Surgical Navigation & System Architecture

RBE 580 / ME 5205
Biomedical Robotics
Fall 2018
Class 7

Prof. Fischer

Course Logistics

- **Projects**

  Thank you for submitting written project proposals, I will provide feedback to each team shortly/

  Please continue to use Canvas discussion board to provide updates and ask questions for the rest of the class.

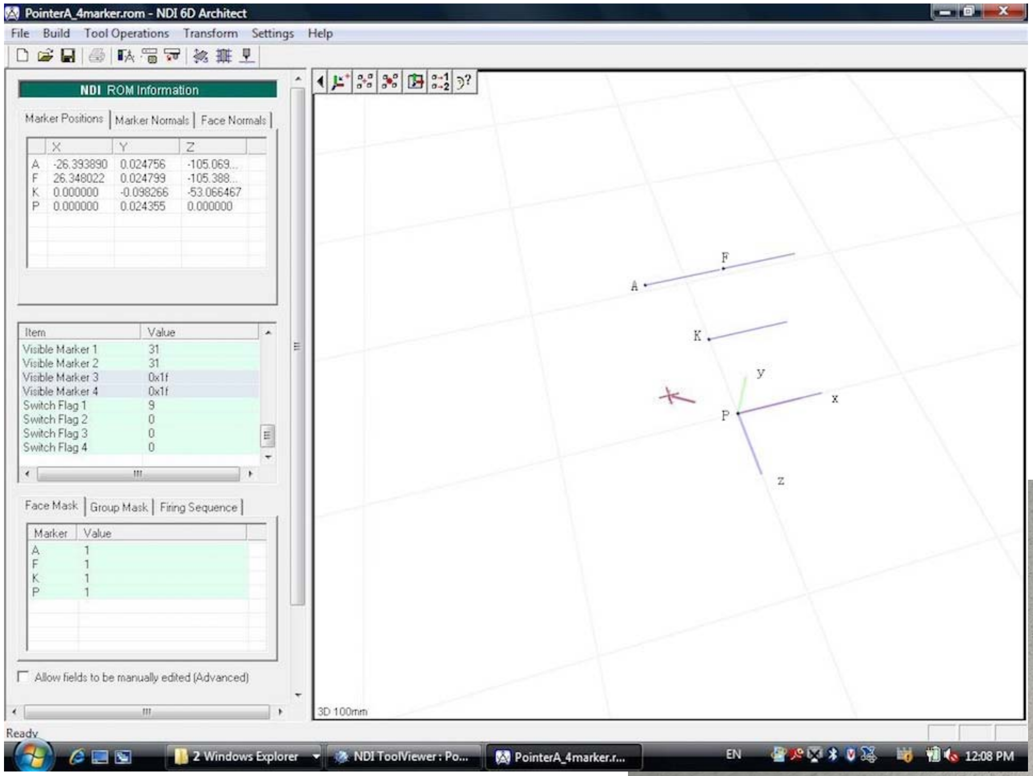
- **Paper Reviews – "Journal Club"**

  Comment on Paper #2 discussion by Friday, Nov 16 by 11:59pm EST

- **Homework**

  HW #1 is due Tuesday, Nov 20 by 11:59pm EST
  See Monday's recorded office hours for more help

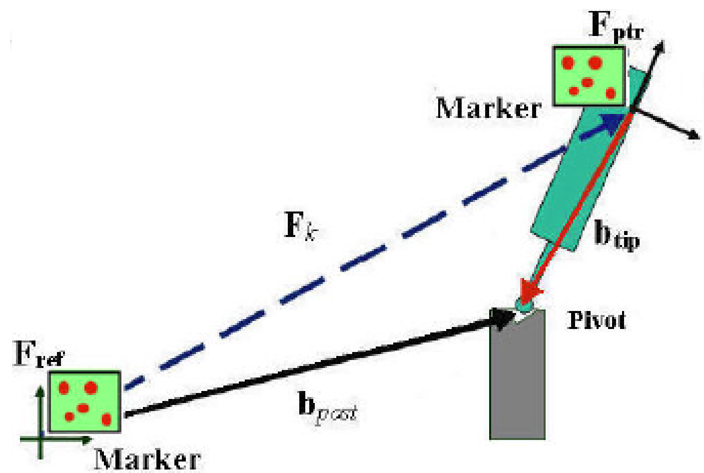
HW #1 – Problem 1



Pivot Calibration Formulation

For each measurement:

$$\vec{\mathbf{b}}_{post} = \mathbf{R}_k \vec{\mathbf{b}}_{tip} + \vec{\mathbf{p}}_k \ .$$



Rewriting the equation:

$$\mathbf{R}_k \vec{\mathbf{b}}_{tip} - \vec{\mathbf{b}}_{post} = -\vec{\mathbf{p}}_k \ .$$

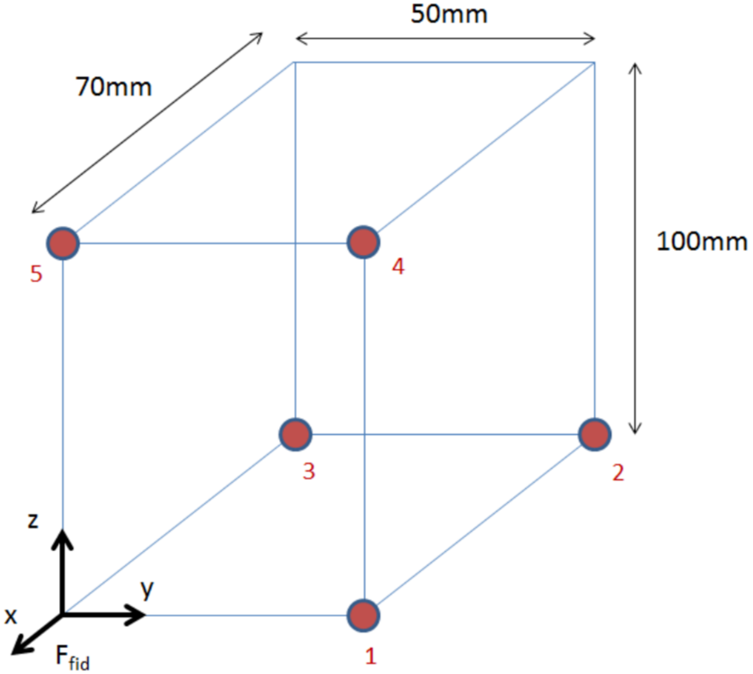
Putting in matrix form:

$$\begin{bmatrix} \vdots & \vdots \\ \hline \mathbf{R}_k & -\mathbf{I} \\ \hline \vdots & \vdots \end{bmatrix} \begin{bmatrix} \vec{\mathbf{b}}_{tip} \\ \vec{\mathbf{b}}_{post} \end{bmatrix} \cong \begin{bmatrix} \vdots \\ \hline -\vec{\mathbf{p}}_k \\ \hline \vdots \end{bmatrix}$$

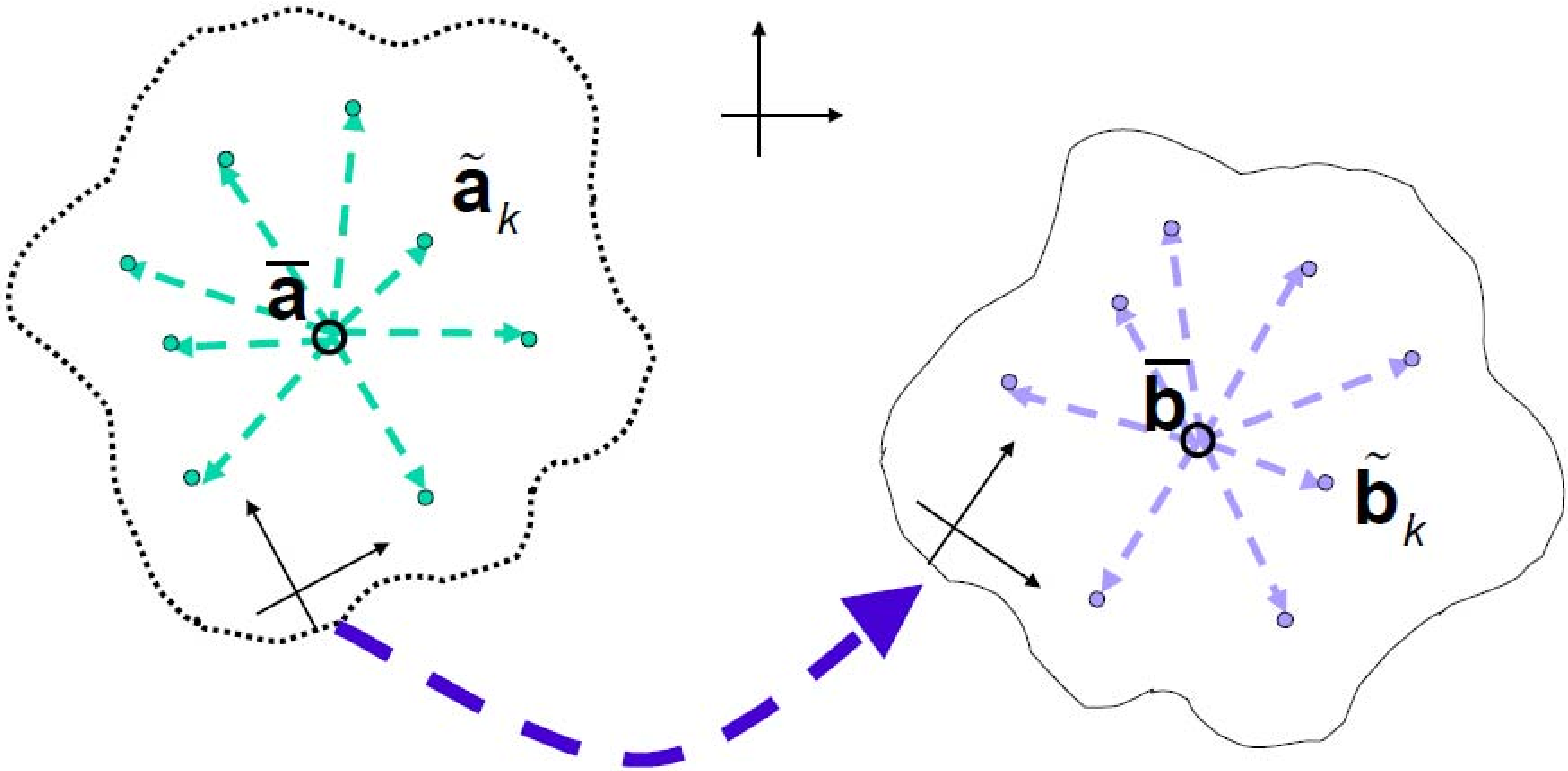
Solve for unknown parameters & calculate residual error:

$$\vec{x} = A^{+}\vec{b} \qquad\qquad A\vec{x} - \vec{b} = \text{Residual}$$

HW #1 – Problem 2



Point Cloud to Point Cloud Registration



$$\mathbf{R} \bullet \vec{\mathbf{a}}_k + \vec{\mathbf{p}} = \vec{\mathbf{b}}_k$$

Solving for R using the Arun Method

Method due to K. Arun, et. al., IEEE PAMI, Vol 9, no 5, pp 698-700, Sept 1987

Step 1: Compute

$$\mathbf{H} = \sum_i \begin{bmatrix} \tilde{a}_{i,x}\tilde{b}_{i,x} & \tilde{a}_{i,x}\tilde{b}_{i,y} & \tilde{a}_{i,x}\tilde{b}_{i,z} \\ \tilde{a}_{i,y}\tilde{b}_{i,x} & \tilde{a}_{i,y}\tilde{b}_{i,y} & \tilde{a}_{i,y}\tilde{b}_{i,z} \\ \tilde{a}_{i,z}\tilde{b}_{i,x} & \tilde{a}_{i,z}\tilde{b}_{i,y} & \tilde{a}_{i,z}\tilde{b}_{i,z} \end{bmatrix}$$

Step 2: Compute the SVD of $\mathbf{H} = \mathbf{USV}^{\mathbf{t}}$

Step 3: $\mathbf{R} = \mathbf{VU}^{\mathbf{t}}$

Step 4: Verify $Det(\mathbf{R}) = 1$. If not, then algorithm may fail.

Registration Error Terminology

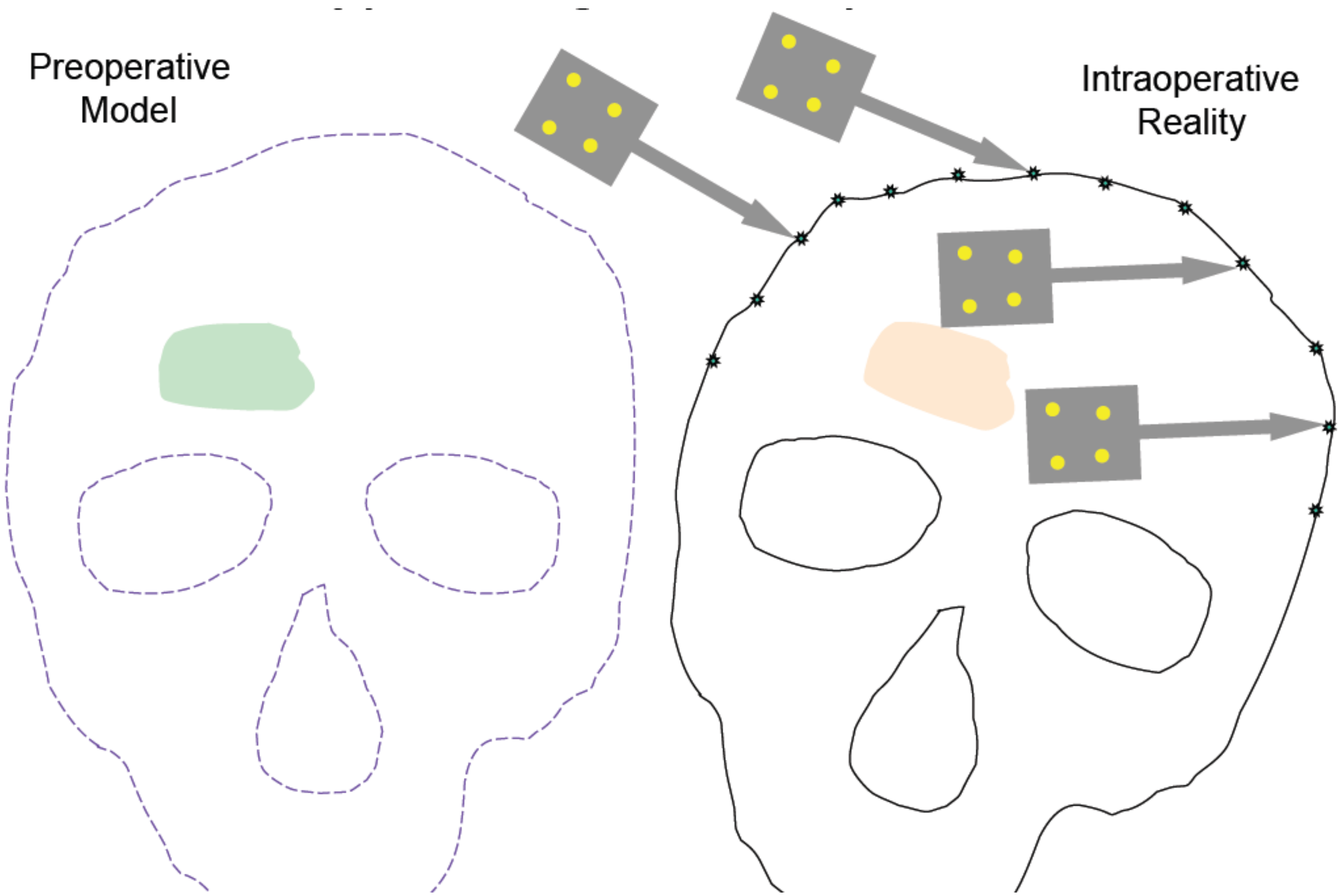
1. *Fiducial localization error (FLE)*, which is the error in locating the fiducial points.
2. *Fiducial registration error (FRE)*, which is the root-mean-square distance between corresponding fiducial points after registration.
3. *Target registration error (TRE)*, which is the distance between corresponding points other than the fiducial points after registration.

Wrapping Up Registration…

Types of Registration to Consider

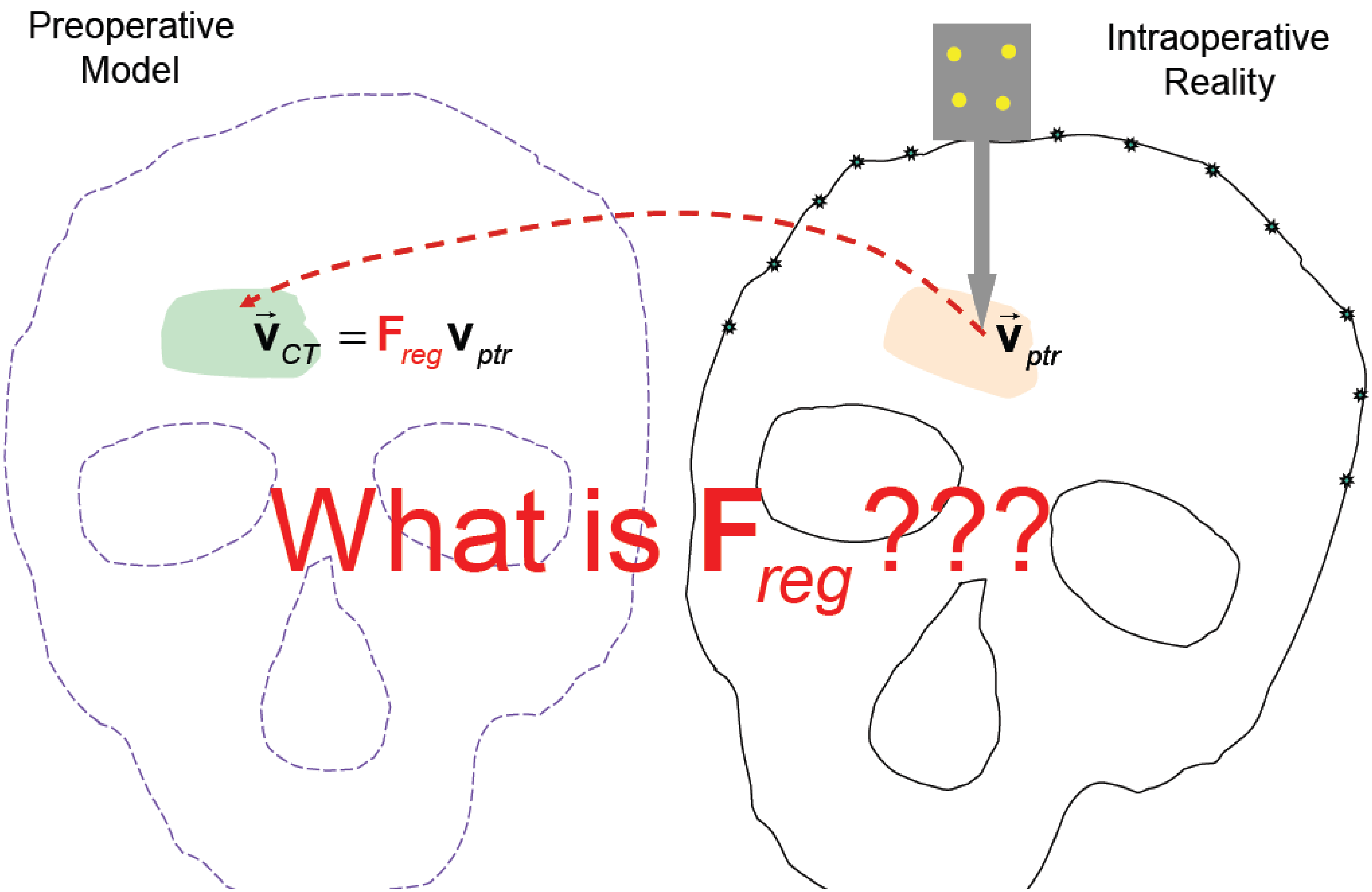
- **Preoperative Data**
  - 2D & 3D medical images/volumes
  - Models & atlases
  - Preoperative positions & plans
- **Intraoperative Data**
  - 2D & 3D medical images/volumes
  - Models
  - Intraoperative positioning information & updated plans
- **The Patient**
  - May or may not be same coordinates as imaging system

Intraoperative Registration



https://www.youtube.com/watch?v=C9ngfY97Bkg

Registered Intraoperative Guidance



Goal of Image-based Registration

Overall Goal: Given two coordinate systems,

$$\mathbf{Ref}_{A} \ \& \ \mathbf{Ref}_{B}$$

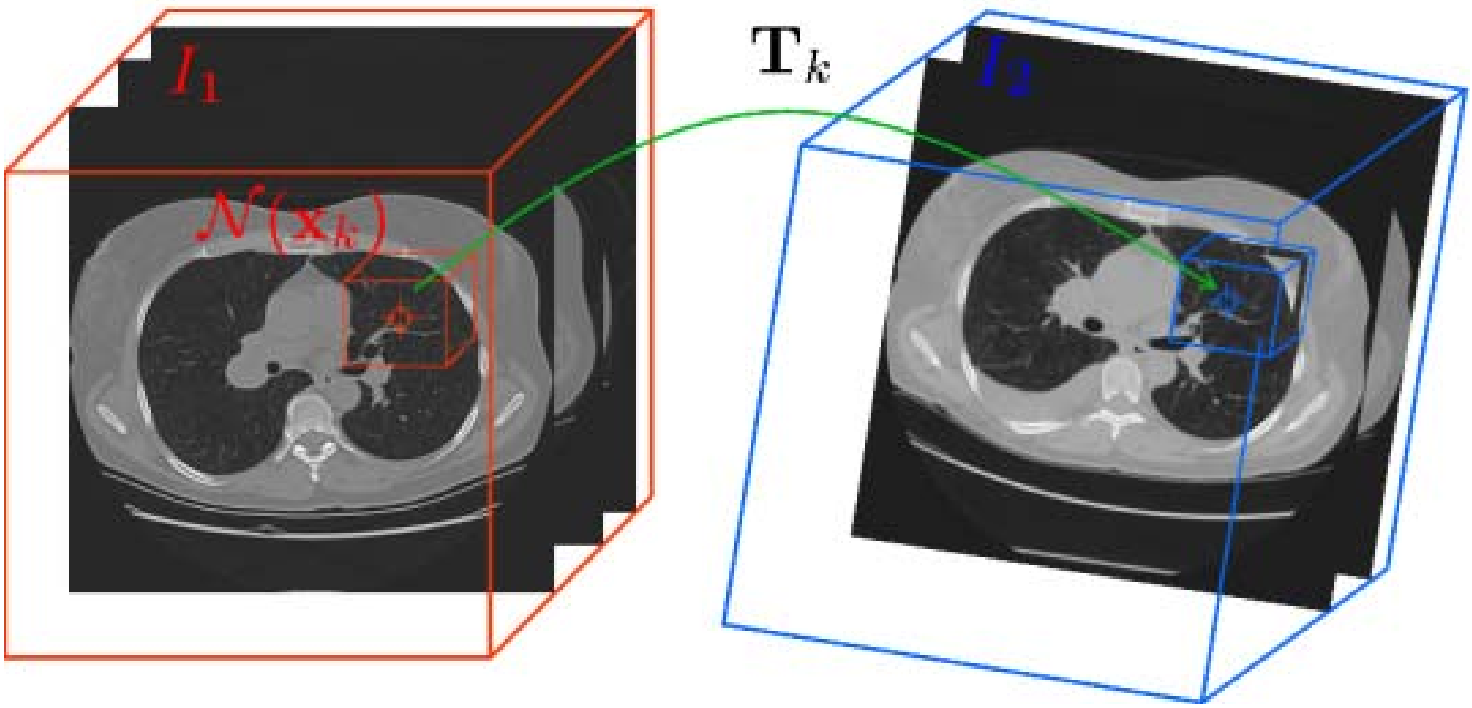
and coordinates

$$\mathbf{x}_{A} \ \& \ \mathbf{x}_{B}$$

associated with homologous features in the two coordinate systems, the general goal is to determine a transformation function T that transforms one set of coordinates into the other:

$$\mathbf{x}_{A} = \mathrm{T}(\mathbf{x}_{B})$$

Goal of Image-based Registration



Types of Image-based Registration

- **Rigid Transformation:** Essentially, 2D & 3D coordinate transformations:

  $$T(x) = R \cdot x + p$$

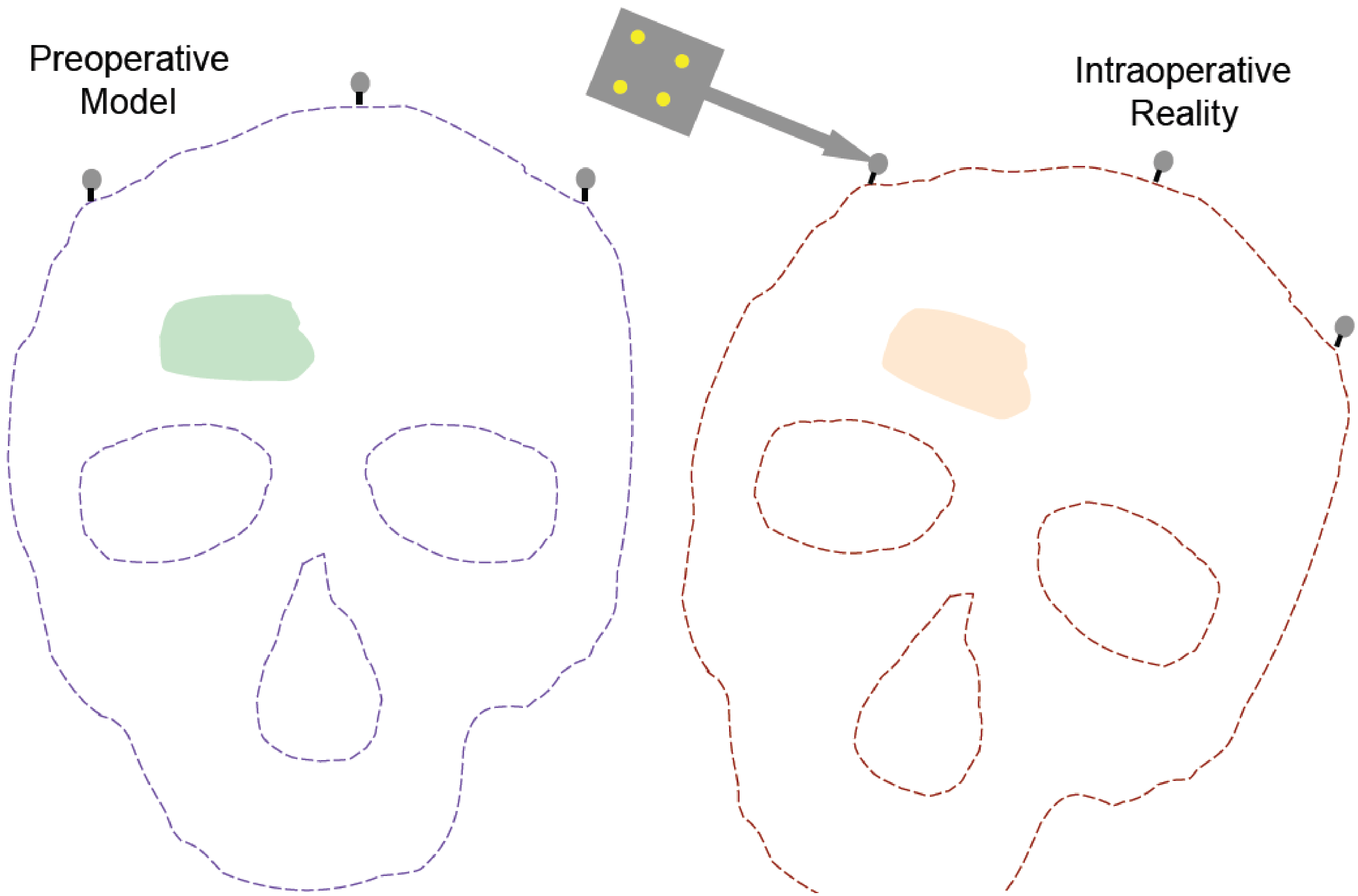
  The key assumption is that deformations may be neglected.

- **Elastic Transformation:** Cases where must take deformations into account. Many different flavors, depending on what is being deformed

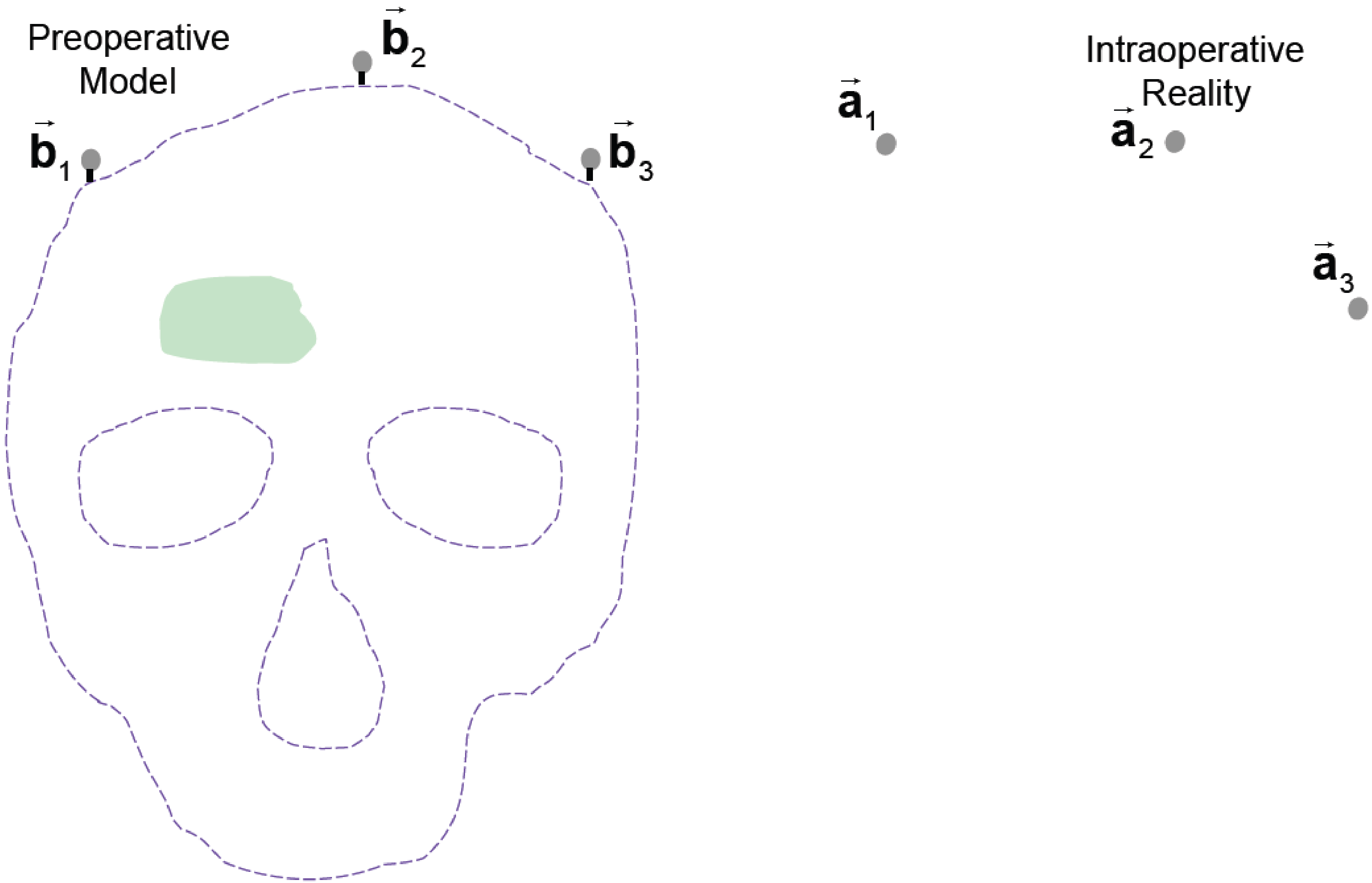
Features for Registration

- Point fiducials
- Point anatomical landmarks
- Ridge curves
- Contours
- Surfaces
- Line fiducials

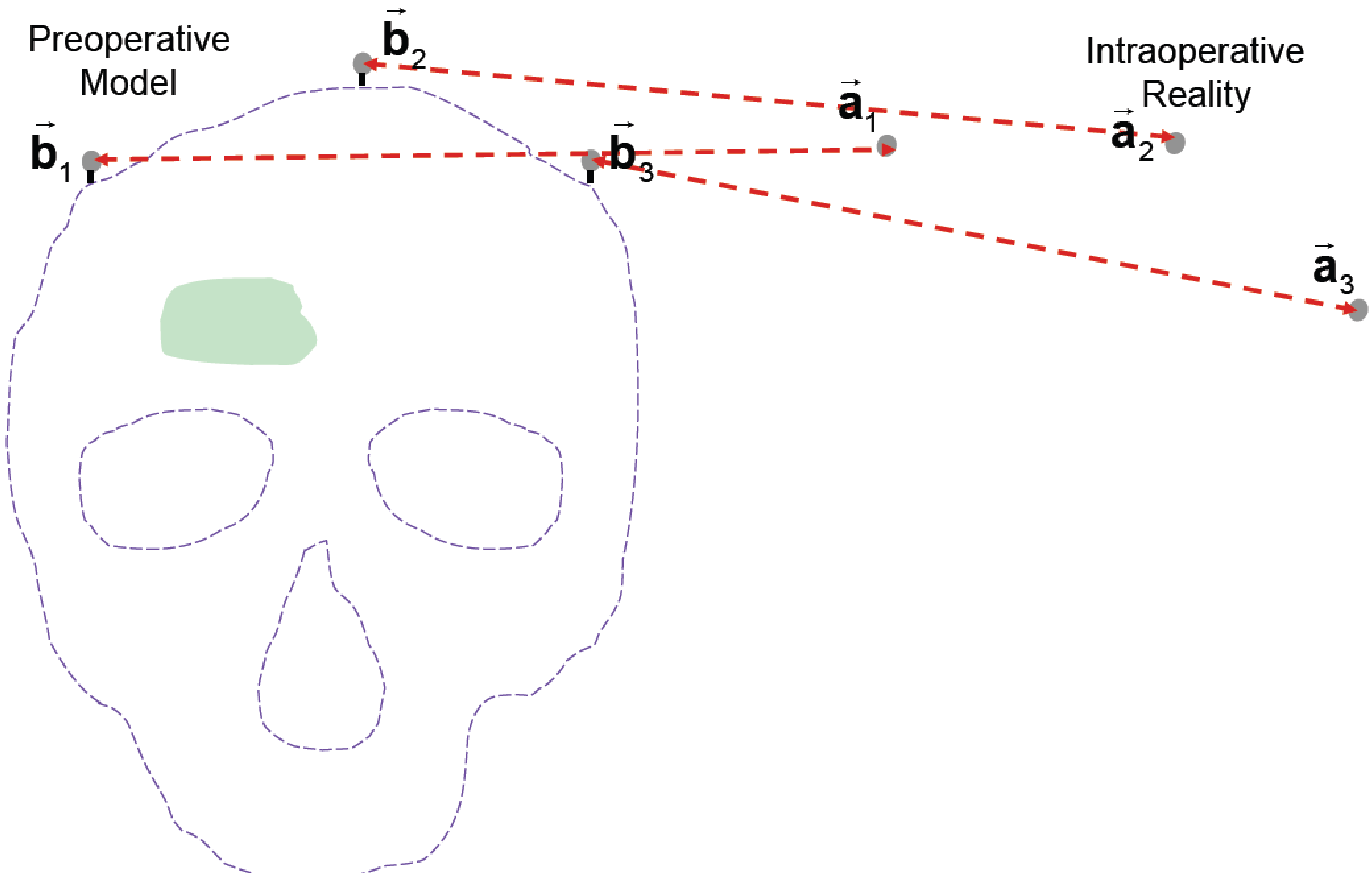
Simple Rigid Registration Problem



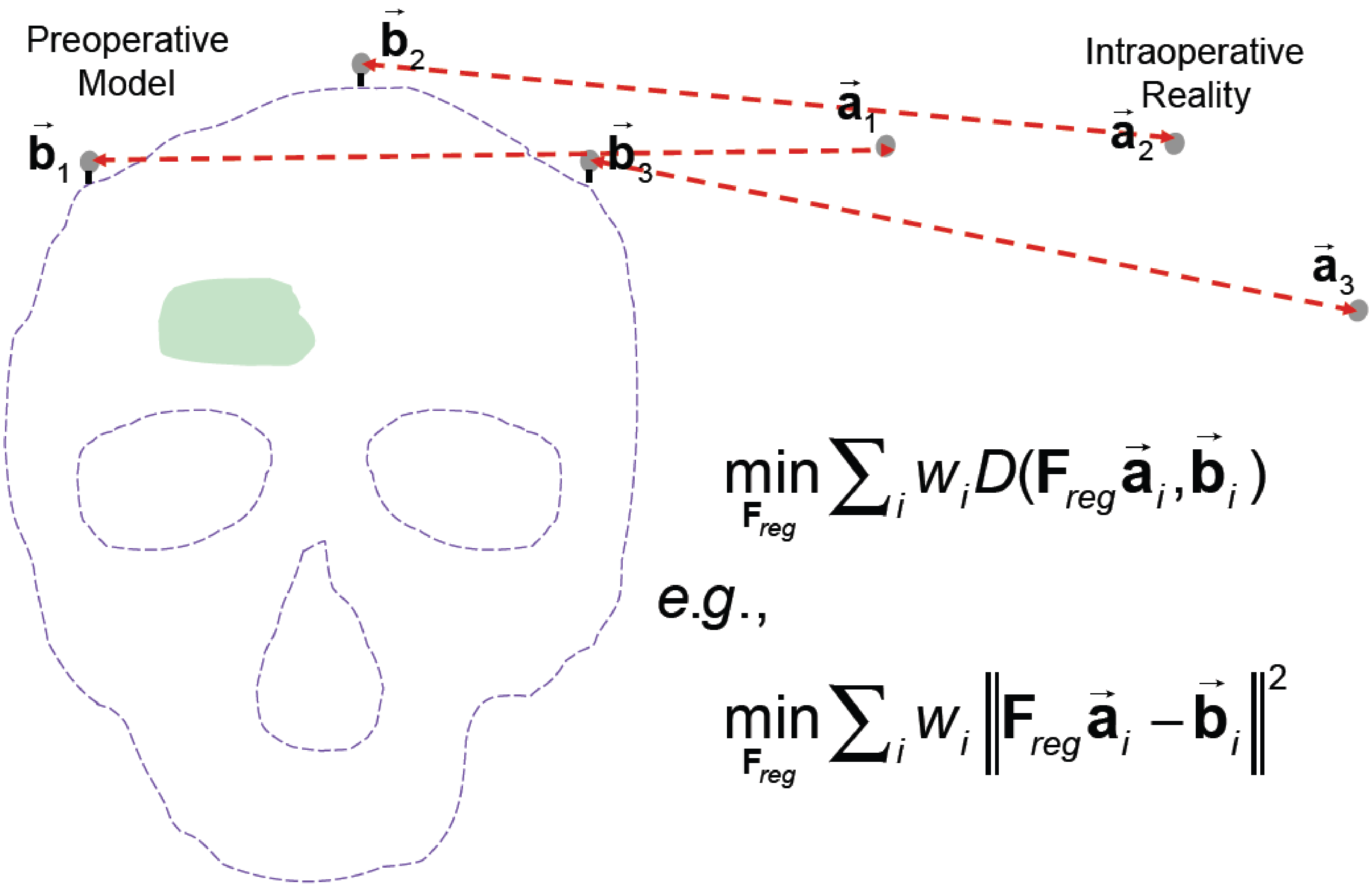
Corresponding Known Data



Correspondence Between the Data



Solve for "Best" Rigid Transformation

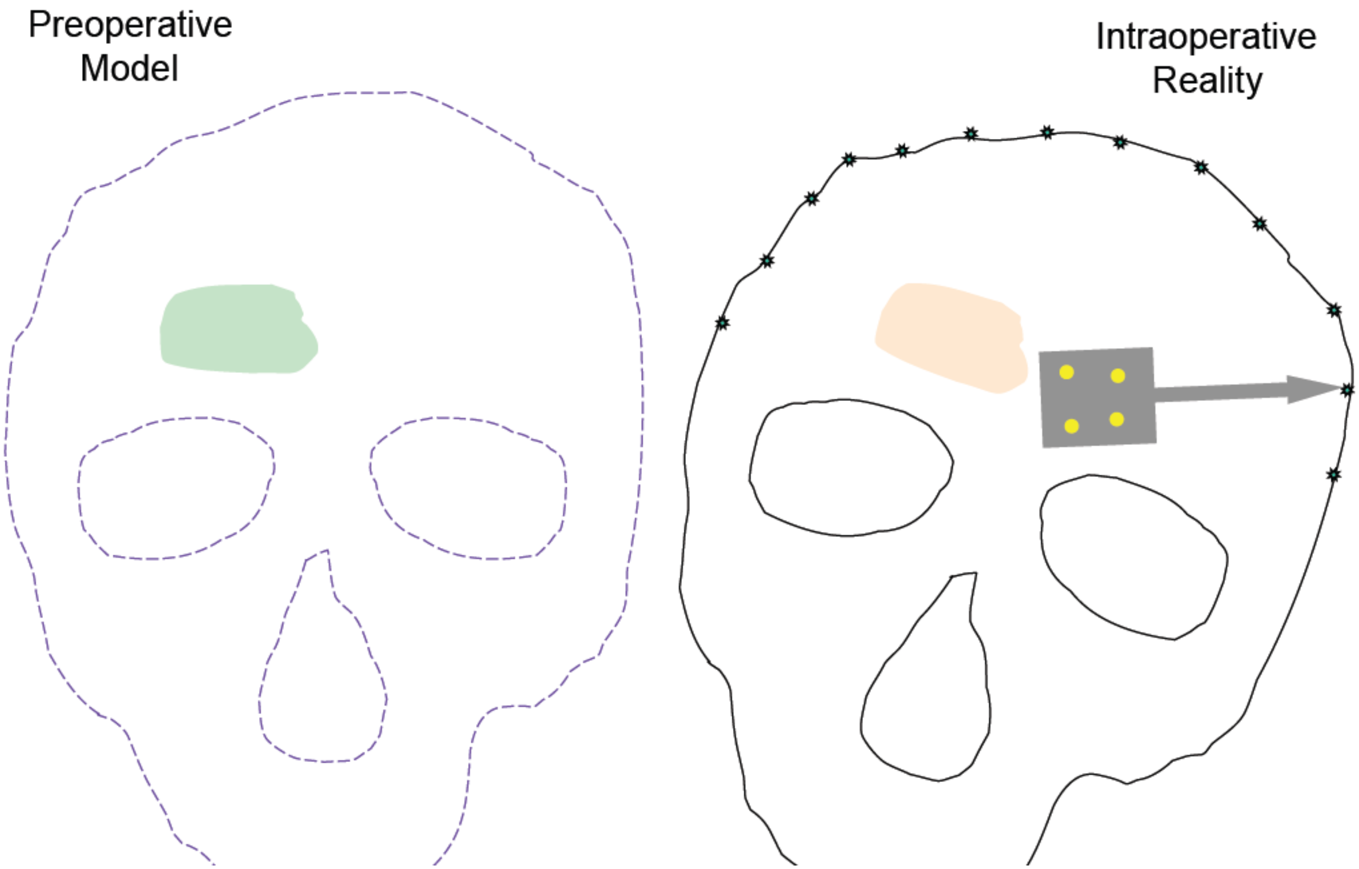


$$\min_{\mathbf{F}_{reg}} \sum_i w_i D(\mathbf{F}_{reg}\vec{\mathbf{a}}_i, \vec{\mathbf{b}}_i)$$

e.g.,

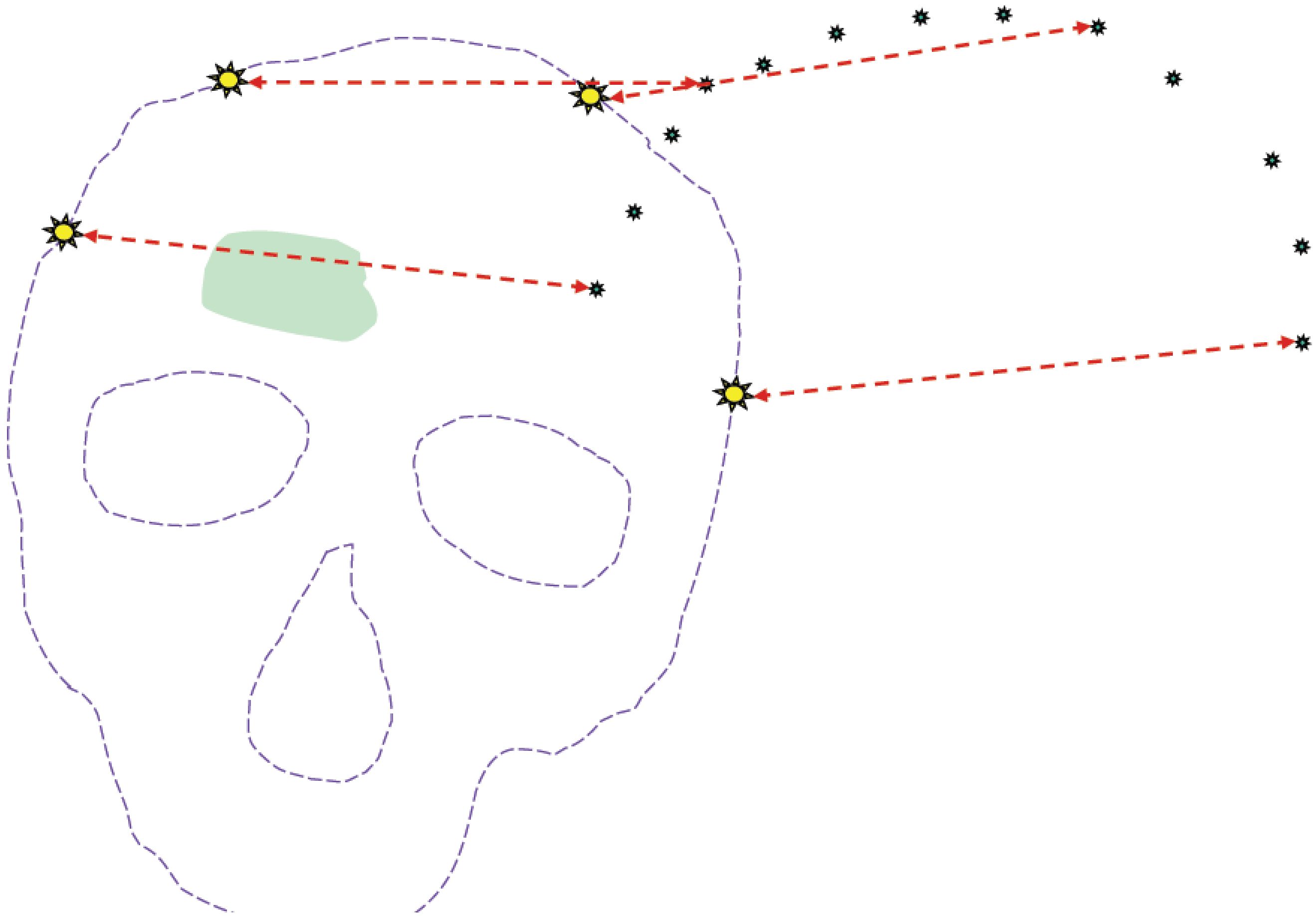
$$\min_{\mathbf{F}_{reg}} \sum_i w_i \left\| \mathbf{F}_{reg}\vec{\mathbf{a}}_i - \vec{\mathbf{b}}_i \right\|^2$$

The Surface Registration Problem



Corresponding Known Data

Try to Align Homologous Points



Approaches

Outline:

- Select large number of sample points
- Determine distance function $d_S(\mathbf{f}, \mathcal{F})$ for a point $\mathbf{f}$ to a surface feature $\mathcal{F}$.
- Use d_S to develop disparity function D.

Examples

- Head-in-hat algorithm [Levin et al., 1988; Pelizzari et al., 1989]
- Distance maps [e.g., Lavallee et al]
- Iterative closest point [Besl and McKay, 1992]

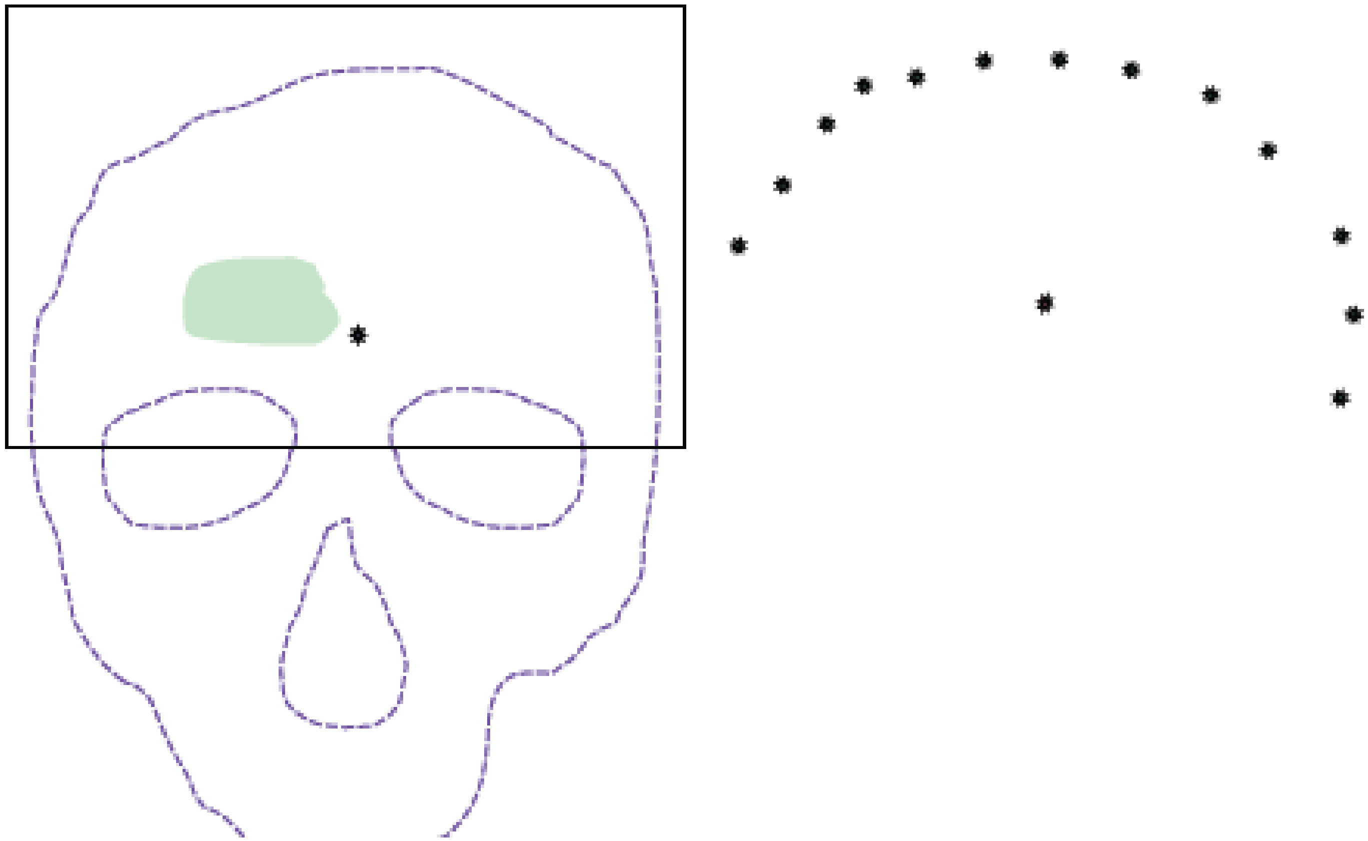
Iterative Closest Point (ICP)

- Besl and McKay, 1992
- Start with an initial guess, $\mathbf{T}_0$, for $\mathbf{T}$.
- At iteration k
  1. For each sampled point $\mathbf{f}_i \in \mathcal{F}_A$, find the point $\mathbf{v}_i \in \mathcal{F}_B$ that is closest to $\mathbf{T}_k \cdot \mathbf{f}_i$.
  2. Then compute $\mathbf{T}_{k+1}$ as the transformation that minimizes

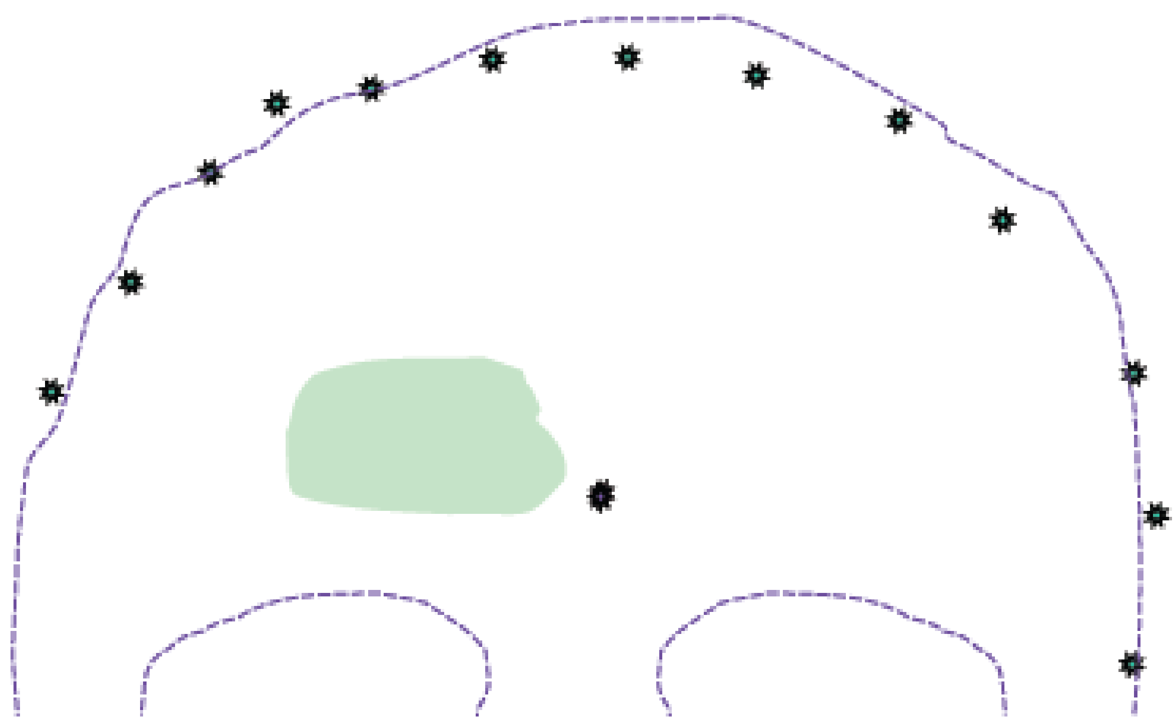
$$D_{k+1} = \sum_i \|\mathbf{v}_i - \mathbf{T}_{k+1} \cdot \mathbf{f}_i)\|^2$$

- Physical Analogy

Iterative Closest Point (ICP)

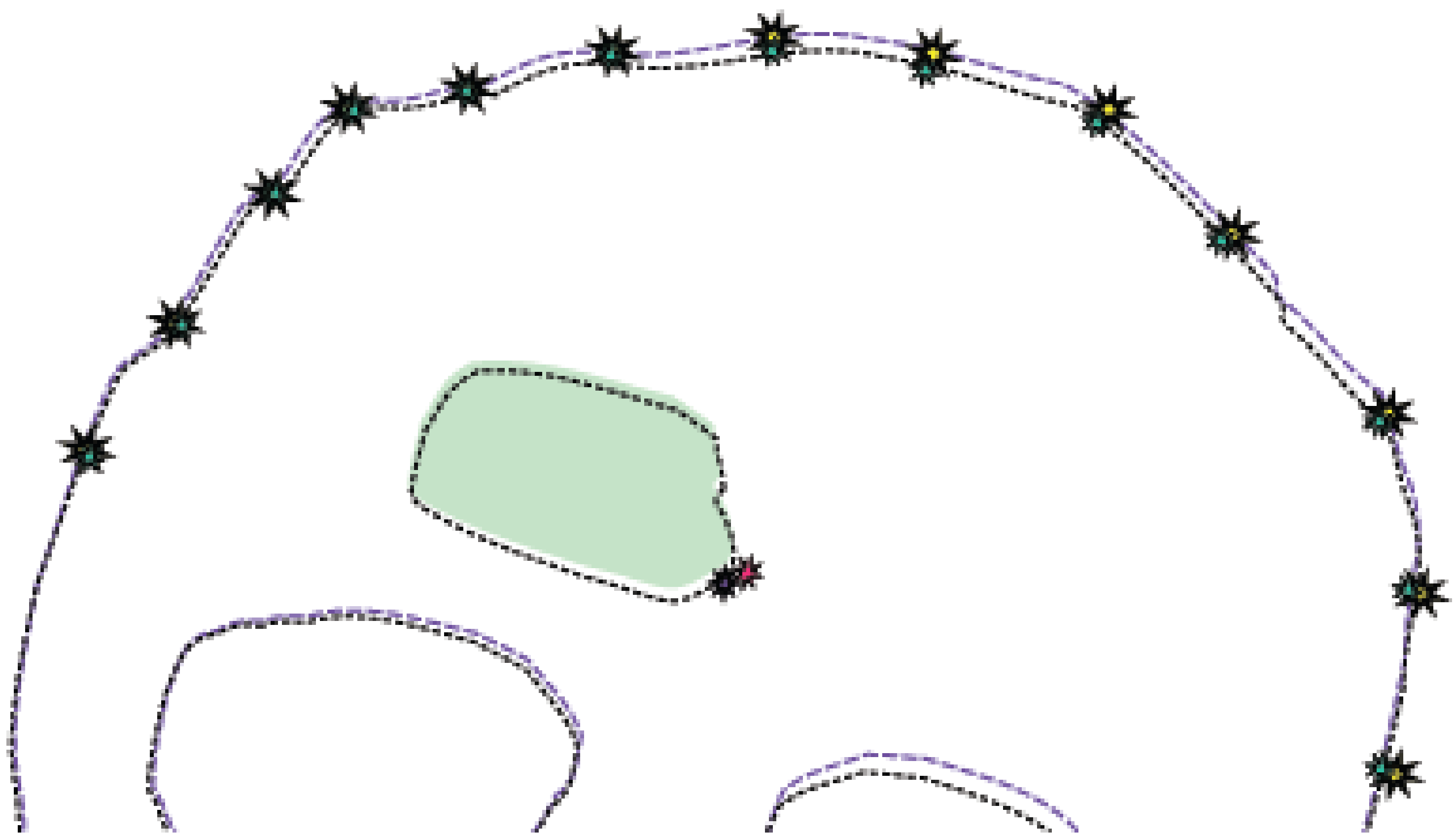


Iterative Closest Point (ICP)



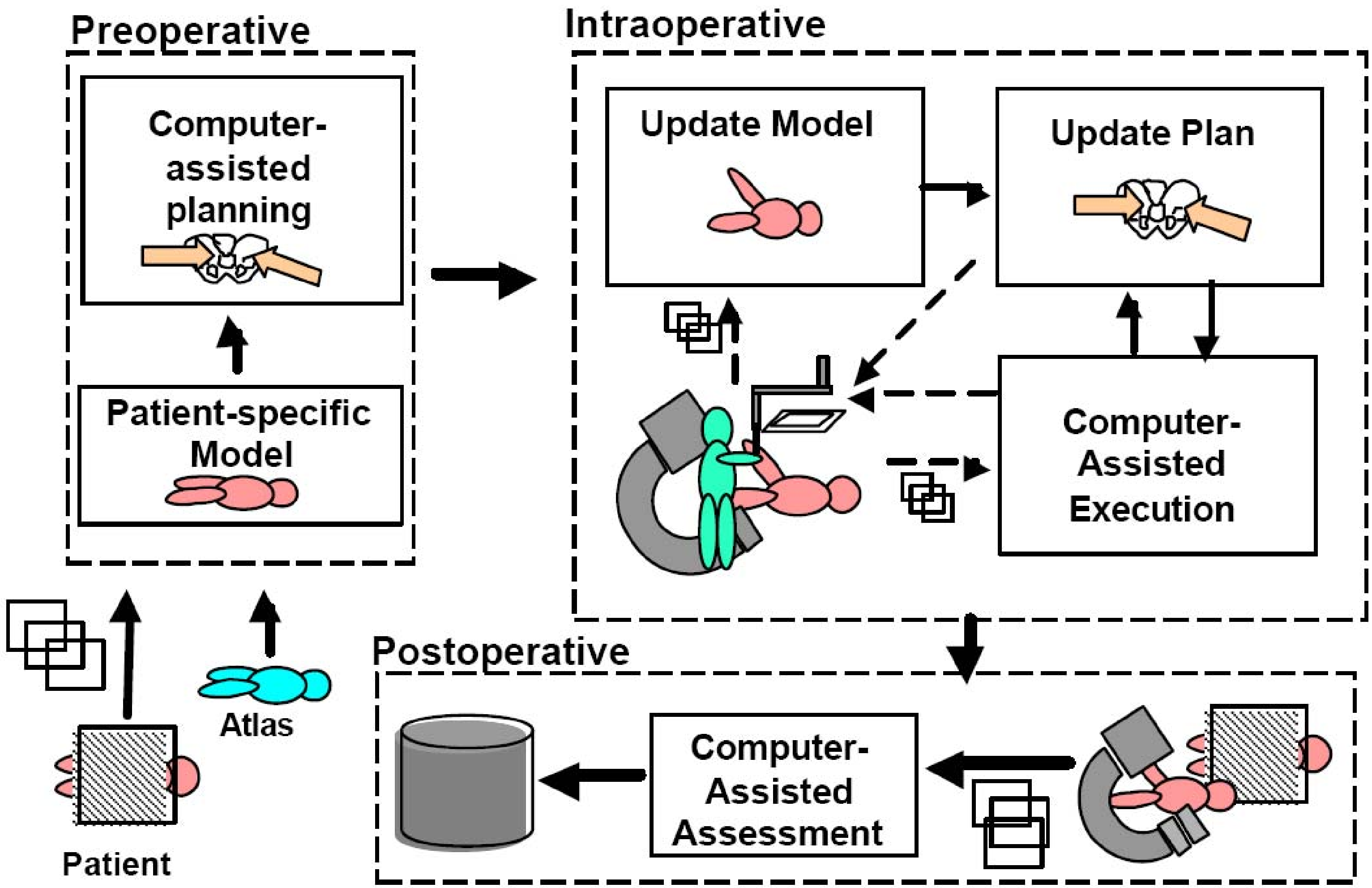
Iterative Closest Point (ICP)

Iterative Closest Point (ICP)



System Architecture

Image-Guided Robot-Assisted Surgery System Architecture



Credit: CISST ERC, Johns Hopkins University

https://www.youtube.com/watch?v=2fnv_3qn3Yc

Commercial Surgical Navigation Systems (SNS)

http://www.medtronic.com/us-en/healthcare-professionals/products/neurological/surgical-navigation-imaging/surgical-navigation-systems/systems-software-instruments.html

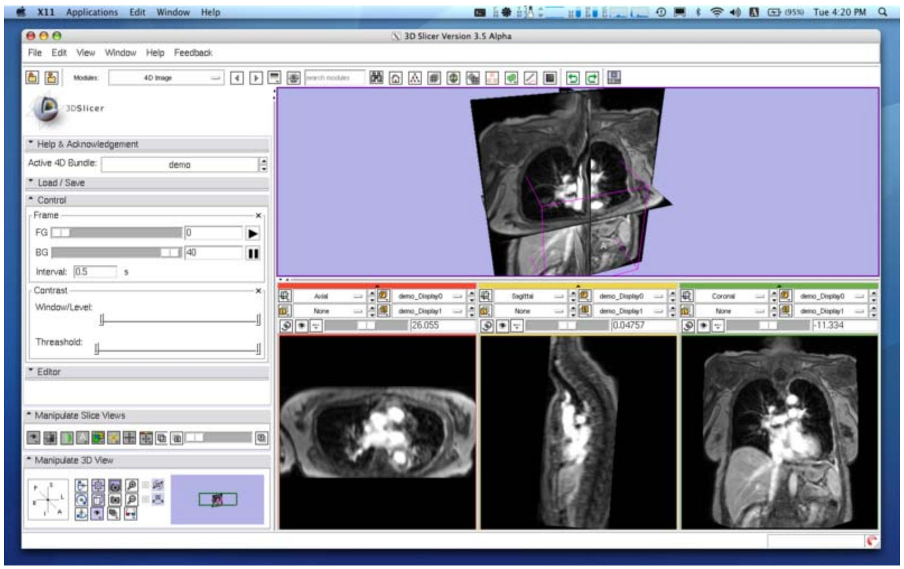
http://www.stryker.com/en-us/products/OREquipmentConnectivity/SurgicalNavigation/SurgicalNavigationSystems/index.htm

https://www.brainlab.com/en/surgery-products/overview-neurosurgery-products/cranial-navigation/

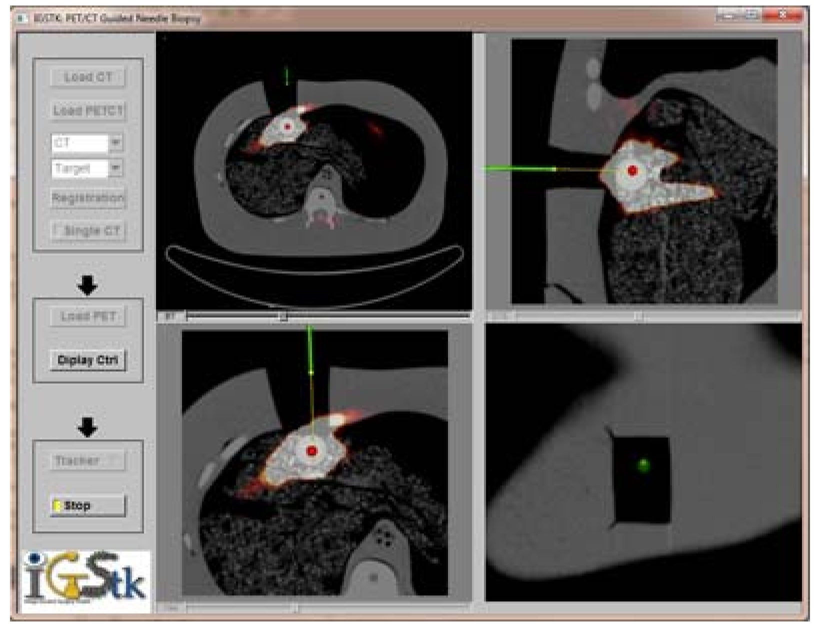
New Mazor X Robot

https://www.youtube.com/watch?v=v6mZG8W7Qck

Navigation Software Interfaces



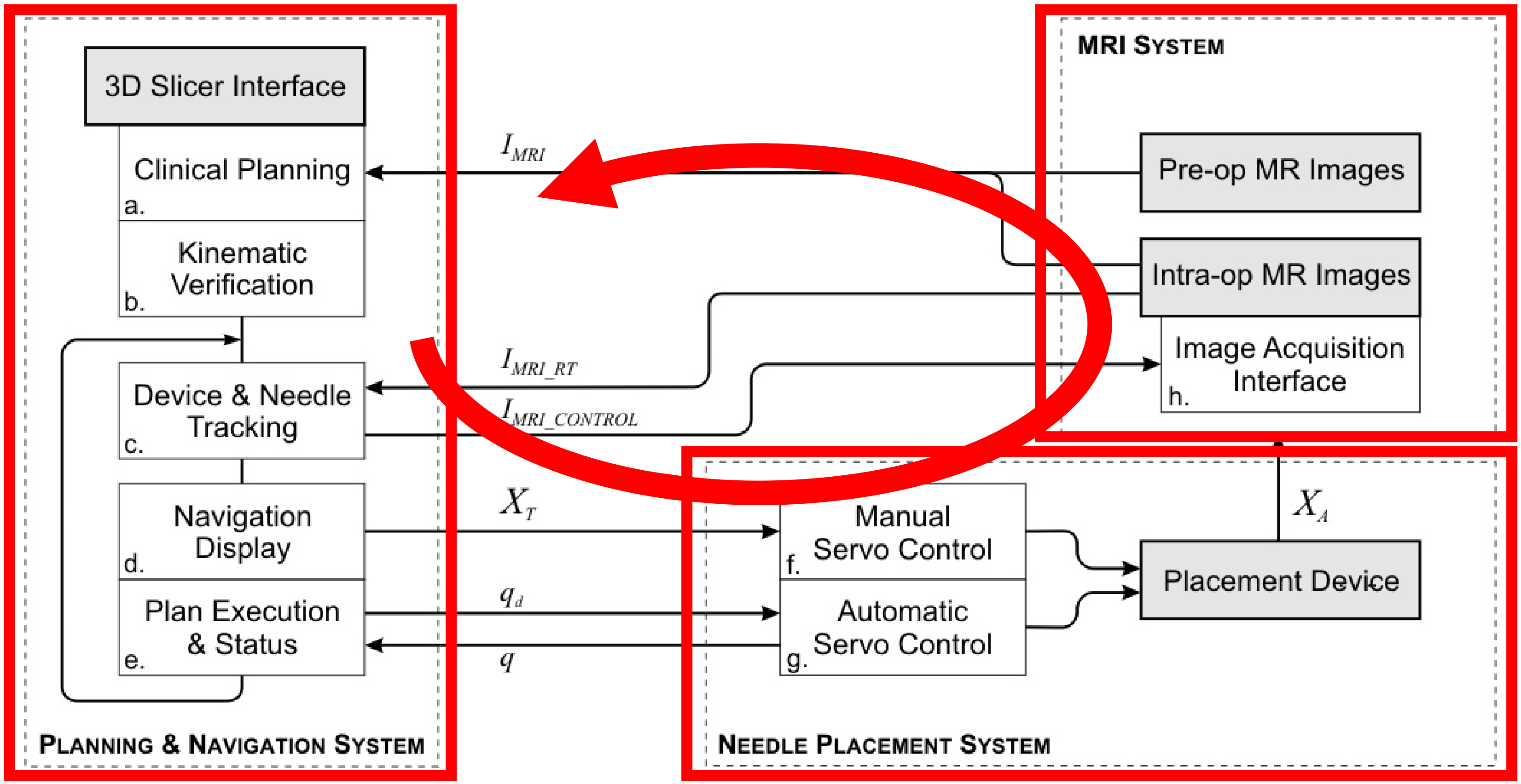
http://www.slicer.org/



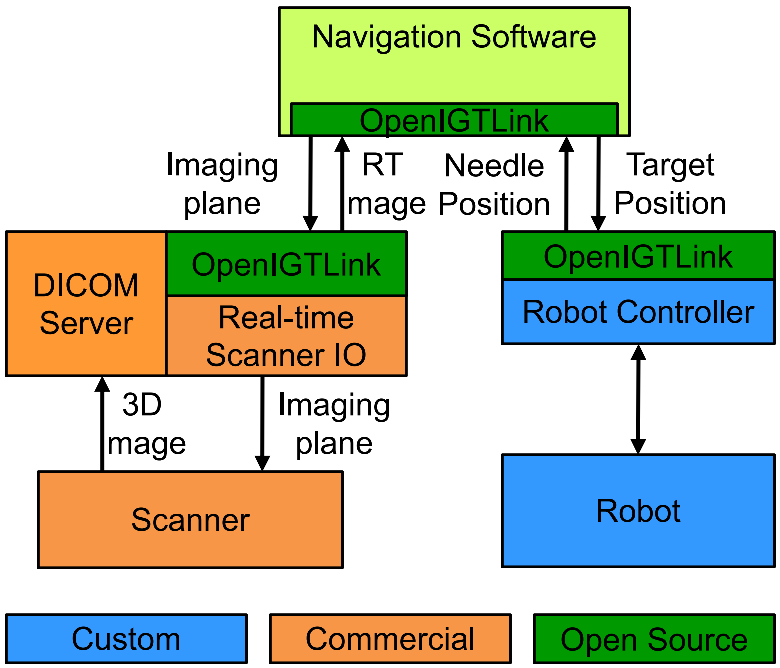
[*www.**igstk**.org/*](http://www.igstk.org/)

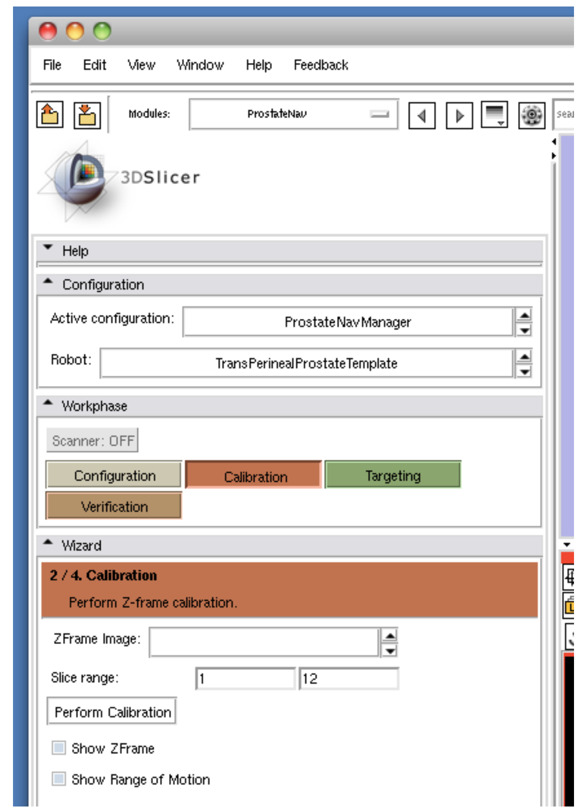
https://www.youtube.com/watch?v=PqtWUYmyuLg

Example Framework

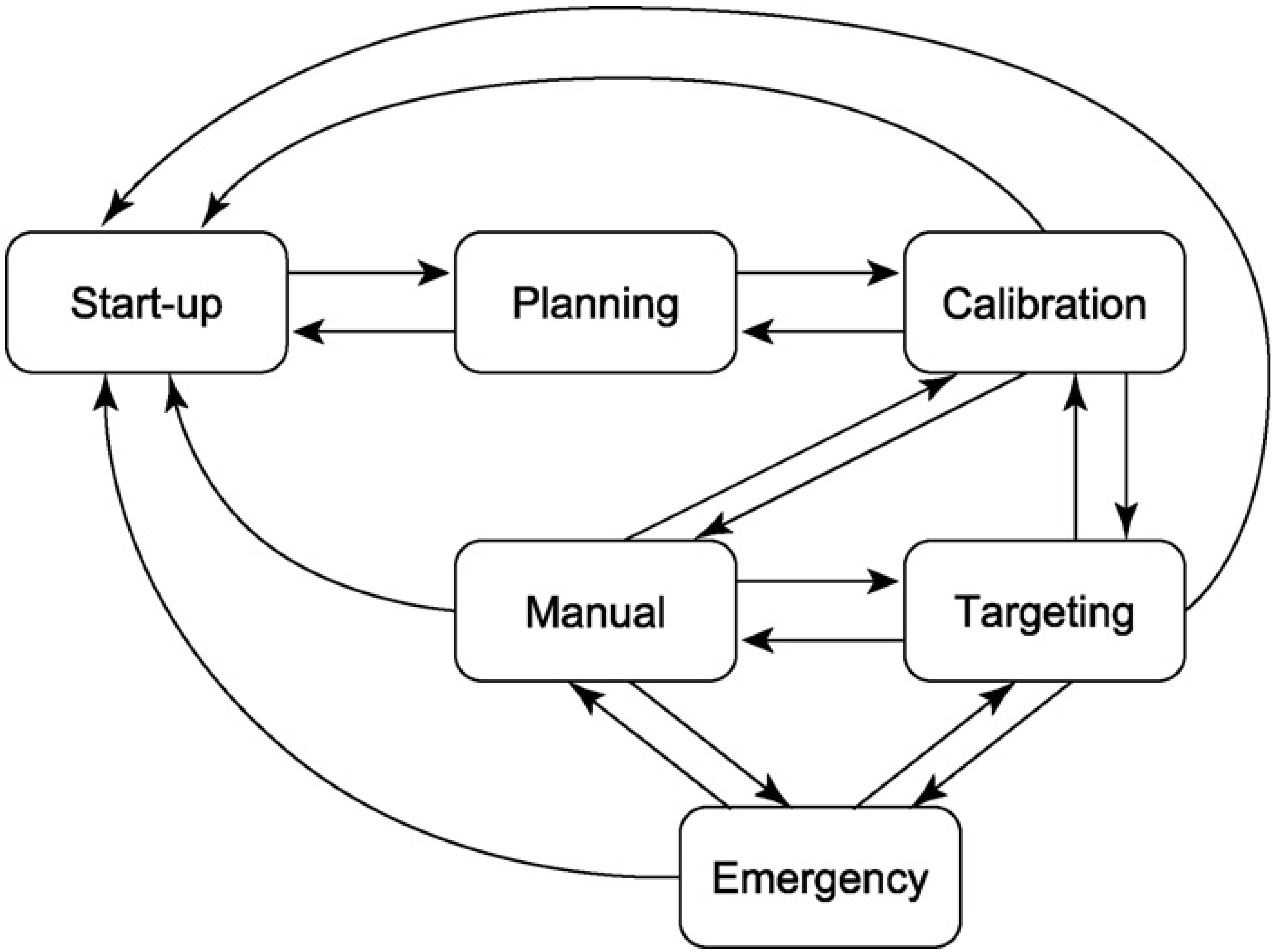


Sample IGT System Architecture





Example Procedural Workflow State Diagram



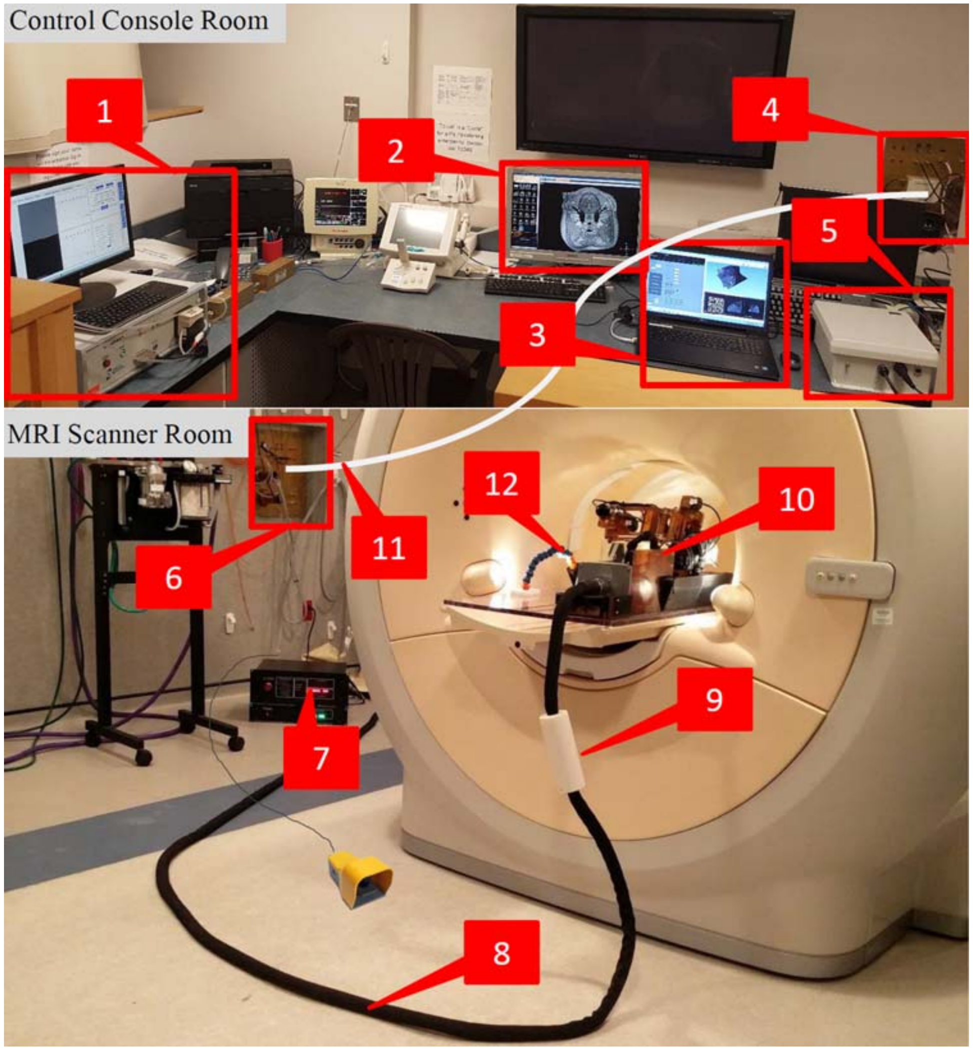
Sample MRI-Guided IGT System Architecture

Console Room

1. AMS Theravision ablation system
2. MRI control console
3. Slicer-based surgical navigation user interface, and robot control application
4. Patch panel
5. Network interface with fiber optics

MRI Room

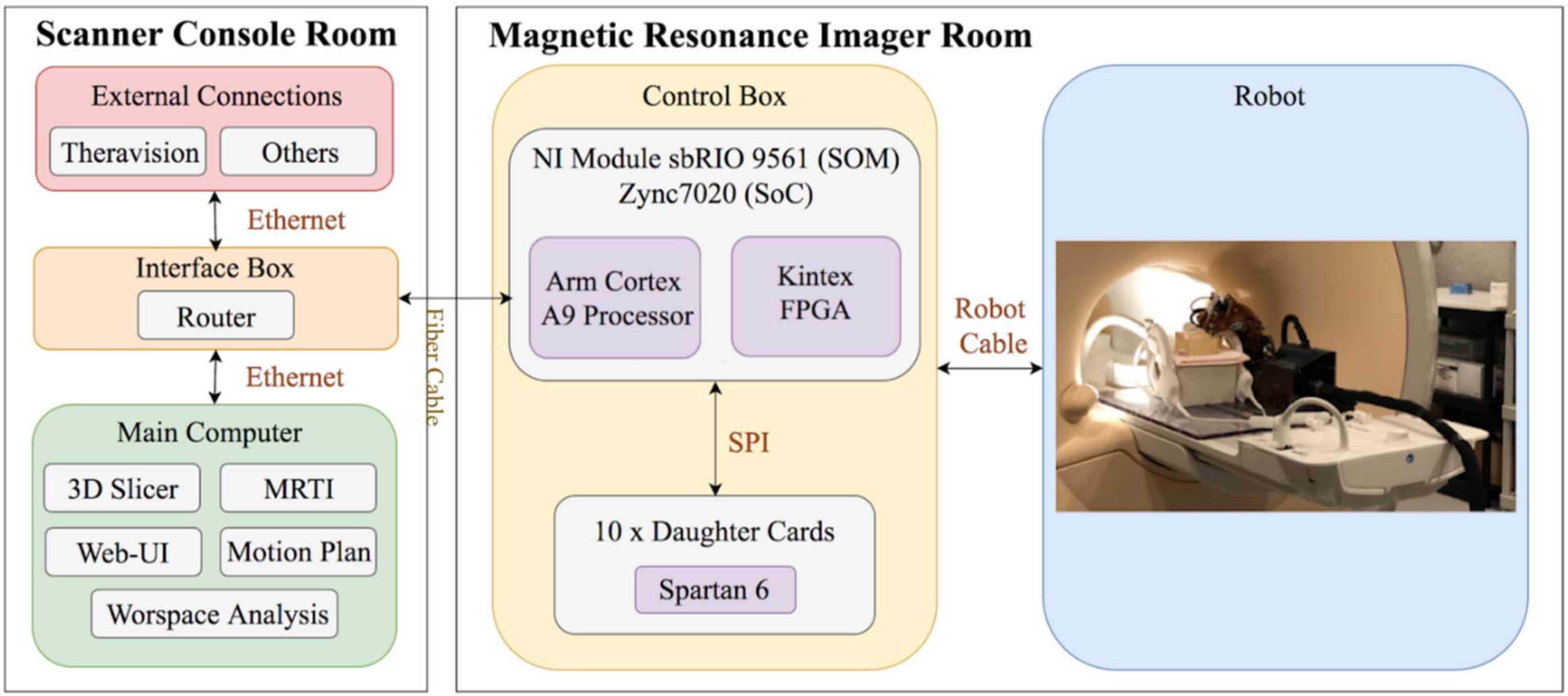
6. Patch panel through which scanner console and components inside the MR room are connected
7. Modular MRI robot controller
8. Custom cable carrying motor and encoder connections
9. Ballen for reducing EMI
10. Robotic manipulator inside bore
11. Fiber optic cable for communication between robot control application and the embedded robot controller
12. Custom MR imaging coil



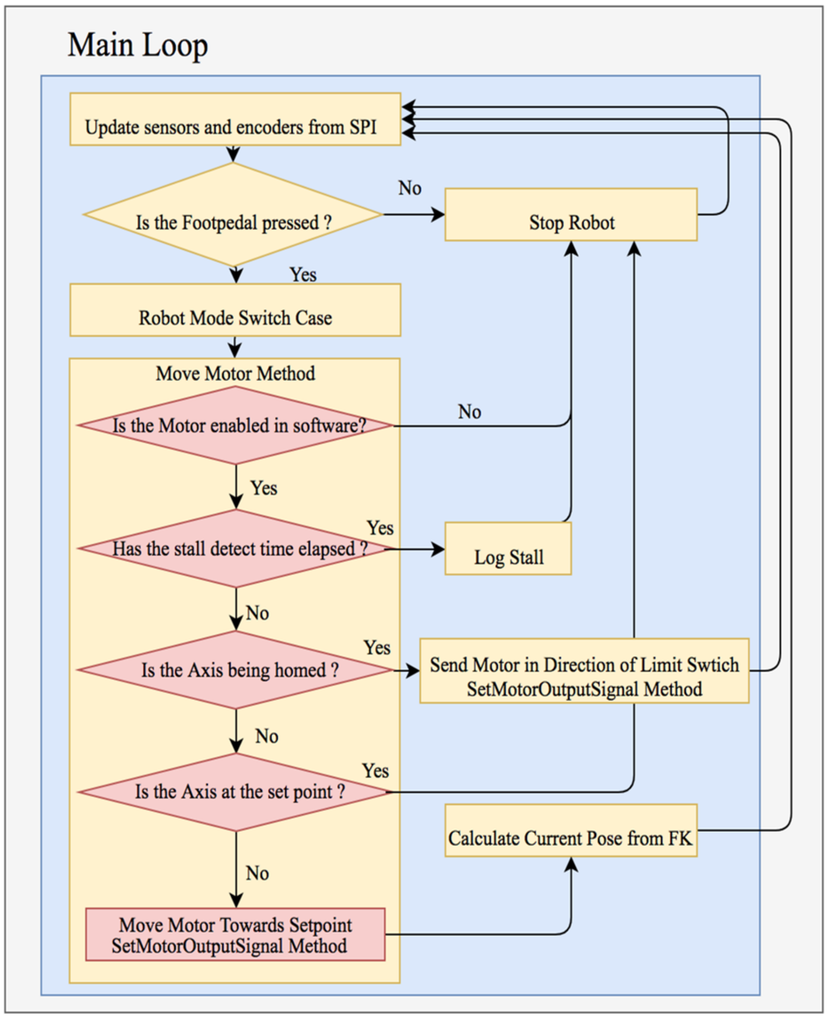
Modular MR-Compatible Robot Control System

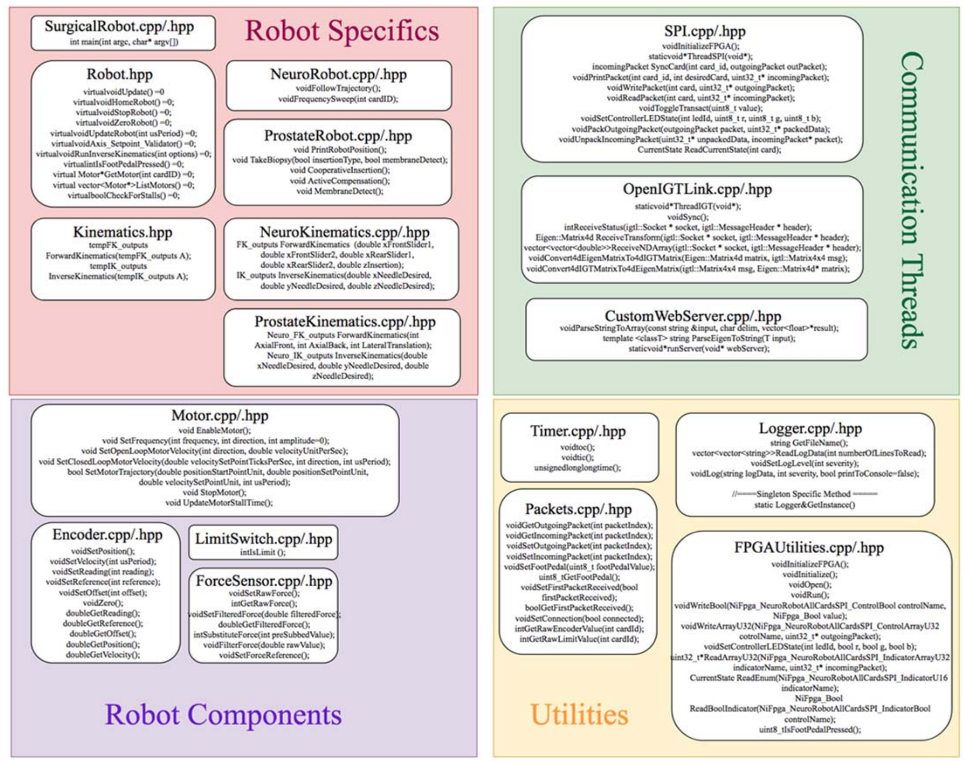
- Fully Shielded Custom Control Box
- Onboard low-noise AC-DC converters
- Fiberoptic communication
- Processing on Zynq-based sbRIO-9651 NI Module
- Supports up to 10 Custom Spartan 6-based Daughter Cards (modular axis configuration)
- 15 ft custom 151-conductor shielded cable connects control box to robot

Robot Controller Architecture

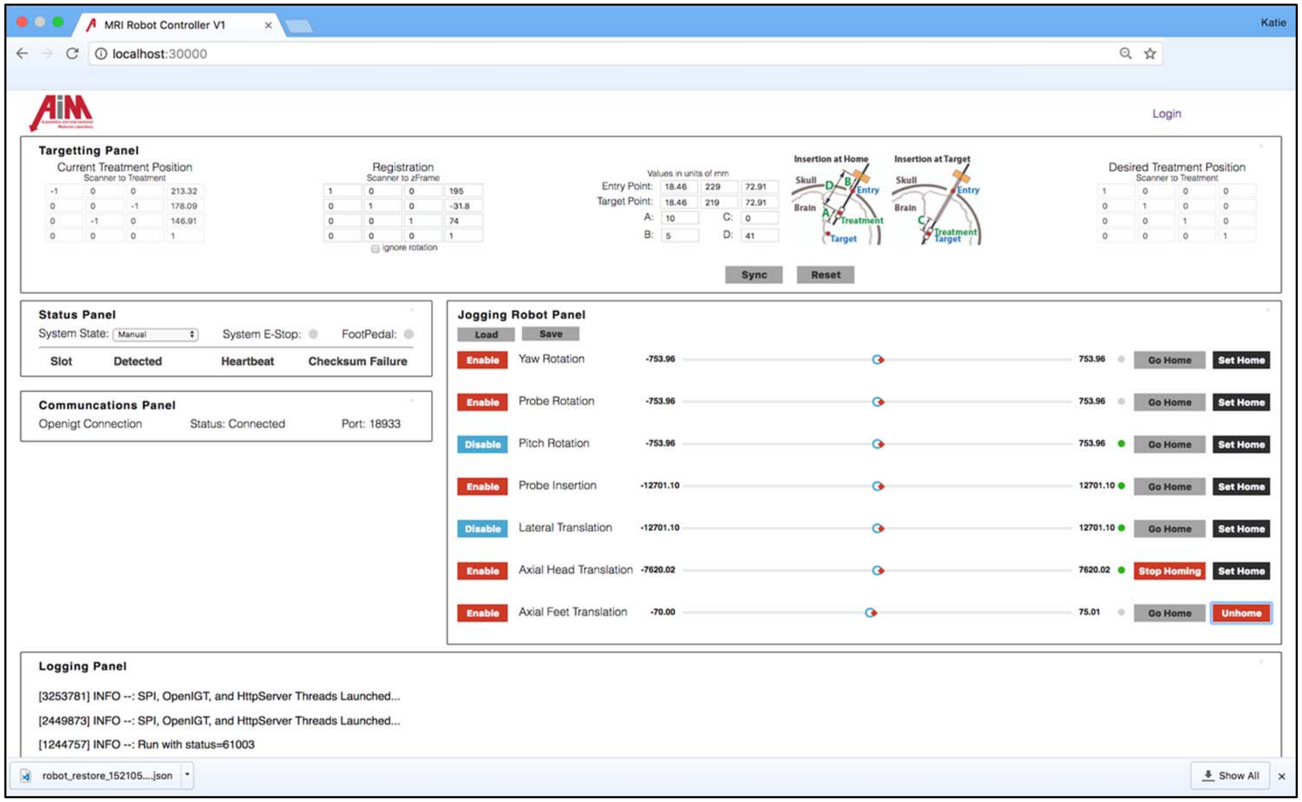


Low Level Software Workflow

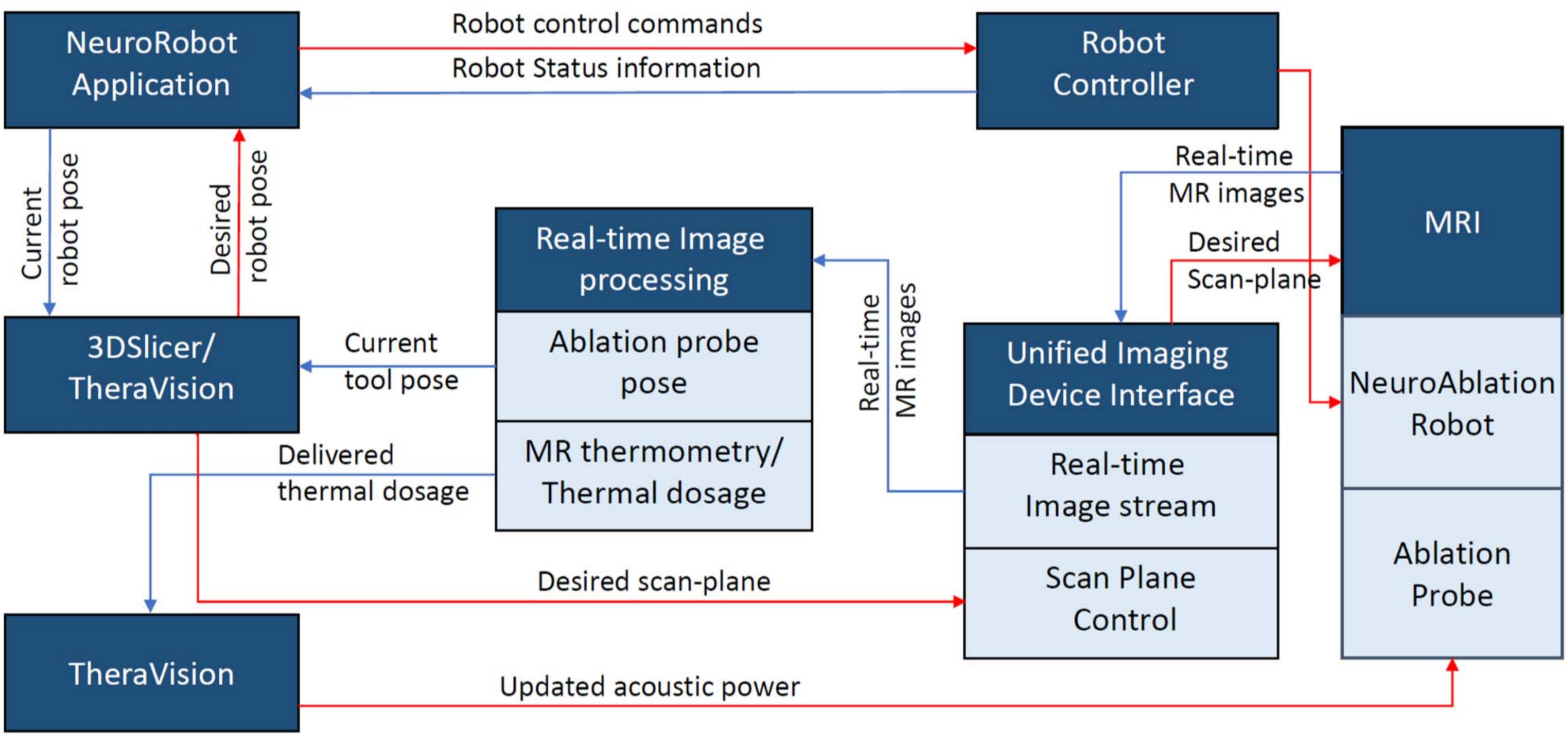




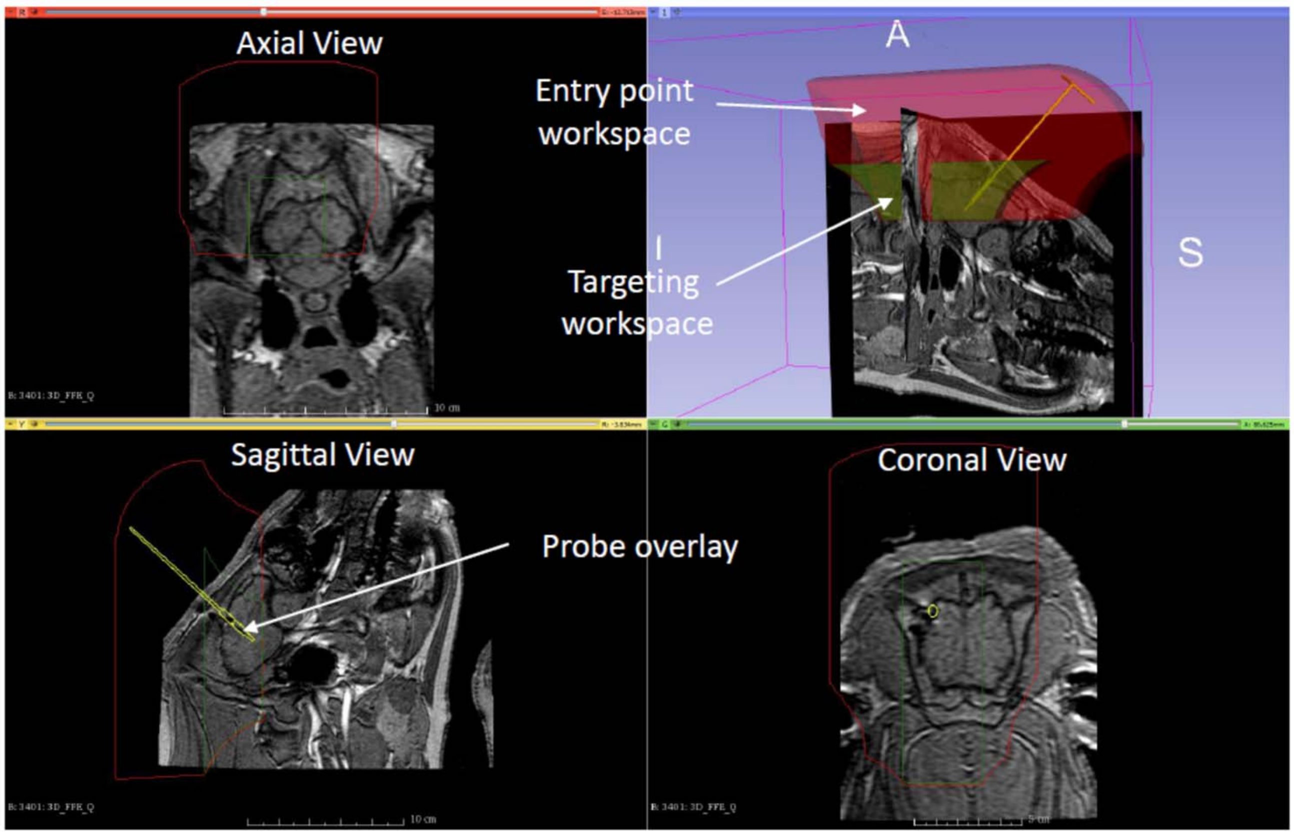
Web Based Robot Operator Panel



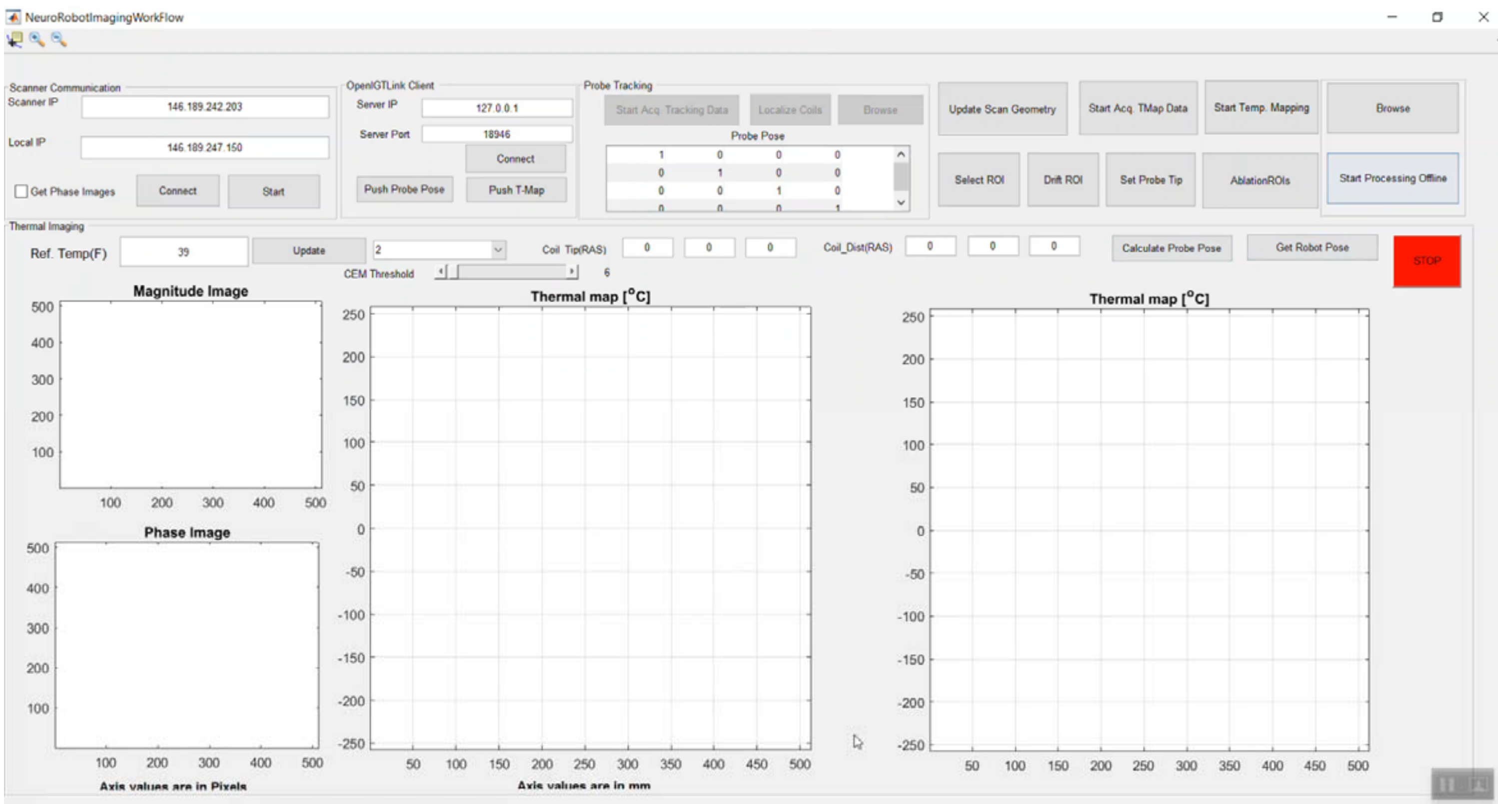
iMRgFUS System Integration



Slicer-based Surgical Planning



MRTI-Based Monitoring of Interstitial Therapeutic US



Alternate System Architecture

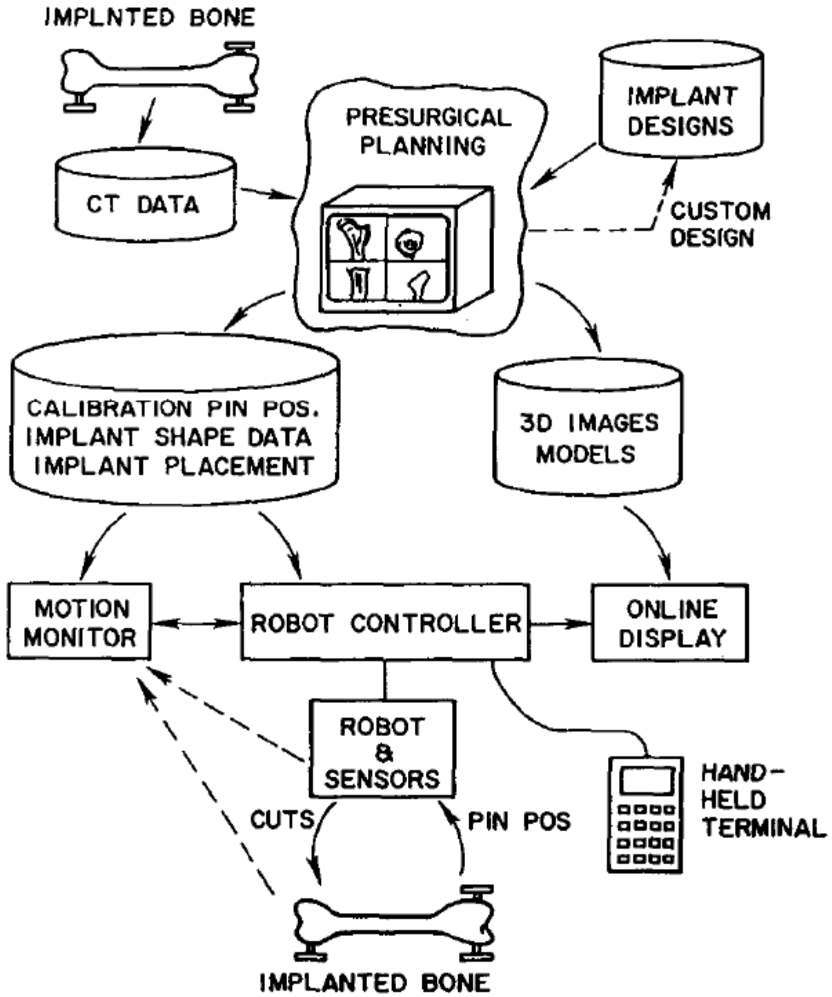


Fig. 3. Architecture of hip replacement surgery system. The system consists of a presurgical planning component and a surgical component. In the system used for the veterinary clinical trial, the motion monitoring and robot control functions are subsumed within the robot controller.

IEEE TRANSACTIONS ON ROBOTICS AND AUTOMATION, VOL. IO, NO. 3, JUNE 1994

Alternate System Architecture

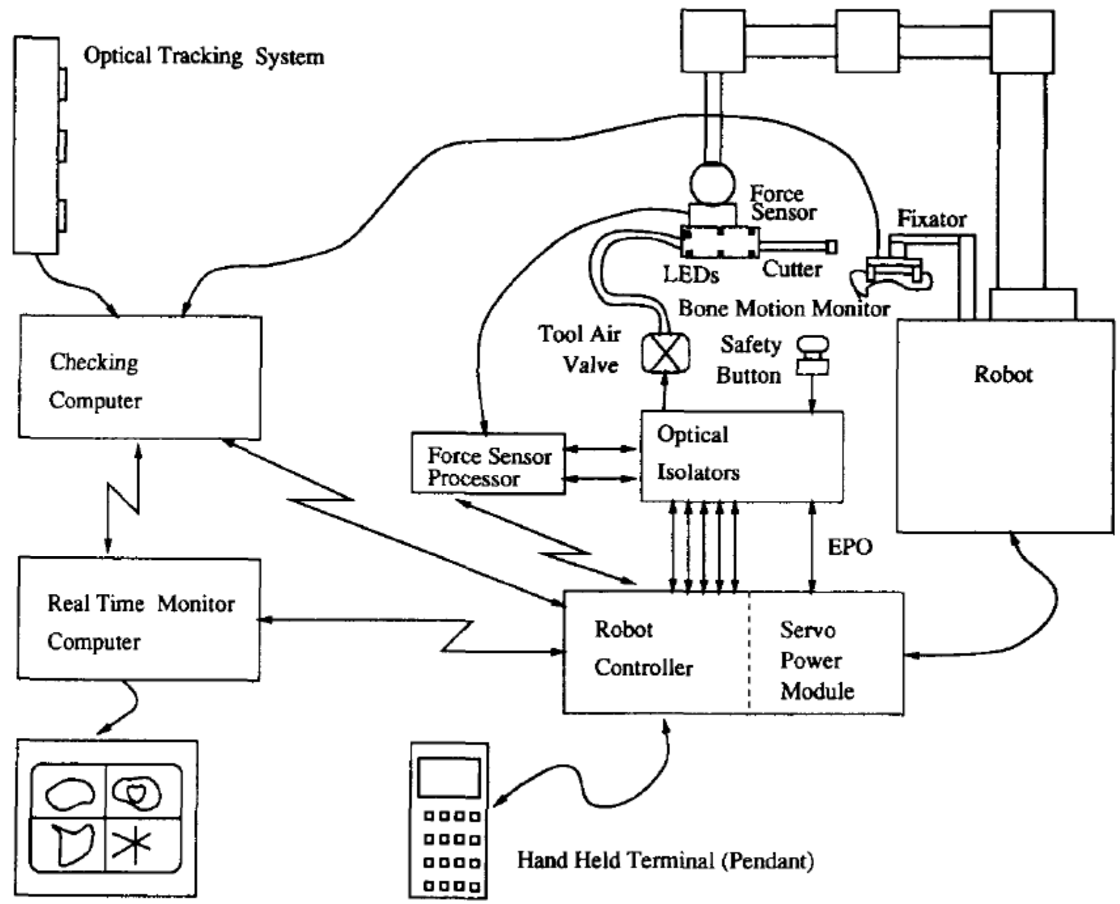
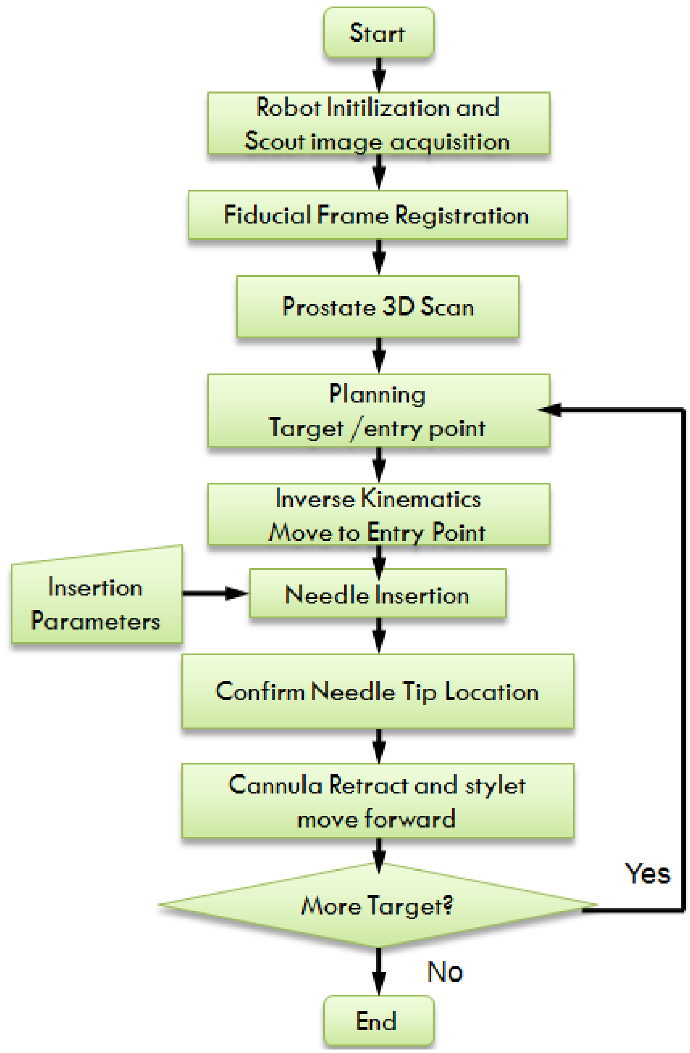


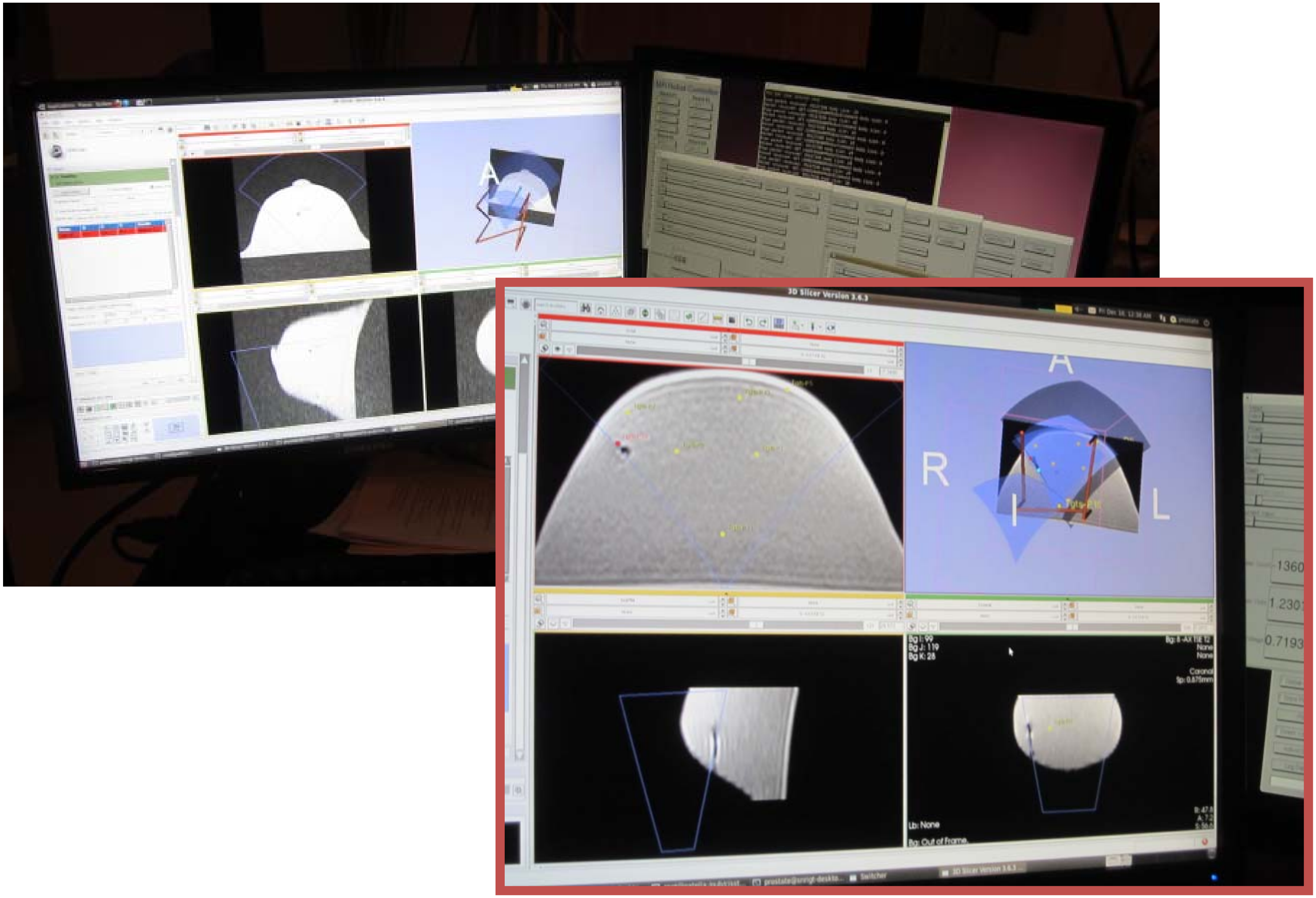
Fig. 4. Operating room system architecture. The operating room system consists of 1) a surgical robot with its associated controller, tooling, and safety interlocks, 2) a fixator to hold the bone securely to the robot, 3) a redundant motion-monitoring subsystem consisting of a checking computer, optical tracking system, and bone motion detector, and 4) a human-machine interface with an online display, display computer, and a hand-held terminal interfaced to the robot controller.

Example Typical IGT Workflow

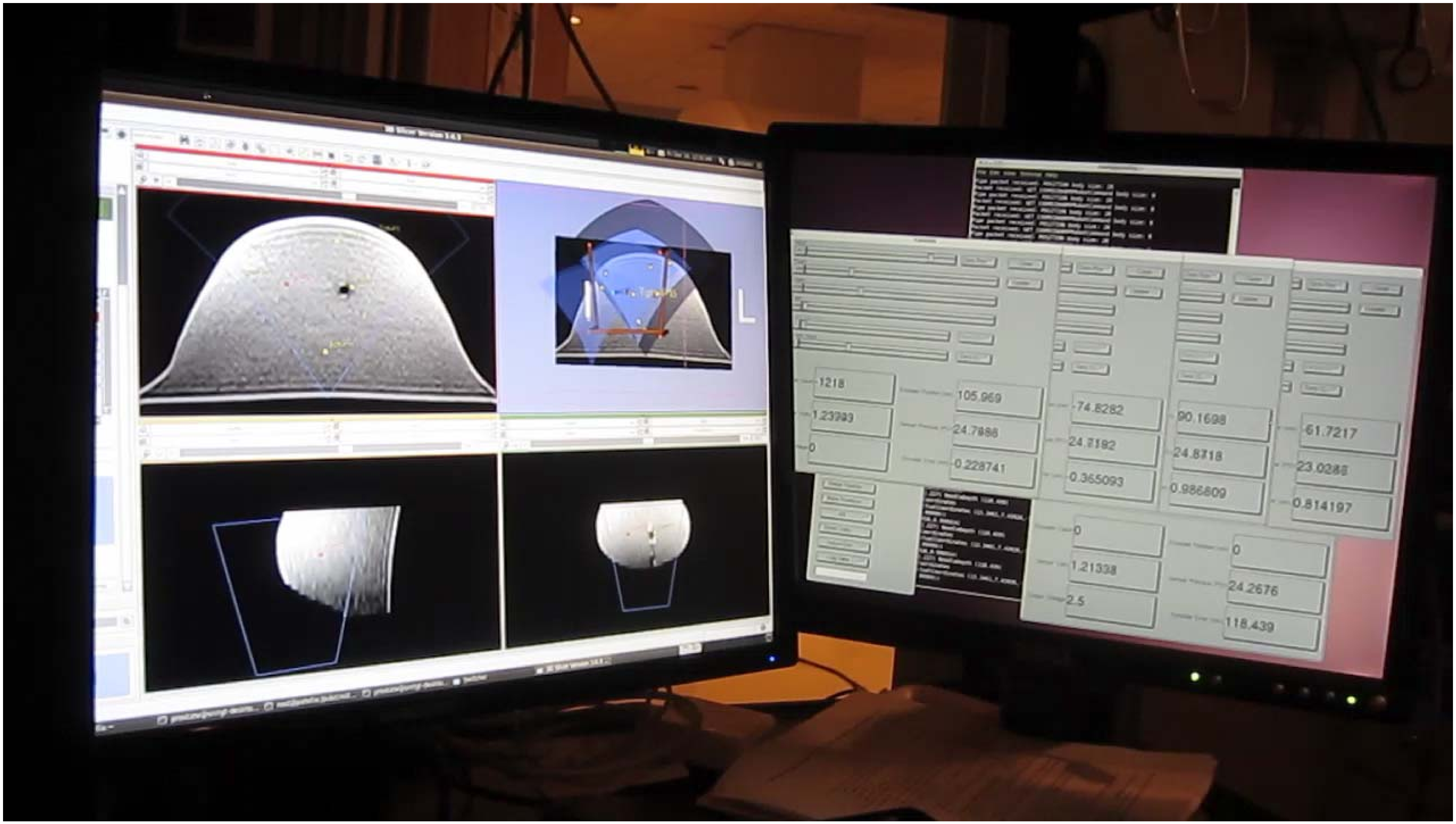
- Planning
- Registration
- Targeting
- Needle Control
- Verification



Sample Results



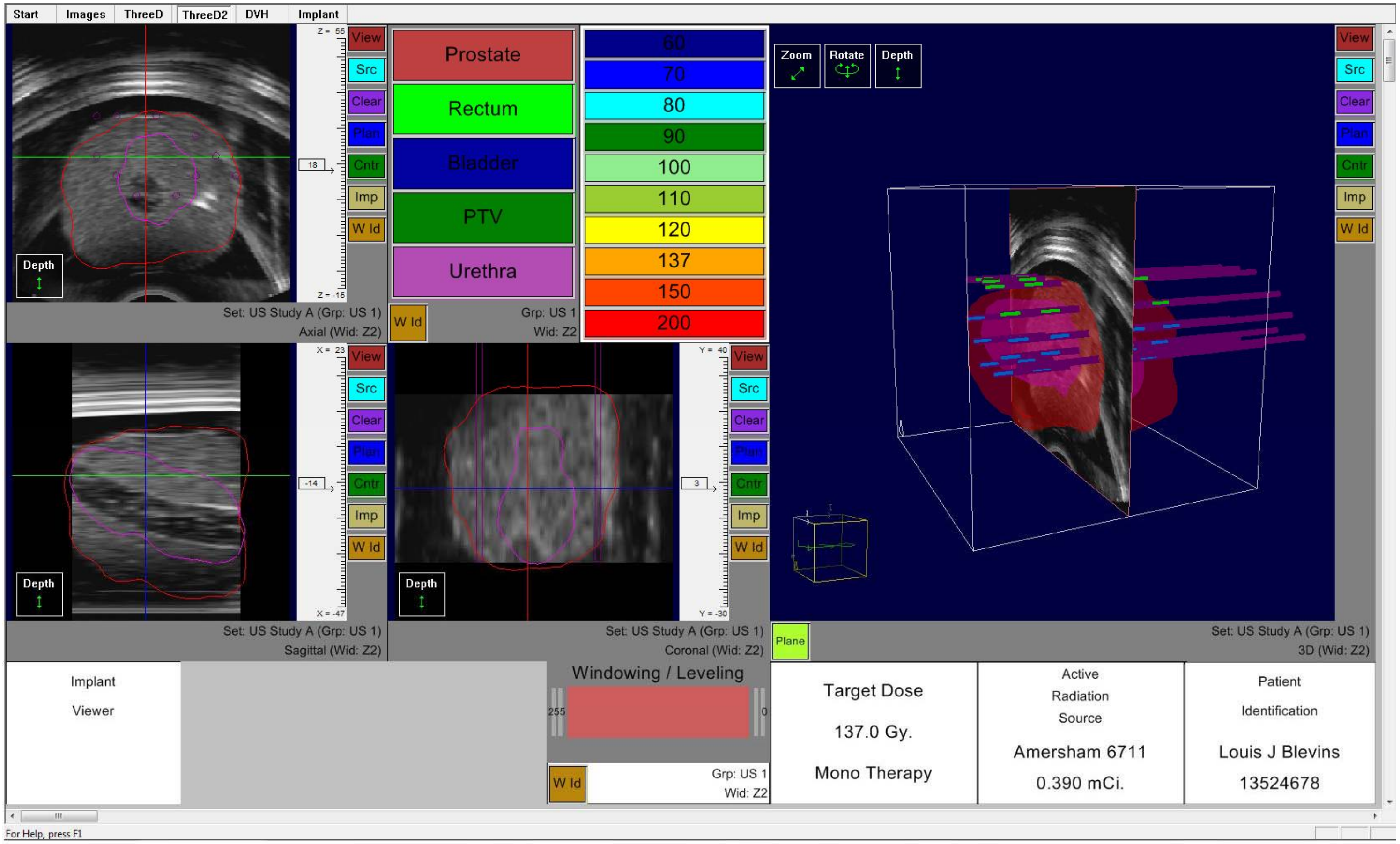
Sample Results



Clinical Results

Incorporating Preplanning

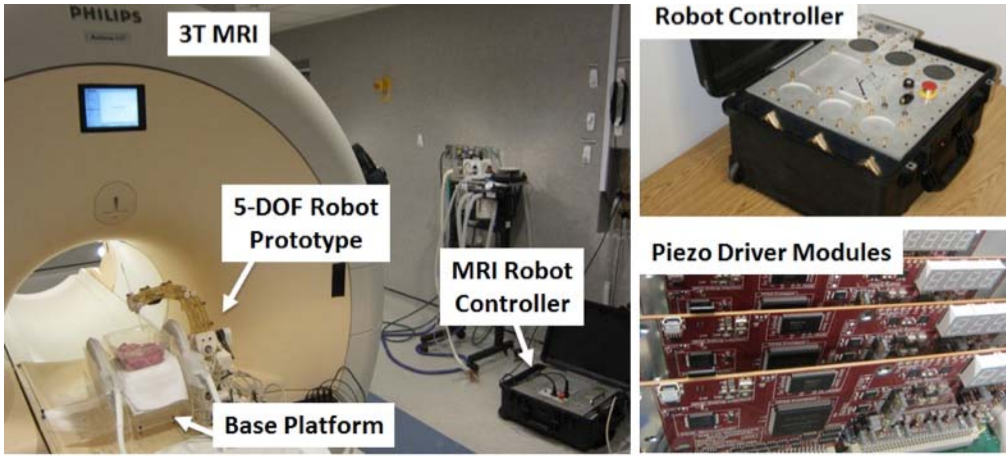
Acoustic MedSystems – RadVision Interface



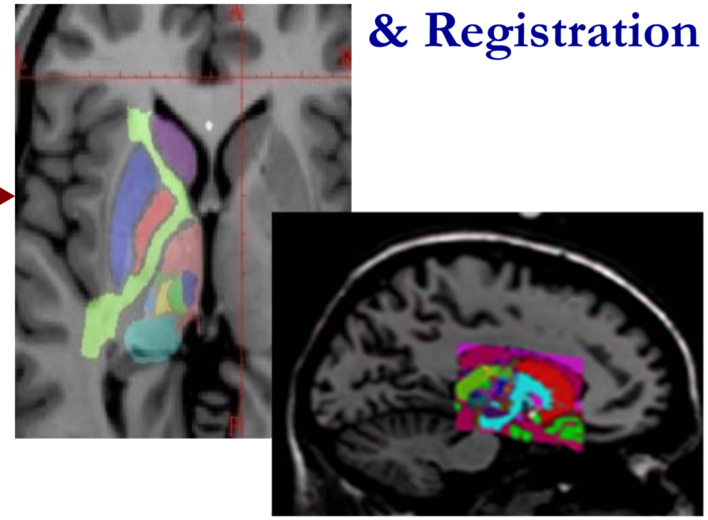
Planning, Guidance, Real-time Dosimetery & Robot Control

Incorporating Preplanning

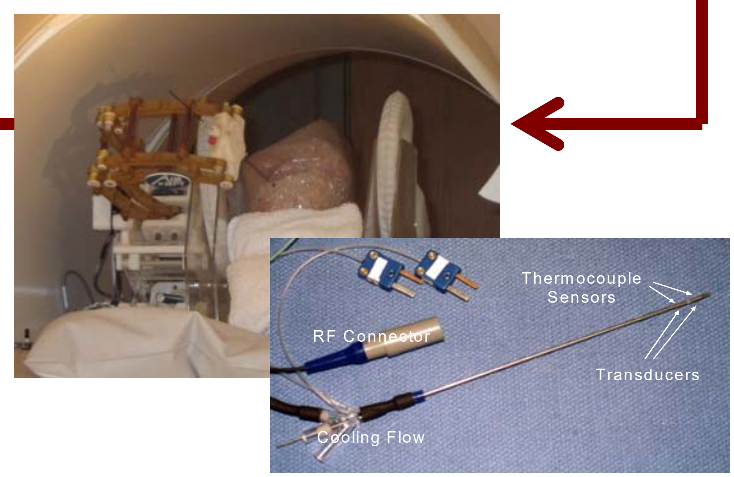
MRI-Compatible Neurosurgery System



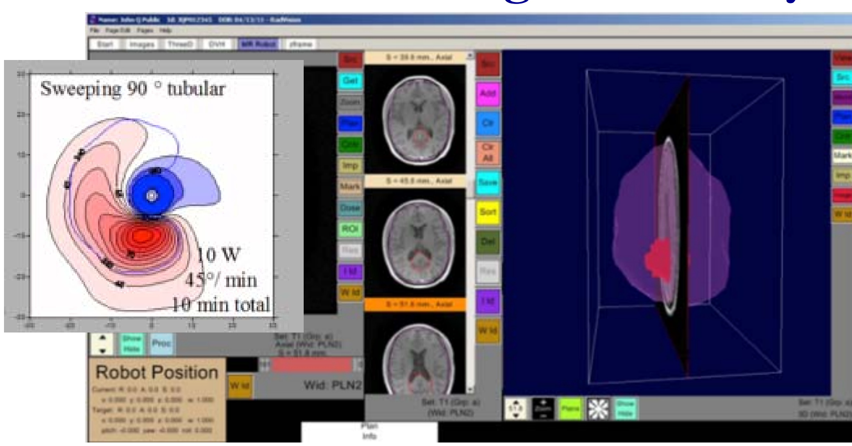
Atlas-Based Planning & Registration



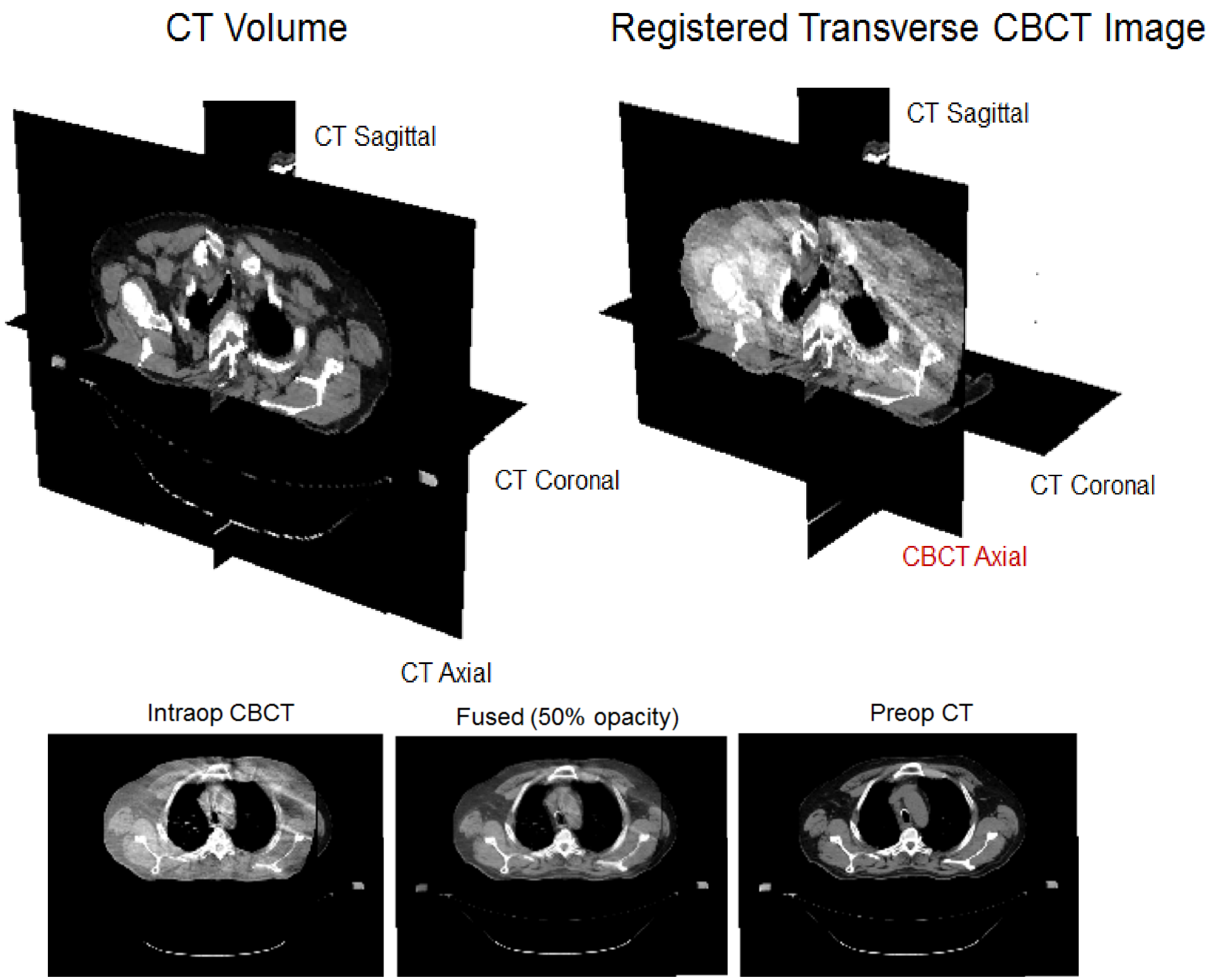
Therapy Delivery



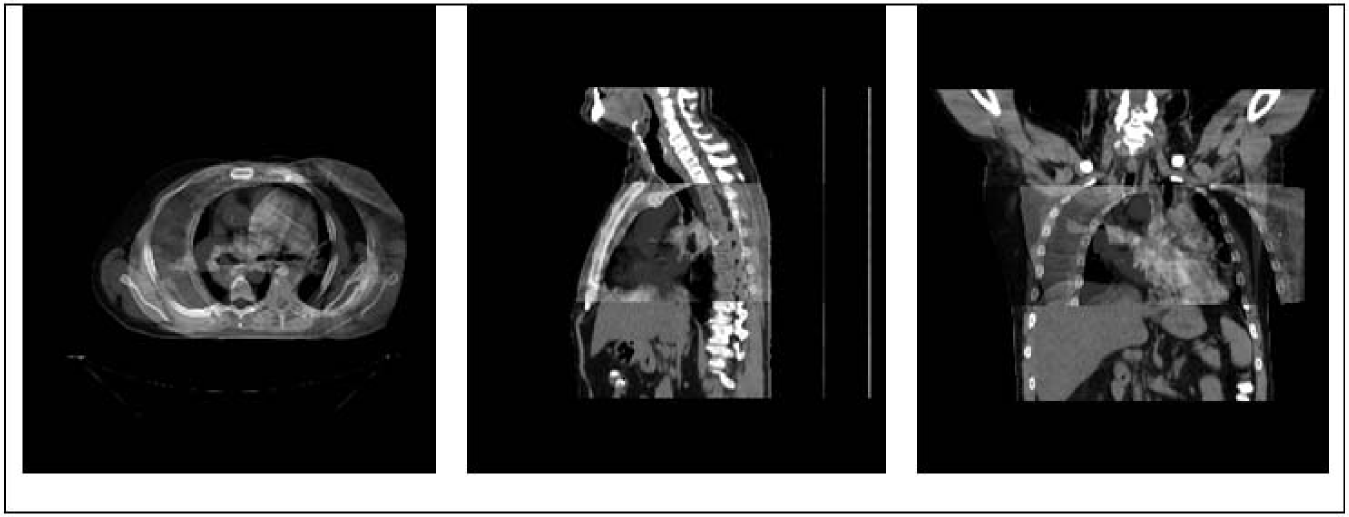
Real-time Monitoring & Dosimity



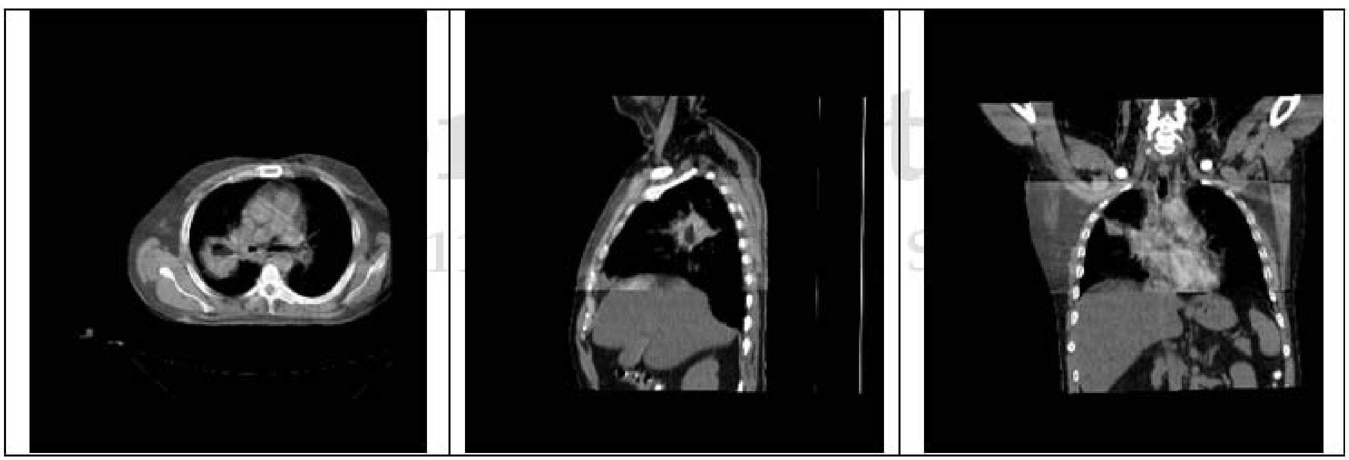
Incorporating Preplanning



Incorporating Preplanning – Registration & Fusion

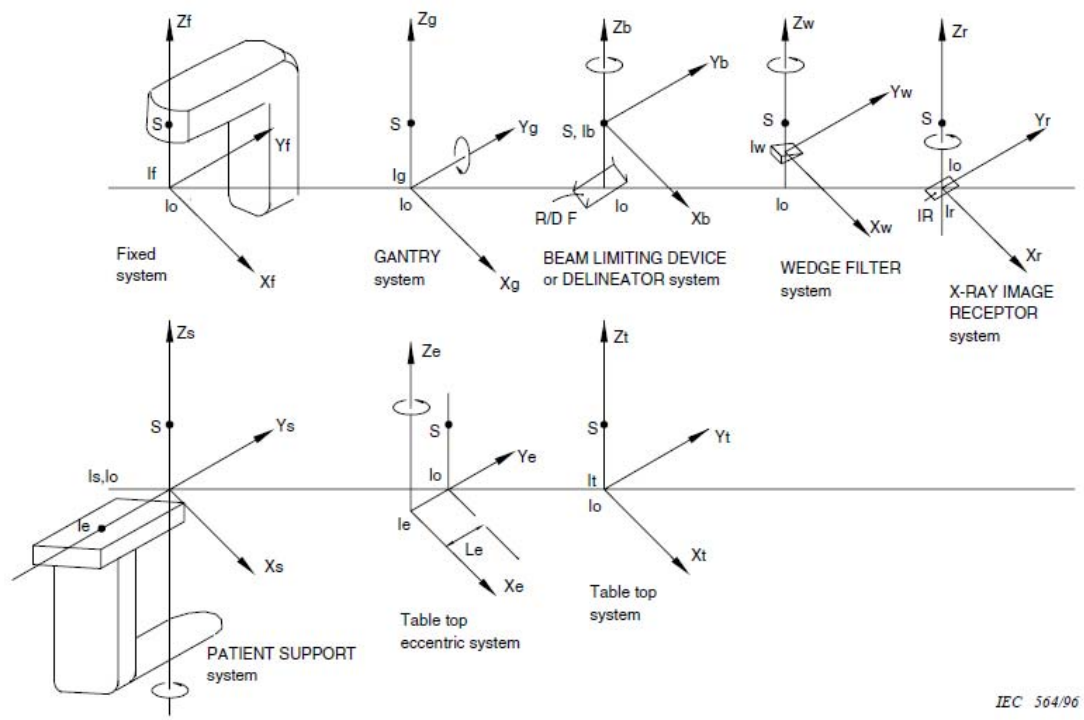


1 Before Rigid Registration with MI



2 After Rigid Registration with MI

Image-Guided Radiation Therapy - IGRT

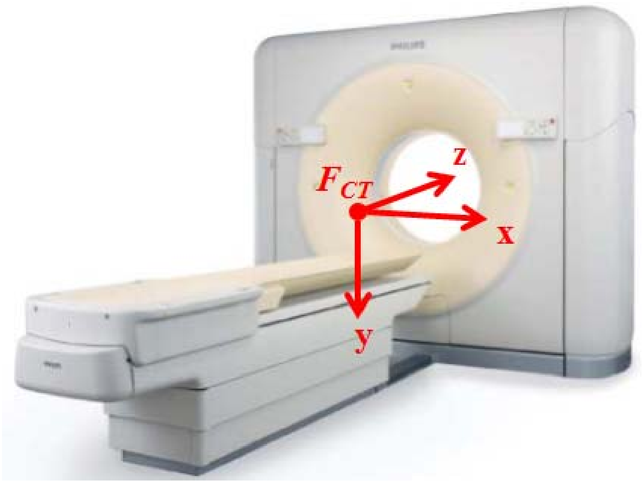


S = RADIATION SOURCE

Io = ISOCENTRE

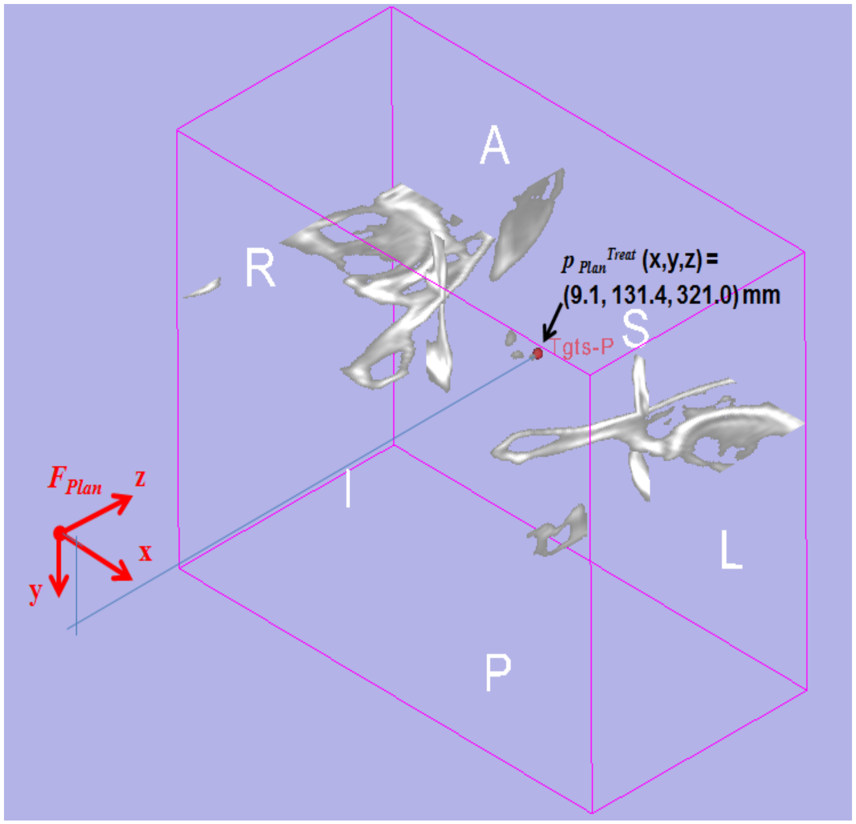
R/D F = RADIATION FIELD or DELINEATED RADIATION FIELD

IR = X-RAY IMAGE RECEPTOR



Coordinate frame of the CT planning images, ***FCT***

Image-Guided Radiation Therapy – IGRT Pre-procedure Planning



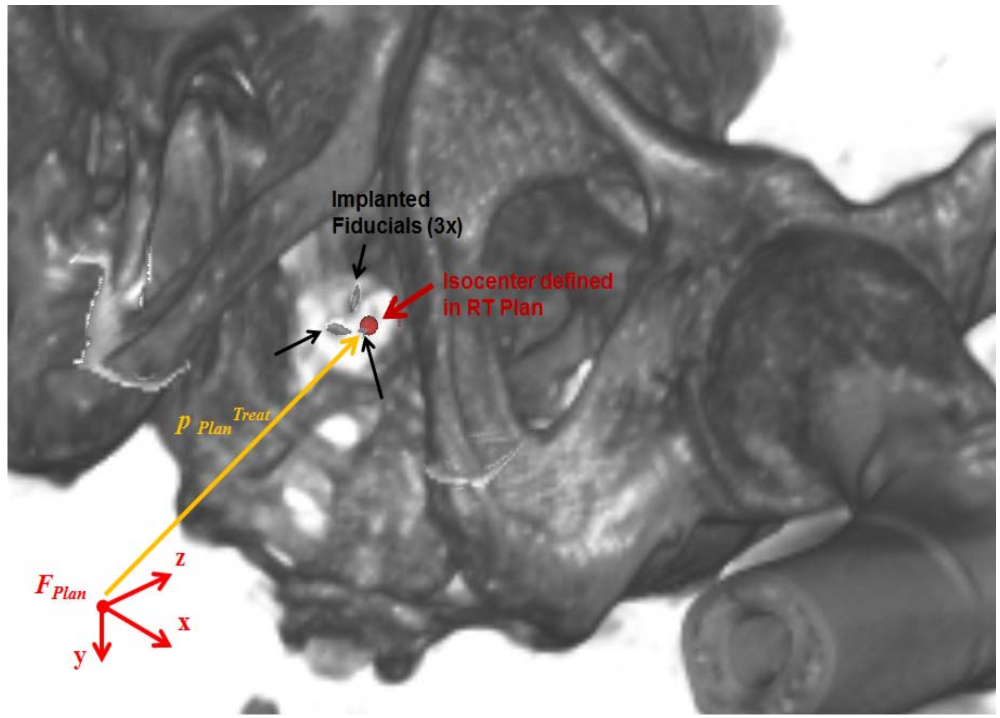


Image-Guided Radiation Therapy – IGRT
Pre-procedure Planning

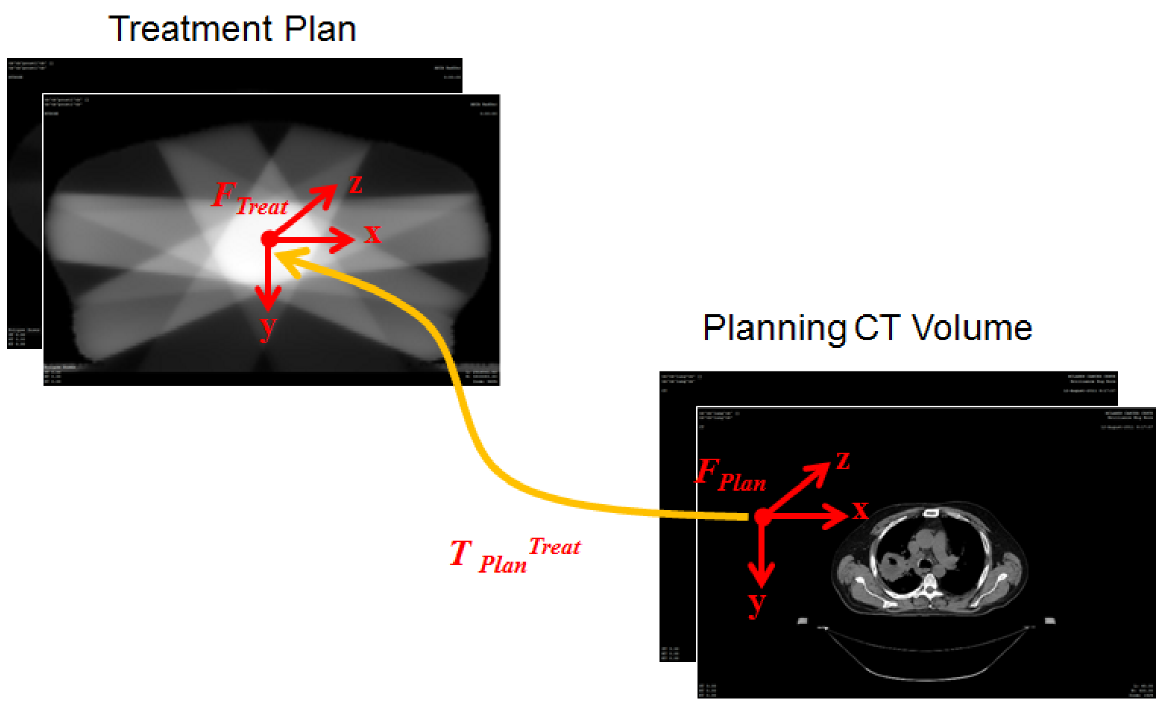
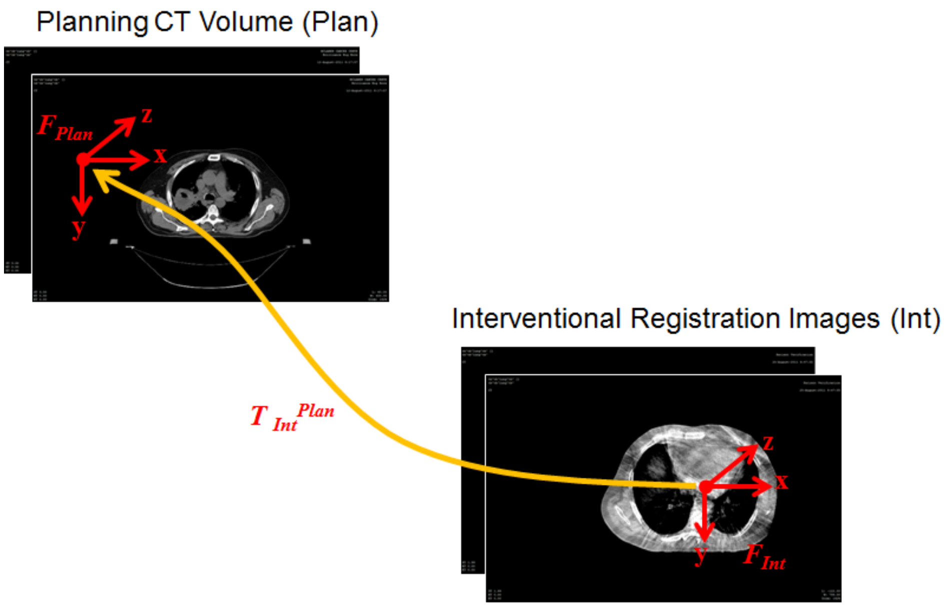


Image-Guided Radiation Therapy – IGRT
Interventional Imaging & Registration



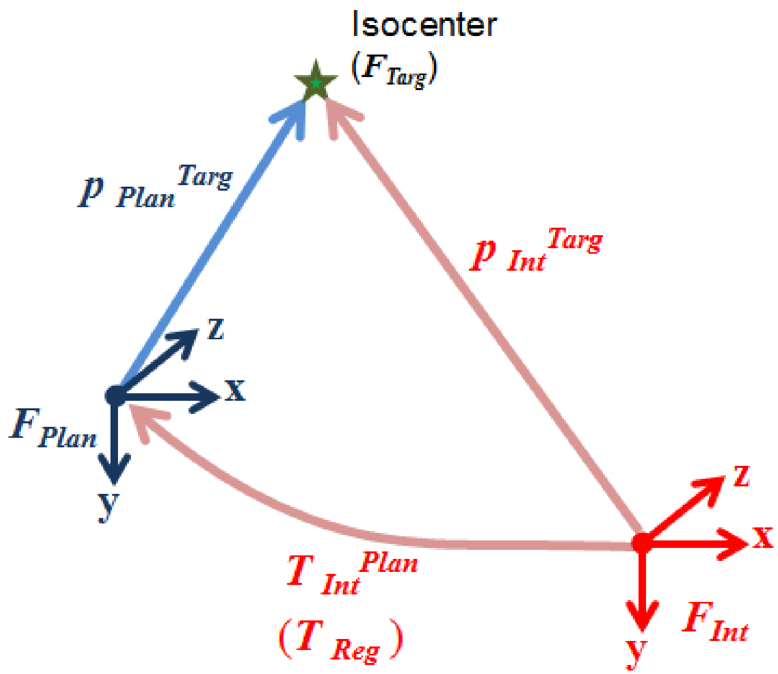


Image-Guided Radiation Therapy – IGRT
Patient Positioning Correction

Image-Guided Radiation Therapy – IGRT
Patient Positioning Correction

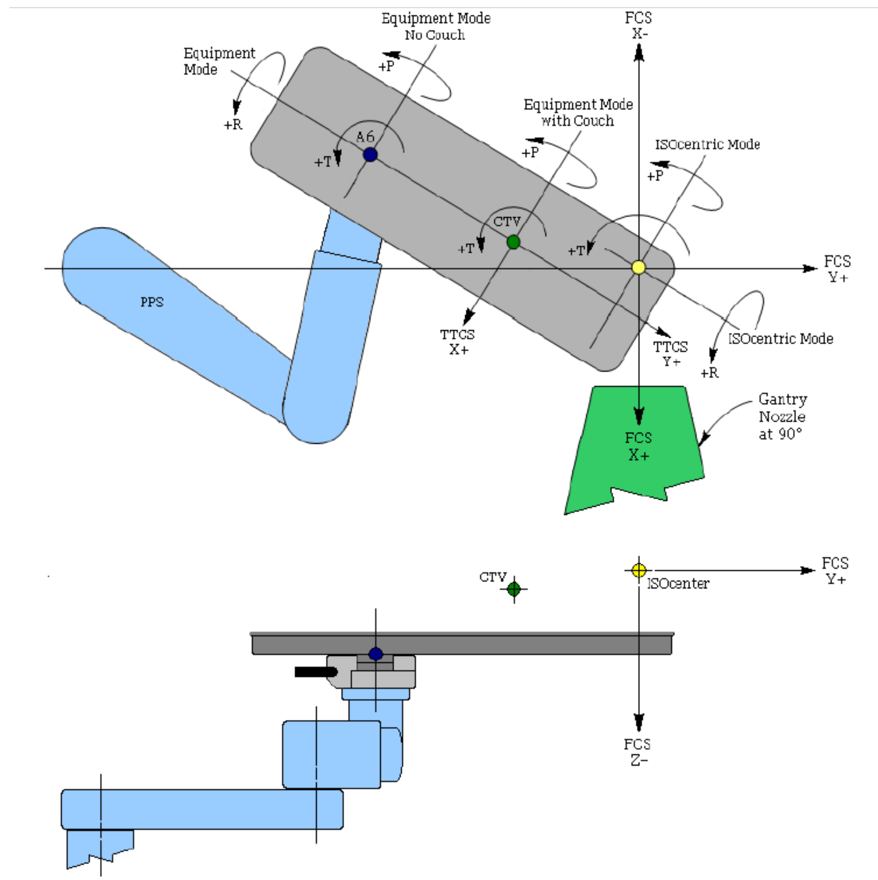


Image-Guided Radiation Therapy – IGRT
Patient Positioning Correction

DICOM Coordinates
(CT & CBCT Images)

IEC Coordinates
(PPS & RT Machine)