Gradient-Based Differential Approach for Patient Motion Compensation in 2D/3D Overlay

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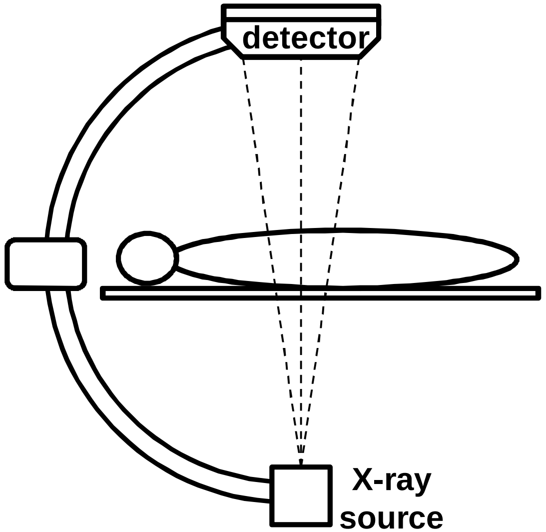
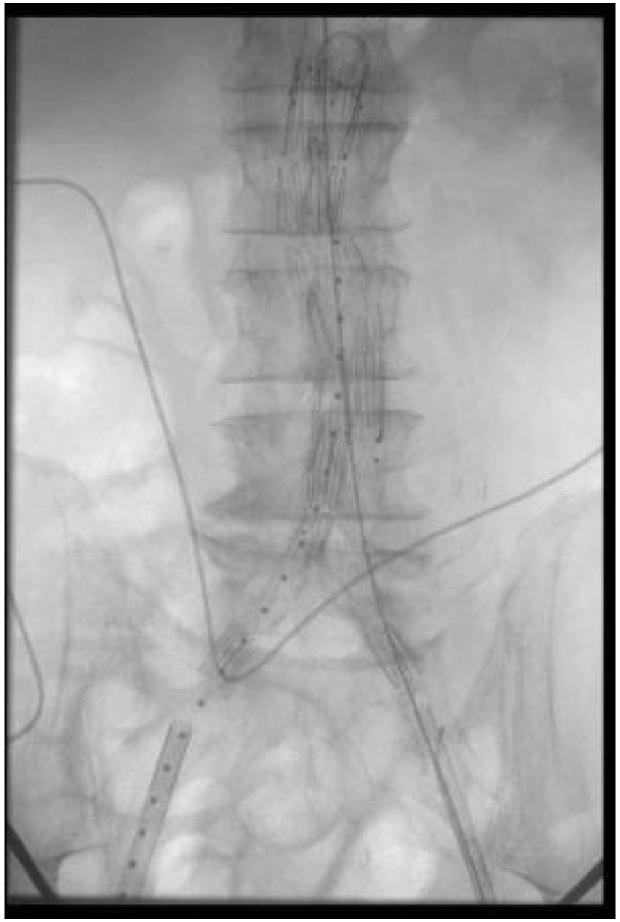
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG
TECHNISCHE FAKULTÄT

Vascular & interventional radiology

- Interventional C-arm system
  - Fluoroscopy: real-time guidance
  - Interventional devices
  - Vascular structure (contrast media)





2D/3D overlay during the intervention

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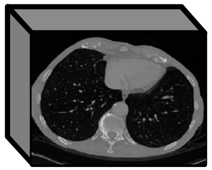
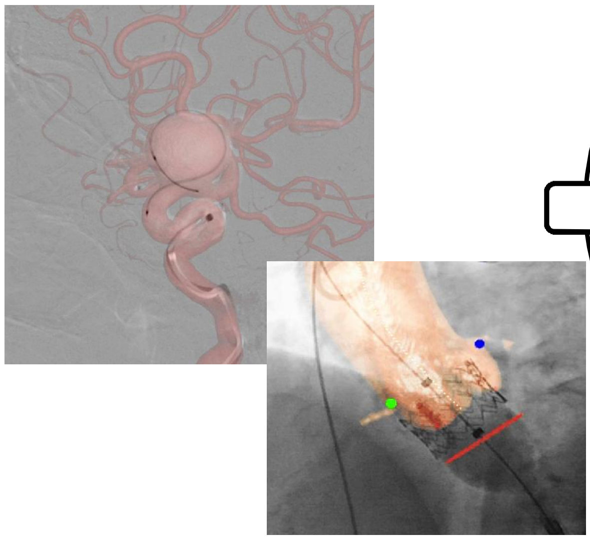
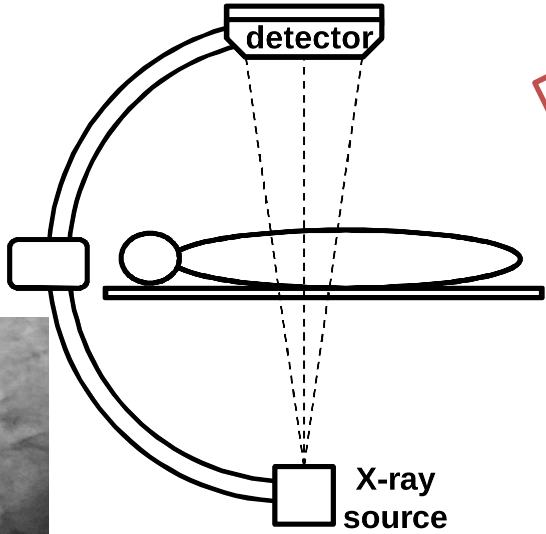
- 3D image (CT/MR …)

  onto 2D fluoroscopy
  - Structures not visible in X-ray images
  - Planning information
- To save
  - Contrast media
  - Radiation dose
  - Time







DRR-Based 2D/3D Registration

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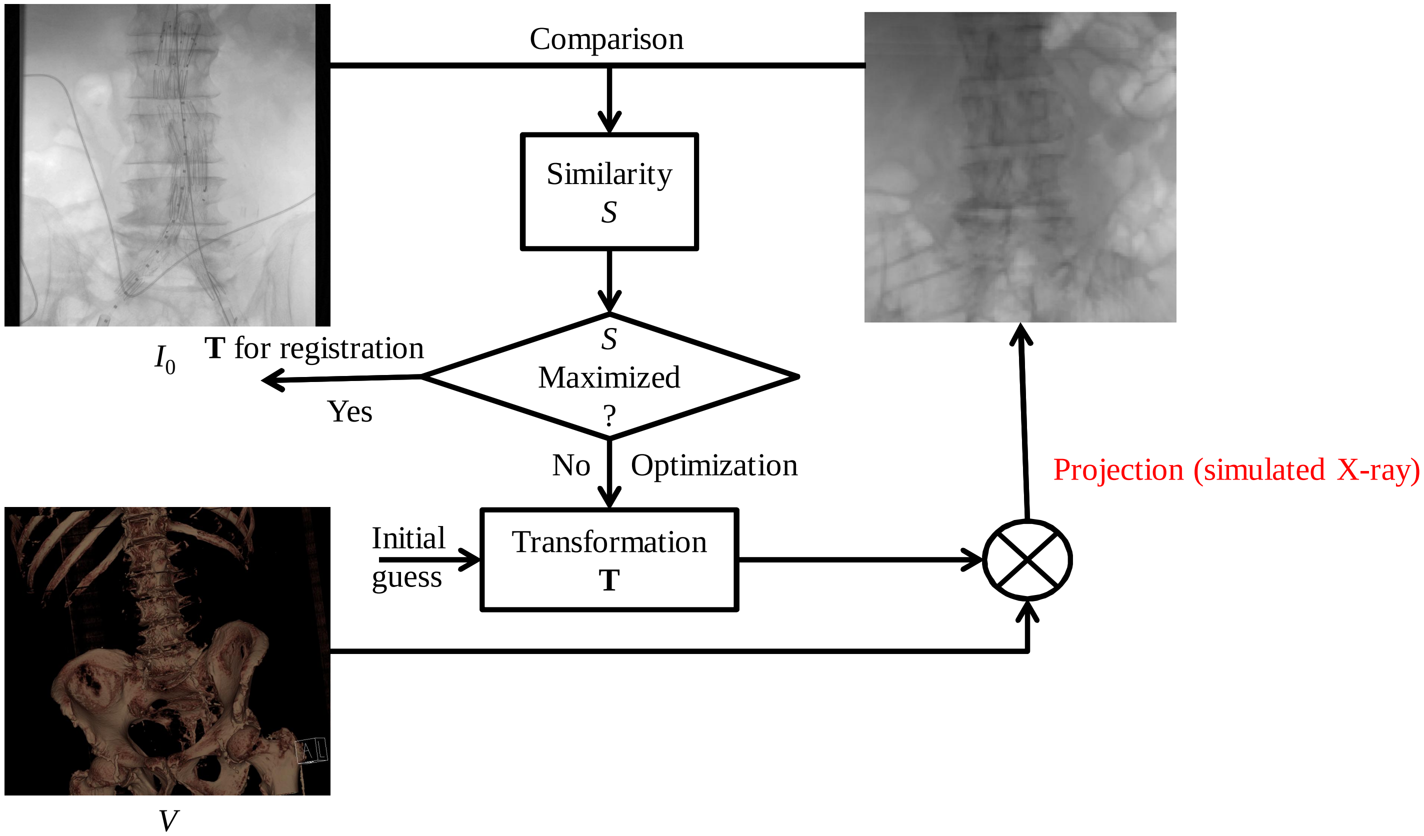
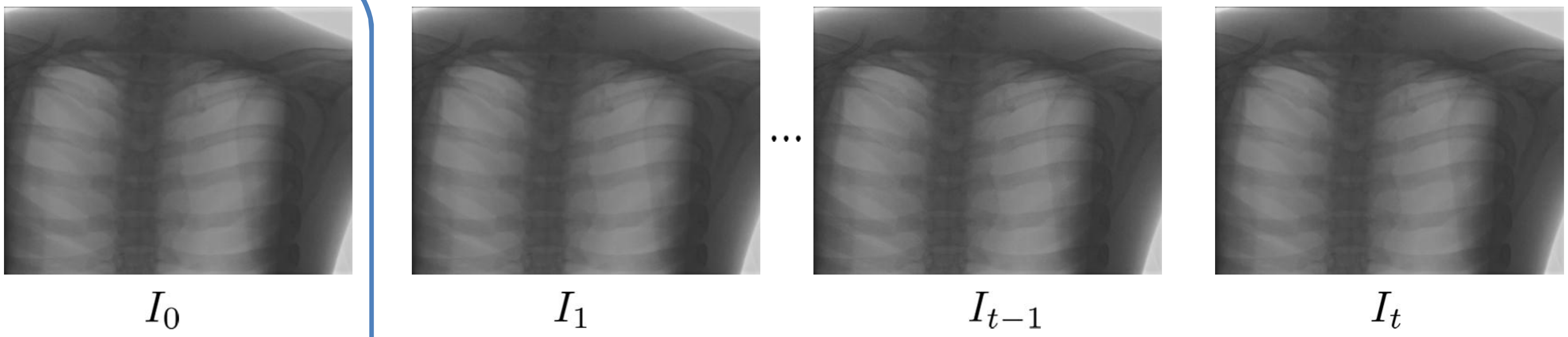
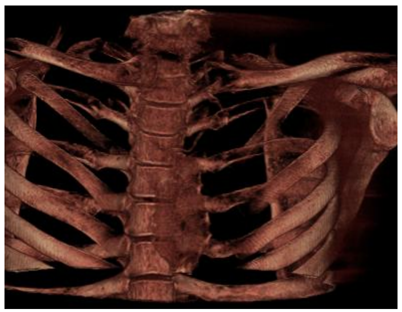
- Iterative optimization based on digitally reconstructed radiograph (DRR)
  - Usually **not real-time capable** for motion correction



Motion Compensation in 2D/3D Overlay





- Initial registration
- Structure in common
- Depth of 2D features

Motion Compensation in 2D/3D Overlay

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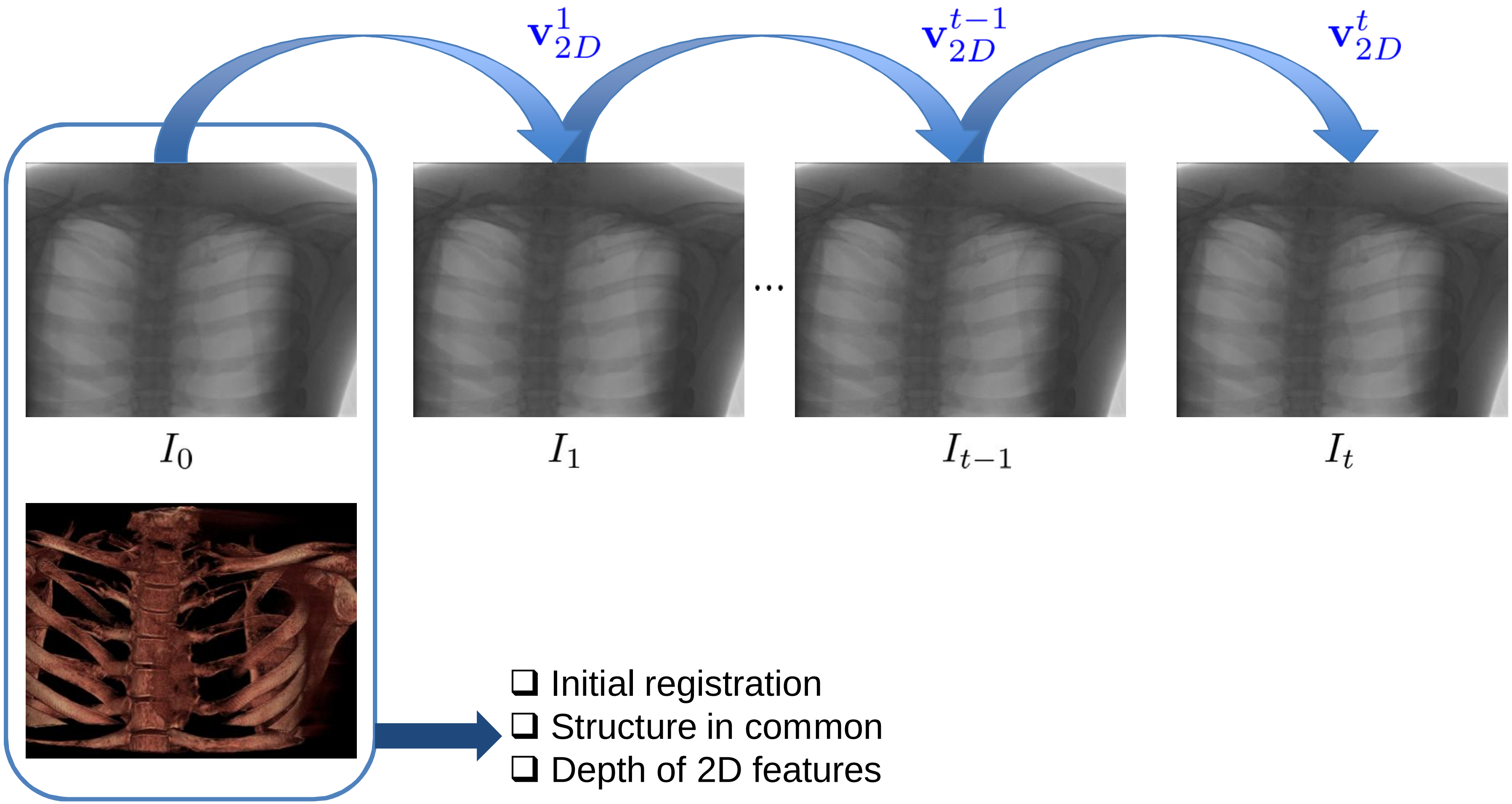

- ❑ Initial registration
- ❑ Structure in common
- ❑ Depth of 2D features

Motion Compensation in 2D/3D Overlay

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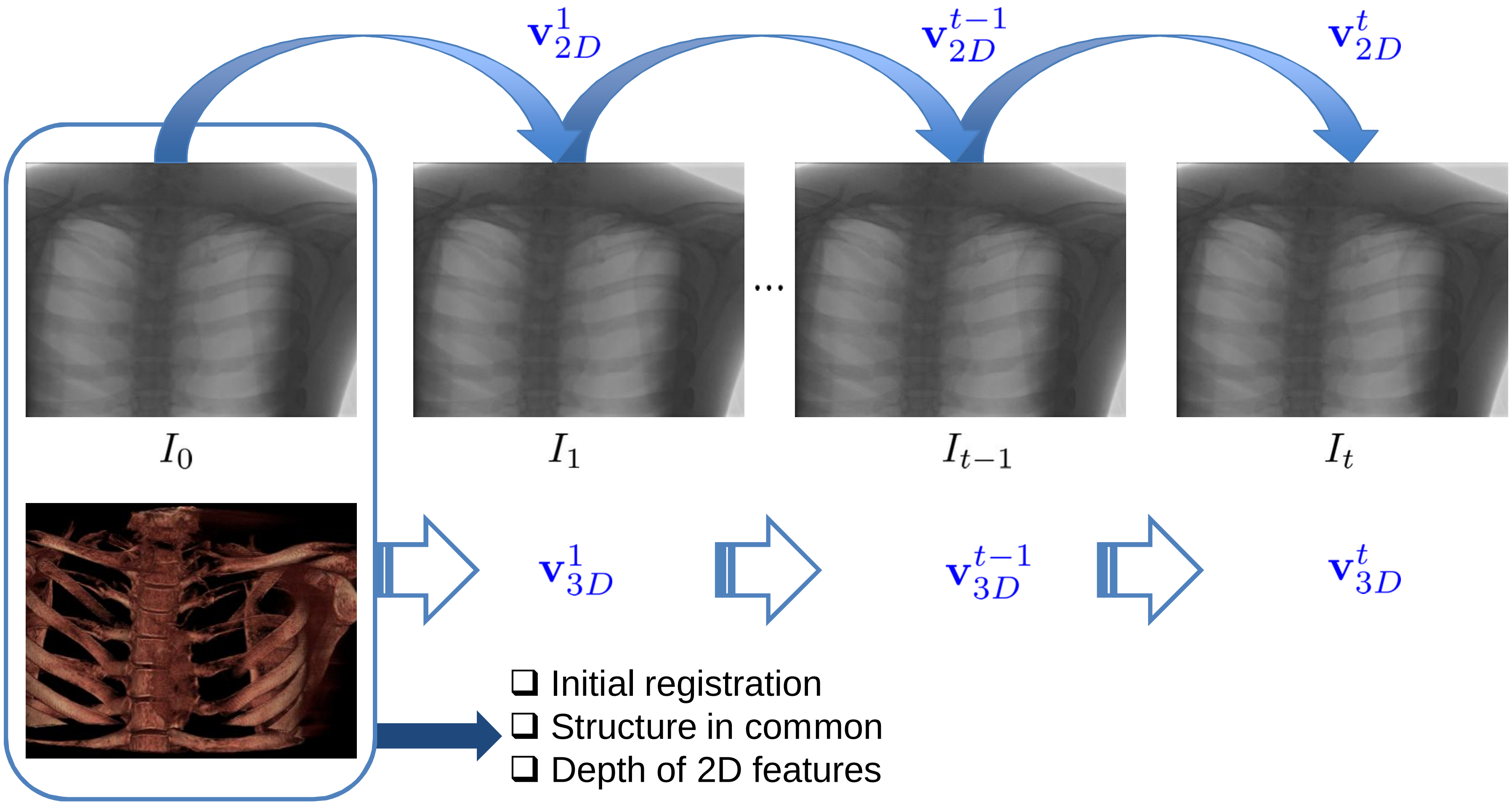

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- ❑ Structure in common
- ❑ Depth of 2D features

Gradient-Based Differential Approach

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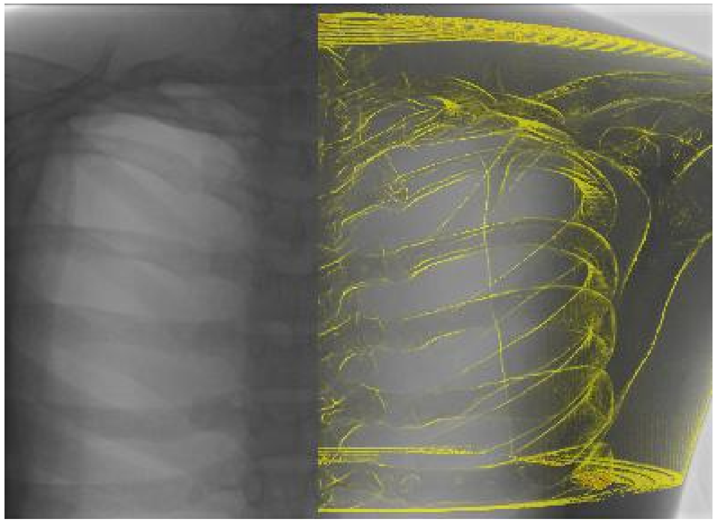
- Small motion assumption
  - Differential form of 3D rigid motion, i.e. rotation and translation
- Observed motion vs. image gradient
  - Motion observed along gradient direction (2D and 3D)
- Contours / edges are important for motion estimation
  - 2D: border of a region with remarkably different attenuation values
  - 3D: gradient perpendicular with viewing direction



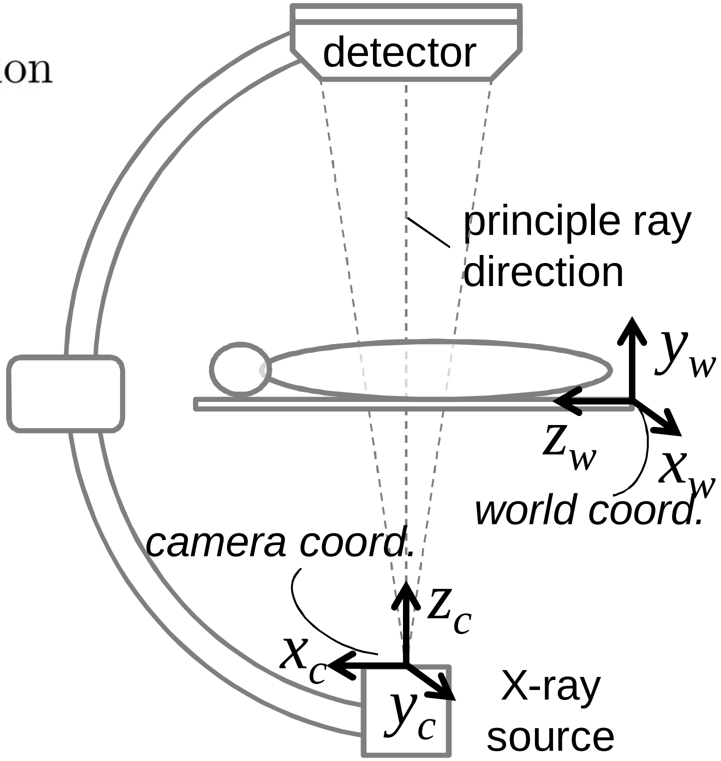
The Projection Model of C-Arm System SIEMENS

- Pinhole camera model

  $\mathbf{x} \doteq \mathbf{P}\mathbf{w}$,
  where $\mathbf{w}$ is 3D point and $\mathbf{x}$ is 2D projection

- The projection matrix in camera coordinate system

$$\mathbf{P}_e = \mathbf{K}\,[\mathbf{I}|\mathbf{0}] \in \mathbb{R}^{3\times 4}$$

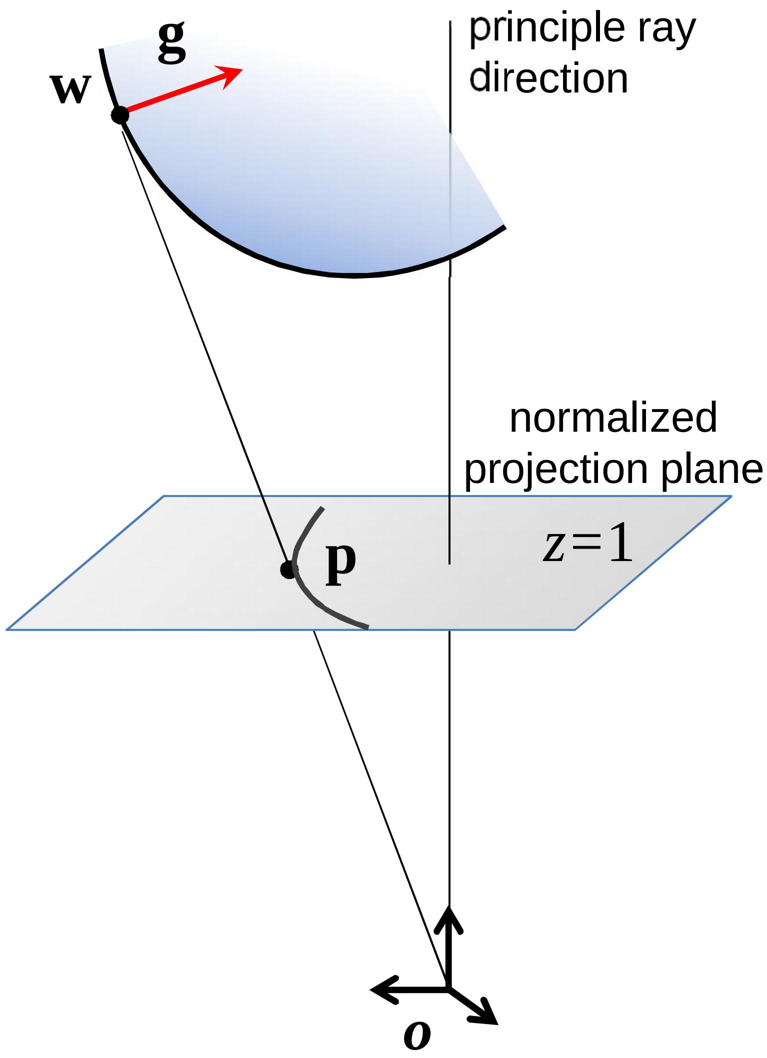


The Geometric Setup

- Normalized back-projection
  - 2D projection point $\mathbf{x} = (u,v)$
  - The normalized back-projection $\mathbf{p}$

$$\mathbf{p} = \left| \mathbf{K}^{-1} \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} \right|_H$$

$$\left| \begin{pmatrix} x \\ y \\ w \end{pmatrix} \right|_H = \begin{pmatrix} x/w \\ y/w \\ 1 \\ 1 \end{pmatrix}$$



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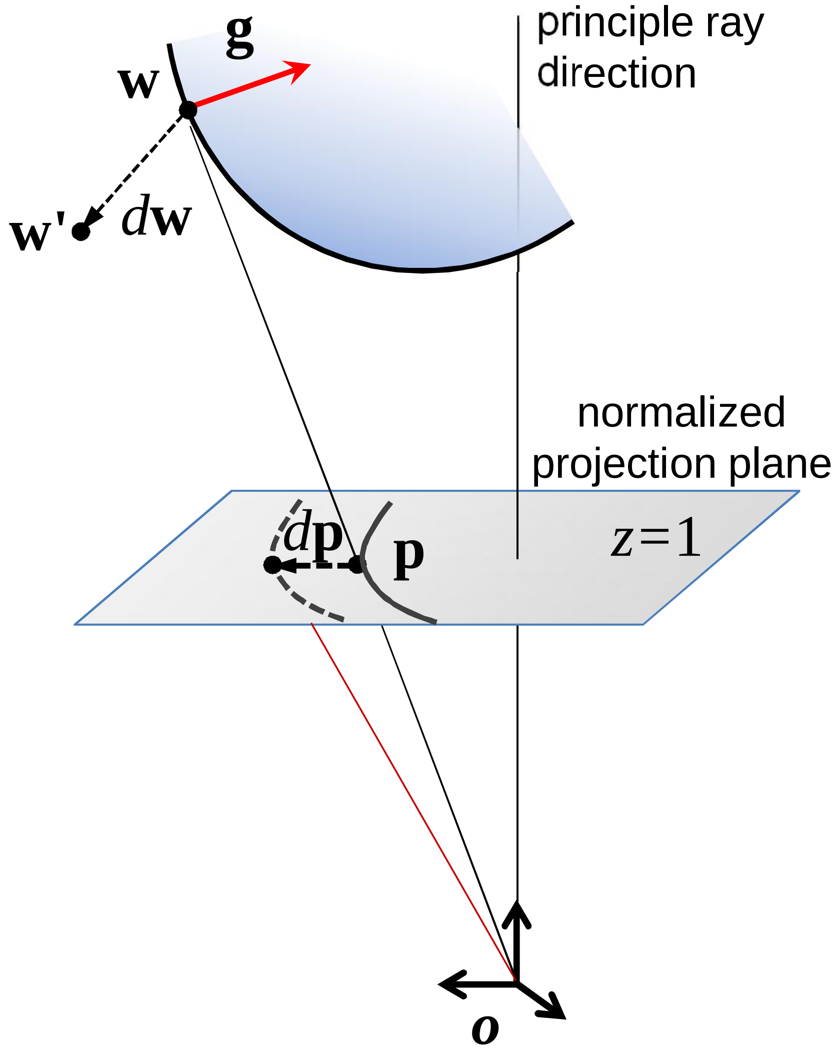
- After small motion $\mathbf{w}' = \mathbf{w} + d\mathbf{w}$



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- Normalized back-projection
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$$\mathbf{p} = \left| \mathbf{K}^{-1} \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} \right|_H$$

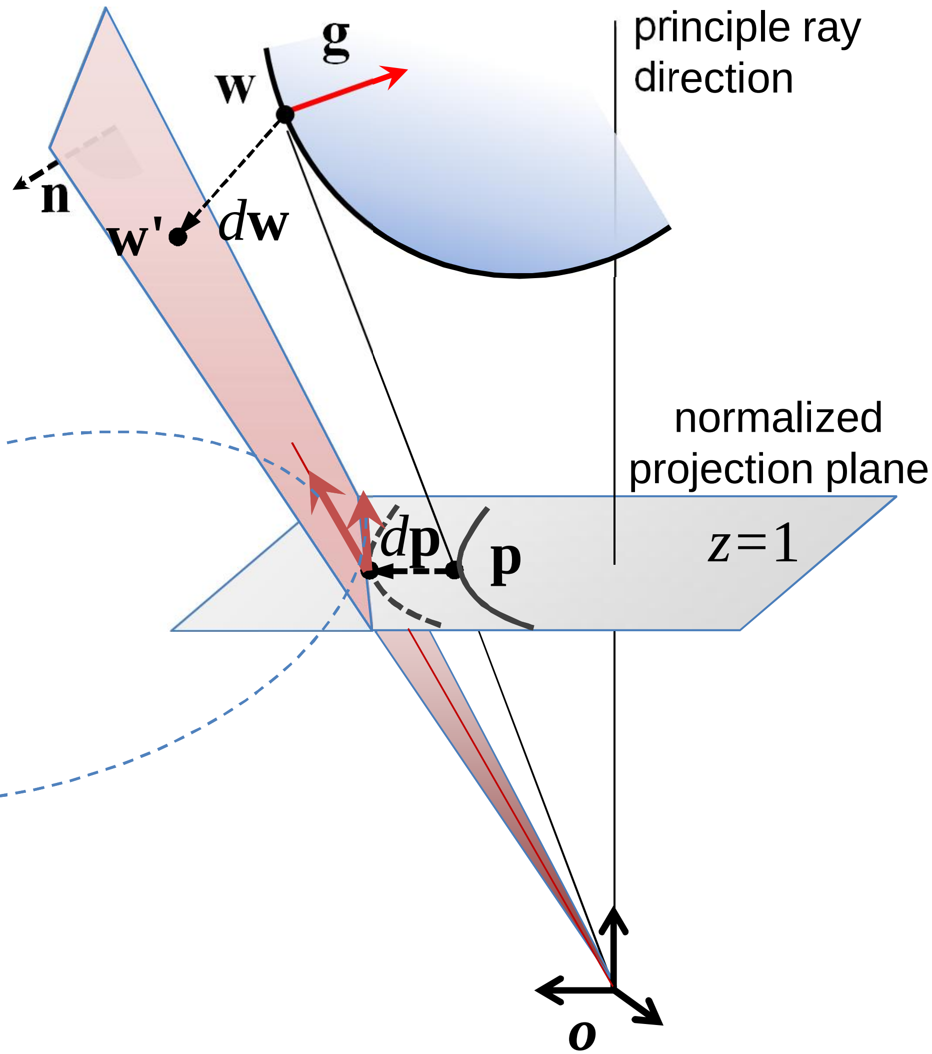
- After small motion $\mathbf{w}' = \mathbf{w} + d\mathbf{w}$
- Plane constraint after motion

unobservable observable

$$\mathbf{n} = \frac{(\mathbf{w} \times \mathbf{g}) \times (\mathbf{p} + d\mathbf{p})}{\|(\mathbf{w} \times \mathbf{g}) \times (\mathbf{p} + d\mathbf{p})\|}$$

- Point on the plane

$$\mathbf{n}^{\mathrm{T}}(\mathbf{w} + d\mathbf{w}) = 0$$



Differential Motion Equation

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- Differential form of 3D rigid motion

$$d\mathbf{w} = \underbrace{d\boldsymbol{\omega} \times \mathbf{w}}_{\text{rotation}} + \underbrace{d\boldsymbol{v}}_{\text{translation}}$$

  - Point-on-plane equation

$$\mathbf{n}^{\mathrm{T}}(\mathbf{w} + d\mathbf{w}) = 0$$

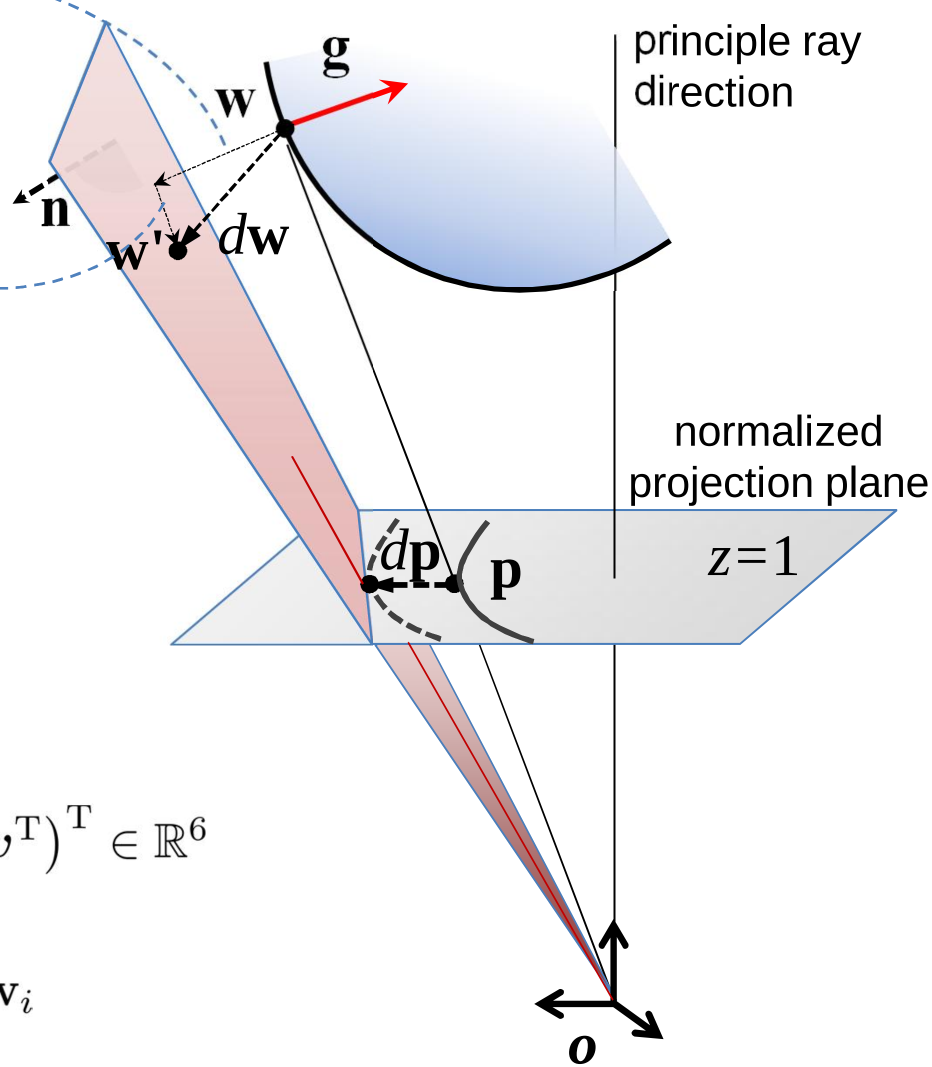
- The differential motion equation

$$\begin{pmatrix} \mathbf{n} \times \mathbf{w} \\ -\mathbf{n} \end{pmatrix}^{\mathrm{T}} \begin{pmatrix} d\boldsymbol{\omega} \\ d\boldsymbol{v} \end{pmatrix} = \mathbf{n}^{\mathrm{T}}\mathbf{w}$$

- The system of equations

$$\mathbf{A}\delta\mathbf{v} = \mathbf{b}, \text{ unknown: } \delta\mathbf{v} = \begin{pmatrix} d\boldsymbol{\omega}^{\mathrm{T}} & d\boldsymbol{v}^{\mathrm{T}} \end{pmatrix}^{\mathrm{T}} \in \mathbb{R}^6$$

$$\mathbf{a}_i^{\mathrm{T}} = \begin{pmatrix} \mathbf{n}_i \times \mathbf{w}_i \\ -\mathbf{n}_i \end{pmatrix}^{\mathrm{T}} \in \mathbb{R}^6 \qquad b_i = \mathbf{n}_i^{\mathrm{T}}\mathbf{w}_i$$



Occluding Contour Point Selection

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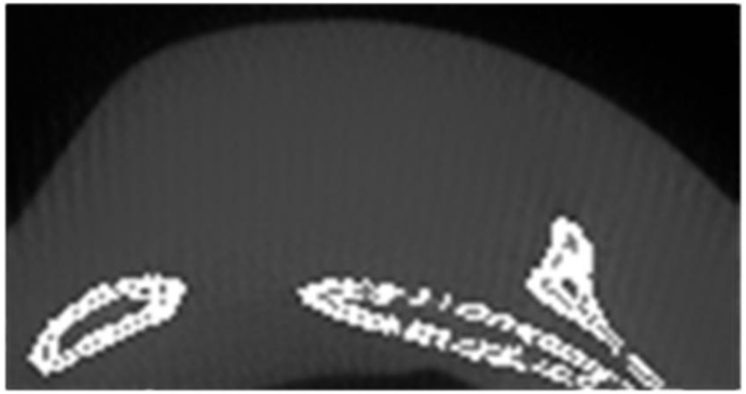
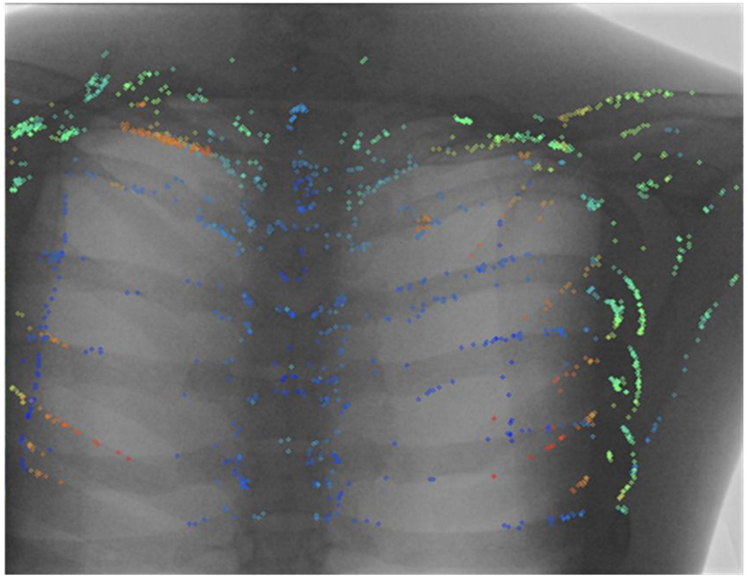
- Volume pre-processing
  - 3D guided image filter
- 3D volume analysis & 3D selection
  - Intensity windowing
  - gradient thresholding
- Occluding contour points selection
  - 2D: gradient magnitude
  - 2D/3D: patch-wise similarity
  - 3D:View-gradient perpendicularity

$$\alpha = \arccos\left(\left|\frac{\mathbf{g}\cdot\mathbf{w}}{\|\mathbf{g}\|\cdot\|\mathbf{w}\|}\right|\right)$$

  - Selection:

$$\{\mathbf{w}_i, \mathbf{g}_i, \mathbf{p}_i\}_{\text{sel}}$$





Tracking and Motion Estimation

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- 2D tracking ($d\mathbf{p}$)
  - Kanade-Lucas-Tomasi optical flow

Reminder of the linear equation

$$\begin{pmatrix} \mathbf{n} \times \mathbf{w} \\ -\mathbf{n} \end{pmatrix}^{\mathrm{T}} \begin{pmatrix} d\boldsymbol{\omega} \\ d\boldsymbol{v} \end{pmatrix} = \mathbf{n}^{\mathrm{T}}\mathbf{w}$$

$$\mathbf{n} = \frac{(\mathbf{w} \times \mathbf{g}) \times (\mathbf{p} + d\mathbf{p})}{\|(\mathbf{w} \times \mathbf{g}) \times (\mathbf{p} + d\mathbf{p})\|}$$

- Iteratively re-weighted least squares (IRLS)

$$\mathbf{A}\delta\mathbf{v} = \mathbf{b} \Rightarrow \widehat{\delta\mathbf{v}} = \arg\min_{\delta\mathbf{v}} \sum_i^N \beta_i \left(\mathbf{a}_i^{\mathrm{T}}\delta\mathbf{v} - b_i\right) \text{ , where } \beta_i = \beta_{z,i} \cdot \beta_{r,i}$$

  - The observation weight $\beta_{z,i}$
    - Tracking error term and the view-gradient perpendicularity
  - The residual weight

$$\beta_{r,i}^{(t)} \sim 1/r(\delta\mathbf{v}^{(t-1)})$$

  - The residual term at t-th iteration is

$$r(\delta\mathbf{v}^{(t-1)}) = \mathbf{a}_i^{\mathrm{T}}\widehat{\delta\mathbf{v}}^{(t-1)} - b_i$$

Experiment: Data Acquisition

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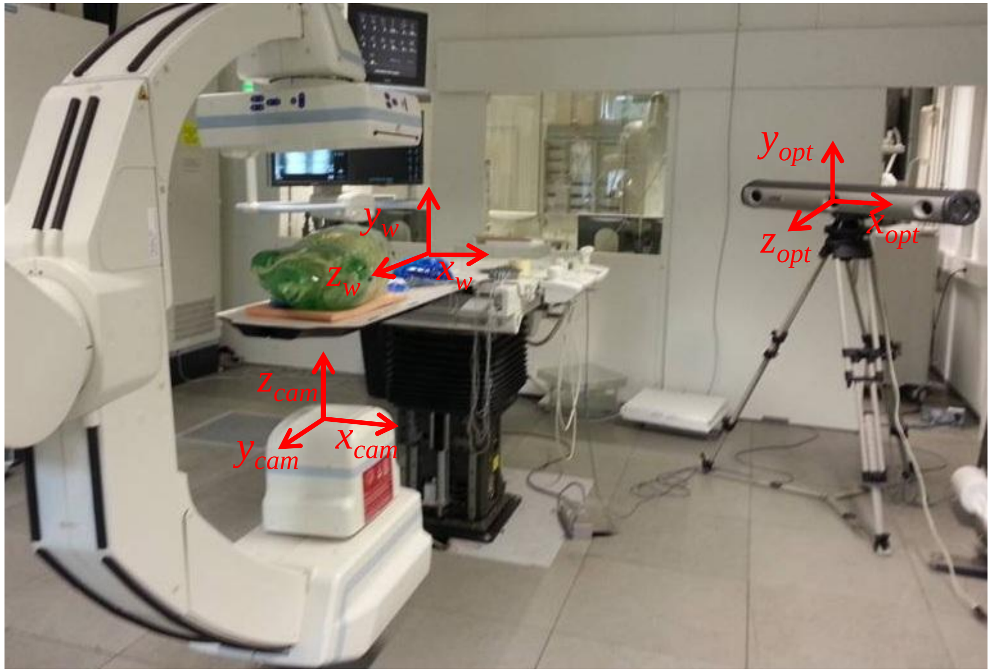
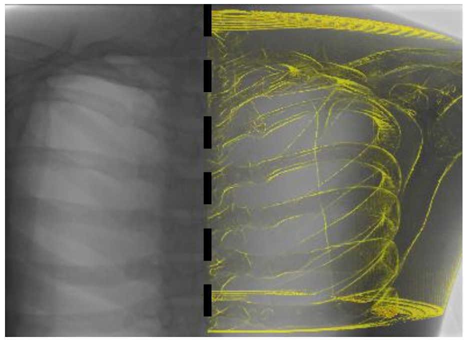
- Image acquisition
  - Interventional C-arm system
  - 3D C-arm CT volume
  - 2D fluoroscopic sequences
  - Motion triggered manually
- Ground-truth motion acquisition
  - OptoTrak motion capture system





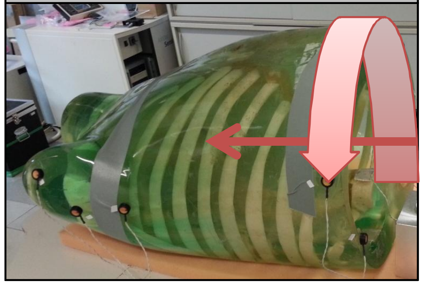
3D Motion Error Statics

- The **motion recovery rate** for motion component m

$$r(m) = 1 - \epsilon(m)/\max|m^*|$$

- Major motion recovery
  - In-plane: $r(R_y) = 97.4\%$, $r(t_x) = 95.4\%$, $r(t_z) = 96.7\%$
  - Off-plane rotation: $r(R_z) = 79.9\%$

Longitudinal rotation



seq.	# fr.	$\max\|R_x^*\|(°)$	$\epsilon(R_x)(°)$	$\max\|R_y^*\|(°)$	$\epsilon(R_y)(°)$	$\max\|R_z^*\|(°)$	$\epsilon(R_z)(°)$
1	33	0.18	0.04 ± 0.02	0.97	0.05 ± 0.03	**4.48**	$\mathbf{0.93 \pm 0.43}$
2	93	0.80	0.43 ± 0.26	0.52	0.05 ± 0.03	**11.93**	$\mathbf{2.82 \pm 1.55}$
3	111	0.63	0.40 ± 0.18	0.38	0.01 ± 0.01	**10.7**	$\mathbf{2.59 \pm 1.04}$
4	111	0.27	0.12 ± 0.11	0.56	0.03 ± 0.02	**8.31**	$\mathbf{1.51 \pm 0.94}$
5*	110	0.06	0.07 ± 0.03	**10.0**	$\mathbf{0.37 \pm 0.16}$	0.04	0.18 ± 0.08
7	105	0.23	0.36 ± 0.26	**4.43**	$\mathbf{0.08 \pm 0.07}$	**6.82**	$\mathbf{1.54 \pm 0.90}$
8	117	0.26	0.32 ± 0.18	1.47	0.04 ± 0.03	**7.93**	$\mathbf{1.32 \pm 0.83}$
9	114	0.18	0.10 ± 0.06	**4.57**	$\mathbf{0.15 \pm 0.08}$	**8.13**	$\mathbf{1.89 \pm 0.92}$

seq.	# fr.	$\max\|t_x^*\|(mm)$	$\epsilon(t_x)(mm)$	$\max\|t_y^*\|(mm)$	$\epsilon(t_y)(mm)$	$\max\|t_z^*\|(mm)$	$\epsilon(t_z)(mm)$
1	33	2.76	1.13 ± 0.67	0.99	2.27 ± 1.66	0.16	0.09 ± 0.07
2	93	4.58	2.96 ± 1.63	0.71	2.06 ± 1.01	0.61	0.64 ± 0.39
3	111	4.19	3.11 ± 1.32	0.66	3.41 ± 1.37	0.65	0.53 ± 0.24
4	111	5.72	2.12 ± 1.26	1.40	1.39 ± 0.56	0.94	0.16 ± 0.13
5*	110	**69.3**	$\mathbf{2.29 \pm 0.93}$	0.45	0.91 ± 0.37	**6.31**	$\mathbf{0.22 \pm 0.10}$
7	105	**30.0**	$\mathbf{2.62 \pm 1.36}$	0.58	1.27 ± 1.06	0.44	0.59 ± 0.32
8	117	9.81	1.68 ± 0.94	1.24	1.13 ± 0.69	0.15	0.63 ± 0.36
9	114	**30.3**	$\mathbf{1.17 \pm 0.57}$	1.69	3.56 ± 1.66	0.11	0.16 ± 0.14

Correction of 2D Misalignment

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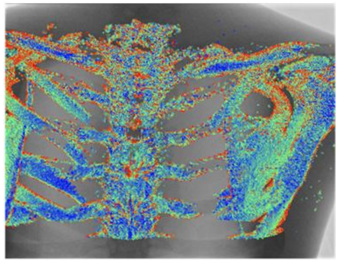
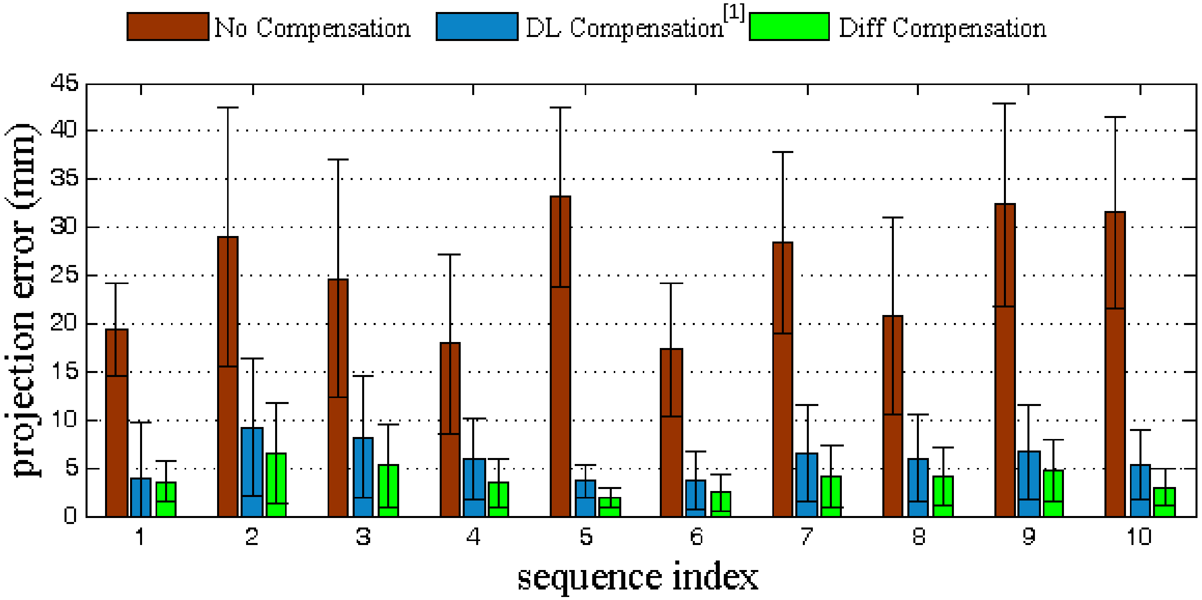
- The evaluation of the misalignment in the overlay
  - Structures of interest: pre-selected feature points
  - Misalignment measurement for each frame k
    $\sum \left(dist(p_i^{est,k}, p_i^{GT,k}) \right)$, where $dist(\cdot,\cdot)$ is the Euclidean distance
  - Choose the frame with largest projection shift $\sum \left(dist(p_i^{\mathbf{I}}, p_i^{GT}) \right)$
  - Correction of misalignment from **[17.3, 33.2] mm** to **[1.9, 6.5] mm**





[1] Wang et al., Depth-Layer Based Patient Motion Compensation for the Overlay of 3D Volumes onto X-Ray Sequences, BVM, 2013

Conclusion & Outlook

- Conclusion
  - Gradient-based differential 3D motion estimation
  - Mathematical model from 2D motion to 3D differential motion
  - An iteratively re-weighted least square (IRLS) minimization
  - Capable of estimating **3D motion** out of **2D tracking**
    - over **95%** recovery rate for in-plane motion
    - **~80%** recovery rate for off-plane longitudinal rotation
  - Correction of misalignment: 8/10 cases under **5 mm** (clinical failure threshold [2])
- Outlook
  - Refinement to compensate the approximation error
  - Re-initialization of the features considering 2D/3D correspondence
  - Robustness enhancement
    - More motion models (articulated motion, free form deformation)
    - External disturbance (interventional device, contrast injection)

[2] Gendrin et al., Validation for 2D/3D registration II: The comparison of intensity-and gradient-based merit functions using a new gold standard data set, Medical Physics, 2011

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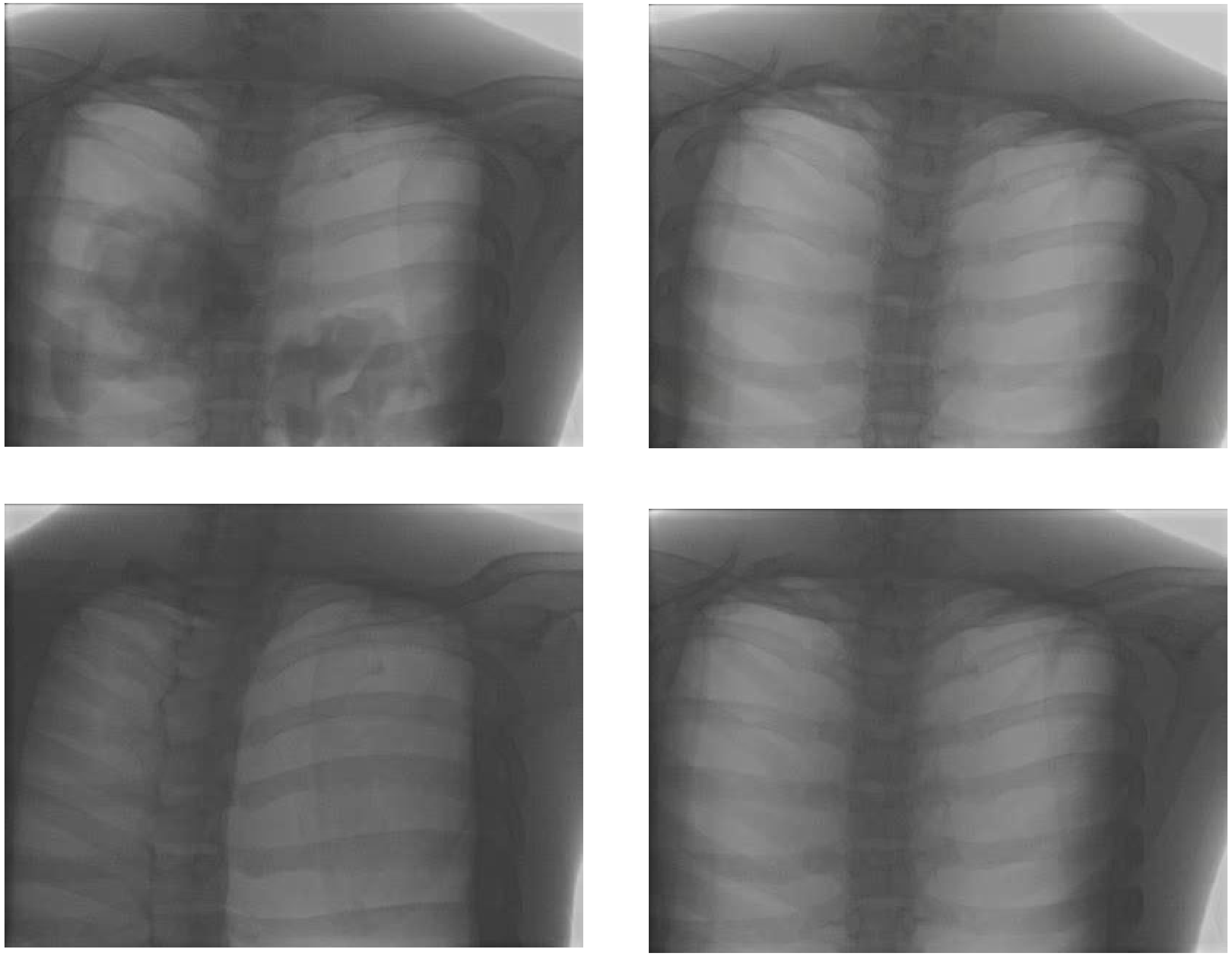
Thank you for your attention!
Poster Session: P2-25



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