Recent Advances in Medical Image Analysis and Pattern Recognition

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Topics

- Introduction
- Selected Examples:
  - 3D Endoscope
  - Segmentation
  - Interventional Cardiac Imaging
- Summary
Reconstruction

- CT reconstruction (1970)
- MR Reconstruction (1980)
- C-arm CT (1995)
- reconstruction of static objects: pretty ok

- Major achievements:
  - Helix CT
  - Multi-slice CT
  - flat panel detectors:
    low contrast resolution
  - large object reconstruction
Hybrid Imaging
Image Segmentation

- Group similar components
- Find structures and primitives
- Middle-level vision task performed by neurons between low-level and high-level cortical areas
- No ground truth segmentation
- Applications: Finding tumors, vessels, organs, etc.
Research Problems

- Segmentation problem in general
- Computation of „mean“ anatomy (atlas)
- Strategies for the optimal combination of different modalities
- Dynamic imaging (unknown motion, perfusion, metabolism)
Regression and Classification

- Feature vector: \( \mathbf{x} \)
- Regression problem:

\[
y = f(x)
\]

where \( y \) is real valued.

- Classification problem:

\[
y = \zeta(x)
\]

where \( y \) is a categorical variable.
3D Endoscope
3-D ToF/RGB Endoscopy
Development of Hybrid Endoscope
3-D ToF/RGB Endoscopy

- **System calibration:**
  1. Print self-encoded marker
  2. Use computer vision techniques to find and identify checkerboard
  3. Find correspondences in both views
  4. Use OpenCV to calculate homography

- **Sensor fusion:**
  1. Calculate 3-D world coordinate for ToF
  2. Use homography to transform into RGB coordinate system
  3. Use intrinsics to map 3-D point on sensor plane
Super-Resolution
Super-Resolution

Given a number of low-resolution images differing in:

- geometric transforms
- illumination
- camera blur (point-spread function)
- image quantization
- noise.

Problem: Estimate high-resolution image
Super-Resolution

Image $x$ is mapped to degraded sequence $y^{(1)} \ldots y^{(K)}$ according to

$$y^{(k)} = W^{(k)} x + \epsilon^{(k)}$$

with

- $x$: Ideal, high-resolution image (as 1-D vector, $x \in \mathbb{R}^N$)
- $y^{(k)}$: $k^{th}$ low-resolution image as (as 1-D vector, $y^{(k)} \in \mathbb{R}^M$)
- $W^{(k)}$: System matrix of $k^{th}$ image (modeling of warp, blur, downsampling)
- $\epsilon^{(k)}$: Additive noise
Maximum a-posteriori Estimation

- Specify blur kernel (point spread function) and upsampling factor
- Estimate motion using image registration → compose system matrices $W^{(1)} \ldots W^{(K)}$ from motion and static imaging parameters
- MAP estimation for ideal image:

$$x^* = \arg\min_x \sum_{k=1}^K \left\| y^{(k)} - W^{(k)} x \right\|_2^2 + \lambda R(x)$$
High Resolution ToF/RGB Registration

- Estimate affine transformation $M_c^{(k)}$ for high-resolution RGB images
- Determine affine transformation $M_r^{(k)}$ for corresponding ToF images:
  $$M_r^{(k)} = HM_c^{(k)}H^{-1}$$
  
  $H$: Affine homography for RGB/ToF points
  → Fixed, determined via point correspondences
- $M_r^{(k)}$ is used for MAP estimation
Super-Resolution

(a) ground truth  (b) range guided  (c) RGB guided  (d) improved guided

(e) raw frames  (f) range SR  (g) range/RGB SR
Super-Resolution

<table>
<thead>
<tr>
<th>Method</th>
<th>Mean error [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Raw frame</td>
<td>2.01</td>
</tr>
<tr>
<td>(b) Range guided</td>
<td>1.39</td>
</tr>
<tr>
<td>(c) RGB guided</td>
<td>1.25</td>
</tr>
<tr>
<td>(d) Improved guided</td>
<td>1.14</td>
</tr>
<tr>
<td>(e) Range SR</td>
<td>1.01</td>
</tr>
<tr>
<td>(f) Range/RGB SR</td>
<td>0.91</td>
</tr>
</tbody>
</table>

![Box plot comparing different methods](image)
Super-Resolution
Super-Resolution
Interventional Cardiac Imaging
• Interventional cardiac imaging with C-arm systems

Fig. 1: Artis zeego multi-axis system, Siemens AG, Healthcare Sector.

Fig. 2: Rotational angiograms of human left heart ventricle. Image courtesy of Thorax Center, Erasmus MC, Rotterdam. Dr. Schultz.

• Slow rotating scanner  ➤ inconsistent projection data  ➤ dynamic images of the heart from one rotation
Projection Data of the Heart

Image data provided by Klinikum Coburg, Germany

RCA

LCA

CS

CS
Scientific goal

- Interventional cardiac imaging with C-arm system

- Anatomical and functional information direct in the catheter lab about cardiac chambers

- Approaches:
  - Motion compensation with surface models
  - Motion compensation with 3-D/3-D registration
• **Hard problem:**
  • 3-D reconstruction of different heart states to gain morphological information over time

• **Applications:**
  • Ventricular applications:
    • ventricle ablation guidance
    • stem-cell injection of ventricular infarcts
  • Mitral valve repair:
    • guidance of annuloplasty

*Fig.3:* Mitral valve guidance. Image courtesy of the University of Leuven, Leuven, Belgium. Dr. Heidbüchel.
Motivation

- **Standard:**
  - 3-D FDK reconstruction [1] → no temporal resolution → image blurring

![Image](image_url)

Fig. 4: Standard FDK reconstruction of heart chambers of a porcine model from a single sweep. Image courtesy of the University of Leuven, Leuven, Belgium. Dr. Heidbüchel.

Motivation

- Retrospective ECG-gating
  - Single rotation
    - degraded image quality for heart chambers
  - Multiple rotations [2,3]
    - high radiation dose and contrast burden

Fig.5: Single sweep ECG-gated reconstruction of the heart chambers of a porcine model from a single sweep. Image courtesy of the University of Leuven, Leuven, Belgium. Dr. Heidbüchel.

Fig.6: Multi sweep ECG-gated reconstruction of the heart chambers of a human data set. Image courtesy of Klinikum Coburg Prof. Brachmann, Dr. Nölcker

[3] Prümmer et al.: Cardiac C-Arm CT: A Unified Framework for Motion Estimation and Dynamic CT, IEEE TMI, 28(11), 2009
ECG Gated Motion Compensation
General Idea

Combined Multiple Heart Phase Registration (CMHPR)

1. Deformable ECG-gated FDK volumes
2. Final Image
3. Reference Image
4. Minimize Objective function

Update 4-D Motion Field

Goal:
Similar final and reference image
Unknown:
smooth, dense, motion vector field
**Method**

**Combined Multiple Heart Phase Registration (CMHPR)**

1. ECG-gated FBP Volume Reconstruction
   - Retrospective ECG-gating of a number of $H$ heart phases:
     - Rectangular or cosine weighting function
     - Here strict gating, i.e. only one projection per heart cycle

![Example of ECG-gated FBP volume reconstruction with 32 views.](image)

*Left:* relative heart phase of ~30%.
*Right:* relative heart phase of ~80%.
Combined Multiple Heart Phase Registration (CMHPR)

2. Final Volume
   - The final volume is defined as a sum volume $f(x, s)$ consisting of the deformed ECG volumes $f_h(x + s_h, x)$

   $$f(x, s) = \sum_{h=1}^{H} f_h(x + s_h, x)$$
Method

Combined Multiple Heart Phase Registration (CMHPR)

3. Reference Volume Reconstruction
   - Reconstruction of reference heart phase volume $f_r(x)$ with few-view reconstruction algorithm
   - Low-artefact level, sharp edges, e.g. PICCS [4] and/or iTV [5] algorithm

![Example of reference volume reconstructions of a porcine model with PICCS + iTV. Left: relative heart phase of ~30%. Right: relative heart phase of 80%.

[5] Ritschl et al.: Improved total variation-based CT image reconstruction applied to clinical data, Physics in Medicine and Biology, 56(6), 2011
4. **Objective Function**
   
   - Minimize negative normalized cross correlation (NCC) between final volume and reference volume

\[
\mathcal{L}_{NCC} = -\frac{1}{|\Omega|} \sum_{x \in \Omega} \frac{(f(x, s) - \bar{f})^2 \cdot (f_r(x) - \bar{f}_r)^2}{\sigma_f \cdot \sigma_{f_r}}
\]

\( \bar{f} \), \( \bar{f}_r \) mean values
\( \sigma_f \), \( \sigma_{f_r} \) standard deviations
\( \Omega \) area of optimization
Method

**Combined Multiple Heart Phase Registration (CMHPR)**

5. Optimization strategy

- Gradient based quasi-Newton method, Broyden-Fletcher-Goldfarb-Shanno optimizer (L-BFGS) [6]

- Motion mask $\Omega$

- Spatial and temporal Deriche Filter [7] to smooth 4-D motion vector gradient

Experimental Setup

- Porcine model $p_1$ with systemic contrasted heart chambers
- Siemens Artis zee C-arm system
- Acquisition time: 14.5 s
- 381 projection images with 30 f/s
- Projection size 1240 x 960 pixel
- $(25.6 \text{ cm})^3$ with a $256^3$ voxel grid
- External pacing and image acquisition synchronized
- 32 heart cycles
- $H = 12$ heart phases
- External pacing of $\sim 131$ bpm

Fig.9: Projection data of porcine model $p_1$. Image courtesy of the University of Leuven, Leuven, Belgium. Dr. Heidbüchel.
Results

Fig. 10: Experimental results in porcine model p1 of the central slice and a relative heart phase of 80%. (W 1630 HU, C 50 HU, slice thickness 1.0 mm). The ECG-gated reconstruction was windowed to be visually comparable.

Fig. 10a: Standard FDK reconstruction.

Fig. 10b: ECG-gated reconstruction.

Fig. 10c: PICCS + iTV reference reconstruction.

Fig. 10d: Result of CMHPR algorithm.
Results

Fig.11a: Standard FDK reconstruction.

Fig.11b: ECG-gated reconstruction.

Fig.11c: PICCS + iTV reference reconstruction.

Fig.11d: Result of CMHPR algorithm.

Fig.11e: Porcine model $p_1$ and heart phase 80%.
Results

**Fig. 12a:**
Standard FDK reconstruction.

**Fig. 12b:**
ECG-gated Reconstruction (32 views).

**Fig. 12c:**
PICCS + iTV reference reconstruction.

**Fig. 12d:**
Result of CMHPR algorithm.

**Fig. 12:** Experimental results in porcine model p1 of the central slice and a relative heart phase of 30%. (W 1630 HU, C 50 HU, slice thickness 1.0 mm). The ECG-gated reconstruction was windowed to be visually comparable.
Fig. 13a: Standard FDK reconstruction.

Fig. 13b: ECG-gated reconstruction.

Fig. 13c: PICCS + iTV reference reconstruction.

Fig. 13d: Result of CMHPR algorithm.

Fig. 13e: Porcine model $p_1$ and heart phase 30%.
Results

- **Dynamic imaging**

**Fig.14a:** ECG-gated reconstructions.

**Fig.14b:** PICCS+iTV reconstructions.

**Fig.14c:** CMHPR reconstructions.
• **Combined Multiple Heart Phase Registration (CMHPR)** algorithm for motion estimation and compensation
  - reduces streak artifacts
  - preserves sharp edges
  - no comic-like appearance

• Dynamic imaging of heart chambers in 3-D

• Increases image quality for cardiac angiographic C-arm data

• Evaluation on porcine model is promising
Cardiac Reconstruction: Coronaries
ECG Gated Motion Compensation

(a) Standard

(b) Motion compensated
Big Picture: Motion Compensated Reco

1. Reference image creation for motion estimation
   - Measured projections
   - Initial ECG-gated reconstruction
   - Segmentation of vasculature
   - Sparse reference image

2. Iteration scheme for 4-D non-periodic motion estimation
   - Motion field
   - Acquisition time
   - Motion compensated reconstruction
   - Compute joint intensity (correlation) with ref. image
   - Motion field gradient computation

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Clinical Results

Venous (CS) and arterial (CA) cardiac vasculature

CS

CA