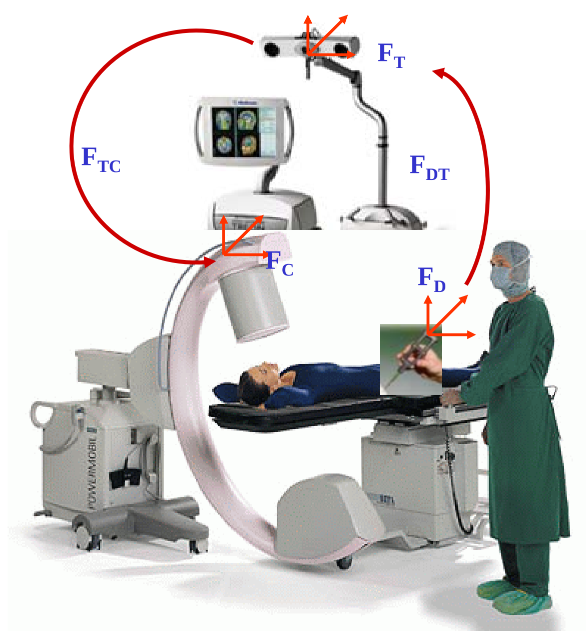
Tracked Navigation Systems

Tracking links information (imager) and action (tool)

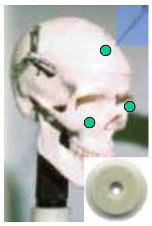


Laboratory for Percutaneous Surgery – The Perk Lab

CT/MR based navigation

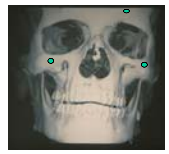
Pre-Operative

1: Attach markers to the patient's skin



2: Localize markers in pre-op MRI and/or CT images

3. Make a 3D model and surgical plan



Intra-Operative

4: Touch markers with tracked surgical too in the OR

5: Superimpose pointer's location on pre-op CT/MRI images

PROS
- Makes use of hi-res imaging

CONS
- No real-time image feedback in OR
- Target motion relative to markers is an issue

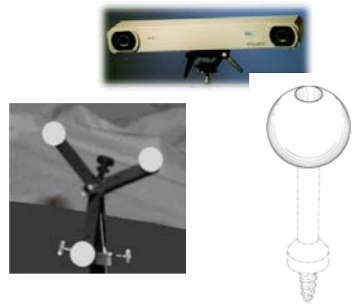
Registration with markers

- Many ways a means to achieve registration.
- The most ancient and still most popular one is: landmarks, a.k.a. markers or fiducials
- Sometimes we use natural landmarks (pros & cons?)
- Mostly man-made fiducials (pros & cons?)
- The good marker is:
  - Rigidly attached
  - Easily seen and recognized in medical image and by tracking device
  - Small (but big enough to see)
  - Non-invasive (or minimally invasive)
  - Multi-Modality Fiducial Markers

Some examples for fiducial markers

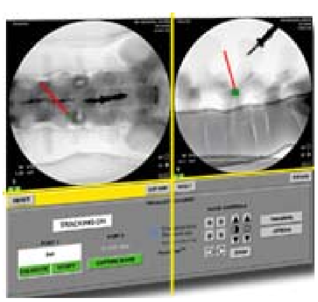
Multimodal CT/MRI surface marker that one can touch with pointer in the OR

Spheres that can be tracked by optical camera tracker

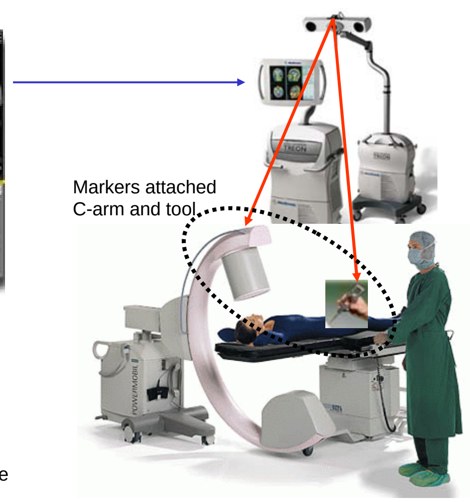


Fluoroscopy navigation

Superimpose tool position on C-arm fluoro images



Track the C-arm and tool simultaneously



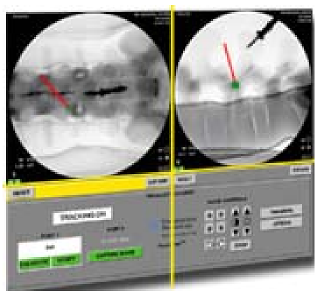
PROS
- Real-time registration of tool and anatomy

CONS
- Continuous beam – high dose
- X-ray is not so good for soft tissue

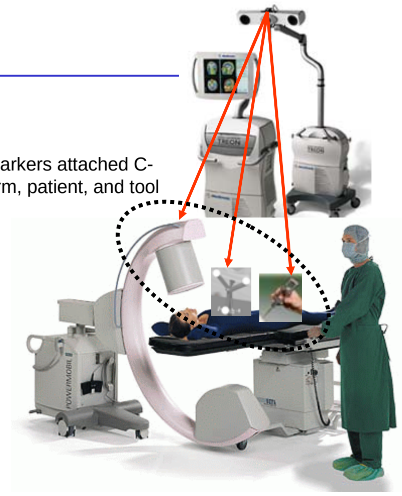
“Virtual” fluoroscopy navigation

Superimpose tool position on C-arm fluoro images

Track the C-arm, tool, and PATIENT simultaneously



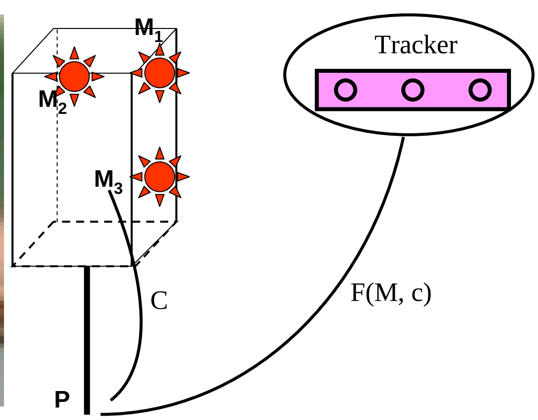
Markers attached C-arm, patient, and tool



PROS
- No need for continuous fluoro beam

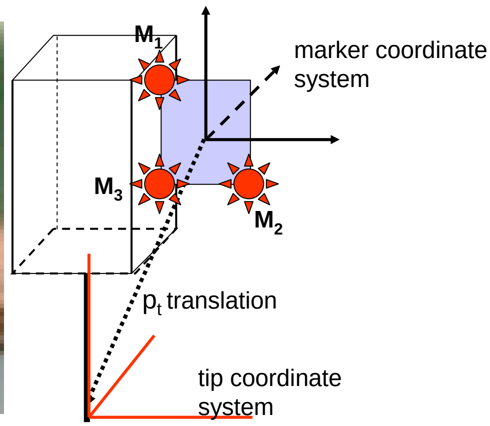
CONS
- Target motion relative to marker

Tracked Pointer Calibration



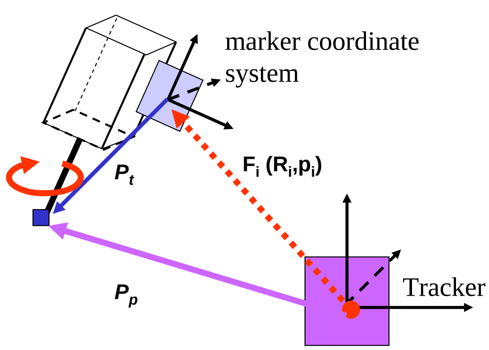
- M = (M1,M2,…Mi) tracker readings
- P = F(M, C) function to get tool tip position from tracker readings, where C = (c1,c2,c3…) is set of constants
- How to get these constants? -- CALIBRATION

Generic Pivot Calibration



- Determine p_t translation between tip and marker coordinate system
- Pivot around a fixed point

Pivot and measure many times…



- **p_t vector is constant if looking from marker coordinate system**
- **Pivot point is constant if looking from the tracker base**
- **M_1,M_2,$M_{3...}$ M_n are reported by tracker**
- **F_i (R_i,p_i) is easily calculated by software package**
- **F_i (R_i,p_i) takes the p_t vector to the pivot point**
- **F_i*p_t =p_p**
- **First rotation by R_i, then translation by p_i**
- **R_i*p_t + p_i = p_p**
- **Unknowns: Pt and Pp**
- **Two poses are sufficient to calculate Pt**
- **Take many poses (i.e. redundancy) to reduce errors!!!**

Solve the math…

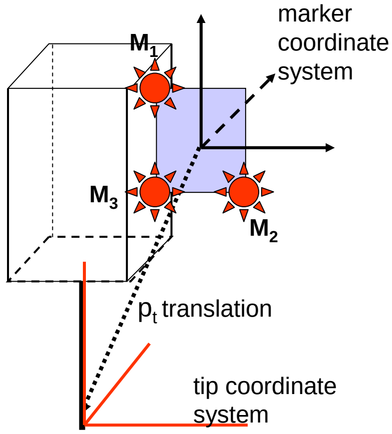
(1) $R_i * p_t + p_i = p_p$
(2) $R_j * p_t + p_j = p_p$ **subtract and 1 and 2**

$R_i * p_t - R_j * p_t + p_i - p_j = 0$
$(R_i - R_j) p_t + p_i - p_j = 0$
$(R_i - R_j) p_t = -(p_i - p_j)$

$p_t = -(R_i - R_j)^{-1}(p_i - p_j)$

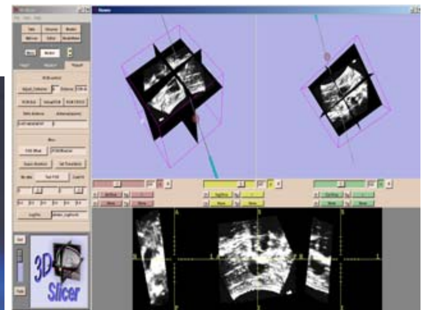
Repeat the above on all pairs of measurements and then take the average p_t

Now how to use the pointer



- **Read $M_1, M_2, M_{3\ldots}$ M_n are reported by tracker**
- **F_i (R_i, p_i) is easily calculated by software package**
- **Plug p_t into $R_i * p_t + p_i = p_p$**
- **If possible, take multiple measurements, reject outliers, and average the rest**

Ultrasound navigation



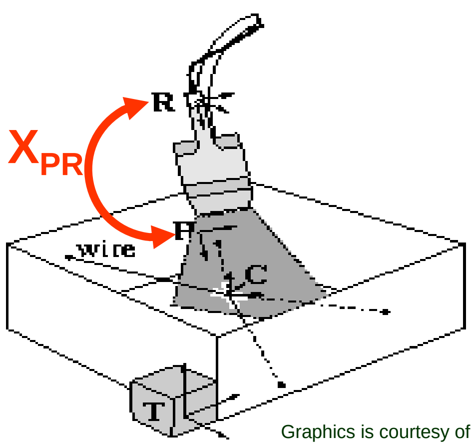
PROS

- Cheap, non- toxic, safe

CONS

- Difficult to coordinate image plane and needle

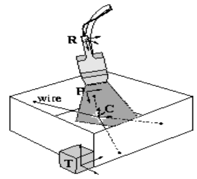
Ultrasound Calibration

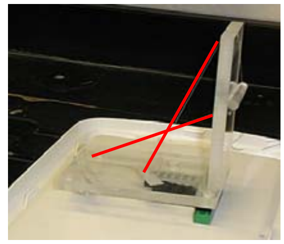


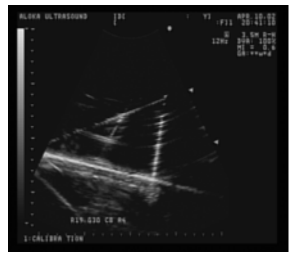
Graphics is courtesy of R. Prager

Phantom Based US Calibration

$$\begin{pmatrix}0\\0\\0\\1\end{pmatrix} = {}^{C}\mathbf{T}_{T}\,{}^{T}\mathbf{T}_{R}\,{}^{R}\mathbf{T}_{P}\begin{pmatrix}s_x u\\ s_y v\\ 0\\ 1\end{pmatrix}$$







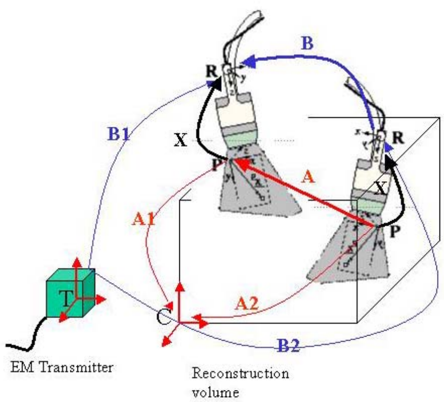
$$ {}^{J}\mathbf{T}_{I}(x,y,z,\alpha,\beta,\gamma) = \begin{pmatrix} \cos\alpha\cos\beta & \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & x \\ \sin\alpha\cos\beta & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma & y \\ -\sin\beta & \cos\beta\sin\gamma & \cos\beta\cos\gamma & z \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\begin{aligned} \mathbf{0} = \mathbf{f}(\theta,\phi) & \approx \mathbf{f}(\theta,\phi_j) + \frac{\partial \mathbf{f}(\theta,\phi_j)}{\partial \phi}(\phi - \phi_j) \\ \Rightarrow \quad \Delta\mathbf{f} & = \mathbf{J}(\phi - \phi_j) = \mathbf{J}\Delta\phi \end{aligned}$$

$$\phi_{j+1} = \phi_j + (\mathbf{J}^T\mathbf{J} + \varepsilon\mathbf{I})^{-1}\mathbf{J}^T\Delta\mathbf{f}$$

- Prager RW, Rohling RN, Gee AH, Berman L. Rapid Calibration for 3-D Freehand Ultrasound, *US in Med. Biol.*, 24(6):855-869, 1998
- Mercier L, Lango T, Lindseth F, Collins DL. A review of calibration techniques for free-hand 3-D ultrasound systems. Ultrasound Med Biol, 2005;31(4):449-471.

AX=XB Closed Formulation



$$B = B_2^{-1}B_1$$

$$A = A_2 A_1^{-1}$$

$$AX = XB$$

Boctor E, et. al., “A Novel Closed Form Solution For Ultrasound Calibration”, ISBI 2004.

Mixed CT/Ultrasound navigation

PROS

- Cheap, non- toxic, safe

CONS

- Easier coordinate image plane and needle

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