2D/3D image registration for X-ray fluoroscopy
SSIP 2007

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GE imagination at work

GE Healthcare

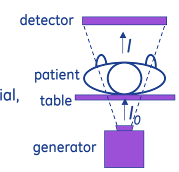
- More than 40000 employees worldwide
- Providing a wide range of healthcare solutions
  - **X-ray**, CT, MR, US, PET Imaging, Bone Densitometry, Anesthesia Delivery, Life Science, Molecular Imaging, Protein Purification, Contrast Media, Women's Health, Patient Monitoring, Information Technologies
- In Hungary:
  - Product development
    - Vascular system engineering (Innova X-ray systems)
    - Clinical Software development (Advantage Workstation)
  - Manufacturing (high-level assembly)
  - Research collaborations, scholarship program

Topics

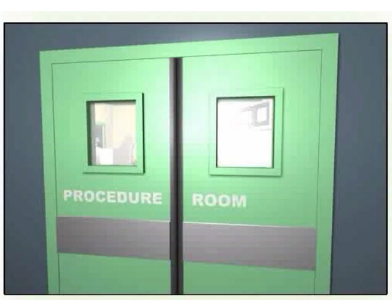
- ➔ Interventional X-ray systems
  - X-ray imaging basics
  - Interventional X-ray devices
  - Basic procedures and image processing techniques
- Registration of 2D X-ray to 3D images
  - Introduction
  - An intensity based registration algorithm (Knaan & Joskovicz)

X-ray imaging basics

- Röntgen, 1895
- Electromagnetic radiation
  - Photon energy 70-100 keV
  - Ionizing
- Attenuation: $I = I_0 \cdot e^{-\mu \cdot x}$
  - x = material thickness
  - μ = attenuation coefficient
  - μ is a characteristic of the absorbing material, also depends on X-ray photon energy



Interventional X-ray system – Innova 2000

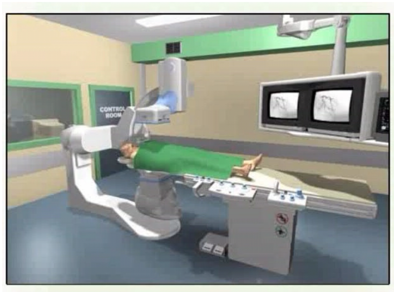


in-room

Interventional X-ray system – Innova 2000

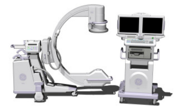
gantry motion

Interventional X-ray system – Innova 2000



control room

Interventional X-ray system designs

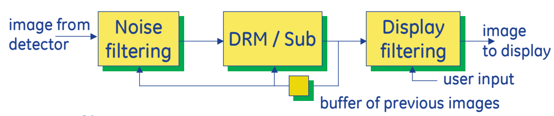


Mobile C-arm
(GE FluoroTrak)

Biplane
(GE AdvantX)

O-arm
(Medtronic – Breakaway)

Image processing pipeline



- Noise filtering
  - moving average, motion compensation
- Dynamic range management, subtraction
  - Gray level conversion 12->8 bits
  - Can be non-linear, changing in time and space
- Display filters
  - sharpening, smoothing
  - linear B/C
  - zoom

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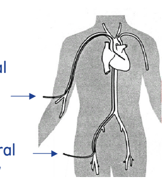
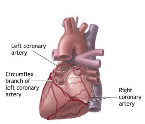
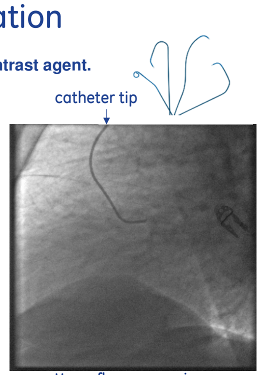
Basic vessel visualization

Vessels are visible only if filled by contrast agent.

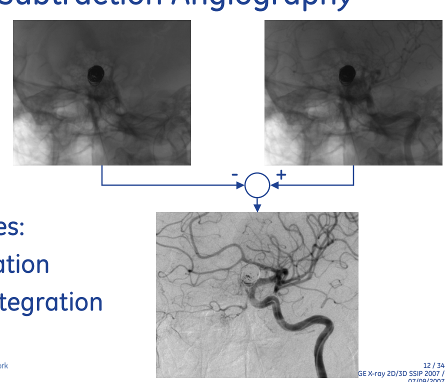






X-ray fluoroscopy image

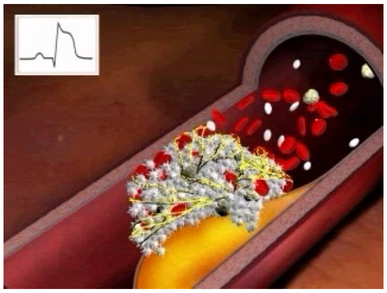
Digital Subtraction Angiography

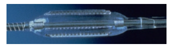


Techniques:

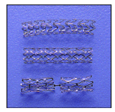
- Registration
- Mask integration

Balloon angioplasty & stenting



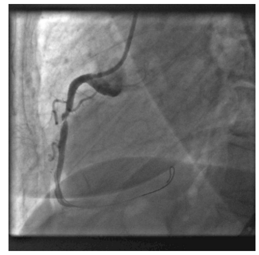


balloon

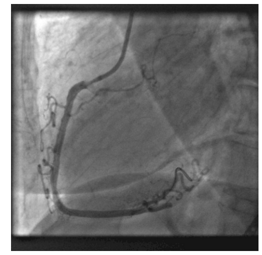


stent

Stenting of coronary artery



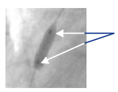
before



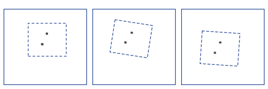
after

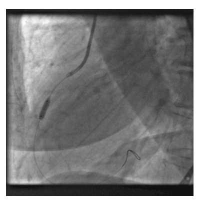
Stent visibility enhancement

1. Balloon marker detection

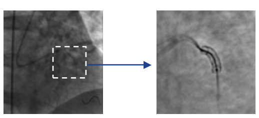


2. Marker tracking

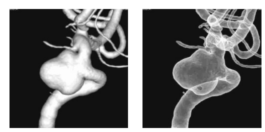




3. Averaging of tracked region

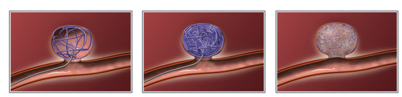


Blocking the blood flow – coiling



aneurysm

coils



steps of coiling procedure

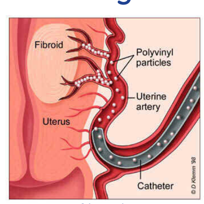
Coiling – enhanced with 3D model

3D model over the 2D image:

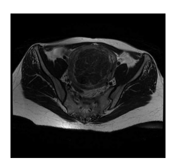
- Better understanding of 3D geometry (small branching vessels)
- Less contrast injection is needed

<u>2D/3D registration is needed!</u>

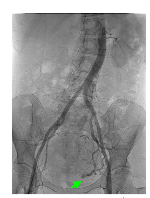
Blocking the blood flow – embolization



Uterine fibroid treatment by blocking of feeding vessels



MR slice (visible: soft tissues, fibroids, tumours; vessels)

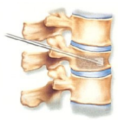


2D - angiography (visible: vessels)

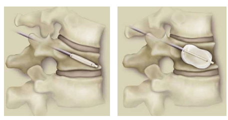
Which vessel shall we block?

<u>2D/3D registration is needed!</u>

Surgical navigation



vertebroplasty

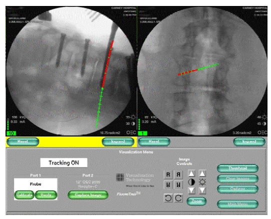


kyphoplasty

Spine CT: complete 3D model of the spine before operation

X-ray: current position of tools, just one 2D projection

2D/3D registration is needed!



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Why we use 2D *and* 3D images?

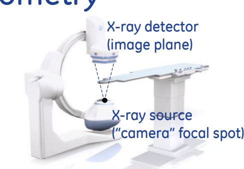
3D image (CT, MR, PET, US, 3DXR)	**2D X-ray image**
Full 3D information ✓	Only 2D projection ✗
High soft tissue contrast, functional images ✓	Low soft tissue contrast ✗
No radiation exposure ✓ (no ionizing radiation used for MR, ultrasound)	Radiation exposure ✗
Usually must be acquired before operation, ✗ can take several minutes ✗	Can be acquired during operation, ✓ in real-time (30fps) ✓
Low resolution (MR, PET, ultrasound) ✗	High resolution (1024^2) ✓

we need both => merge them! => requires 2D/3D registration

2D/3D registration geometry

Coordinate frames:

- M = 3D model
- P = patient (table)
- S = X-ray source
- D = detector (2D coordinate system)

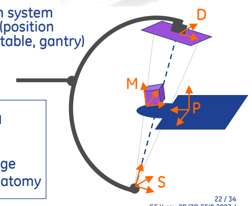


Coordinate frame transformations:

${}^{D}T^{S}$ = projection
${}^{S}T^{P}$ = gantry-patient relative pose } known from system calibration (position sensors on table, gantry)
${}^{P}T^{M}$ = patient-model relative pose } ?

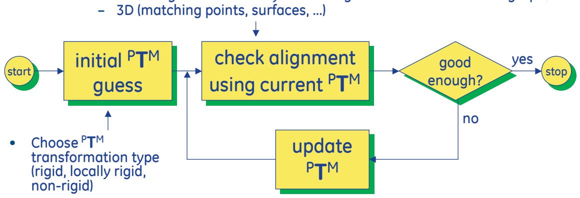
$$p^{D} = {}^{D}T^{S}\,{}^{S}T^{P}\,{}^{P}T^{M}\,p^{M}$$

correspondence through image matching of model and actual anatomy



General 2D/3D registration algorithm

- Similarity measure
  - Feature based (markers, anatomical landmarks, *vessels*)
  - Image based (MI, correlation, ...)
- Working dimension
  - 2D (using simulated X-ray – a.k.a. Digital Reconstructed Radiograph)
  - 3D (matching points, surfaces, ...)



- Choose ${}^{P}T^{M}$ transformation type (rigid, locally rigid, non-rigid)
- Approximate patient position on the table
- Manual correction

Optimization:

- Non-gradient (coordinate ascent, Powell,...)
- Gradient (gradient ascent, LM, ...)

An Intensity-based 2D/3D registration algorithm

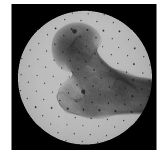
- D. Knaan and L. Joskovicz: Effective Intensity-Based 2D/3D Rigid Registration between Fluoroscopic X-Ray and CT. - *MICCAI 2003*
- Target application: orthopedic surgery (registration of bones)
- Registration requirements: error <1mm, required time <2 minutes, fully automatic
- Input: 2-5 fluoroscopic X-ray images from different viewpoints, foreign objects may be present
- Method:
  - in 2D, intensity-based registration of DRR and fluoroscopic image
  - similarity measure: correlation
  - transformation: rigid
  - optimization: iterative downhill simplex optimization
  - Plus 5 special techniques

Fast DRR generation by "Transgraph"

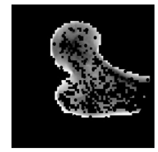
- New DRR (simulated X-ray) image is needed in each iteration
- DRR generation by simple raycasting => about 1 sec
- Fast DRR generation using "Transgraph"
  - Compute gray levels of probable rays in advance
  - Store it in "Transgraph" data structure
  - Gray value of each DRR pixel is computed by interpolation
  - Performance: precomputation (15M rays) => 5 min, full DRR (800x600 pixels) => 0.08 sec

Dynamic ROI selection

- DRR generation & similarity evaluation only in a region of interest (ROI)
- Select from non-overlapping rectangular windows of 7x7 pixels
- Exclude regions that hold no relevant information for matching
  - non-anatomical structures (calibration grid spheres, unexposed image areas, ...)
  - uniform regions:
    - usually correspond to background, soft tissues, bone interior
    - 85-90% of the image



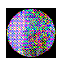
full image



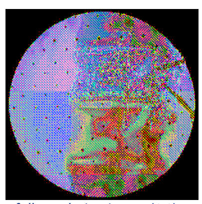
ROIs

Multi-resolution fluoroscopy

- Perform optimization on a downsampled image (1:16)
- Use low-resolution optimization result as the initial value for the optimization at higher resolution
- Advantages:
  - Number of pixels is reduced (DRR generation & similarity evaluation)
  - More likely to find the global optimum



low-resolution image (1:16)



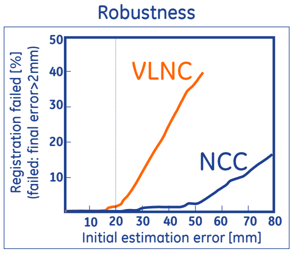
full-resolution image (1:1)

Multiple similarity measures

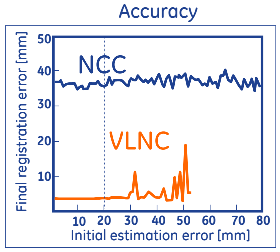
- Similarity measure requirements:
  - fast, robust, accurate, has wide convergence range
  - emphasize rigid bone
  - filter out deformable soft tissues, foreign objects (visible only in X-ray)
  - non-sensitive for image contrast and sharpness differences
- There is no single measure that fulfills all these.
  - **Normalized Cross Correlation (NCC)**: wide convergence range, robust, but not very accurate, invariant to linear changes in image intensity
  - **Variance Weighted Sum of Local Normalized Correlation (VLNC):** high-variance regions (where the relevant information is) get more weight. Improved accuracy, reduced influence of foreign objects.

Numerical comparison

Robustness



Accuracy



NCC is more robust (less failures), especially when **initial error > 20 mm**

VLNC is more accurate (smaller error), especially when **initial error < 20 mm**

Combine them: start with NCC and use its result as initial guess for VLNC based optimization.

Genetic search

- To avoid local minima
- Starting population: n+1 transformation candidates (initial guess + n random guesses)
- Optimization is performed for all of them to maximize the similarity measure
- Transformations yielding the worst similarity results are discarded
- Next population: n/2 new transformations, obtained by random pairwise linear combinations
- Redo the same steps as with the starting population, until only one transformation is left

The complete algorithm

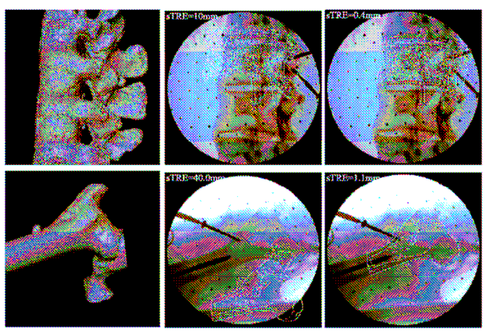
Step	Resolution	ROI	Random samples	Similarity measure
1	low (1:16)	full image	n = 4	NCC
2	full (1:1)	dynamic selection	n = 4	NCC
3	full (1:1)	dynamic selection	n = 0	VLNC

Final result of a step is the initial guess of the next step.

Algorithm performance

- Robustness:
  - 100% success if initial error max. 10mm (spine), 25mm (hip)
  - 95% success if initial error max. 25mm (spine), 40mm (hip)
- Accuracy: registration error average 0.7mm (maximum 1.3mm)
  – probably bound by limited CT resolution
- Computation time:
  - 5 minutes precomputation for Transgraph
  - Registration: average 70 sec
    - Step 1: 5 sec initialization, 10 sec (400 DRRs)
    - Step 2: 30 sec (2400 DRRs)
    - Step 3: 25 sec (200 DRRs)

Qualitative results



Thank you for your attention!

Any questions?

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