in the exams!

Course Schedule

Please scroll down for the exercise schedule.

Date	Topic	Conducted by	Material/Literature
18.10.2011	Introduction	Prof. Dr. N. Navab	
20.10.2011	Reminder: Projective Geometry, Transformations	Prof. Dr. N. Navab	
27.10.2011	Reminder: Camera Models	Prof. Dr. N. Navab	
8.11.2011	Two-view Geometry I (Epipolar Geometry)	Prof. Dr. N. Navab	
15.11.2011	<i>No lecture due to Studentische Vollversammlung</i>	--	
17.11.2011	Two-view Geometry II (Fundamental Matrix)	Prof. Dr. N. Navab	
22.11.2011	Two-view Geometry III (continued)	Prof. Dr. N. Navab	
6.12.2011	Stereo I (Rectification, Disparity)	C. Unger	
13.12.2011	Stereo II (Matching, Reconstruction)	C. Unger	
20.12.2012	Mid-Term Exam	--	
10.01.2012	Multi-view 3D Reconstruction	Dr. S. Ilic	
17.01.2011	N-View Computational Methods	Prof. Dr. N. Navab	
24.01.2012	Time-of-Flight / Kinect Imaging	L. Schwarz	
31.01.2012	Multimodal Detection in Cluttered Background	S. Hinterstoisser	
t.b.a.	Final Exam	Prof. Dr. N. Navab	

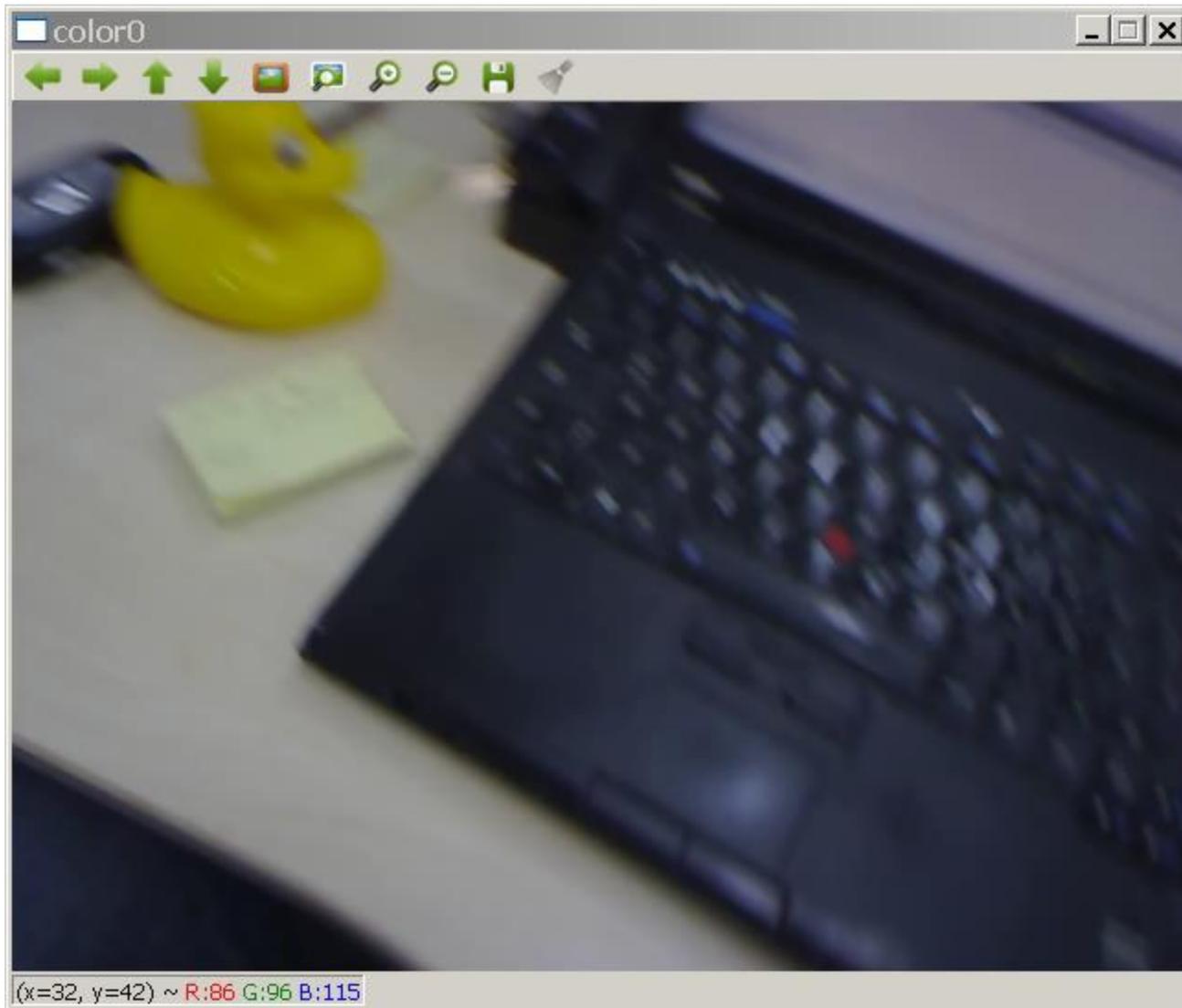


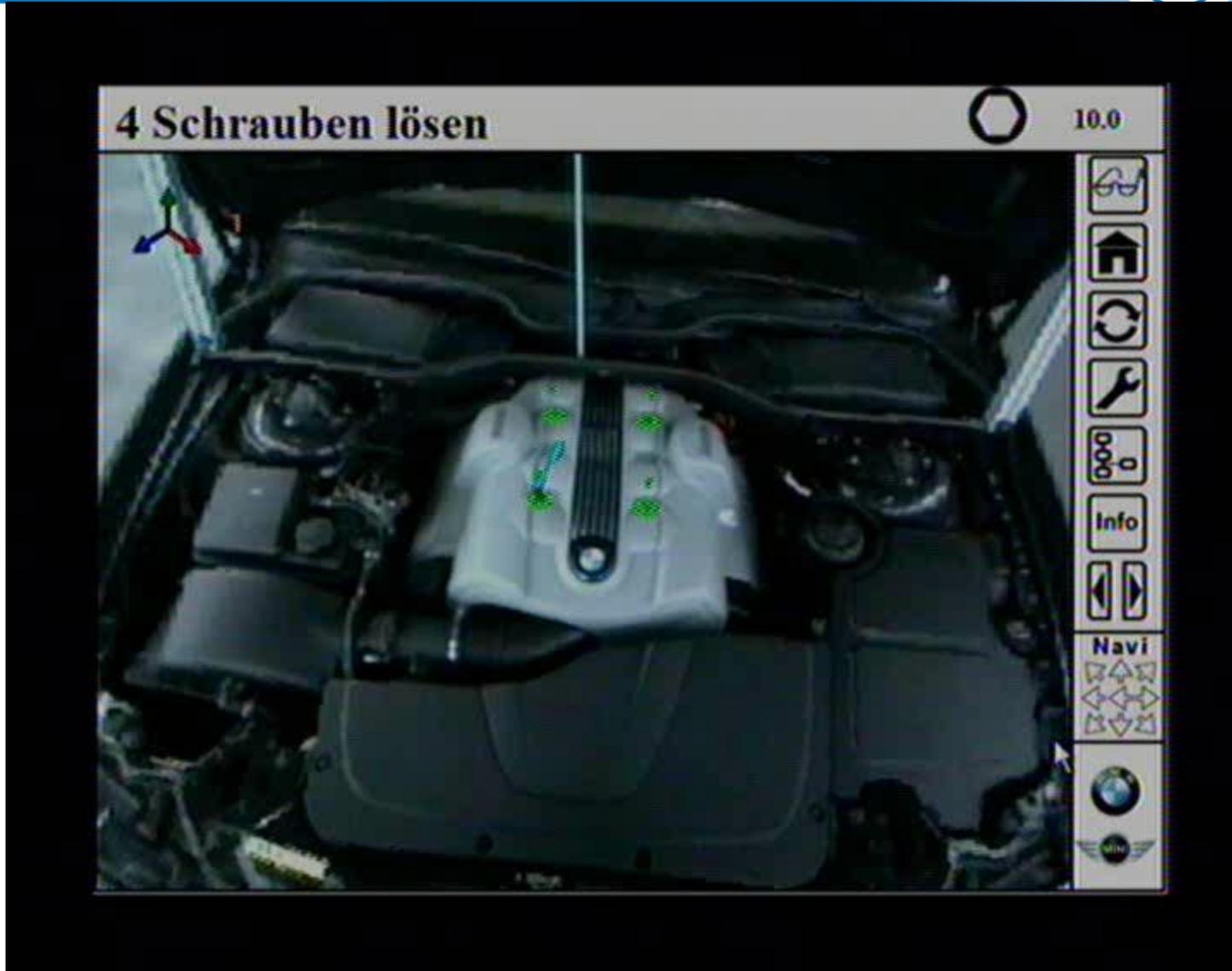
Exercise Schedule

Date	Topic	Conducted by	Exercises	Solutions	Homework due	Notes
25.10.2011	Introduction, MATLAB Tutorial					
03.11.2011	Reminder Projective Geometry					
10.11.2011	Reminder Camera Models, Projection Matrix					
24.11.2011	Epipolar Geometry					
29.11.2011	Estimation of Fundamental Matrix					
01.12.2011	Attestation					
08.12.2011	<i>No Exercise due to Dies Academicus</i>					
15.12.2011	Exercise to Stereo I and II					
22.12.2011	Midterm correction					
12.01.2012	Multi-view 3D Reconstruction					
19.01.2012	Factorization					
26.01.2012	Time of Flight / Kinect					
03.02.2012	Reminder					



More Application Examples ...





Parallel Tracking and Mapping for Small AR Workspaces

Extra video results made for
ISMAR 2007 conference

Georg Klein and David Murray
Active Vision Laboratory
University of Oxford

Photo Tourism

Exploring photo collections in 3D

Noah Snavely Steven M. Seitz Richard Szeliski
University of Washington *Microsoft Research*

SIGGRAPH 2006



SIGGRAPH Talks 2011

KinectFusion:

Real-Time Dynamic 3D Surface Reconstruction and Interaction

**Shahram Izadi 1, Richard Newcombe 2, David Kim 1,3, Otmar Hilliges 1,
David Molyneaux 1,4, Pushmeet Kohli 1, Jamie Shotton 1,
Steve Hodges 1, Dustin Freeman 5, Andrew Davison 2, Andrew Fitzgibbon 1**

1 Microsoft Research Cambridge 2 Imperial College London

3 Newcastle University 4 Lancaster University

5 University of Toronto

PiX4D

Hands free image processing

Pose Estimation

Distance Transform Templates for Object Detection and Pose Estimation

#429

S. Holzer , S. Hinterstoisser, S. Ilic, N. Navab
Distance Transform Templates for Object Detection and Pose Estimation
CVPR 2009

Tracking by classification



S. Hinterstoisser, S. Benhimane, N. Navab, P. Fua, V. Lepetit
Online Learning of Patch Perspective Rectification for Efficient Object Detection
CVPR 2008



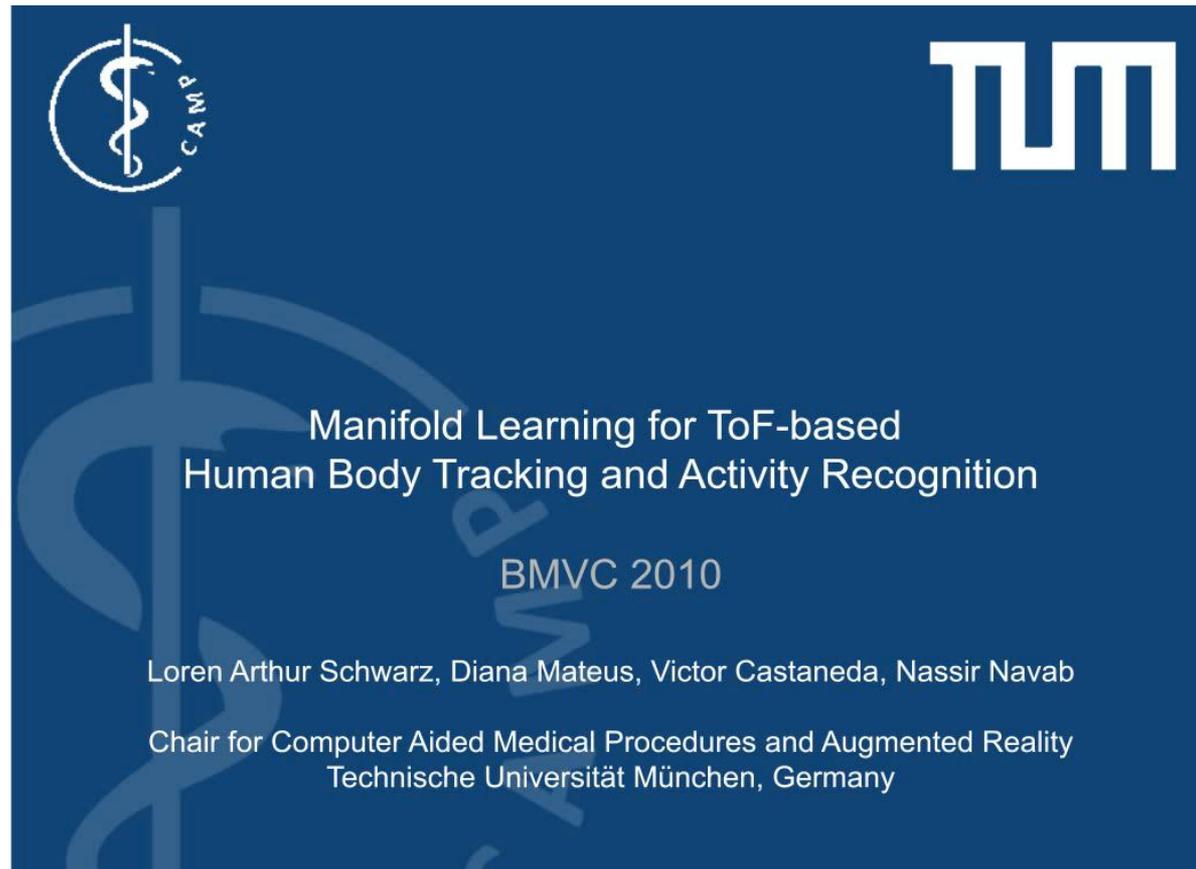
S. Hinterstoisser, S. Benhimane, V. Lepetit, P. Fua, N. Navab
Simultaneous Recognition and Homography Extraction of Local Patches with a Simple Linear Classifier
BMVC 2008

Tracking by classification



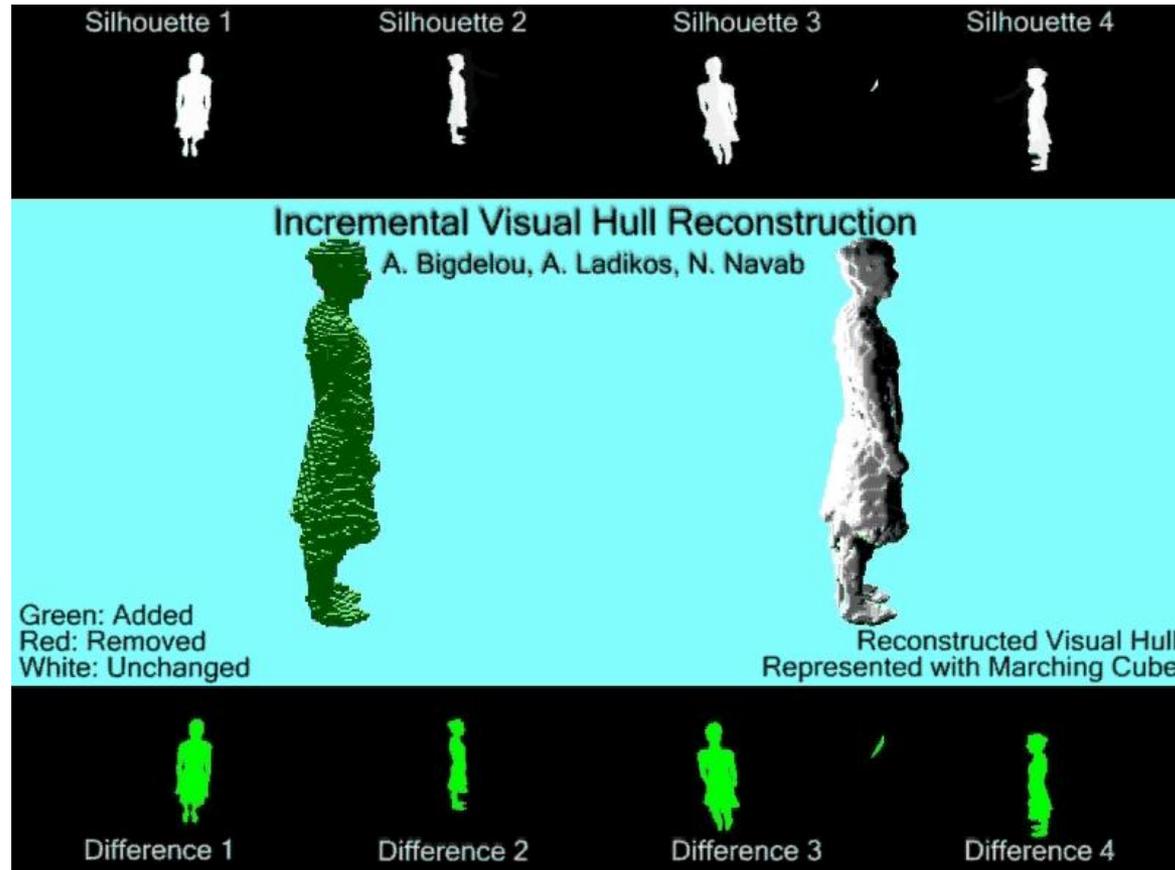
S. Hinterstoisser, O. Kutter, N. Navab, P. Fua, V. Lepetit
Real-Time Learning of Accurate Patch Rectification.
CVPR 2009.

Human Tracking from Time-of-Flight Images



L. Schwarz, D. Mateus, V. Castañeda, N. Navab
Manifold Learning for ToF-based Human Body Tracking and Activity Recognition
BMVC 2010.

3D Reconstruction



A. Bigdelou, A. Ladikos, N. Navab
Incremental Visual Hull Reconstruction
BMVC 2009.

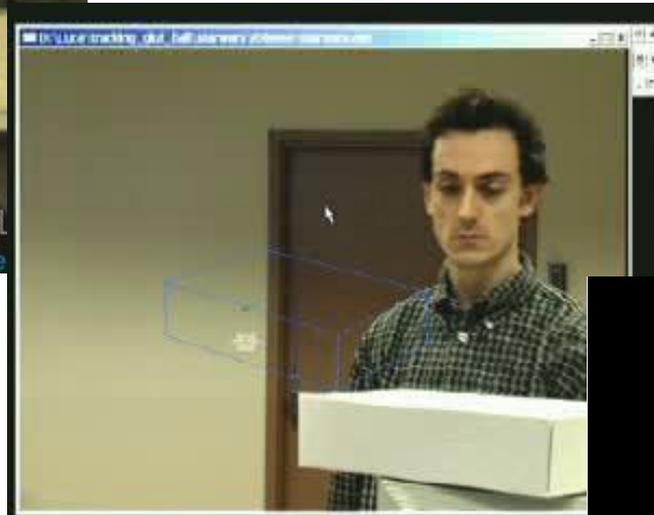
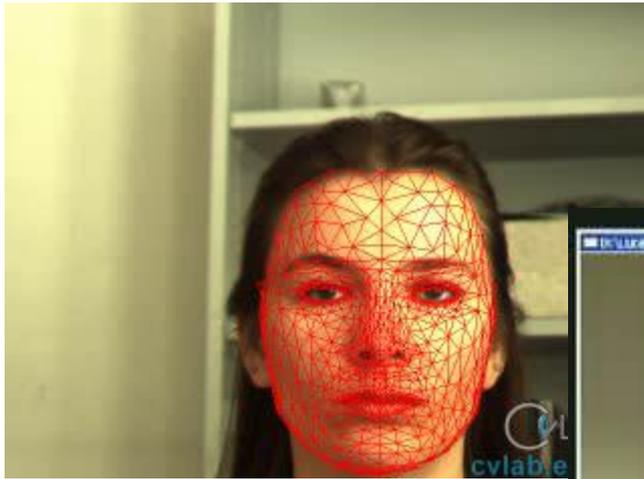
Dense Surface Tracking

PROBABILISTIC DEFORMABLE SURFACE TRACKING FROM MULTIPLE VIDEOS

ECCV ANONYMOUS SUBMISSION #1043

C. Cagniart, E. Boyer, S. Ilic
Probabilistic Deformable Surface Tracking From Multiple Videos
ECCV 2010

More AR Applications



Courtesy of EPFL

Medical AR Applications



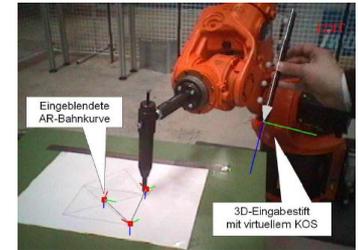
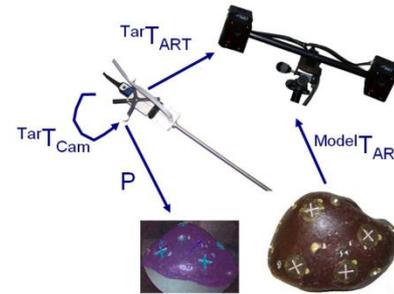
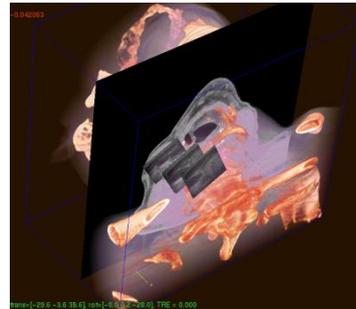
Medical AR Applications





Hello stranger!
Please come closer ...

LOTS OF INTERESTING PROJECTS

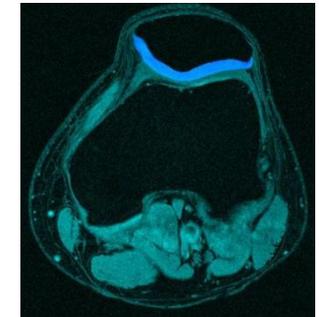
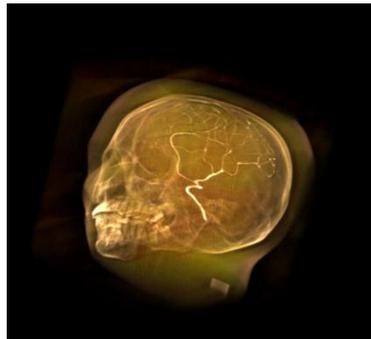
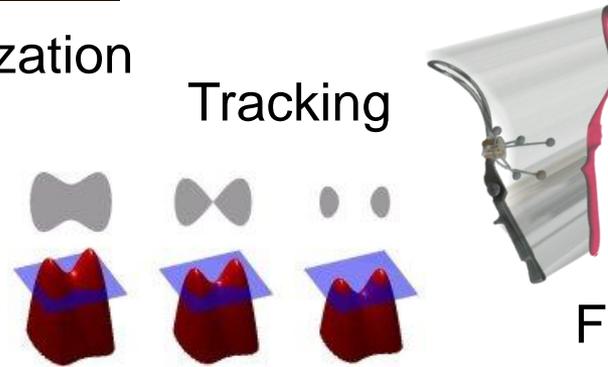
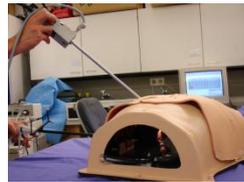


Medical AR

Visualization

Tracking

Feature Recognition



<http://www.navab.in.tum.de/Chair/StudentProjects>