VISION-BASED ANALYSIS OF CONVENTIONAL SURGICAL PROCEDURES

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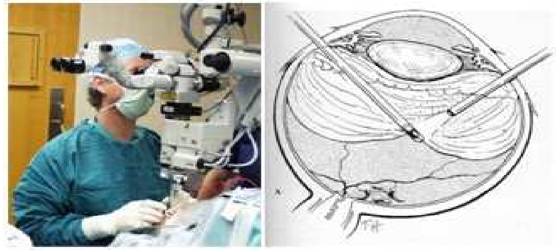
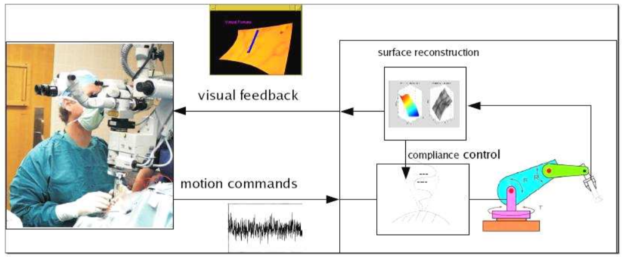
Safety in Surgical Procedures

Virtual Fixtures (prevention of organ injuries)



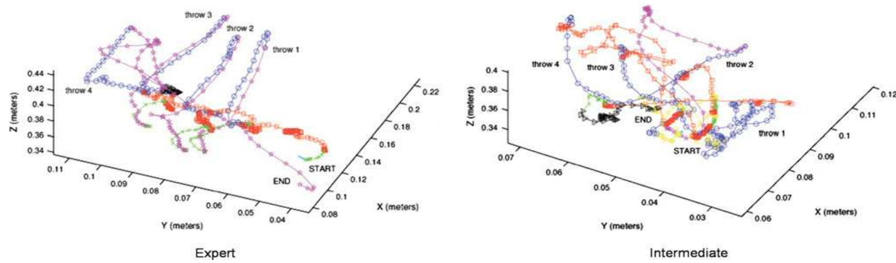
Example:
eye surgery

Task dependent **Motion Constraints** (compensation of human imperfections)



Hand tremor

Skill Evaluation of the surgeons (certification of skills as estimate of success rate for a given procedure)



Source: Surgical Endoscopy, July 2010

All of these tasks (Virtual Fixtures, Motion Constraints, and Skill Evaluation) rely heavily on perception:

- **Virtual Fixtures**:
  Relies on 3D Reconstruction and Motion Capturing.
- **Motion Constrains:**
  Relies on 3D Reconstruction, Motion Capturing and Procedure Modeling.
- **Skill Evaluation:**
  Relies on Motion Capturing.
- There are three major building blocks to discuss:
  - Motion Capturing
  - Procedure Modeling
  - 3D Reconstruction

Our Contributions

- ***Motion capturing:*** common systems are based on robot kinematics from robots like daVinci (e.g. the JHU system).
  Problem: What about standard procedures? They are still most common, thus should not be neglected.
  (→*Motion Constraints*, *Skill Evaluation*)
- ***Procedure Modeling:*** movement constraints in a single step of the procedure are of interest. Operation-relevant properties and actions can be described by means of Object container, Location Map and Functionality Graph.
  (→Motion Constraints)
- ***3D Reconstruction:*** since the anatomy details vary between patients, an accurate reconstruction to map the procedure into the given environment is required.

  Problem: many procedures still use monocular equipment, which generates low-quality image data. Photogrammetric enhancements to the reconstruction process are necessary. View planning algorithms can be used to improve accuracy.

  (→ *Virtual Fixtures*, *Motion Constraints*)

Motion Capture Systems

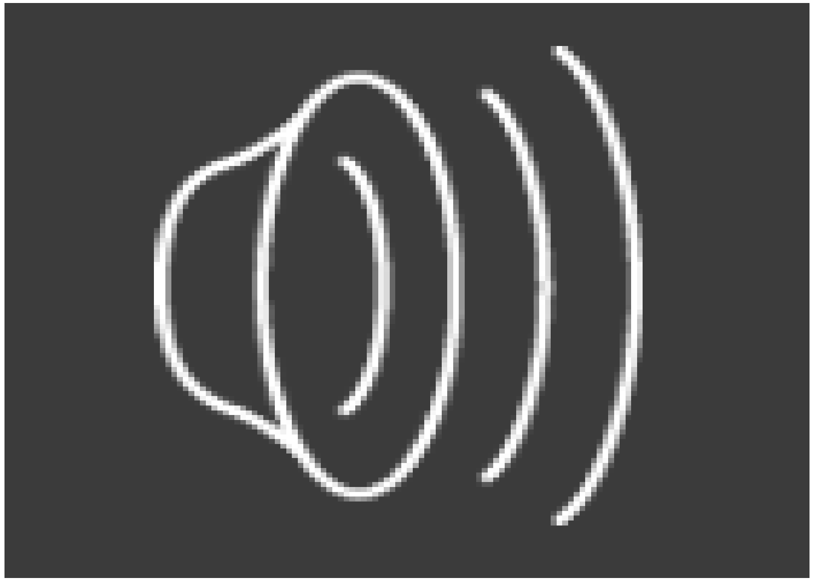
conventional

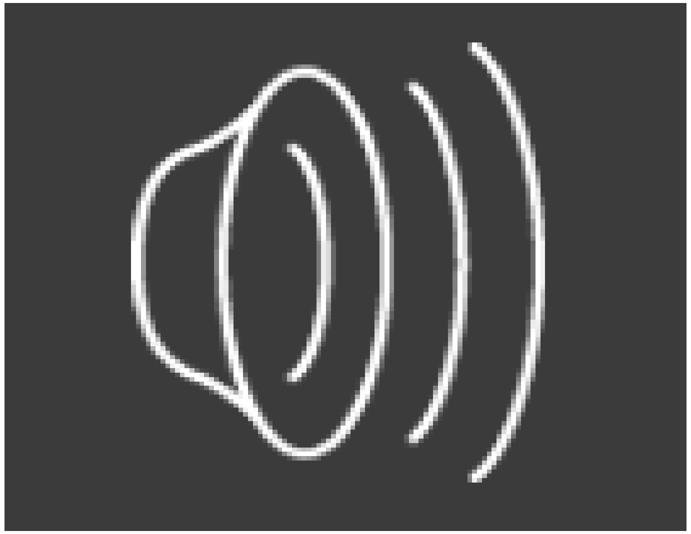
Source: MedGadget

Kinematics-based

We are interested in providing similar motion information about tools as from systems working with kinematics data

A new trend in computer-assisted surgery is usage of IMUs in videoendoscopes.





Problem: high dynamics of the human hand is too fast for the low frame-rates of standard video cameras

Solution: coupling of inertial sensors IMU with visual perception
(Mair et al. IROS 2009)

Template-based Tool Tracking
in image space
Application: guidance of the
camera

(work with G.Hager, JHU)

6DoF pose estimation of tools
manipulated in the scene
The system estimates in real-time
the pose of the moved object

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  (→*Motion Constraints*, *Skill Evaluation*)
- ***Procedure Modeling:*** movement should be task-, object- and location-specific. Manipulation-relevant properties and actions can be described by means of Object container, Location Map and Functionality Graph.
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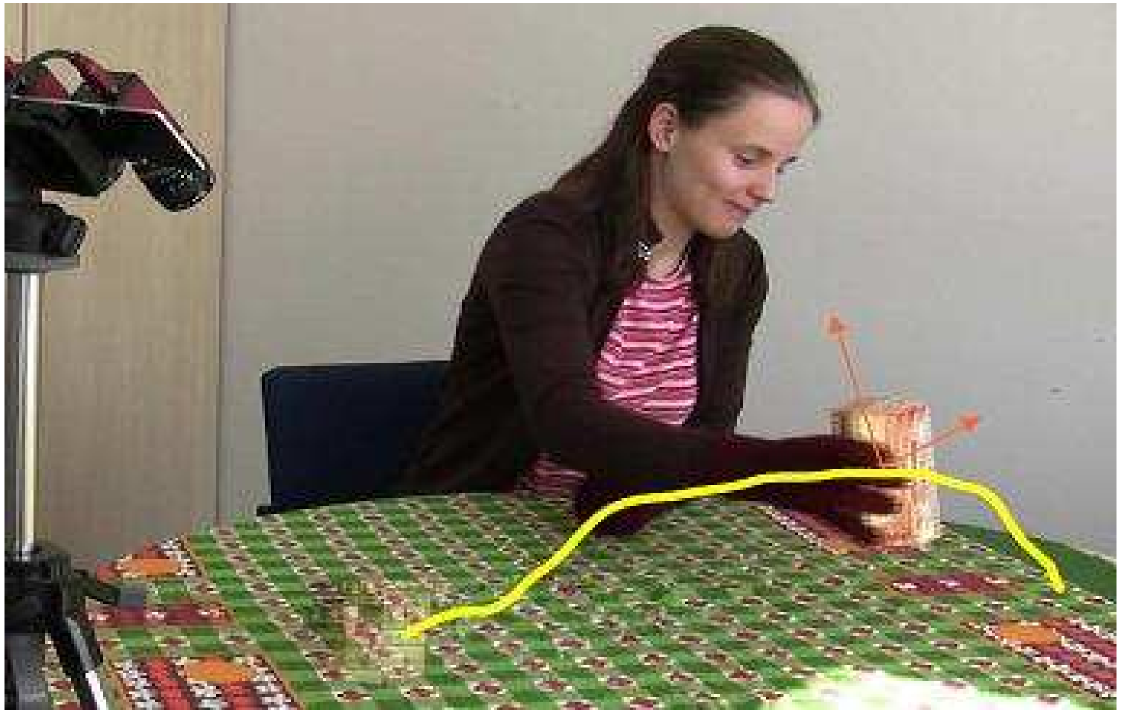
Learning of Action Attributes through Observation of Human Actions



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Representation of Manipulation-Relevant Object Properties and Actions

- Observation of human demonstrations
- Extraction of knowledge:
  - New knowledge
  - Relevance
- Knowledge:
  - Object properties
  - Object functionalities in the environment

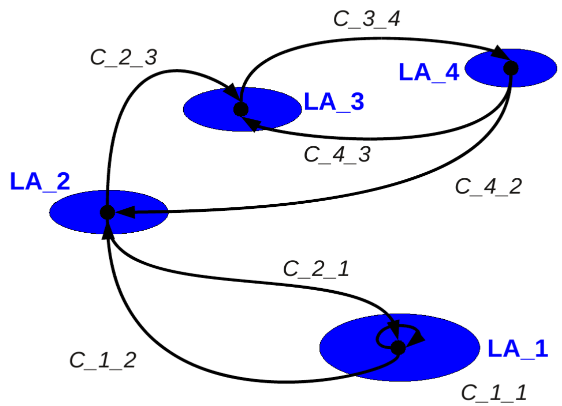
Knowledge Representation

Object container

shape	parametric description	grasp points	actions and handling
			

Functionality Map

Locations Area **LA_i**



C_i_j: connection properties

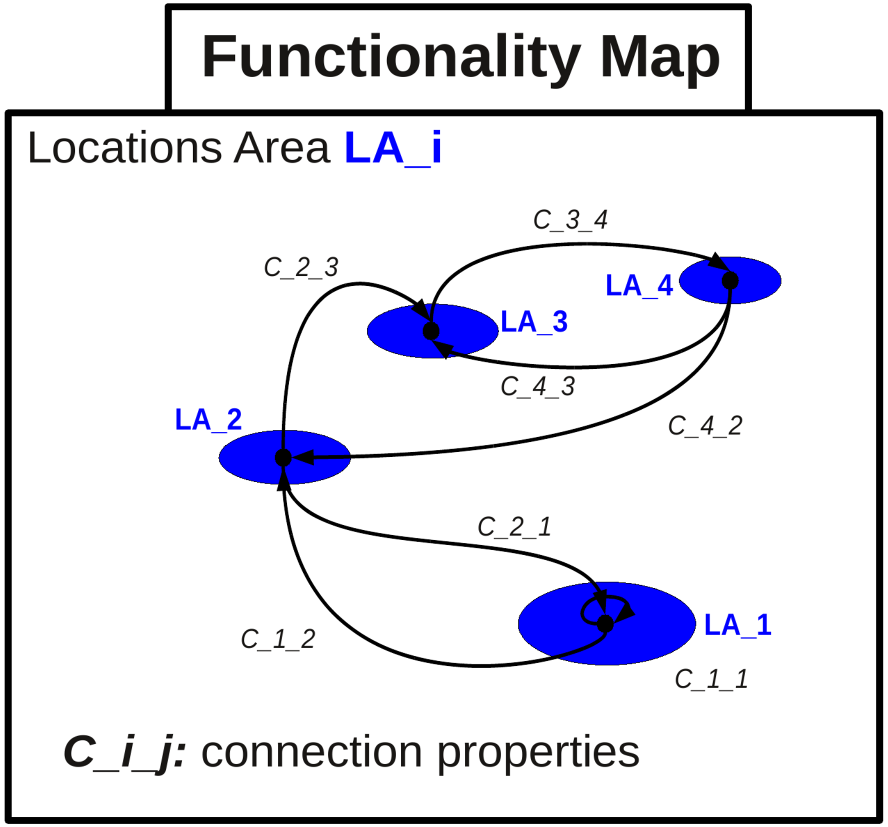
Each tool used in the procedure has its own container describing its shape, handling properties etc.

(Petsch/Burschka IROS2011)

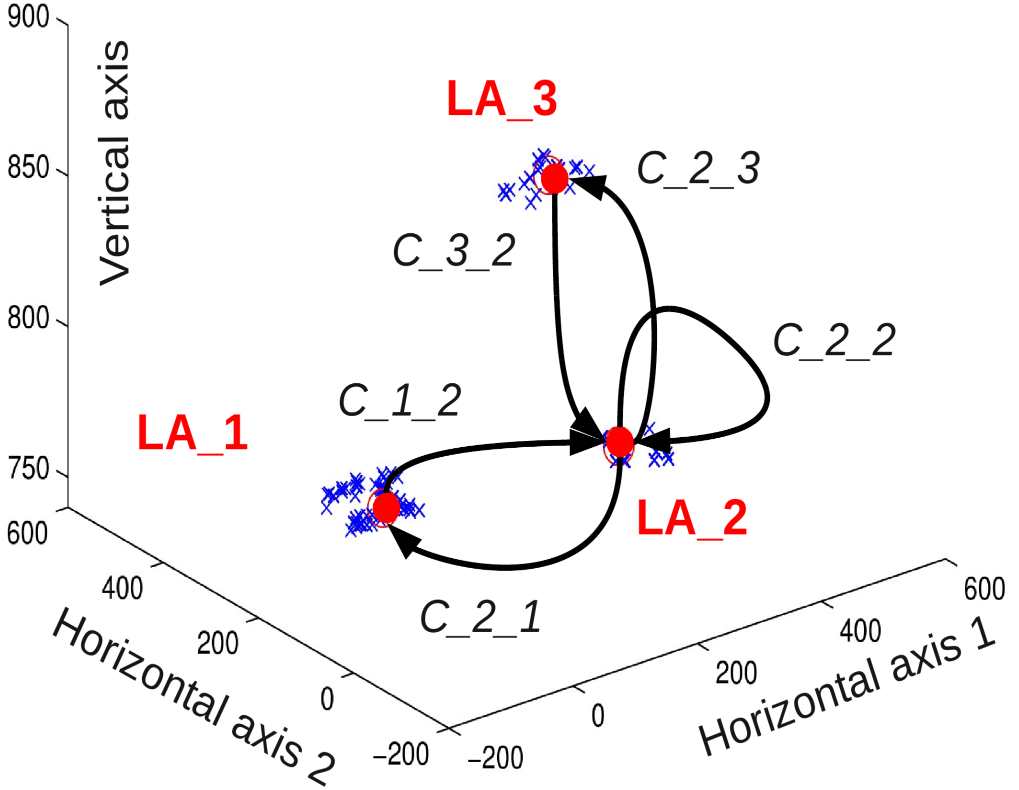
In addition, we store a functionality map for a specific procedure that describes the way how the tool was used during the procedure while moved between points in the body

Functionality Map

- Location Areas
- Connection Properties:
  - Arbitrary movement vs. constrained trajectory
  - Connection relevance
  - Velocity constraint during pick-up
  - Grasp taxonomy



Tracking Data: Location Areas



Legend:

Location Area i with its corresponding center

C_i_j Connecting edge from Location Area i to j

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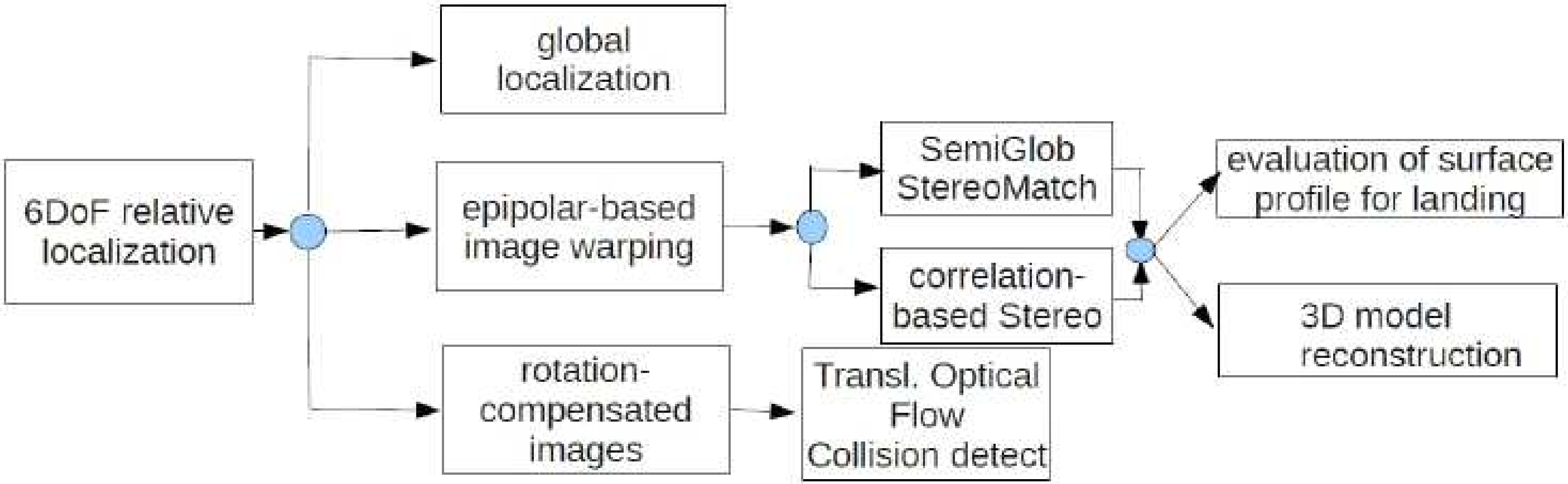
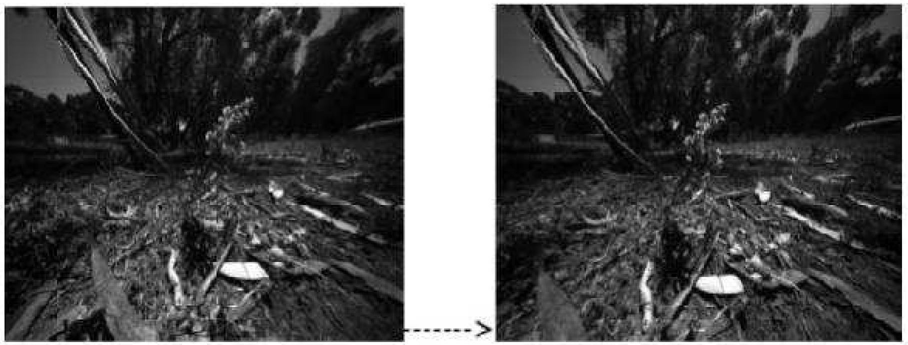
  ($\rightarrow$ *Virtual Fixtures*, *Motion Constraints*)

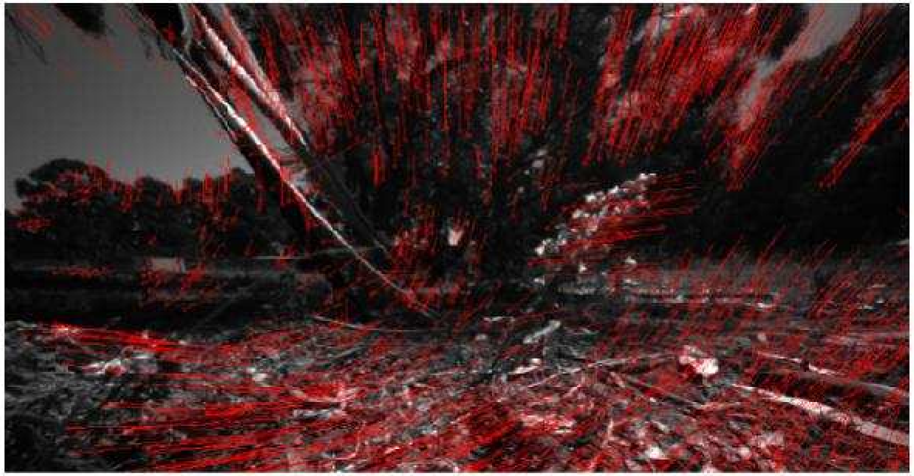


Modular reconstruction pipeline for an easy exchange of modules

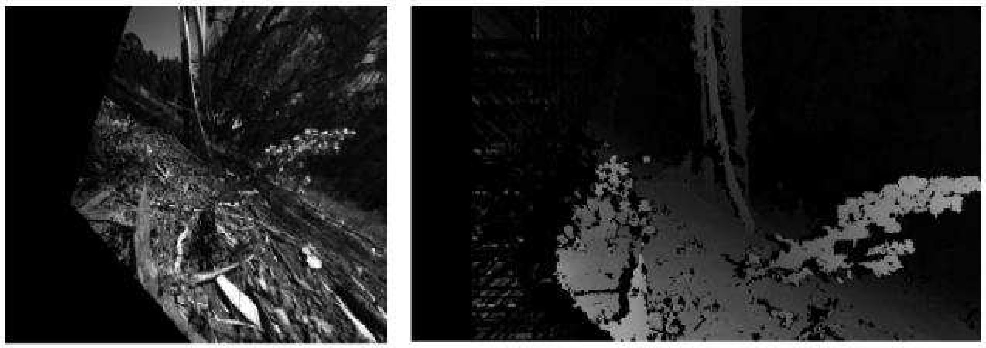
Reconstruction Pipeline (ICRA2012 submission)



Initial images



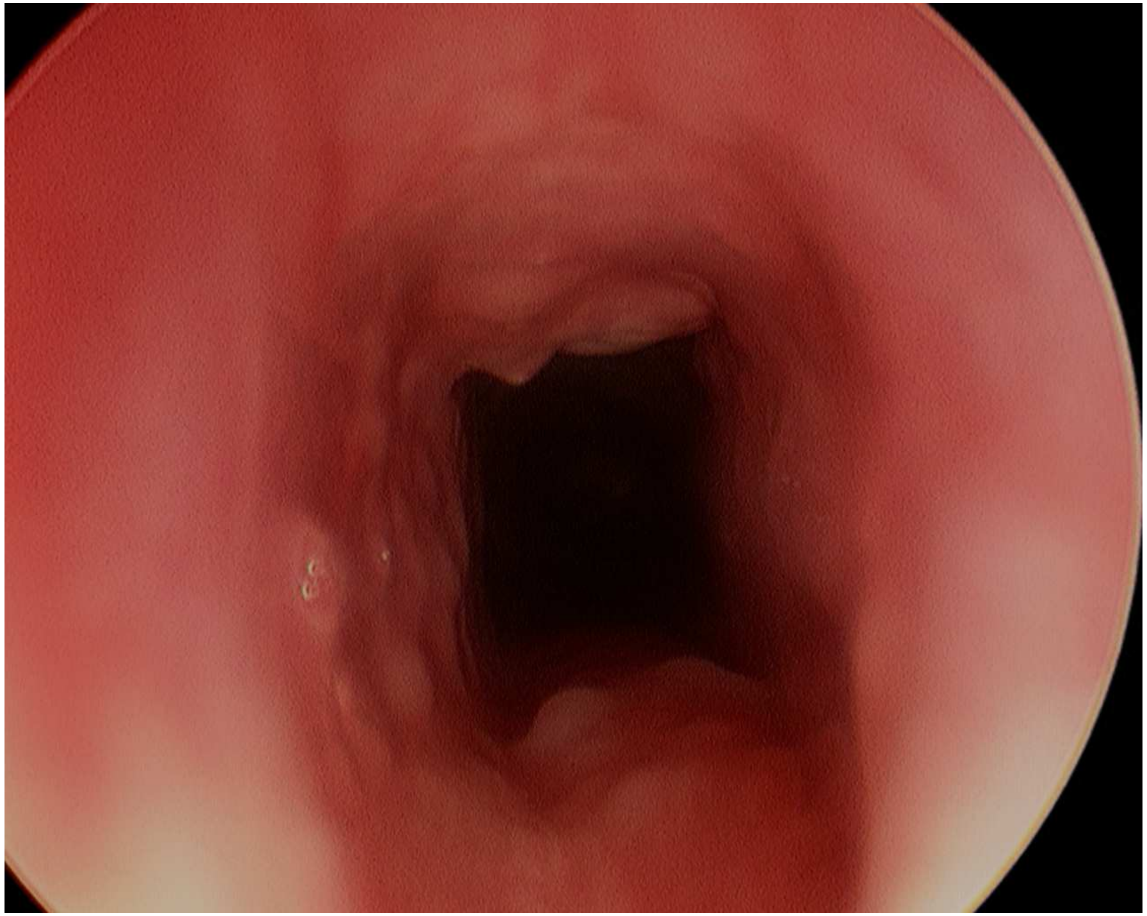
Motion estimation



Motion correction
and reconstruction
result

Scene and Motion Recovery from Monocular Images

- A well-known problem in Computer Vision
- Algorithms for “simple” cases are abundant
- But: Videoendoscopy is difficult!
- Problems:
  - Difficult lighting conditions
  - Bad image quality
  - Very little image structure

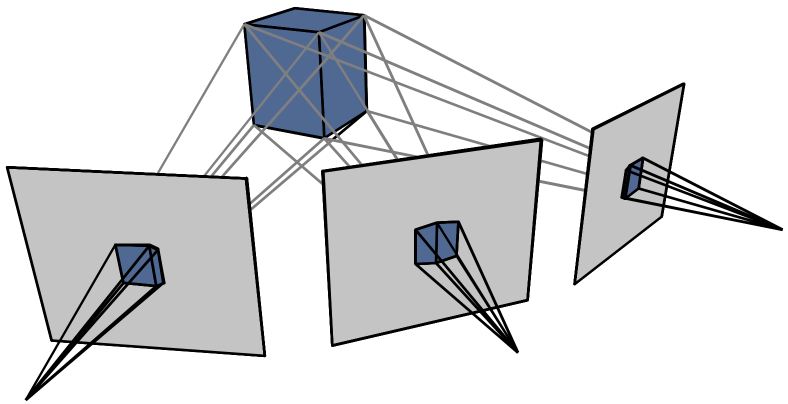


Typical difficulties: image blur, image noise, almost no texture

The Basic Idea

- Bundle adjustment is a well-known algorithm for structure and camera position recovery
- Feature-based and intensity-based variants
- Toy example for feature-based reconstruction:
- Nonlinear optimization minimizes reprojection error of pixel coordinates.

$$\min_{\boldsymbol{a},\boldsymbol{b}} \sum_{i=1}^{n} \sum_{j=1}^{m} d\left(\boldsymbol{Q}\left(\boldsymbol{a}_j, \boldsymbol{b}_i\right), x_{i,j}\right)$$



Intensity-based methods

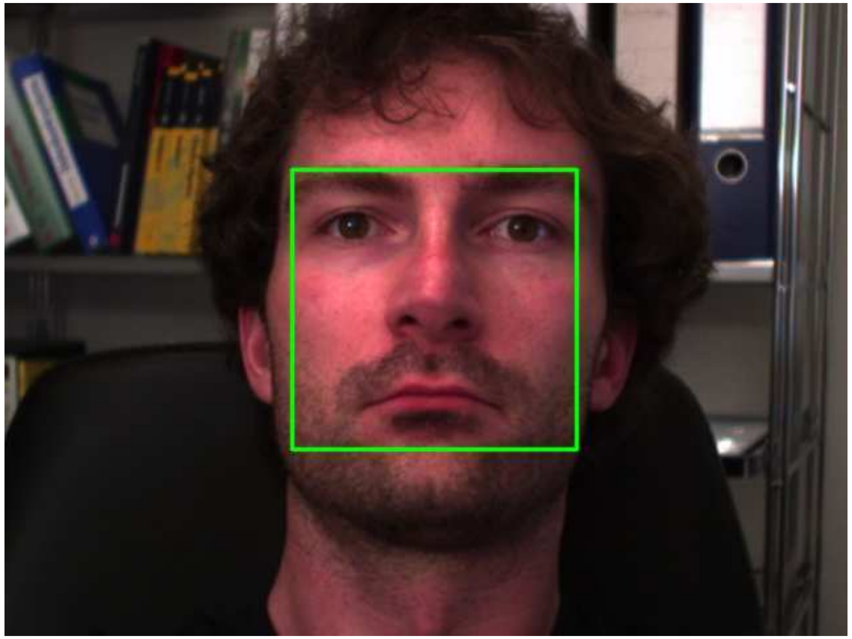
- In videoendoscopy, reliable feature detection is nearly impossible
- We use an intensity based approach
- Price to pay:
  - Computationally expensive
  - Less detailed models (regularization)
- Advantage:
  - Reconstruction is possible where feature-based methods fail!

Reconstruction with constant lighting

- First idea: Apply a multi-view intensity-based reconstruction method
- Important advantage: Intensity-based methods use as much information as there is
- This approach uses the brightness constancy assumption
- Idea: Find parameters that explain images by nonlinear optimization

$$\min_{\boldsymbol{a},\boldsymbol{b}} \sum_{i=1}^{n} \sum_{j=1}^{m} d\left(I_j\left(\boldsymbol{Q}\left(\boldsymbol{a}_j,\boldsymbol{b}_i\right)\right), I_0\left(\boldsymbol{p}_i\right)\right)$$

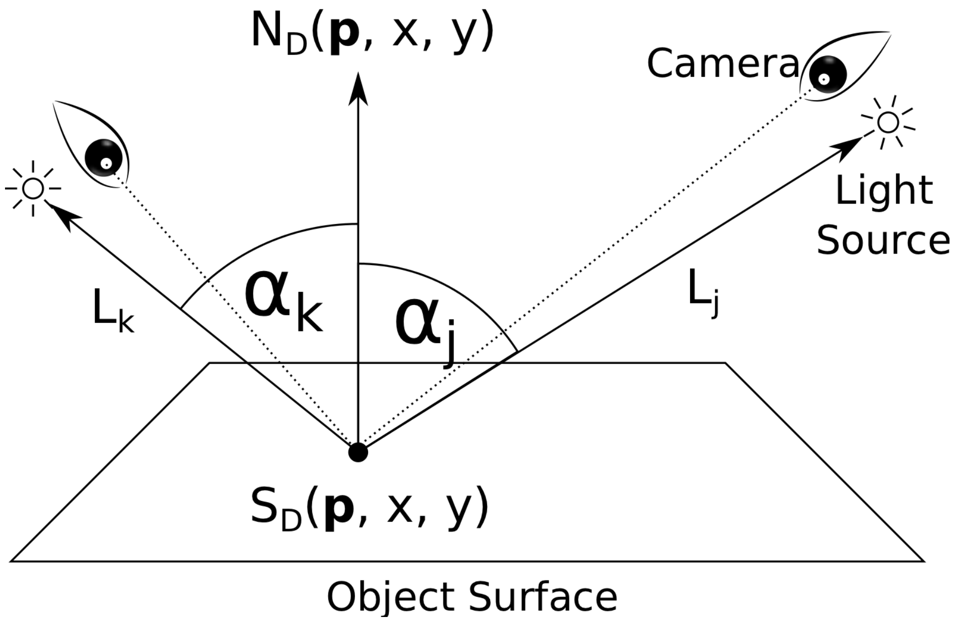
- Works well for Lambertian surfaces



Ruepp and Burschka. Fast recovery of weakly textured surfaces from monocular image sequences. ACCV 2010

Under changing lighting conditions

- In videoendoscopy, the brightness constancy assumption is violated!
- The light source is moving with the camera
- This can be modeled by the reconstruction algorithm



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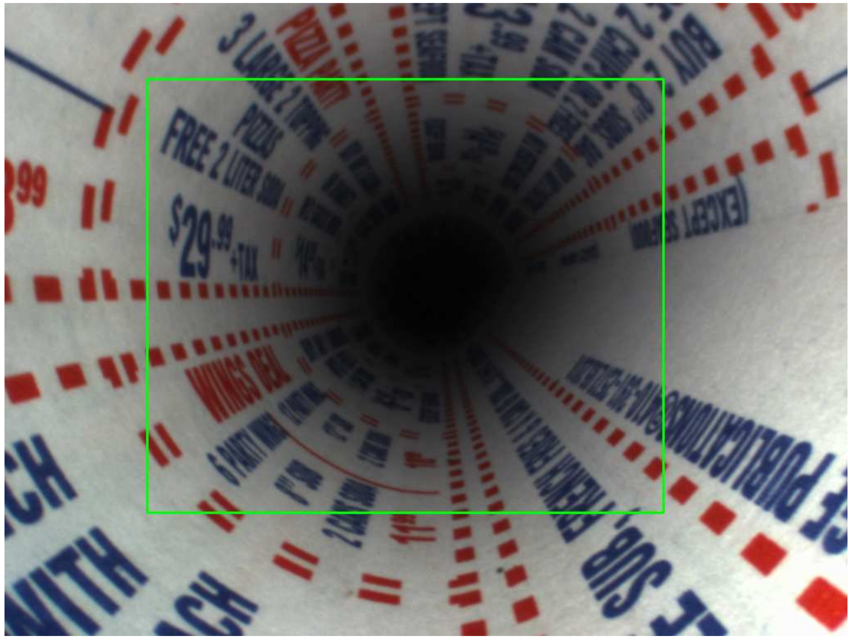
Reconstruction results



Current and Future Research

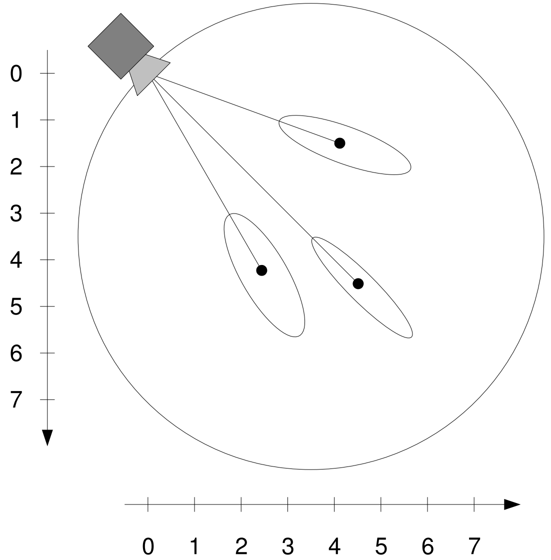
- The algorithm makes idealizing assumptions that lead to suboptimal results:
  - Linear camera response, no vignetting
  - Singular point light source
  - Uniform light source intensity
  - Light source coincident with camera position
- A calibration method is needed!
- Also: Performance can be improved
- Deal with partial occlusions

View planning

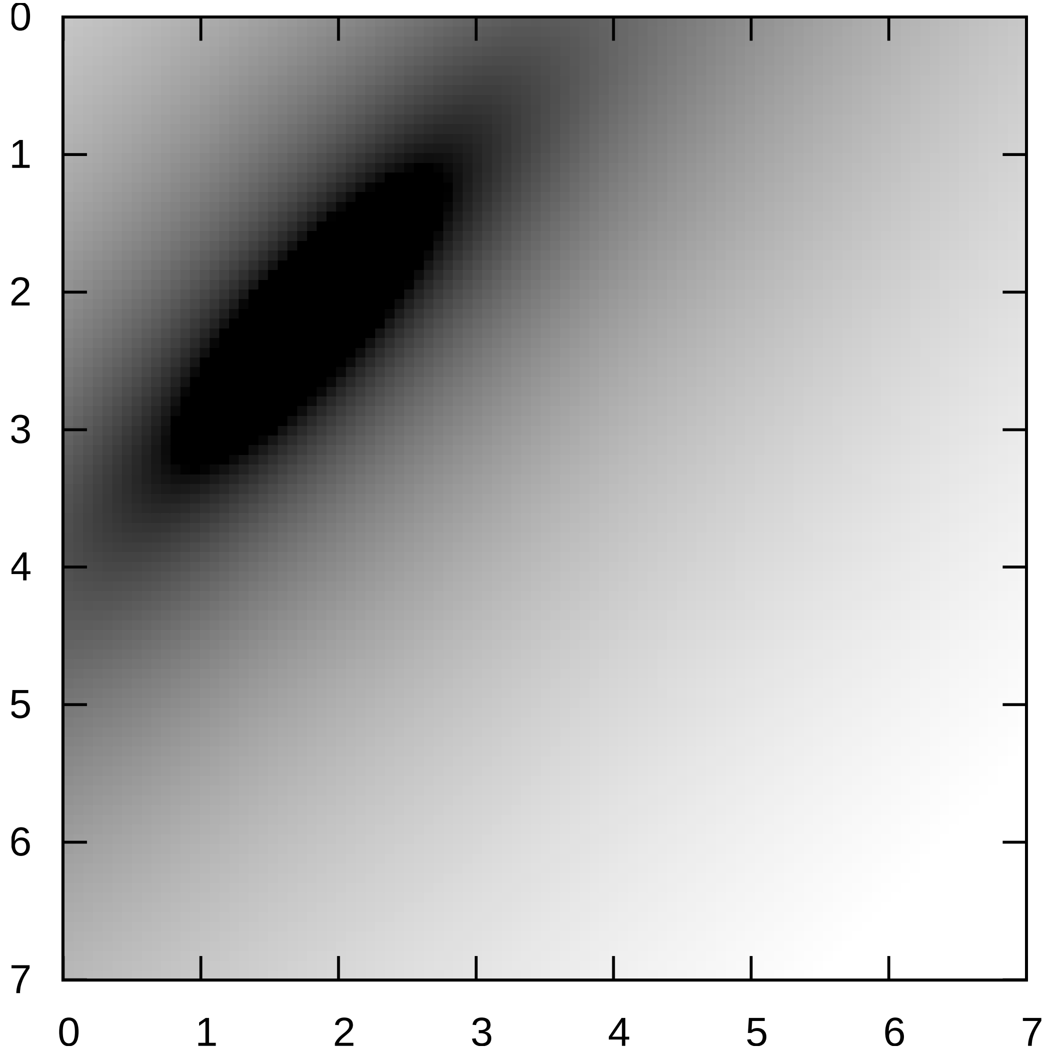
- Reconstruction accuracy is crucial for safety.
- How do we evaluate the accuracy?
- How can we improve it?
- View planning algorithms help to determine camera movement so as to maximize accuracy

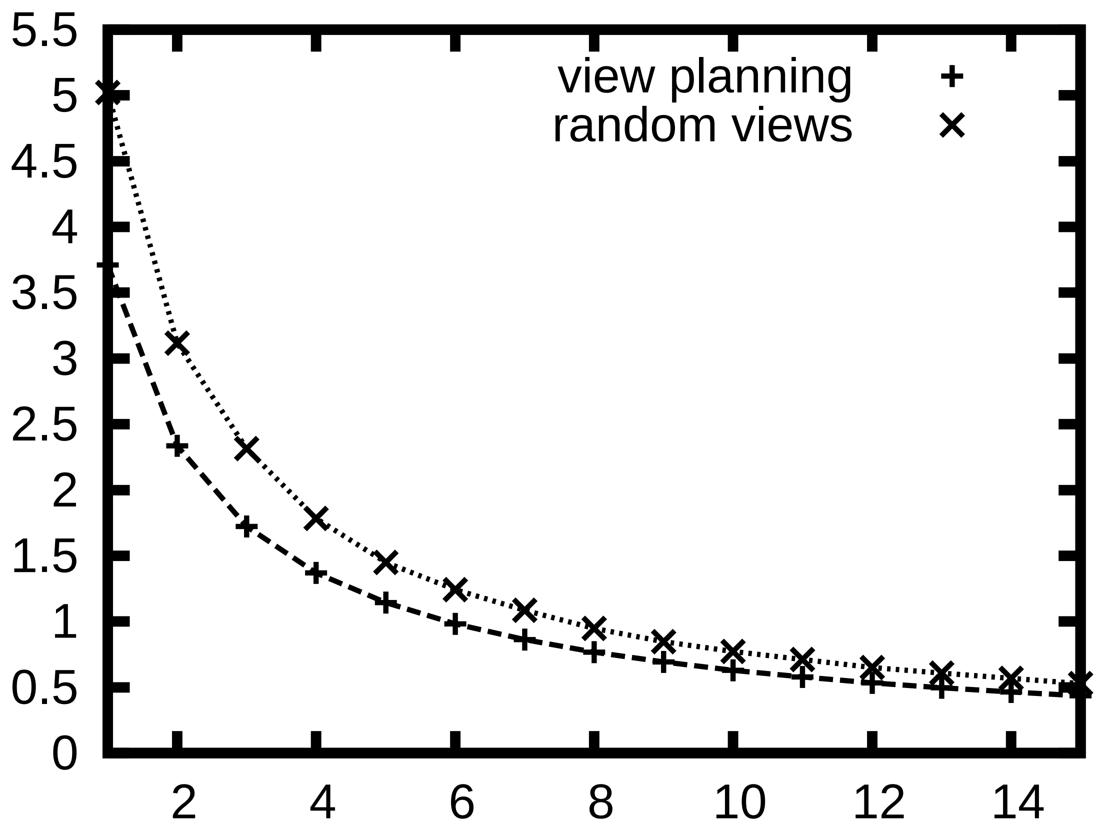
Schematic Overview

- Reconstruction results are typically affected by uncertainty
- Viewing direction should be orthogonal to maximum uncertainty
- This leads to an evaluation function for camera positions



Camera Position Evaluation





Especially in the first few steps, uncertainty is reduced significantly

Future Research

- Until now: Camera movement restricted to a circular path around target
- Needs to be adapted to videoendoscopy, where movement is more restricted
- Deal with partial occlusions

Thank you for your attention!

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