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Optical Guidance

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Photogrammetry

- Quantitative Measurements using images
- Camera Calibration
  - Intrinsic Parameters
  - Extrinsic Parameters
- Triangulation
- Pose Estimation
- Structured Light Techniques

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Image Guided Surgery

Grimson, W.E.L., et al., An automatic registration method for frameless stereotaxy, image guided surgery, and enhanced reality visualization. IEEE Transactions on Medical Imaging, 1996. 15(2): p. 129-140

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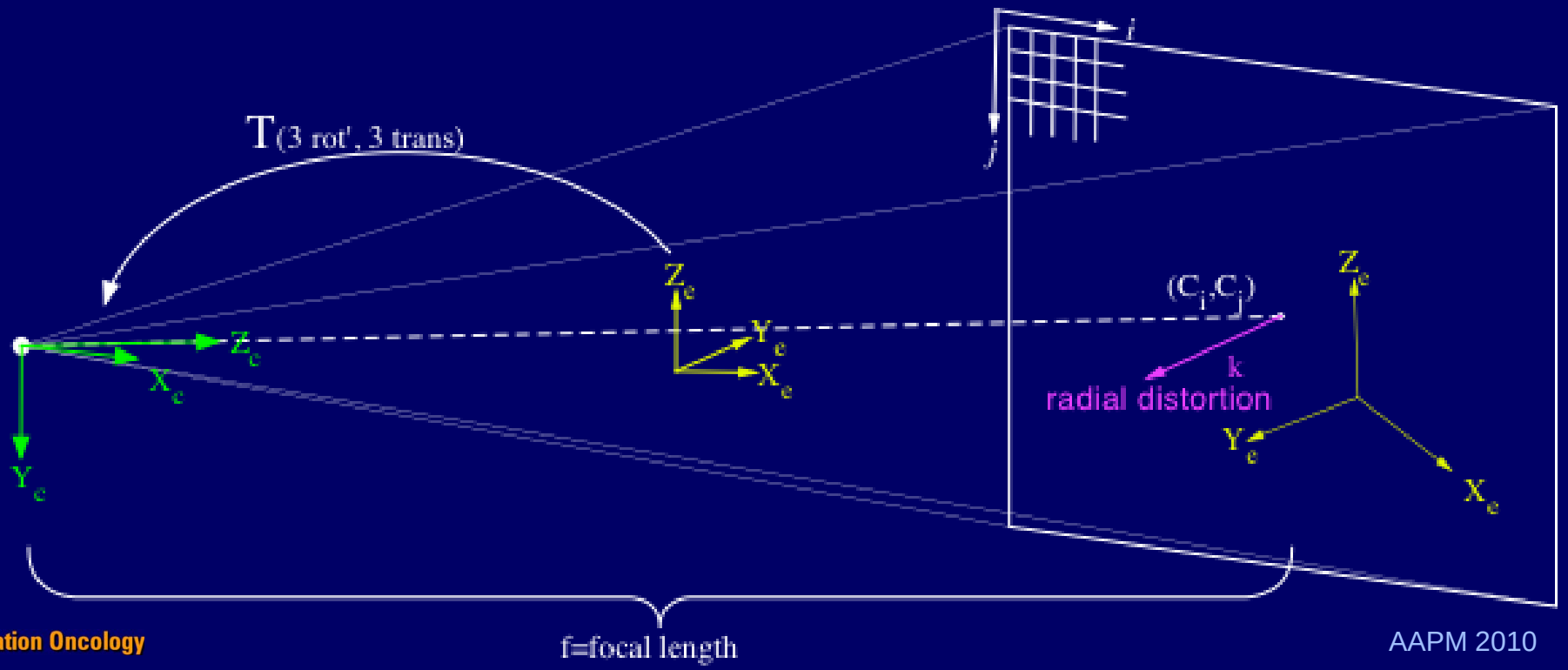
Camera Calibration

- Pinhole Camera Model
  - Orientation and Position T
  - Focal Length, image center, distortion, zoom



2D-3D Projection Linear System

$$\begin{bmatrix} s_n i_n \\ s_n j_n \\ s_n \end{bmatrix} = \begin{bmatrix} 1 & & C_i / f \\ & 1 & C_j / f \\ & & 1/f \end{bmatrix} \begin{bmatrix} r_{11} & r_{12} & r_{13} & T_x \\ r_{21} & r_{22} & r_{23} & T_y \\ r_{31} & r_{32} & r_{33} & T_x \end{bmatrix} \begin{bmatrix} X_n \\ Y_n \\ Z_n \\ 1 \end{bmatrix} = P\vec{V}_n$$

$$\begin{bmatrix} s_n i_n \\ s_n j_n \\ s_n \end{bmatrix} = \begin{bmatrix} P_1 \bullet \vec{V}_n \\ P_2 \bullet \vec{V}_n \\ P_3 \bullet \vec{V}_n \end{bmatrix} = P\vec{V}_n$$

- 3 intrinsic parameters
- 6 extrinsic parameters

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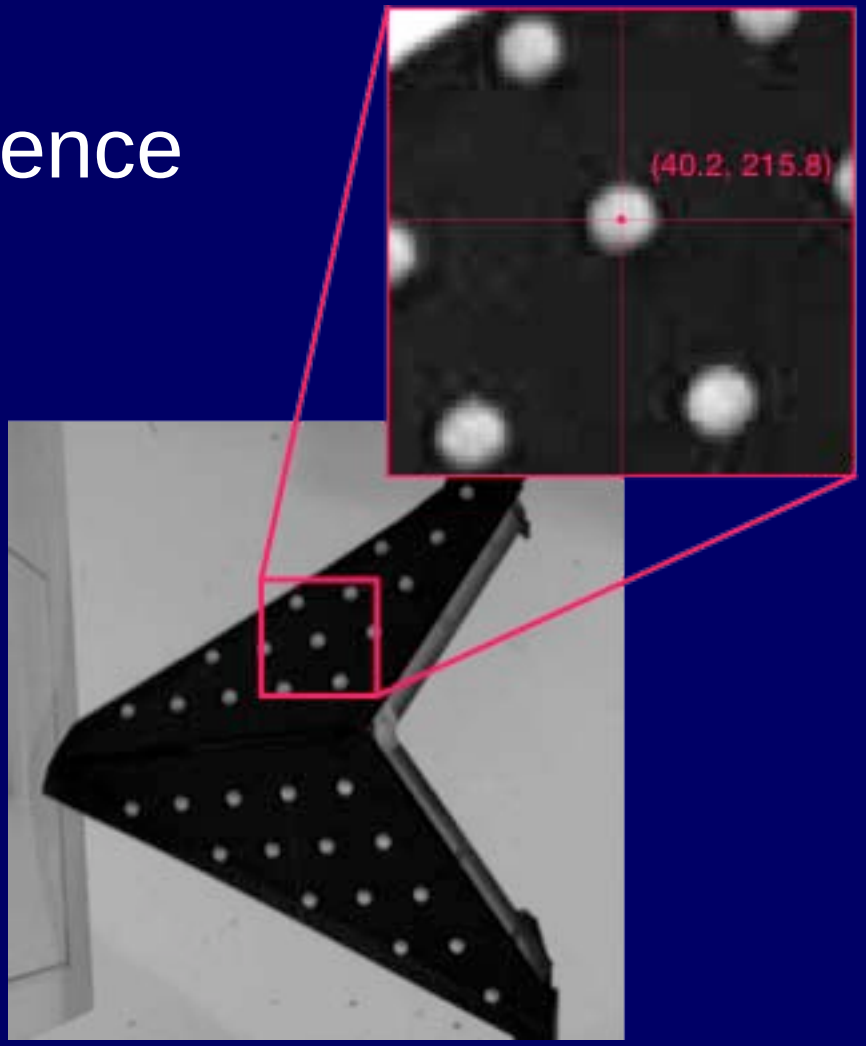
Camera Calibration

- 2D-3D Correspondence

Pixel i	Pixel j	X	Y	Z
40.2	215.8	-13	13	5
215.8	215.8	13	13	5
215.8	40.2	13	-13	5
40.2	40.2	-13	-13	5
48.9	207.1	-13	13	-5
207.1	207.1	13	13	-5
207.1	48.9	13	-13	-5
48.9	48.9	-13	-13	-5
109.7	137.1	-3	2	-5
128.0	128.0	0	0	0
44.8	211.2	-13	13	0
211.2	211.2	13	13	0



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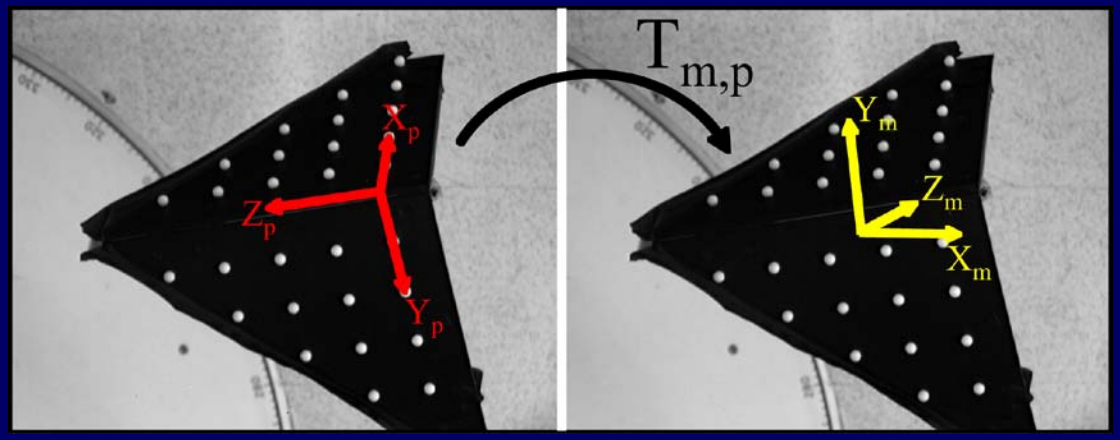
Calibration to Isocenter

- "Fix" external calibration
  - Rigid transform from calibration phantom to camera
  - Rigid transformation from machine scale to camera system



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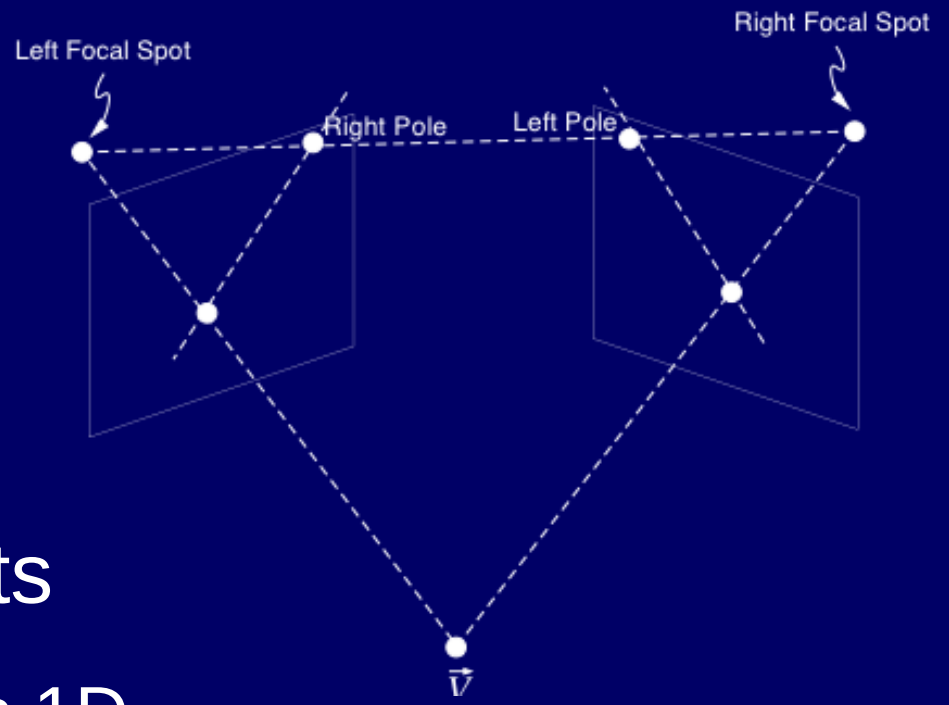
Epipolar Geometry



- Aid to finding corresponding points
  - 2D search becomes 1D search

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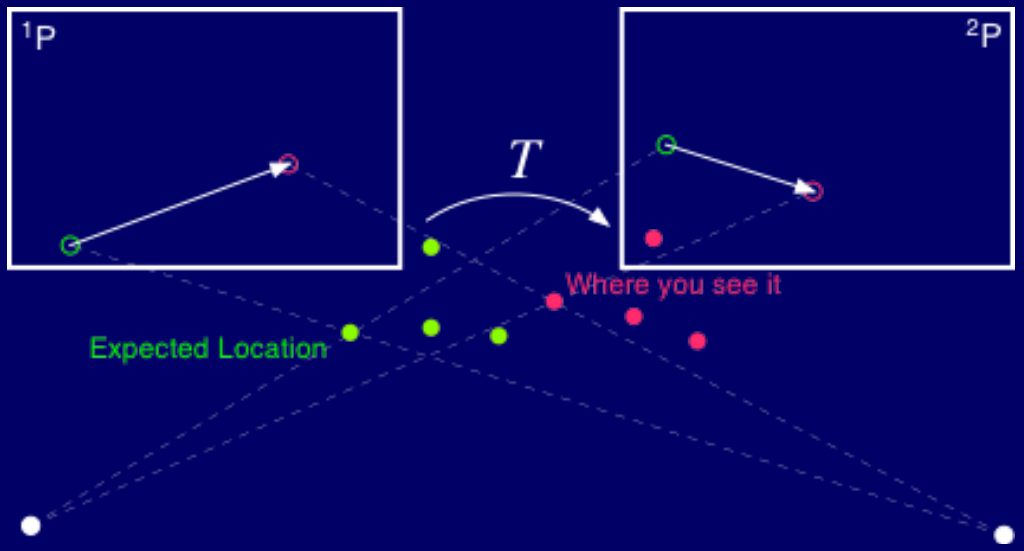
Pose Estimation

- Known 3D model
- Two Views
- T is the Pose

$$\begin{bmatrix} {}^1\begin{bmatrix} si \\ sj \\ s \end{bmatrix}_1 & \cdots & {}^1\begin{bmatrix} si \\ sj \\ s \end{bmatrix}_n \end{bmatrix} = {}^1PT\left[\vec{V}_1 \cdots \vec{V}_n\right]$$

$$\begin{bmatrix} {}^2\begin{bmatrix} si \\ sj \\ s \end{bmatrix}_1 & \cdots & {}^2\begin{bmatrix} si \\ sj \\ s \end{bmatrix}_n \end{bmatrix} = {}^2PT\left[\vec{V}_1 \cdots \vec{V}_n\right]$$



Menke et al. Photogrammetric accuracy measurements of head holder systems used for fractionated radiotherapy. Int. J. Radiat. Oncol. Biol. Phys. (1994) vol. 29 (5) pp. 1147-55

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Rigid Transformations

- Translation plus ..
- Rotation about an axis
  - Roll, Pitch, Yaw; Euler angles … 27 different rep's
  - Quaternions
  - Vector and Angle

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Pose Estimation

- T = Rigid Transformation

$$T = R_z(\phi)R_y(\theta)R_x(\psi)Trans$$

$$T = \begin{bmatrix} \cos(\phi) & -\sin(\phi) & & \\ \sin(\phi) & \cos(\phi) & & \\ & & 1 & \\ & & & 1 \end{bmatrix} \begin{bmatrix} \cos(\theta) & & \sin(\theta) & \\ & 1 & & \\ -\sin(\theta) & & \cos(\theta) & \\ & & & 1 \end{bmatrix} \begin{bmatrix} 1 & & & \\ & \cos(\psi) & -\sin(\psi) & \\ & \sin(\psi) & \cos(\psi) & \\ & & & 1 \end{bmatrix} \begin{bmatrix} 1 & & & t_x \\ & 1 & & t_y \\ & & 1 & t_z \\ & & & 1 \end{bmatrix}$$

Paul. Robot Manipulators. (1981)

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Solving Rotations

- Going backwards

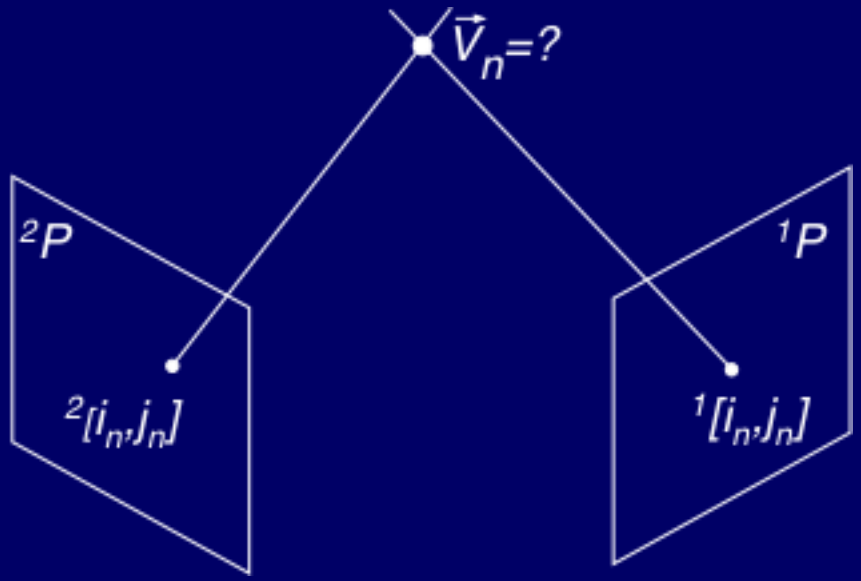
$$T = R_z R_y R_x \rightarrow R^{-1}_z T = R_y R_x$$

$$R_Z^{-1}T = R_Z^{-1}(\phi)\begin{bmatrix} r_{11} & r_{12} & r_{13} & 0 \\ r_{21} & r_{22} & r_{23} & 0 \\ r_{31} & r_{32} & r_{33} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} \cos(\theta) & \sin(\theta)\sin(\psi) & \sin(\theta)\cos(\psi) & \\ 0 & \cos(\psi) & -\sin(\psi) & \\ -\sin(\theta) & \cos(\theta)\sin(\psi) & \cos(\theta)\cos(\psi) & \\ & & & 1 \end{bmatrix}$$

- At least 2 solutions!

Paul. Robot Manipulators. (1981)

Triangulation – Two Views



$$\begin{bmatrix} \left({}^1P_3 \bullet \vec{V}_n\right){}^1i_n \\ \left({}^1P_3 \bullet \vec{V}_n\right){}^1j_n \\ \left({}^2P_3 \bullet \vec{V}_n\right){}^2i_n \\ \left({}^2P_3 \bullet \vec{V}_n\right){}^2j_n \end{bmatrix} = \begin{bmatrix} {}^1P_1 \bullet \vec{V}_n \\ {}^1P_2 \bullet \vec{V}_n \\ {}^2P_1 \bullet \vec{V}_n \\ {}^2P_2 \bullet \vec{V}_n \end{bmatrix}$$

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Pose Estimation

- Two 3D datasets
  - Center on each average … Translation
  - From 3x3 matrix from matrix of centered vectors
  - SVD to determine Rotation Matrix
  - Solve Rotation Matrix for RPY angles

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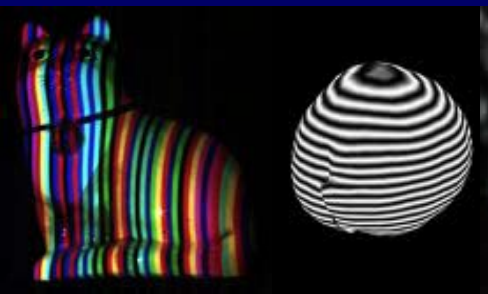
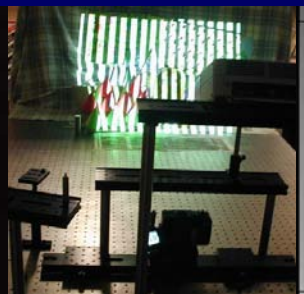
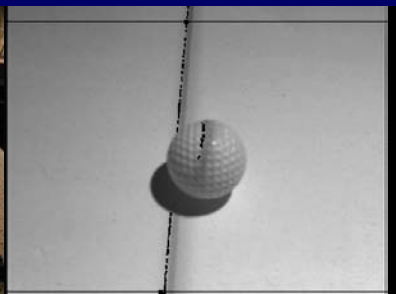
Structured Light

- Light source is used to encode, infer, or disambiguate 3D object
  - Light source can be another calibrated projection system
  - Light source can aid in extraction of corresponding points
  - Light source can aid in edge finding using image processing







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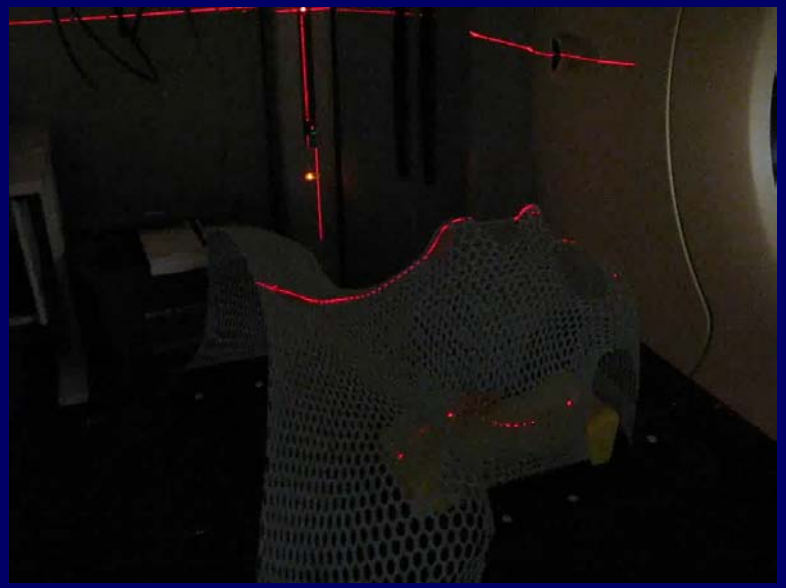
Constrained Triangulation

- Structured Light
  - Laser/Light/Shadow Plane
  - Constrains 3D coordinate by 1D
  - e.g. Z=0 plane
  - Easy image processing



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Triangulation to Triangles

- Dense cloud of points from stereo system
  - 3D points to triangulated surface
  - 3D-3D Surface matching problem to determine pose

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Positioning Errors

- Absolute vs Relative Positioning
  - Absolute requires information from simulation or planning to be used in the treatment room
  - Relative can use information derived in treatment room to reposition or monitor during treatment

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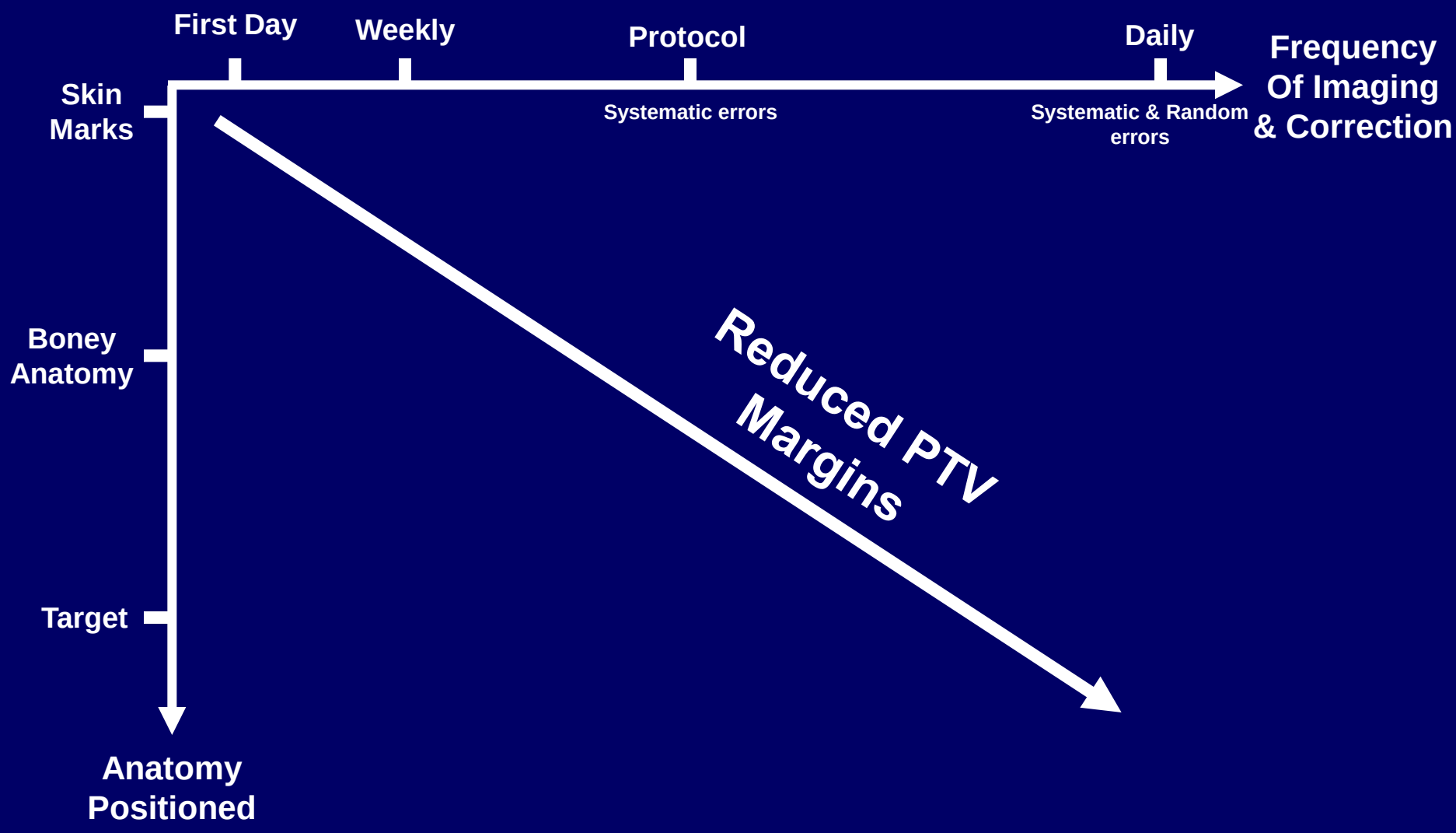
Margin Reduction



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Computer Vision Example

- Camera Calibration for Patient Safety