Clinical IGRT: In-Room Imaging Technologies and Image Processing for Patient Alignment

Essential Image Processing Techniques for IGRT

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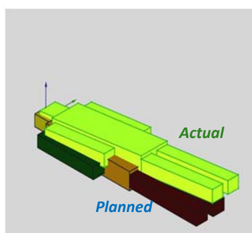
Conflict of Interest Disclosure

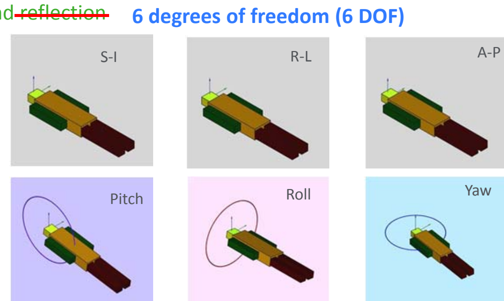
- I have no conflict of interest to disclosure.

Regardless of which image modality is used, image-guided radiotherapy

- Employ imaging techniques to
  - Guide patient setup and/or
  - Monitor intra-fractional motion
- Common strategy:
  - Image the *actual* patient location
  - Calculation the correction
  - Move the patient to the *planned* location



Patient motion is rigid transformation : translation, rotation and ~~reflection~~ 6 degrees of freedom (6 DOF)



Homogeneous coordinates are usually used to describe rigid body transformation

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{11} & r_{11} & t_x \\ r_{11} & r_{11} & r_{11} & t_y \\ r_{11} & r_{11} & r_{11} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

R **t**

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} r_{11} & r_{11} & r_{11} \\ r_{11} & r_{11} & r_{11} \\ r_{11} & r_{11} & r_{11} \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \end{bmatrix} + \begin{bmatrix} t_x \\ t_y \\ t_z \end{bmatrix}$$

- Transformation matrix has 12 elements
  - 3 translations: **t**
  - 9 rotations: **R**

However, only 6 independent (i.e., 6 DOF) motions:

$$\mathbf{p}' = (\mathbf{R}+\mathbf{t})\mathbf{p} = (\mathbf{R}_x\mathbf{R}_y\mathbf{R}_z+\mathbf{t})\mathbf{p}$$

- 3 translations: R-L (t_x), A-P (t_y), and S-I (t_z)
- 3 rotations: around R-L (θ_x), A-P (θ_x) and S-I (θ_x) axes

$$\mathbf{p} = \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}, \quad \mathbf{p}' = \begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix}, \quad \mathbf{t} = \begin{bmatrix} t_x \\ t_y \\ t_z \\ 1 \end{bmatrix}, \quad \mathbf{R}_x = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta_x & -\sin\theta_x & 0 \\ 0 & \sin\theta_x & \cos\theta_x & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix},$$

$$\mathbf{R}_y = \begin{bmatrix} \cos\theta_y & 0 & -\sin\theta_y & 0 \\ 0 & 1 & 0 & 0 \\ \sin\theta_y & 0 & \cos\theta_y & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \mathbf{R}_z = \begin{bmatrix} \cos\theta_z & -\sin\theta_z & 0 & 0 \\ \sin\theta_z & \cos\theta_z & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

More complex imaging schemes provide more information for correcting positioning errors

Simple → Complex

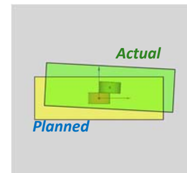
- 1 markers
- 2 markers
- A 2D pair of projection (2D-2D)
- A 2D pair of projection (3D-2D)
- 3 markers
- A reconstructed surface
- A 3D CBCT scan

3 DOF correction → 3 DOF correction

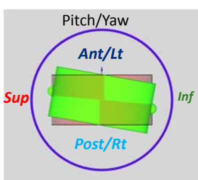
Solving the rigid transformation for translation (or 3 DOF) only requires the location of a single point

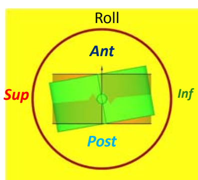
$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & t_x \\ 0 & 1 & 0 & t_y \\ 0 & 0 & 1 & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \Rightarrow \begin{bmatrix} t_x \\ t_y \\ t_z \\ 1 \end{bmatrix} = \times \begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} - \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

- 1 markers
- 2 markers
- A 2D pair of projection images (2D-2D)
- A 2D pair of projection (3D-2D)
- 3 markers
- A reconstructed surface
- A 3D CBCT scan



Two markers provides 5 DOF corrections: 3 DOF for translation and 2DOF for rotations

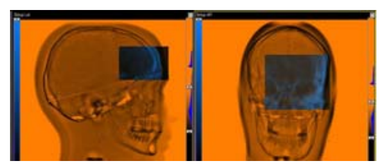




- Rotation around the axis connecting the two markers cannot be detected.

Similarly, 2D/2D Rigid registration misses the roll rotation

- 2D radiograph vs. 2D DRR
  - Single pair: 2 translations (S-I and R-L/A-P), 1 rotation (pitch/yaw)
  - Two (stereotactic) pairs: 3 translations, 2 (pitch and yaw) rotations

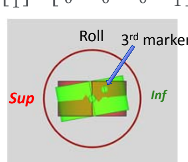


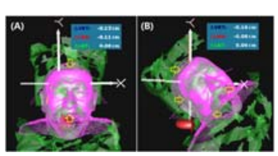
S-I, A-P and pitch — S-I, R-L and yaw

Solving the rigid transformation for 6DOF correction requires at least a plane or a 3D surface

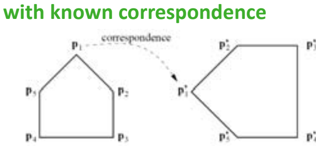
$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{11} & r_{11} & t_x \\ r_{11} & r_{11} & r_{11} & t_y \\ r_{11} & r_{11} & r_{11} & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix}$$

- A 2D pair of projection (3D-2D)
- 3 markers
- A reconstructed surface
- A 3D CBCT scan





Registration is relatively straightforward if markers are used with known correspondence

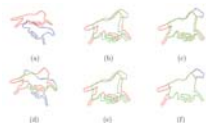


Planned — Actual

- Correspondence: markers with known relative locations
- At least 3 markers, more for redundancy
- Can be simplified to a series of linear equations: **Ma** = **b**, and
- Solved analytically using e.g., linear least square method
  a = $(\mathbf{M}^T\mathbf{M})^{-1}\mathbf{M}^T\mathbf{b}$

Similarity Test and Iterative Method are used with unknown correspondence

- Compare the similarity using:
  - Correlation of image intensity
  - Mutual information
  - Texture
  - …

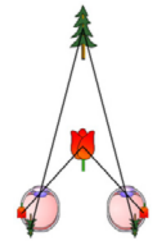


Du et al. Opt. Eng. 50(8):087001--4.

- Register the two images iteratively:
  - Calculate the directions that will increase similarity
  - Update the predicted
  - Repeat until reaching an accepted threshold

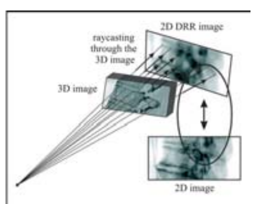
2D/2D pair actually contains 6DOF information when used together: "Stereo Imaging"

- Similar to depth perception of human eyes
- A pair of 2D images: x-ray or optical
- No motion of source, imager and object being images
- Stereo images look similar but are different
- 3D depth information can be extracted using:
  - Repeated educational guess to find the best match for the difference: 3D/2D registration
  - Triangulation: phtogrammetry
  - …



3D/2D rigid registration achieves 6 DOF correction by iteratively rendering 2D pairs of DRRs in real time

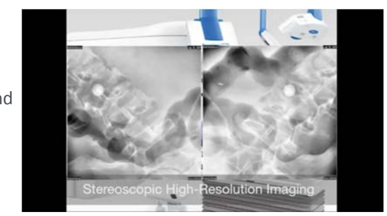
- 2D DRR generated from 3D volume
- Similarity test – radiograph vs. DRR
- Calculate the direction of correction- usually the direction that will increase similarity quickly
- 3D volume translated and rotated
- Repeat until reaching an accepted threshold



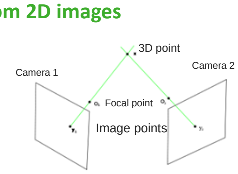
Markelj et al. MIA.16(3):642-61 (2012)

In comparison to 2D-2D registration, 3D-2D registration:

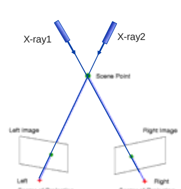
- All 6 (3translations and 3 rotations) DOF corrections
- Slow: multiple rounds of forward projection, fusion and optimization
- Require a fast, high-quality DRR rendering method



Triangulation is extensively used in IGRT to derive 3D information from 2D images



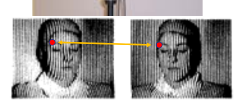
Source: Triangulation (computer vision). From Wikipedia, the free encyclopedia



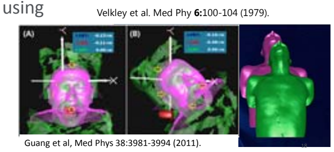
- Triangulation: the determination of a point in 3D space using 2D images
- Determine marker locations or reconstruct surface

Photogrammetry: extraction of 3D information from 2D image data.

- Stereoscopic camera
- Illuminate the objects with light source of known pattern
- Capture 2D reflection images of the objects
- Reconstruct 3D surface information using triangulation
- 6 DOF correction: rigid-body transformation maximizing surface congruence.



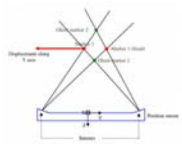
Velkley et al. Med Phy **6**:100-104 (1979).



Guang et al, Med Phys 38:3981-3994 (2011).

Stereoscopic Tracking using reflective Infrared Markers

Meeks et al. *IJROBP* **46**: 291-1299 (2000).



Stroian et al. Med Phy **31**:2008-2019 (2004).

- Identify potential marker locations by triangulation of stereo images
- Eliminate ghost: markers in predefined geometric arrays
- At least 3 visible markers, more for redundancy and better accuracy
- 6 DOF correction by comparing imaged and planned marker locations

Conclusions

- Devil's advocate of JACMP, 2017/07, Parallel opposed editorial, "The more IGRT systems, the merrier?"

> In conclusion, complexity is the ultimate enemy. The statement "more IGRT systems implemented in clinic are better for radiotherapy outcomes" is only true in theory but could not materialize in practice because most clinics do not have enough machine time and man power to deal with the added complexity.

- Given that the underline working principle for image-guided correction are essentially the same regardless of the imaging modality, the added complexity for physics might not be as daunting as it looks like.

Thank You!

Followed by " " by Jussi Sillanpaa, PhD