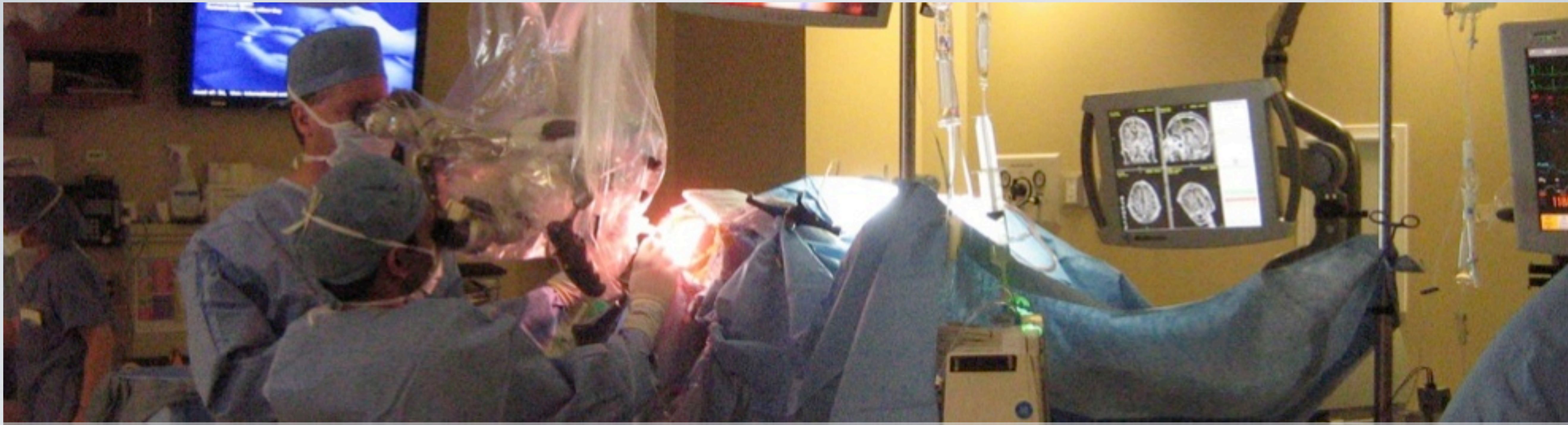


VISE SUMMER SEMINAR SERIES

Intraoperative Digitization and Image-to-Physical Registration

Dr. Amber Simpson
Research Assistant Professor
Biomedical Engineering

VANDERBILT

ACKNOWLEDGEMENTS

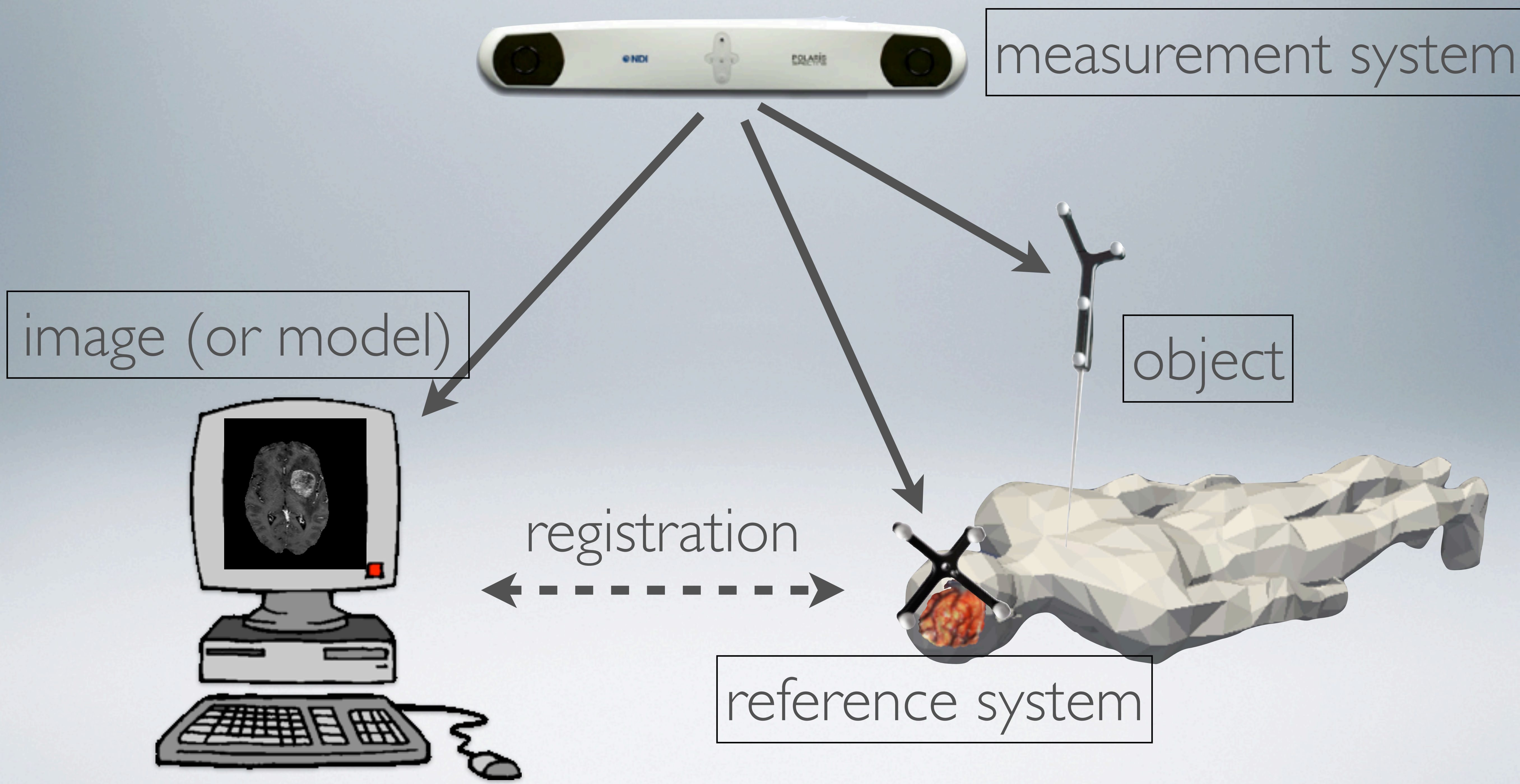
Diagrams, photos, and inspiration ...

Queen's University
Gabor Fichtinger, PhD
Manuella Kunz, PhD

Vanderbilt University
Jessica Burgner, PhD
Bob Galloway, PhD
Ankur Kumar, MS
Thomas Pheiffer, MS

Pathfinder Therapeutics Inc.

SURGICAL NAVIGATION



preoperative procedure

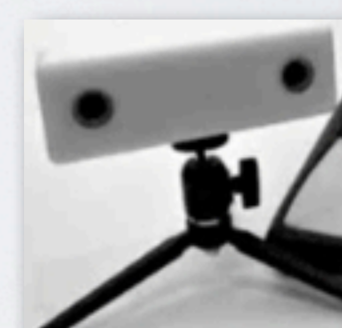
intraoperative procedure

LOCALIZATION

INTRAOPERATIVE TRACKING

Coordinate Measurement

Mechanical | Acoustic | Magnetic/RF | Inertial | Optical

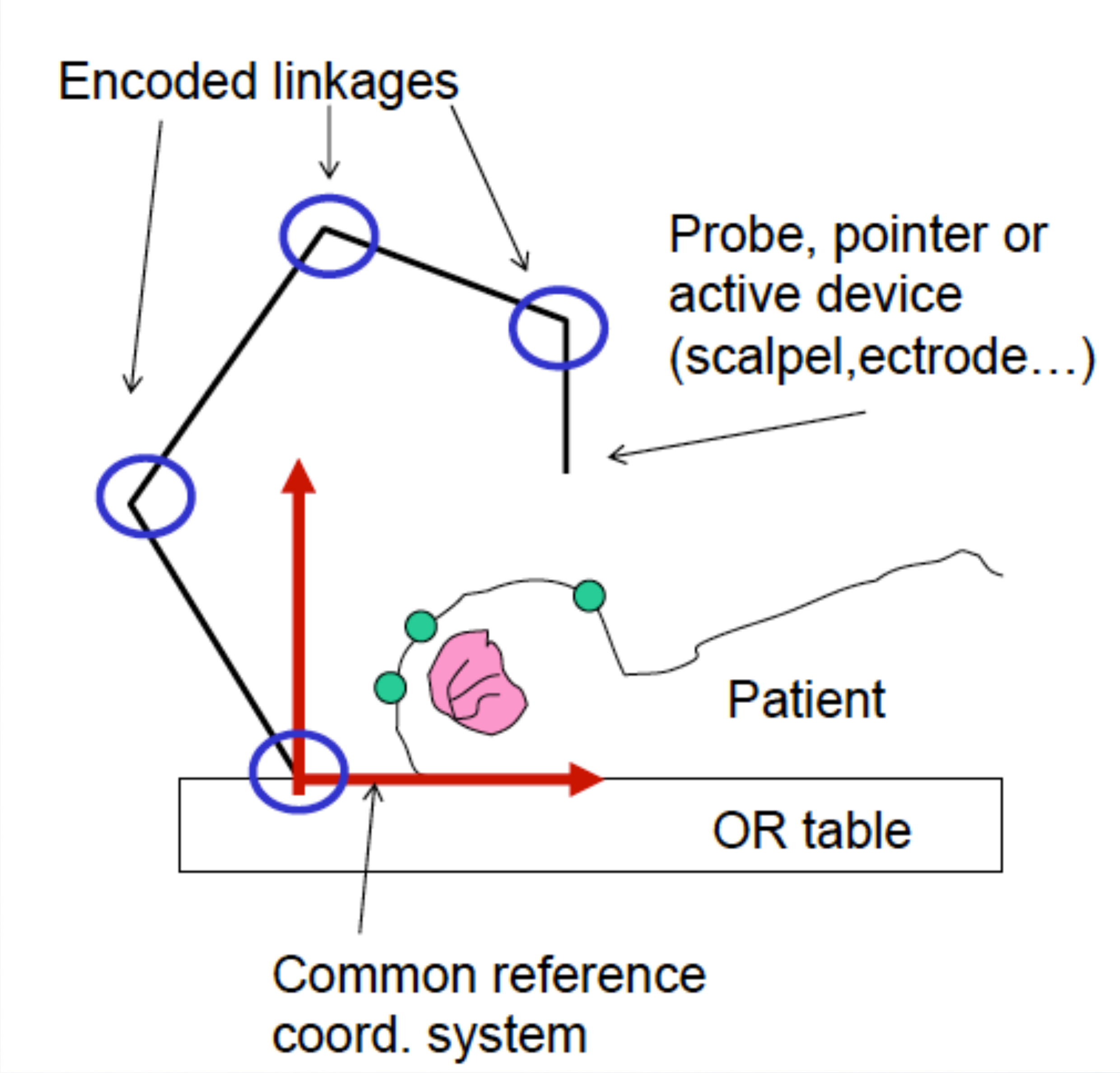


More details on July 26

MECHANICAL LOCALIZATION

- Advantages: simple concept, no line of site issues, reliable, repeatable, accurate

- Disadvantages: clumsy, confined range, single reference frame, error propagation/aggregation, each joint requires calibration, head ring is very invasive



Source: Gabor Fichtinger, Queen's University

ARTICULATED ARM IN SURGERY

Media Source: Bob Galloway

MAGNETIC/RF LOCALIZATION

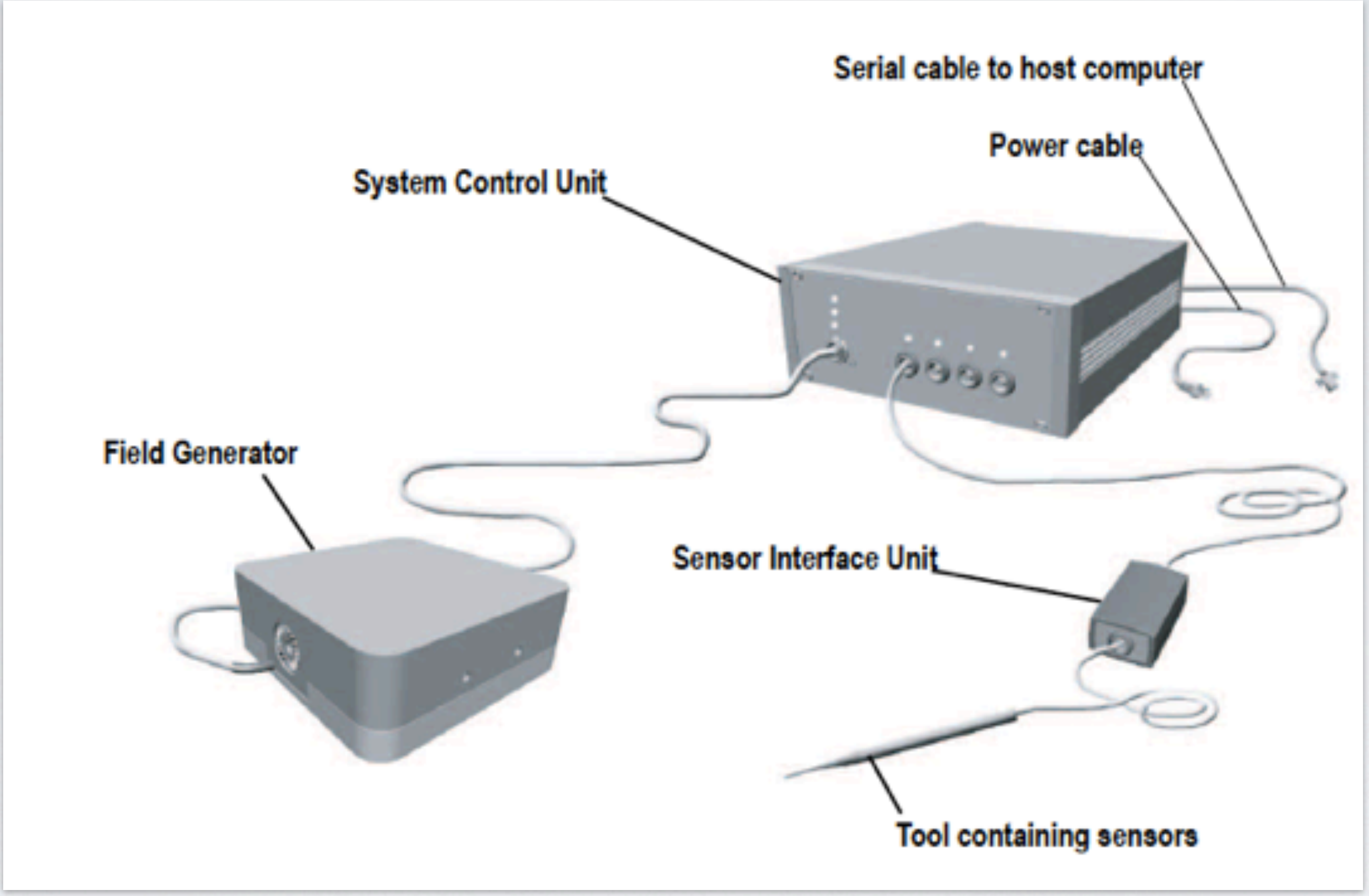
Aurora, NDI

Flock of Birds, Ascension (now NDI)

Fastrak, Polhemus

G4, Polhemus

AURORA SYSTEM



- SCU powers field generator – field generator produces a series of varying magnetic fields, creating a known volume of varying magnetic flux.

Source: Aurora User Guide, Northern Digital Inc.

ELECTROMAGNETIC TRACKING

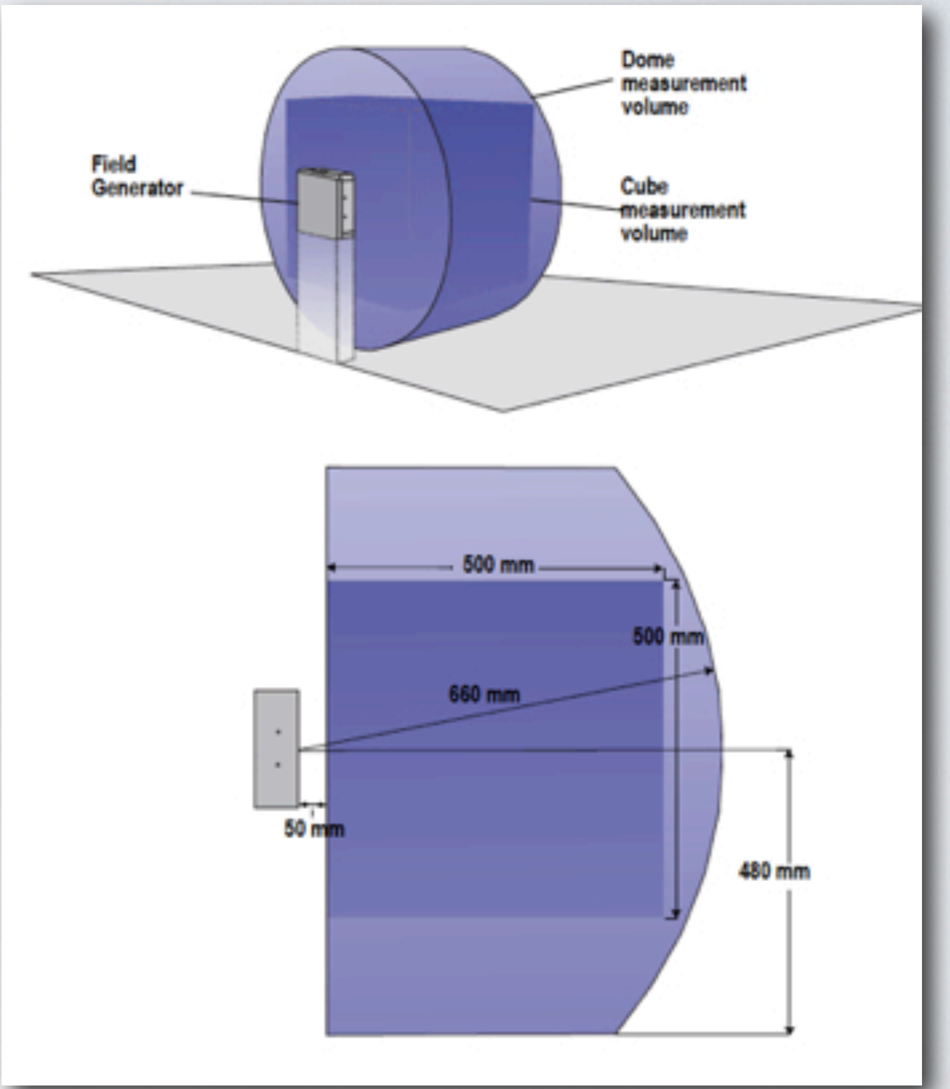
- Sensor coils are connected to SCU via SIU.

- Sensor coils inside measurement volume = voltage induced in them

- Characteristic of induced voltage: depends on sensor coil position and orientation in measurement volume and strength and phase of varying magnetic field

- SIU converts the voltage into digital data and sends it to the SCU

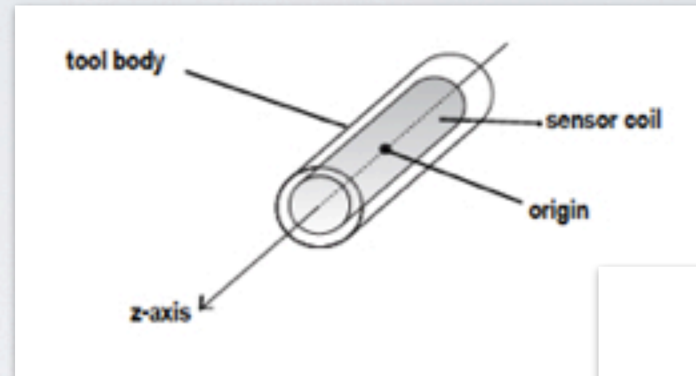
- SCU calculates position and orientation of coil and sends result to host computer



Measurement Volume

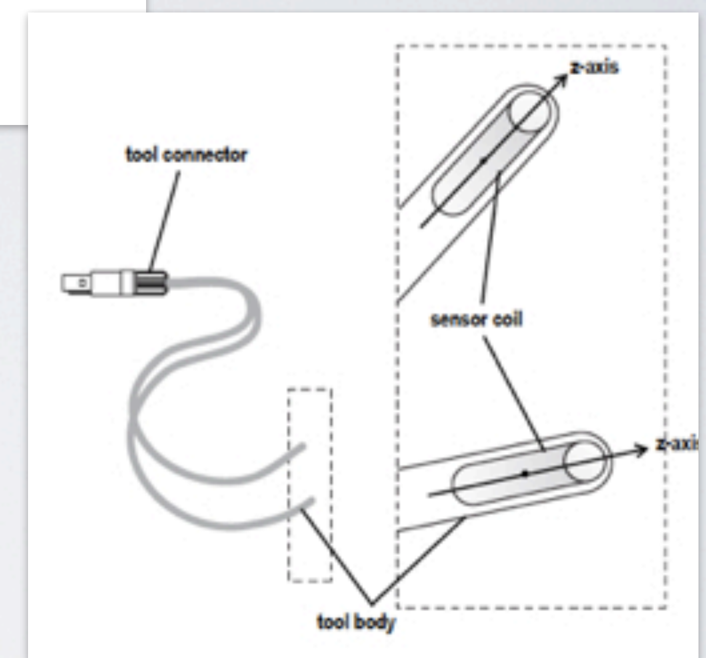
EM SENSOR COIL

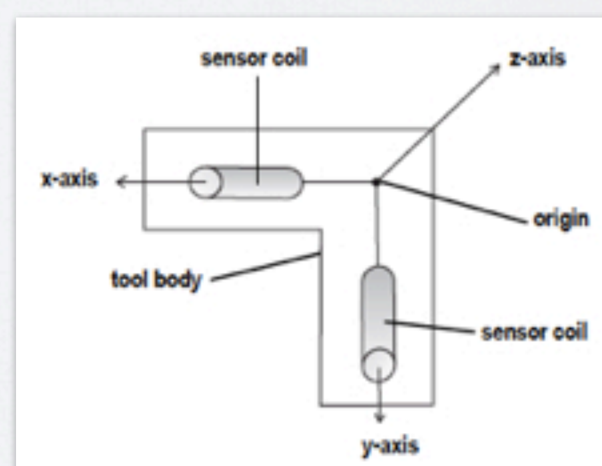
- Single Sensor Coil:
  - Comprises a wire wound around a small metal core
  - Local coordinate system: Z-axis along the sensor coil's length, origin in coil's center
- 5DOF sensor: 3 Translation, 2 Rotation, two single sensors joined to a connector, both with a local coordinate system
- Multiple Sensor Tools:
  - 6 DOF, two or more sensor coils fixed relative to each other



single sensor

5DOF sensor





6DOF sensor

EM TRACKING ACCURACY

- directly related to the distance of the sensor from the field generator

5DOF Sensor

Distance from field generator (mm)	RMS (mm)
100-200	0.9
200-300	0.7
300-400	0.8
400-500	1.3

Orientation: 0.3°

6DOF Sensor

Distance from field generator (mm)	RMS (mm)
250	0.5
450	0.6

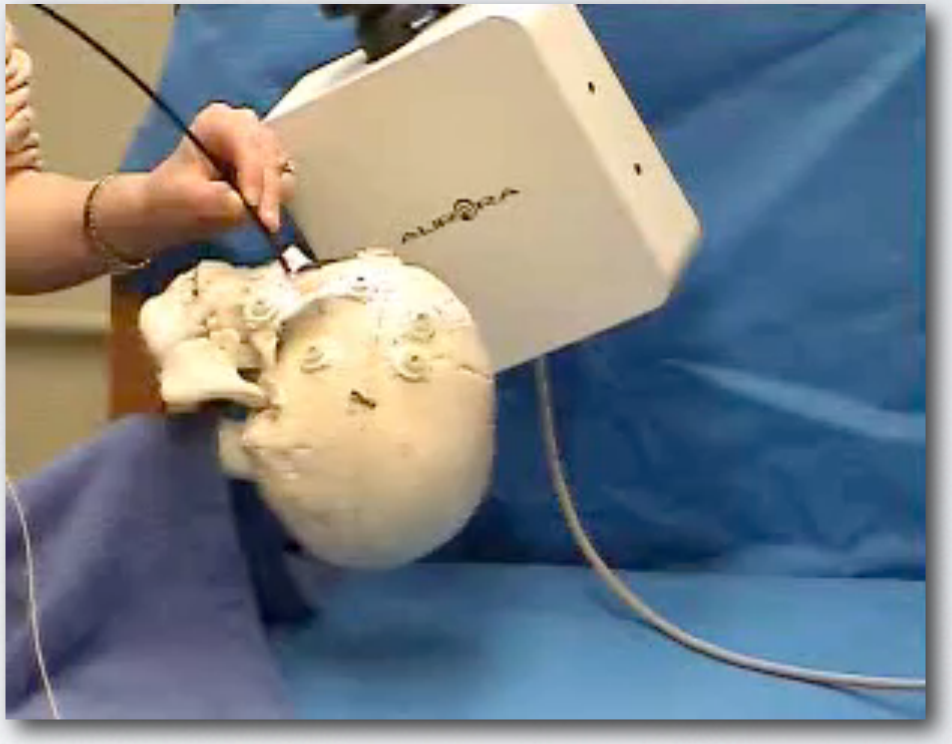
Orientation:

250	0.5°
450	0.3°

Source: Kirsch et al. New form factors for sensors and field generators of a magnetic tracking system, SPIE 2005.

EM TRACKING

- Advantages: no line of site issues
- Disadvantages: limited measurement volume, accuracy over work volume, speed of acquisition, angular accuracy, interference



Media Source: Bob Galloway

OPTICAL TRACKING: MICRON TRACKER

- detects the presence of the marked objects in the sensor's field of measurement and reports the pose of each detected object

Micron Tracker by Claron

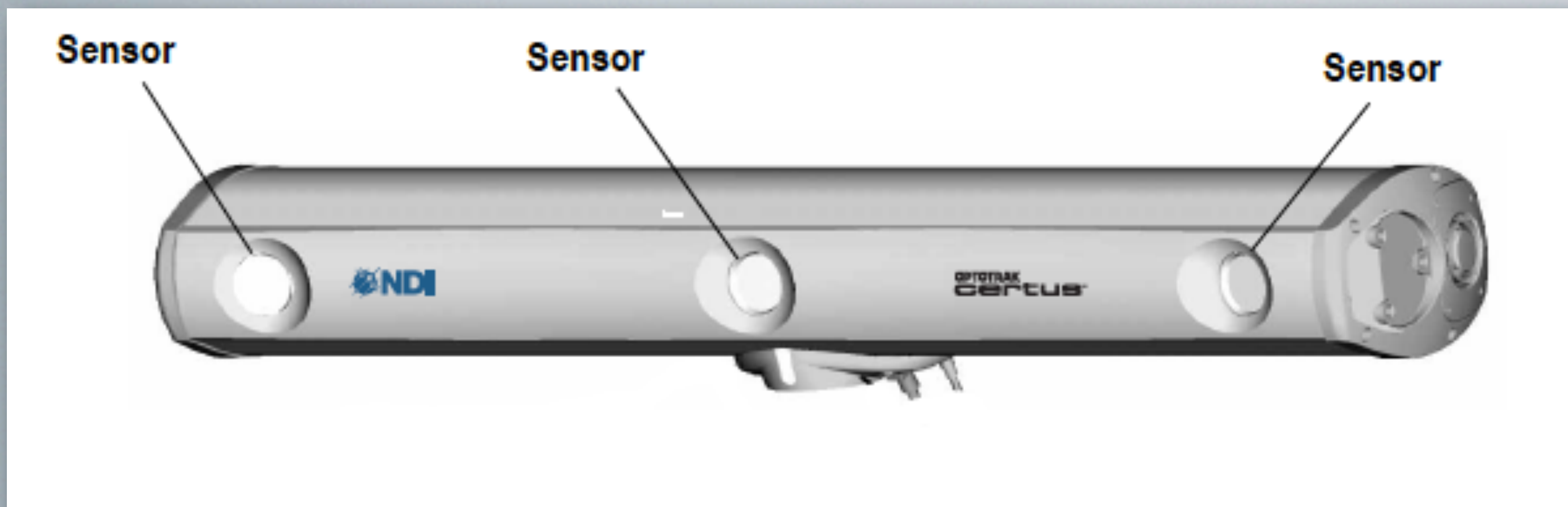
Image Source: Jessica Burgner

MICRON TRACKER

- sensor observes marked locations, or targets, on each tracked object from multiple angles, then triangulating the lines of sight to the targets to calculate 3D position
- 3D locations of at least 3 targets are needed to calculate each object's pose, i.e., its position and orientation in space relative to the camera.
- accuracy: 0.20-0.35 mm (moving object of known size through volume)

Source: http://www.clarontech.com

ACTIVE OPTICAL TRACKING



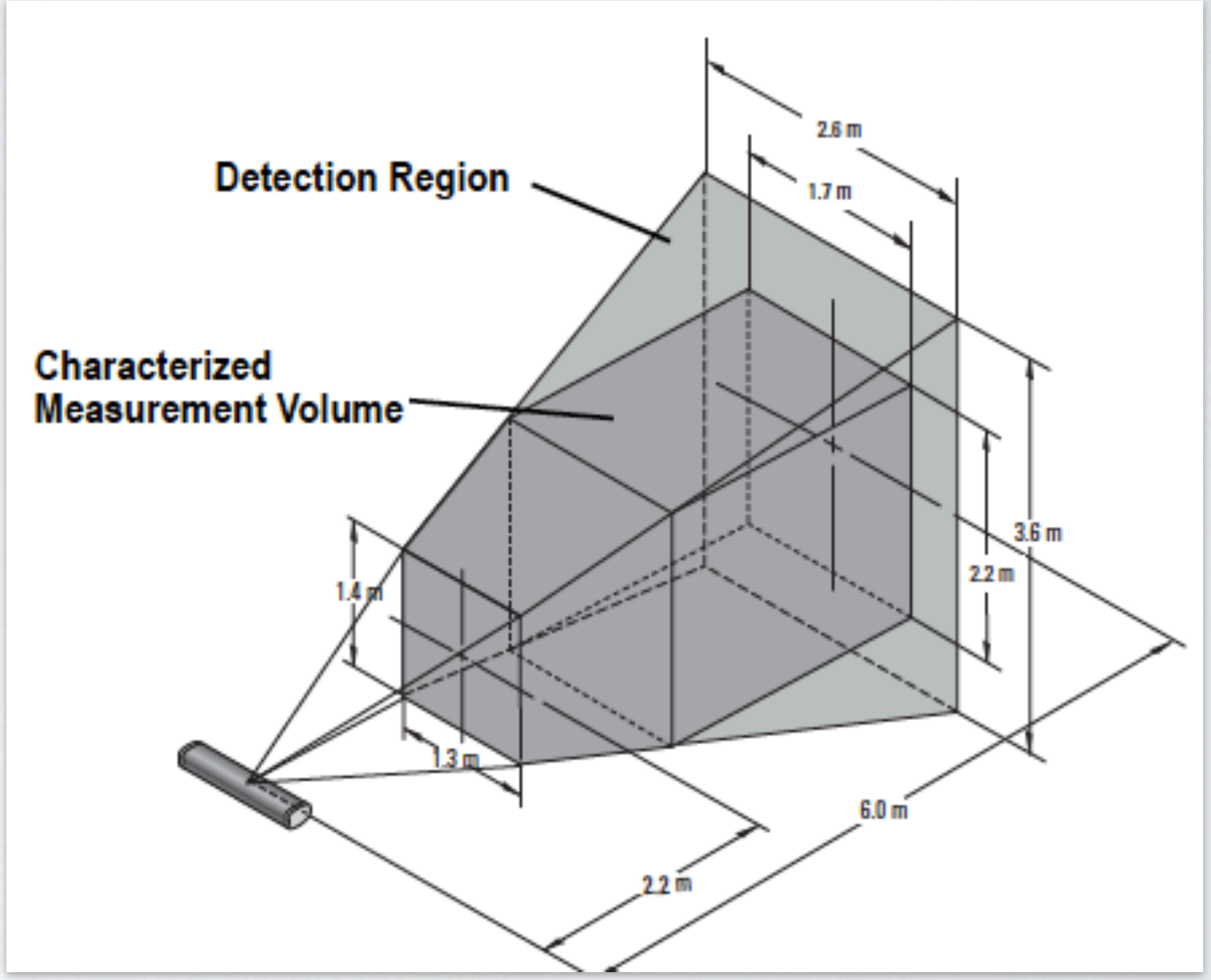
Optotrak Certus

Optotrak 3020

Hybrid Polaris Spectra

ACTIVE OPTICAL TRACKING

- based on the principle of triangulation
- strobers individually activate/deactivate each marker's infrared light emission
- position sensor detects infrared light
- 3D marker positions can be returned or 3D data can be computed
- markers are wired
- multiple sensors can be daisy-chained together to increase measurement volume

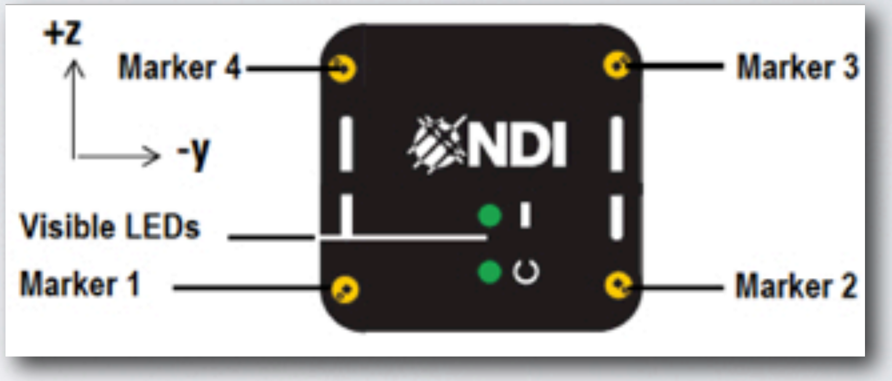


Certus Measurement Volume

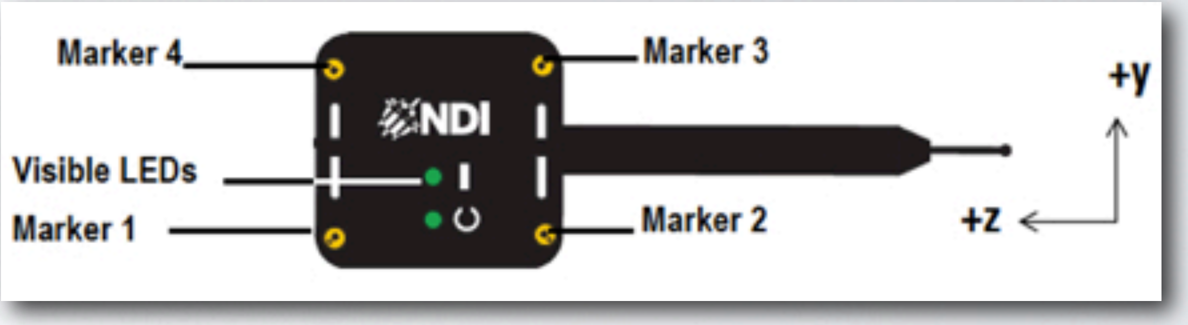
Source: Optotrak Certus User Guide, Northern Digital

RIGID BODIES

- a rigid structure with > three markers firmly attached such that there are no relative movements between the markers
- this allows the system to track rotational movements of the rigid body as well as each marker's translational movements
- can track up to 170 rigid bodies (10 with position and orientation, likely due to system performance)
- characterize the rigid body for the system



4 marker rigid body



4 marker tool with rigid body

COORDINATE REFERENCE FRAME

Image Source: Bob Galloway

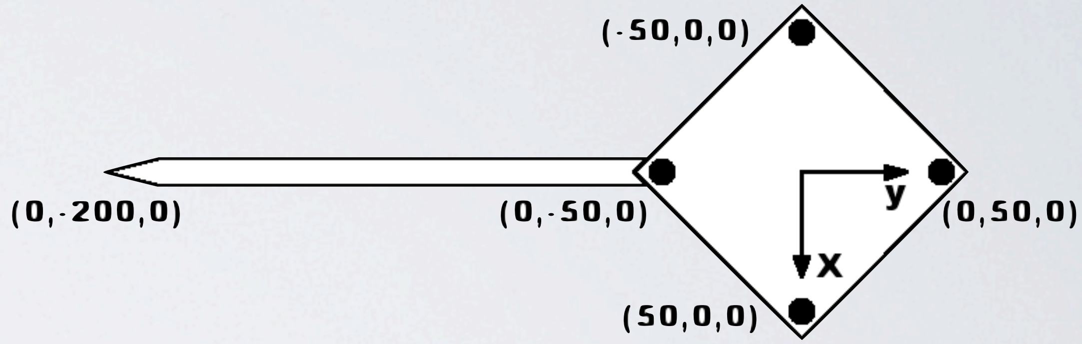
WHY USE A CRF

- position and orientation of all tools are measured with respect to the position and orientation of the reference tool
- camera movements don't matter
- it's mathematically simple
- significantly improves tracking accuracy
- disadvantages: additional equipment requires sterilization, needs to be rigidly affixed to patient

Sources:

[1] West & Maurer, Designing optically tracked instruments for image-guided surgery, IEEE TMI 2004.
[2] Wiles & Peters, Improved Statistical TRE Model When Using a Reference Frame, MICCAI 2007.

ACTIVE OPTICAL TRACKING ACCURACY



- number of markers (3 ok, 4 recommended)
- tracking error increases when
  - distance from the instrument tip to the CRF fiducials increases
  - size of the CRF fiducial configuration decreases
  - distance of the instrument tip to the instrument fiducials increases
- tracking error is better with:
  - regular tetrahedron configuration
  - non-planar configuration (reduces rotational component of TRE)

Sources:
[1] West & Maurer, Designing optically tracked instruments for image-guided surgery, IEEE TMI 2004.
[2] Ma et al, Estimation of optimal fiducial target registration error in the presence of heteroscedastic noise, IEEE TMI 2010.

PASSIVE OPTICAL TRACKING

- position sensor's illuminator floods surrounding area with IR for whole integration time by flashing at 20 Hz
- passive sphere markers have a retro-reflective coating that reflect IR directly back to sensor instead of scattering it
- sensor collects IR for a period of time called the integration time which acts like an electronic shutter
- system automatically adjusts the integration time so that the intensity of the brightest IR detected is set to a maximum value and all other IR falls below
- sensitive to other sources of IR

Polaris Spectra

Source: Passive Polaris Spectra User Guide, Northern Digital

DESIGN OF PASSIVE TOOLS

- markers aren't a perfect point source of light; mounting posts will begin to occlude part of the marker (need to specify the maximum viewing angle)
- requires unique geometry: mirror image of tools is out (no symmetry)
- max of 6 passive tools (32 passive markers) (too many tools degrades performance)
- can have multi-faced tools

Source: Passive Tool Design Guide, Northern Digital

OPTICAL TRACKING

- Active tools:
  - advantages: very accurate, can have multiple rigid bodies
  - disadvantages: big, expensive, wired instruments, line-of-sight issues
- Passive tools:
  - advantages: wireless, reasonably large measurement volume
  - disadvantages: limited # of tools, line-of-sight, camera resolution is limited, complex tool design

ACCURACY COMPARISON

System	Positional Errors (mm)			Rotational Errors (deg)	
	RMS	Mean	Std. Dev.	Mean	Median
Active Rigid Body	0.233	0.190	0.135	0.362	0.256
Passive Rigid Body	0.231	0.185	0.137	0.383	0.208

*Measured using Hybrid Polaris Spectra.

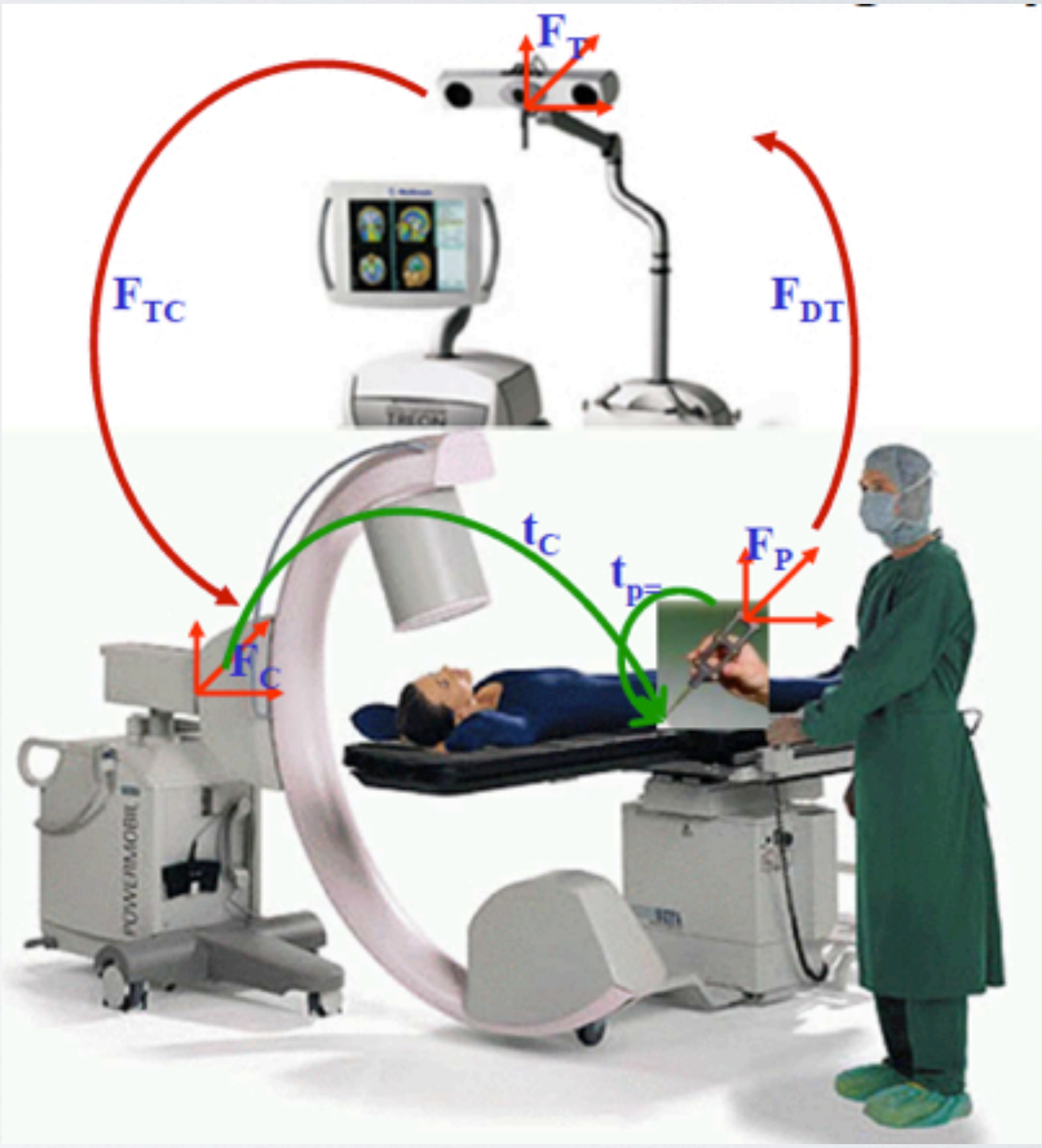
System	Accuracy
Passive Polaris Spectra	0.25 mm
(Active) Certus	0.15 mm

A. D. Wiles et al. Accuracy assessment and interpretation for optical tracking systems, SPIE 2004.
Certus and Spectra Technical Specifications, http://www.ndigital.com/ .

DIGITIZATION

TOOL CALIBRATION

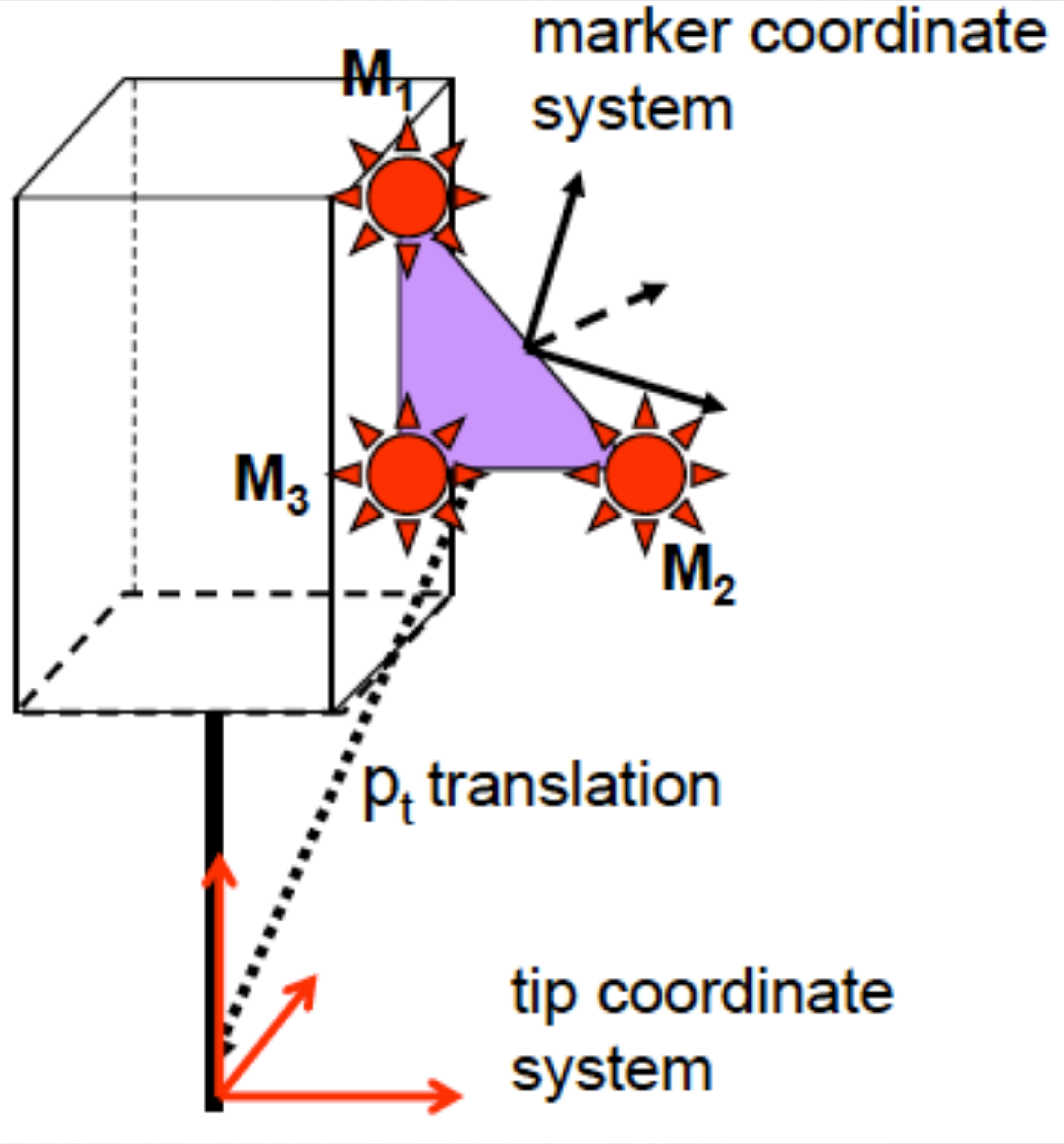
- $p_c = (F_{TC} (F_{DT} t_p))$
- need to know t_p prior to using the surgical tool
- need to calibrate



Source: Gabor Fichtinger

SIMPLE PIVOT PROCEDURE

- determine p_t translation between tip and marker coordinate system
- create a geometric constraint - pivot around a fixed point
- tool tip MUST remain fixed



Source: Gabor Fichtinger

CALIBRATION CODE EXAMPLE

- two algorithms: one using least squares sphere fit (assumes isotropic noise) and one using unscented Kalman filter sphere fit (assumes anisotropic noise)
- UKF outputs covariance estimate
- includes simulation framework

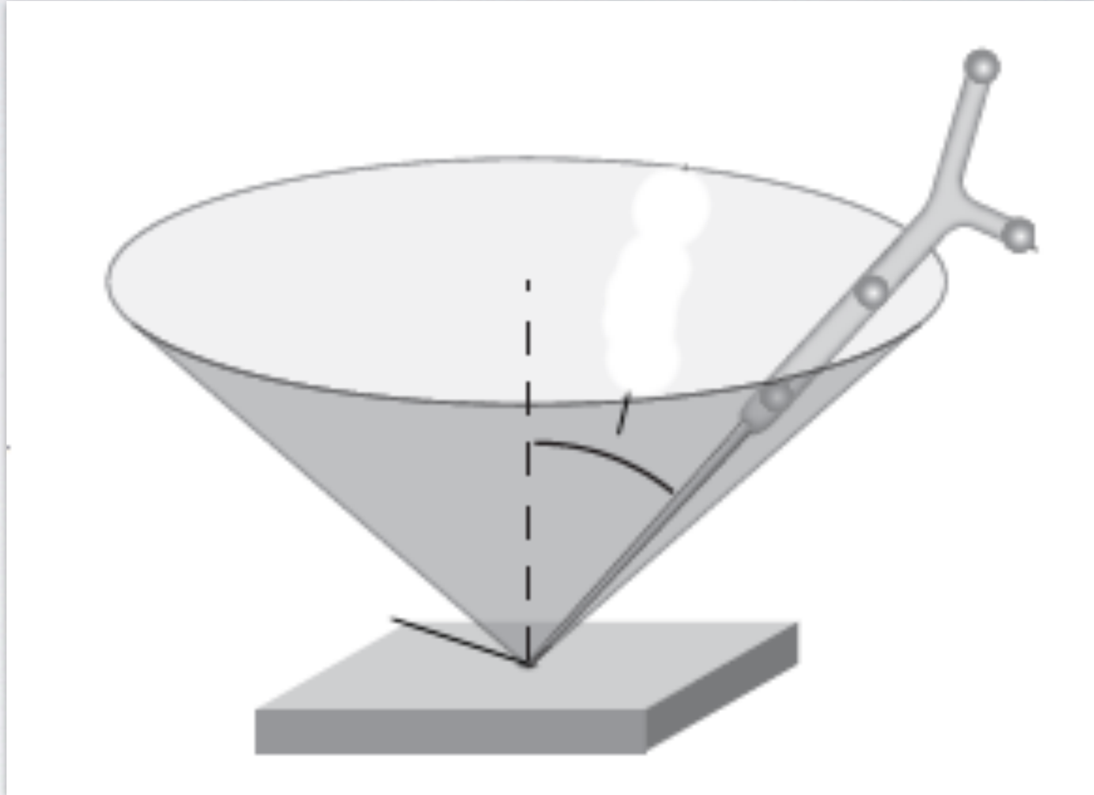
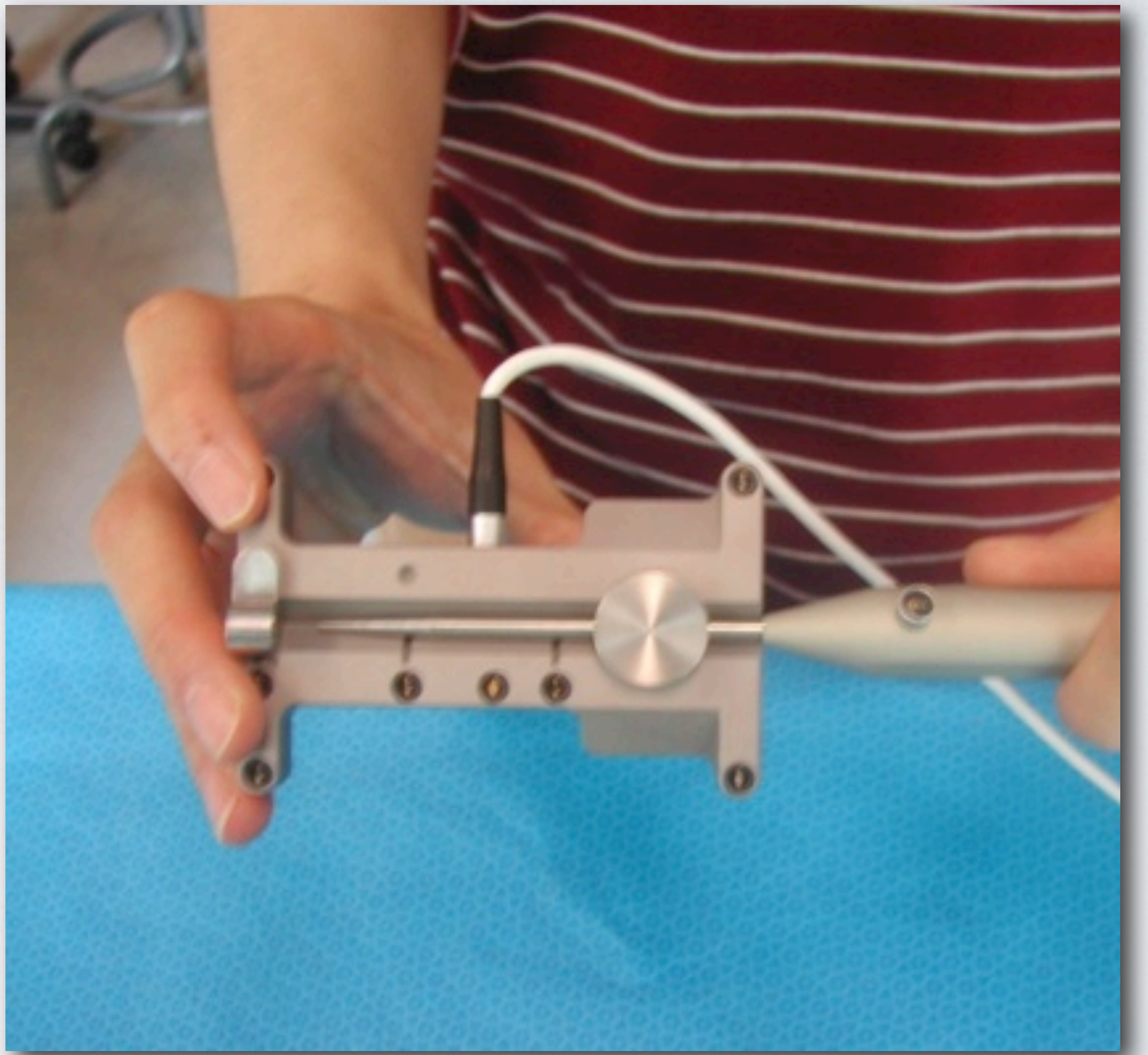


Image source: Polaris Spectra User Guide, NDI.

ANOTHER METHOD

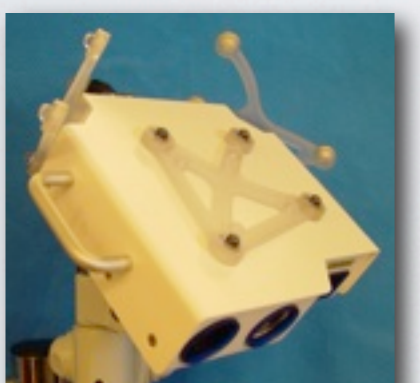
- spin the tool in the tracked calibrator
- requires calibration of the calibrator

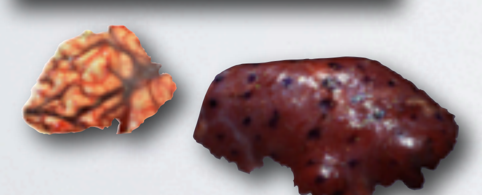


Tool calibrator by Traxtal Technologies (now Phillips Healthcare)

INTRAOPERATIVE DIGITIZATION

Laser Range Scanning

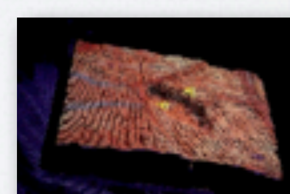




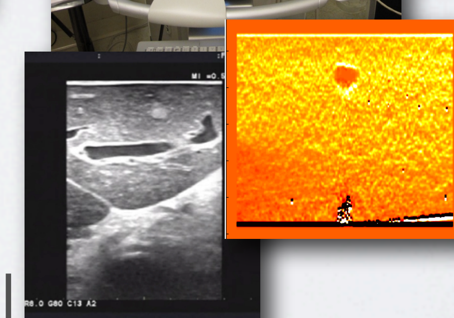
Imaging

Conoscopic Holography

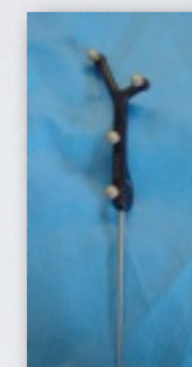
Stereo



Ultrasound



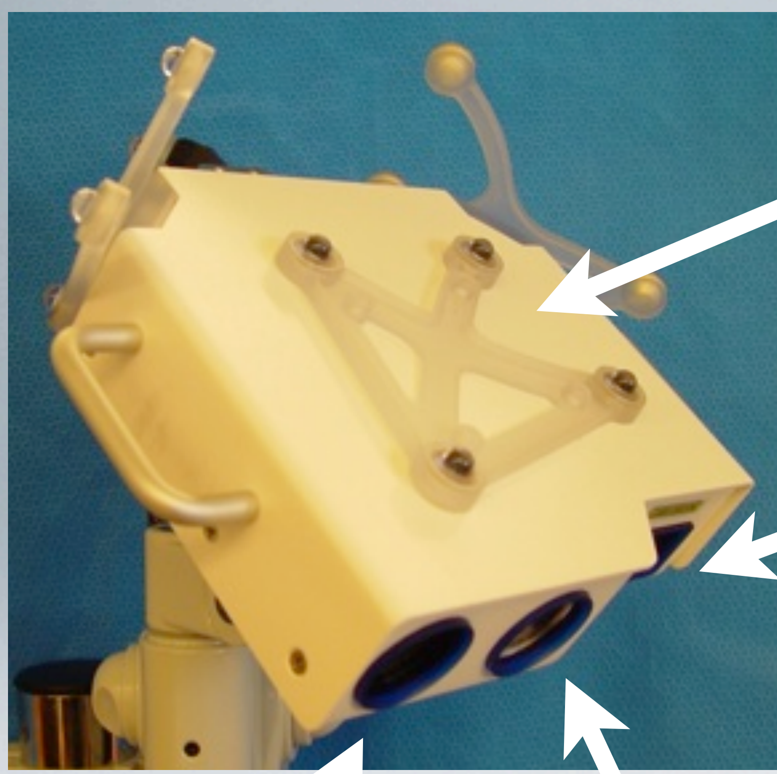
Pointer



non-contact

contact

INTRAOPERATIVE LASER RANGE SCAN ACQUISITION



tracking targets

laser port

light source

CCD

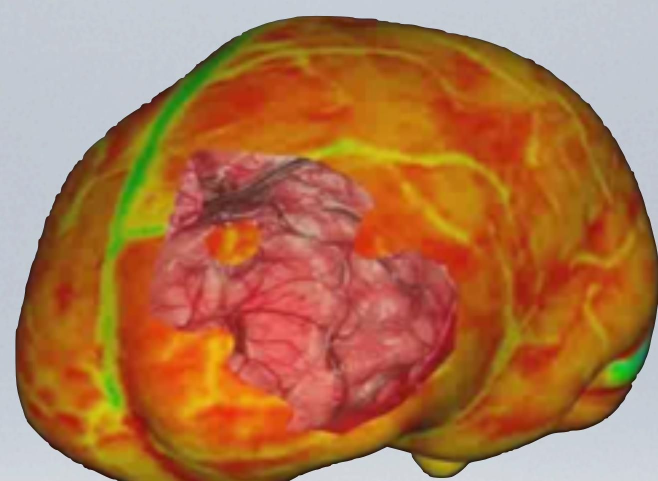
LRS

textured point cloud from LRS

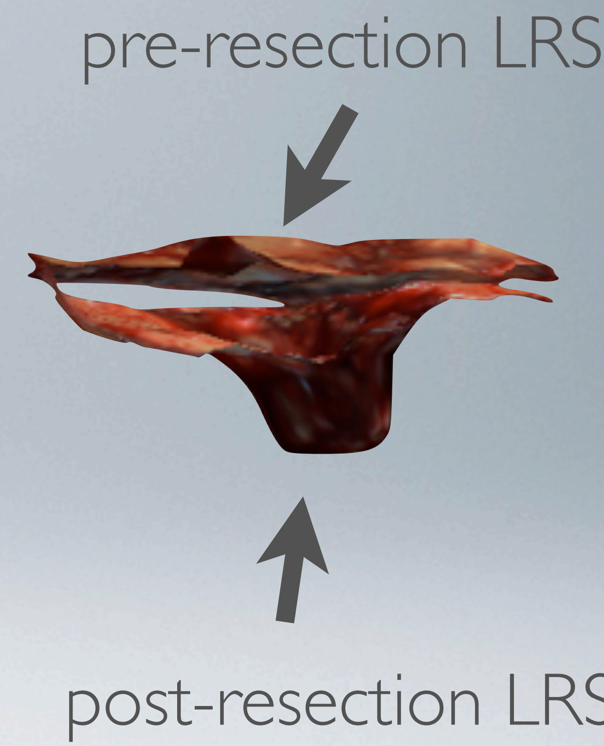
Source: T. S. Pheiffer, A. L. Simpson, B. Lennon, and M. I. Miga. Development and evaluation of a novel laser range scanner. Medical Physics, 39:2012.

REGISTRATION WITH LRS

face LRS after registration



subsequent LRS will align with MRI model

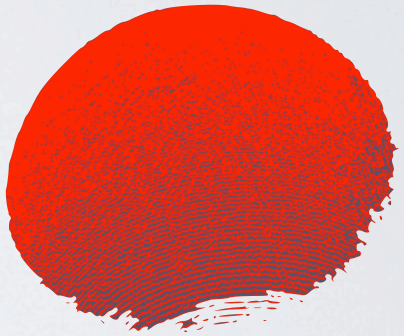


shift measurement

LRS NOISE MODELING

- measurement noise: in practice, measurements are not perfect
- recent results show a significant decrease in TRE is possible if optimal algorithms are used in the presence of anisotropic noise and if noise covariances are approximately known
- working on a rigid registration algorithm that uses this approach with the LRS as an acquisition method

Billiard Ball

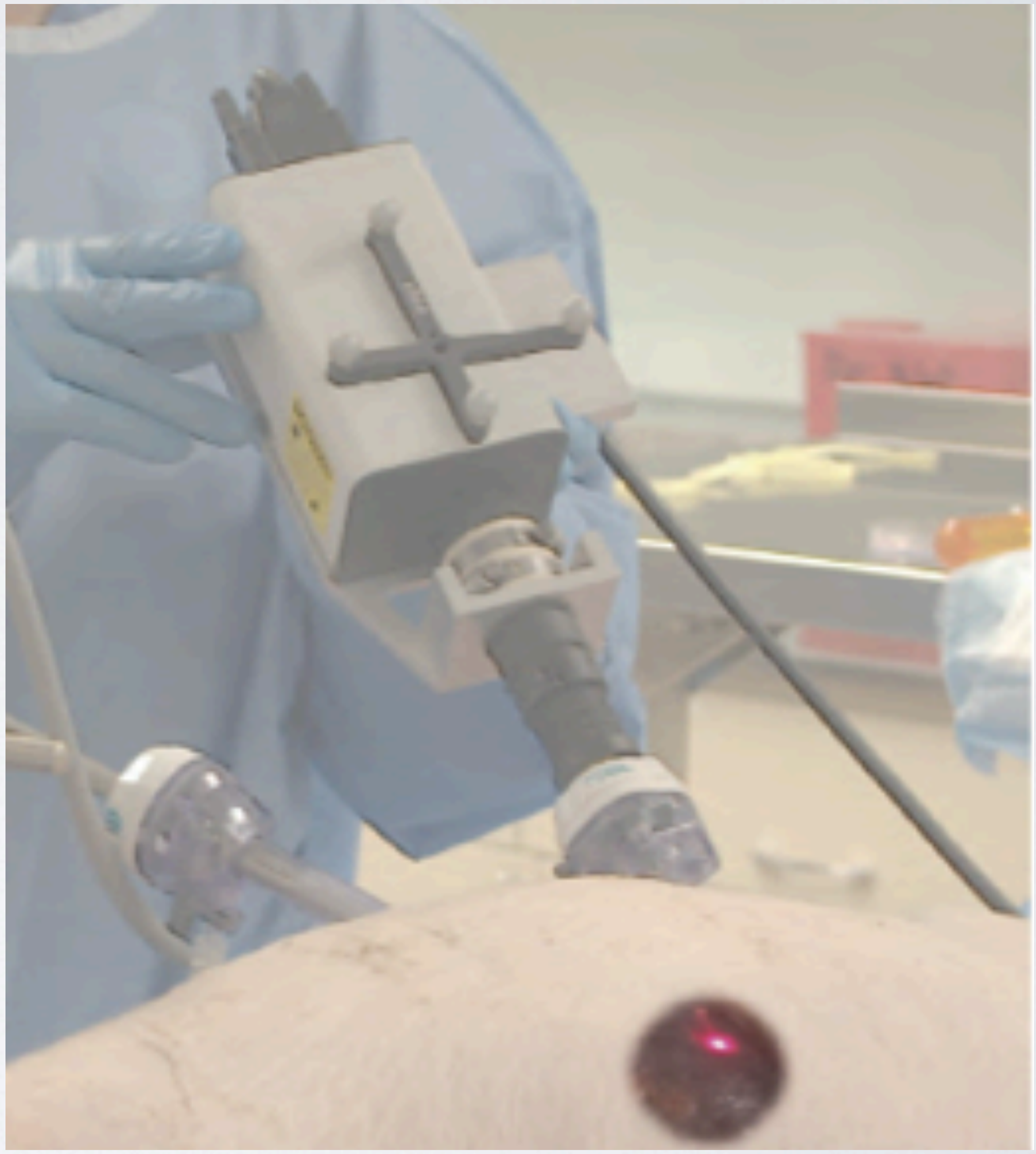


LRS of Ball

[1] B. Ma, M.H. Moghari, R. E. Ellis, and P. Abolmaesumi, Estimation of Optimal Fiducial Target Registration Error in the Presence of Heteroscedastic Noise, IEEE TMI 29(3), 2010.

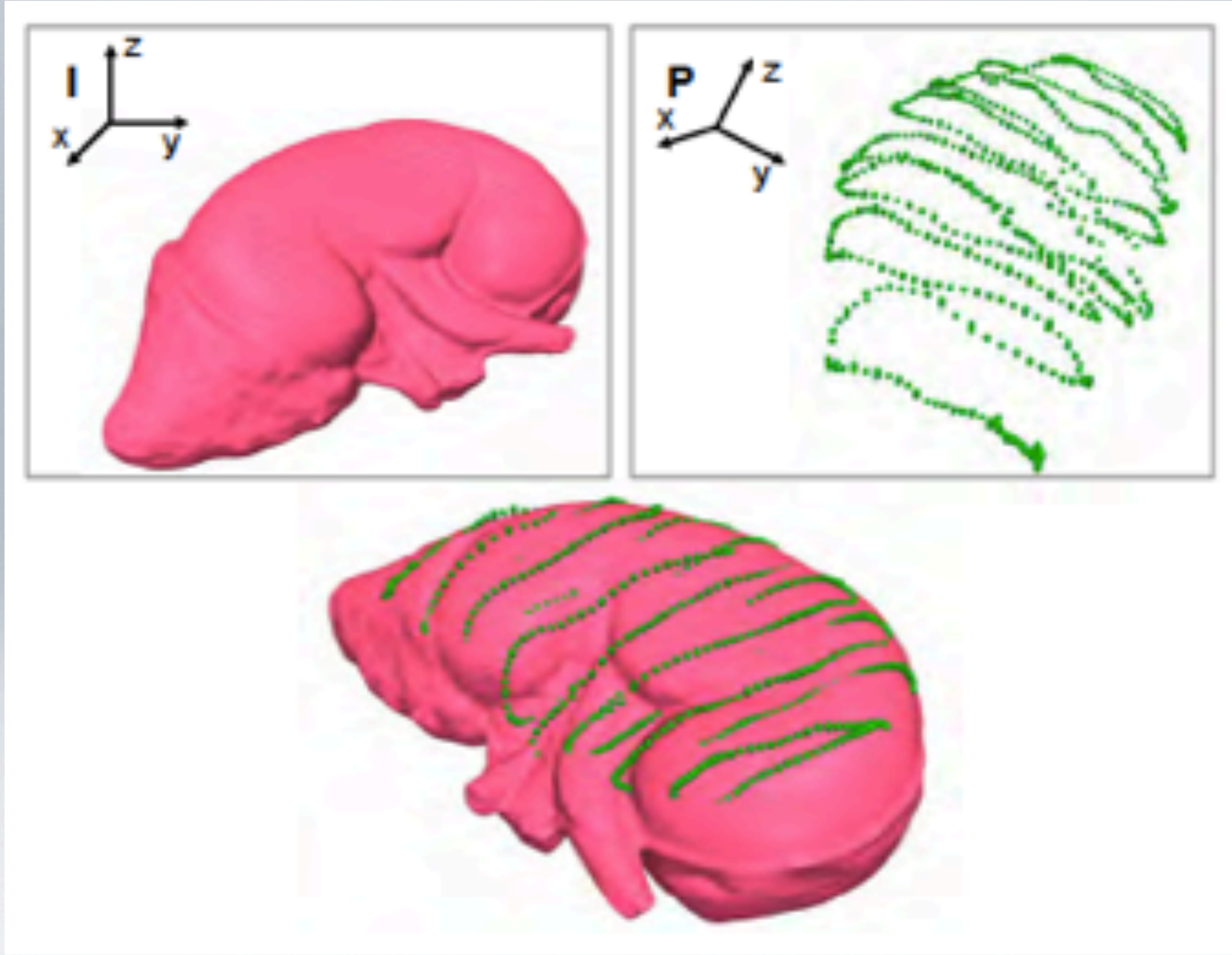
CONOSCOPIC HOLOGRAPHY

- conoscopic holography device reports distance from laser source to laser spot
- when tracked and calibrated, provides 3D point cloud
- conceived by Lathrop et al.



[1] R. A. Lathrop, D. M. Hackworth, and R. J. Webster. Minimally invasive holographic surface scanning for soft-tissue image registration. IEEE TBME, 57(6):1497–1506, 2010.

EXAMPLE REGISTRATION



Surface model of anthropomorphic kidney phantom and the conoscopic point data after surface registration.

Source: J. Burgner, A. L. Simpson, J. M. Fitzpatrick, R. A. Lathrop, S. D. Herrell, M. I. Miga, and R. J. Webster III. A Study on the Theoretical and Practical Accuracy of Conoscopic Holography-Based Surface Measurements: Toward Image Registration in Minimally Invasive Surgery, Accepted to IJMR-CAS, 2012.

ACCURACY OF CH

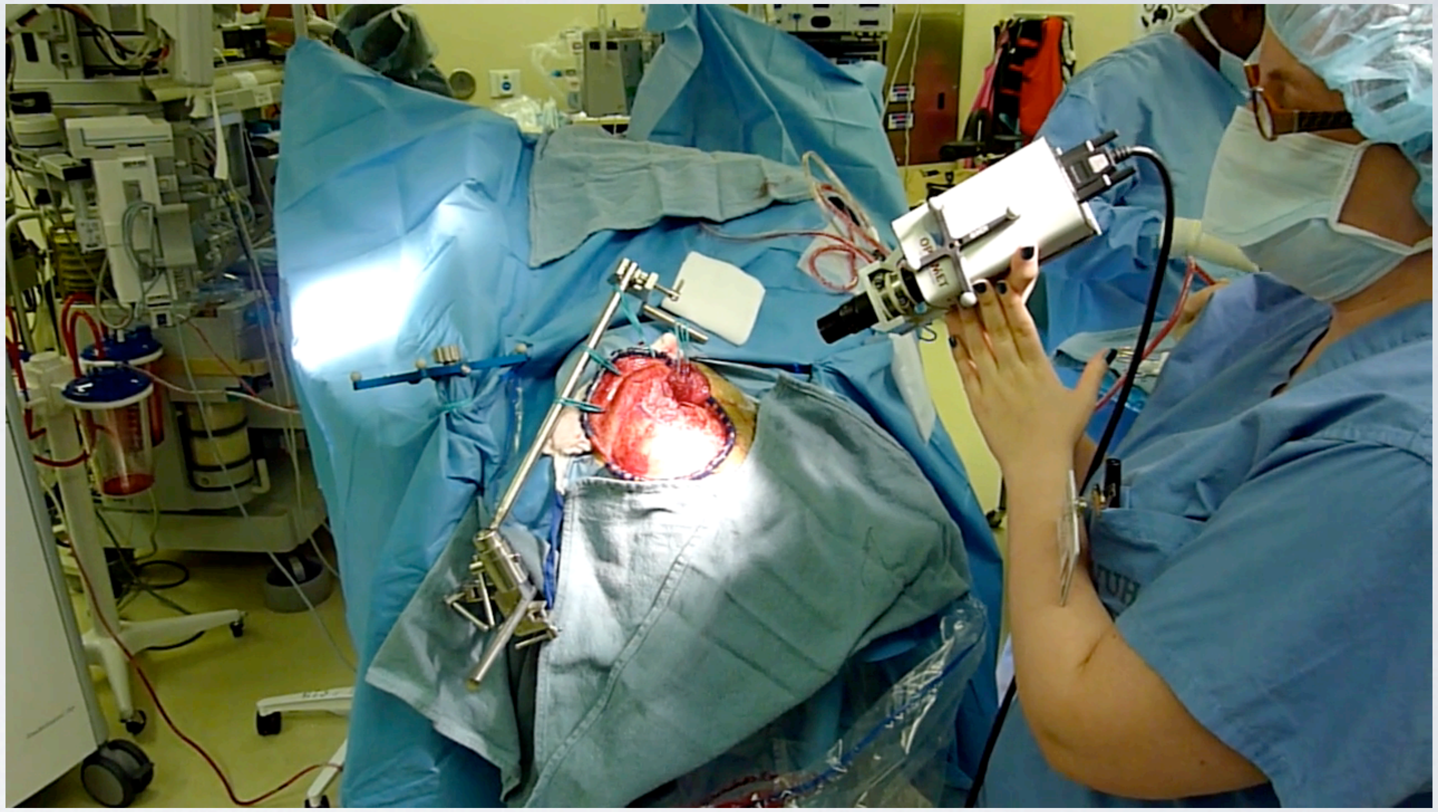
- FLE characteristics for the NDI Polaris Spectra and Optotrak Certus
- RMS TRE for the tracking system and variances are estimated for targets representing the the measurement range of the conoprobe (f - Δ/2,f ,f + Δ/2) for focal length f
- overall RMS TRE including the FLE of the conoprobe is stated. All values in mm.

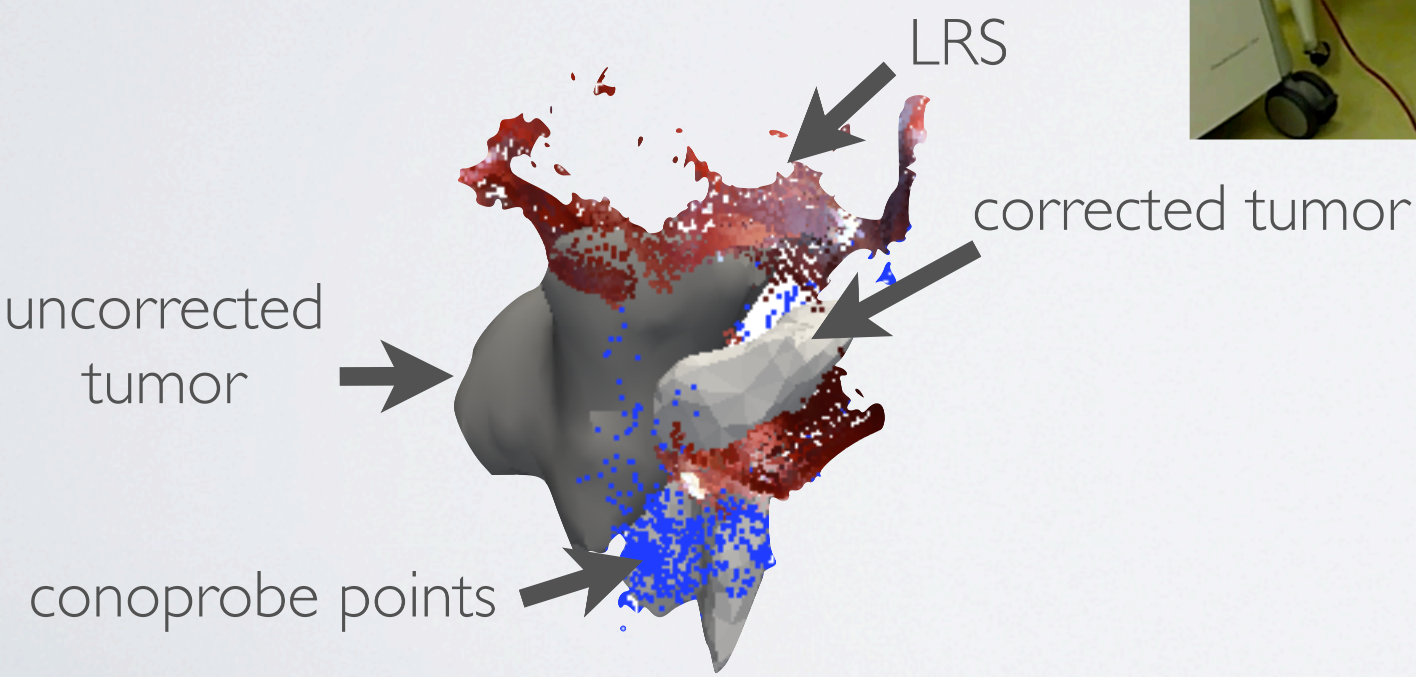
		Polaris Spectra	Optotrak Certus
	$RMS_{TRE}(T)$	0.70	0.27
$f-\Delta/2$	$[\sigma_x^2,\sigma_y^2,\sigma_z^2]\,(T)$	[0.33, 0.14, 0.02]	[0.05, 0.03, 0.0008]
	Total TRE_{min}	0.72	0.32
	$RMS_{TRE}(T)$	0.95	0.37
f	$[\sigma_x^2,\sigma_y^2,\sigma_z^2]\,(T)$	[0.63, 0.26, 0.02]	[0.08, 0.05, 0.0008]
	Total TRE_{focus}	0.97	0.40
	$RMS_{TRE}(T)$	1.21	0.46
$f+\Delta/2$	$[\sigma_x^2,\sigma_y^2,\sigma_z^2]\,(T)$	[1.03, 0.42, 0.02]	[0.14, 0.08, 0.0008]
	Total TRE_{max}	1.22	0.49

Source: J. Burgner, A. L. Simpson, J. M. Fitzpatrick, R. A. Lathrop, S. D. Herrell, M. I. Miga, and R. J. Webster III. A Study on the Theoretical and Practical Accuracy of Conoscopic Holography-Based Surface Measurements: Toward Image Registration in Minimally Invasive Surgery, Accepted to IJMR-CAS, 2012.

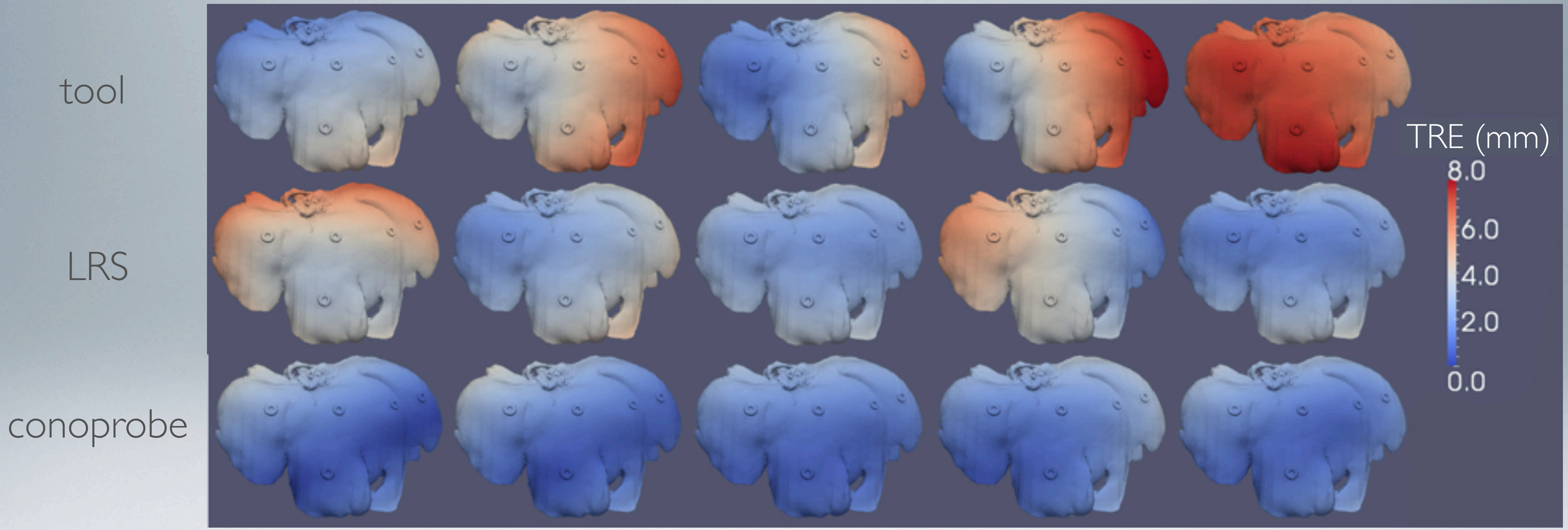
CH FOR VALIDATION

- use as independent measure for validation purposes
- swab resection cavity and compare to model prediction





EFFECT OF CONTACT VS NON-CONTACT ON REGISTRATION ERROR

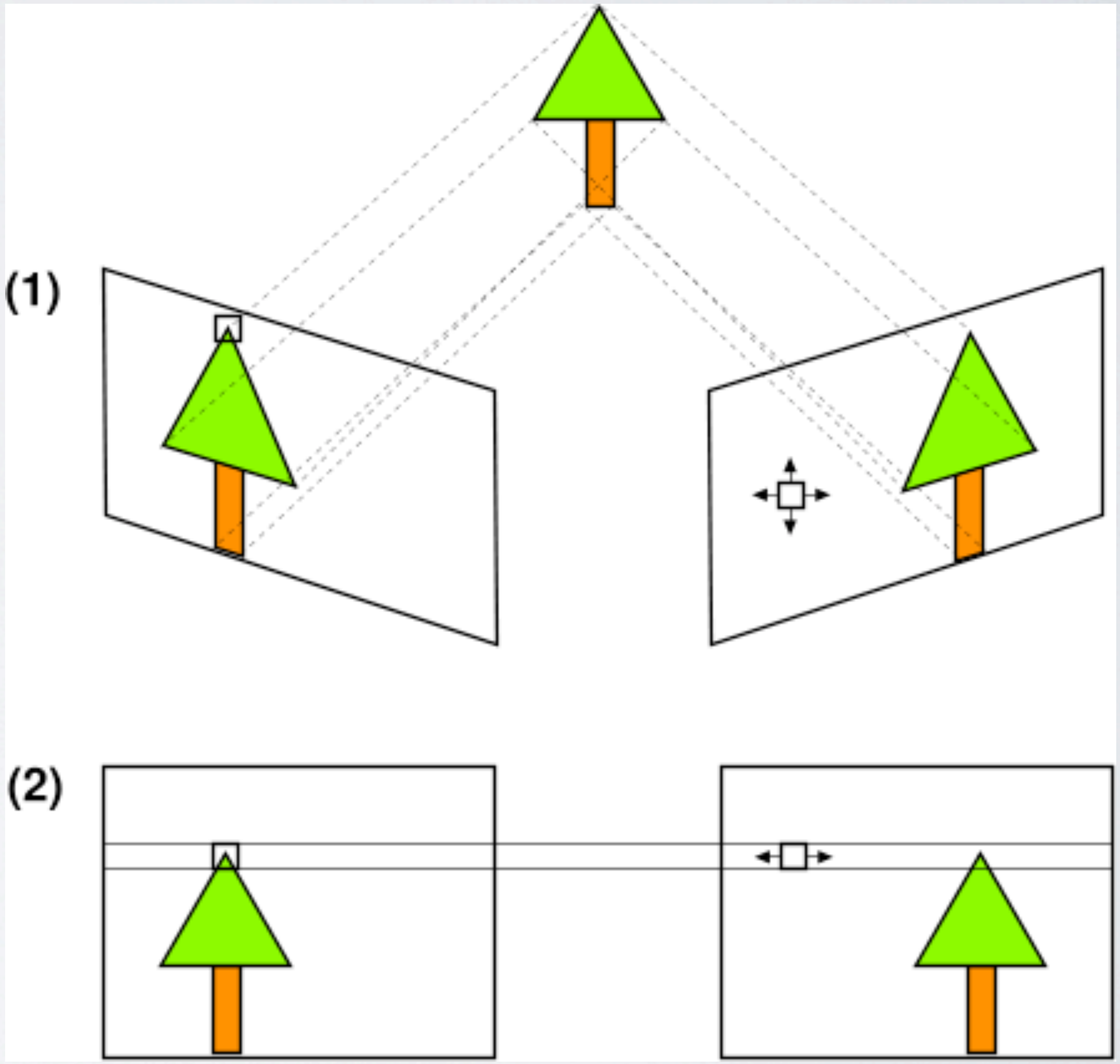


TRE computed using data from three acquisition methods for five trials. TRE increases from blue to white to red.

Source: A. L. Simpson, J. Burgner, C. L. Glisson, T. S. Pheiffer, S. D. Herrell, R. J. Webster III, and M. I. Miga. A comparison study of contact and non-contact surface acquisition methods with application to image-guided interventions, Submitted to IEEE TBME, November 2011 (in revision).

STEREO RECONSTRUCTION

- stereo vision uses triangulation to determine distance to an object
- using two cameras, we want to find a point viewed in one camera, in another camera



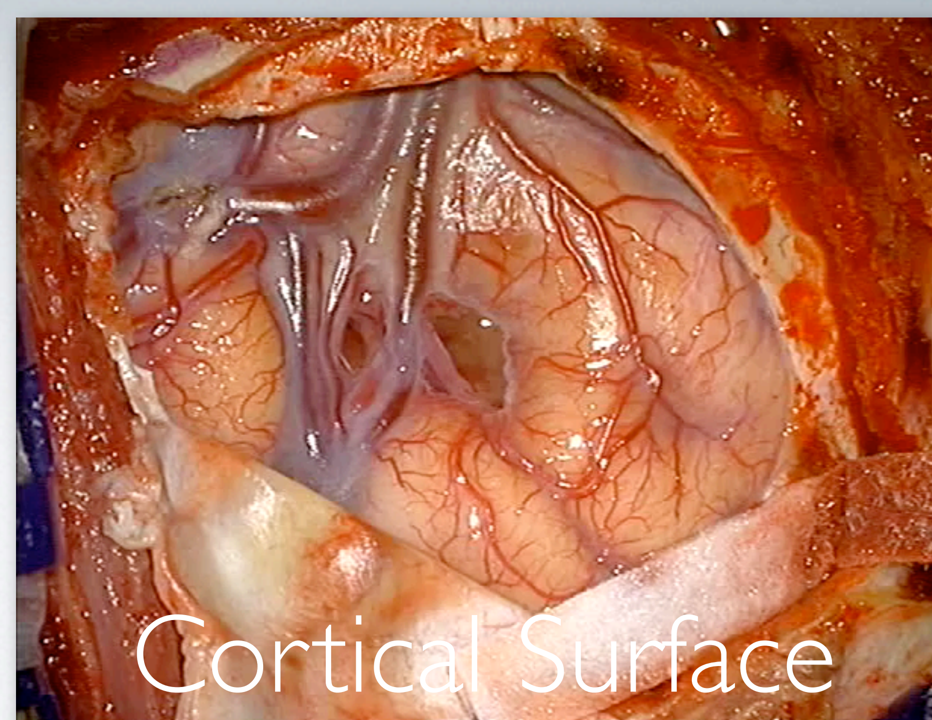
(1) before and (2) after rectification

Image Source: http://en.wikipedia.org/wiki/Image_rectification

OPERATING MICROSCOPE

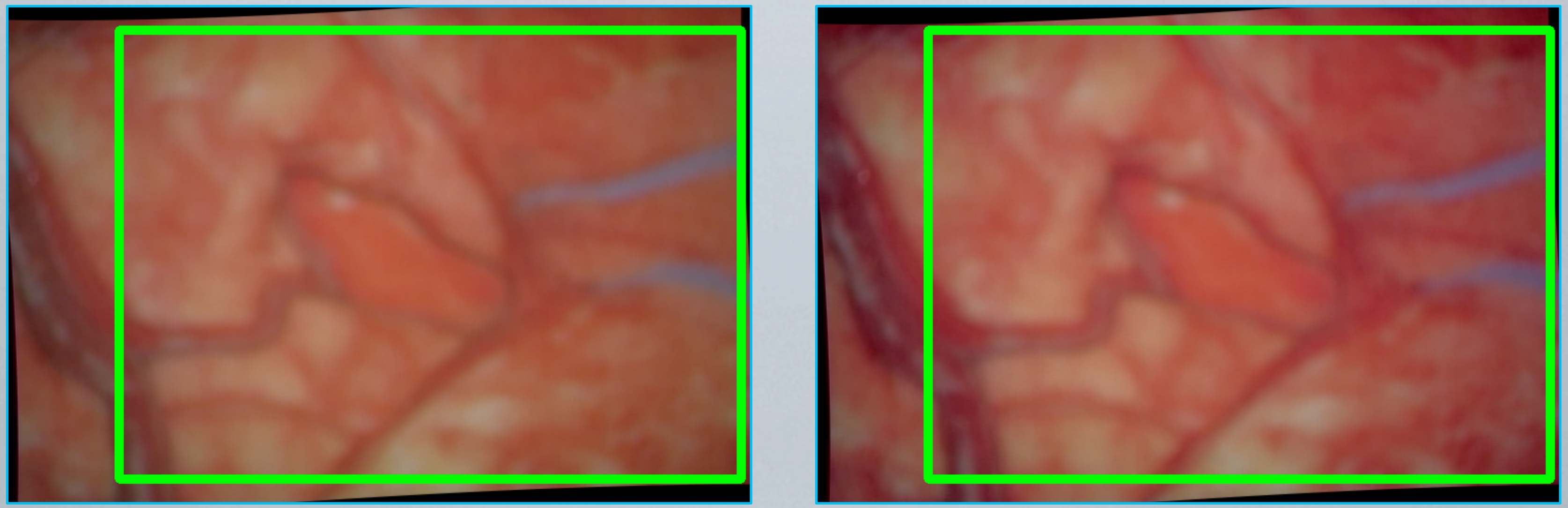
Zeiss Microscope at VUMC

Eye Piece



Cortical Surface

AFTER RECTIFICATION



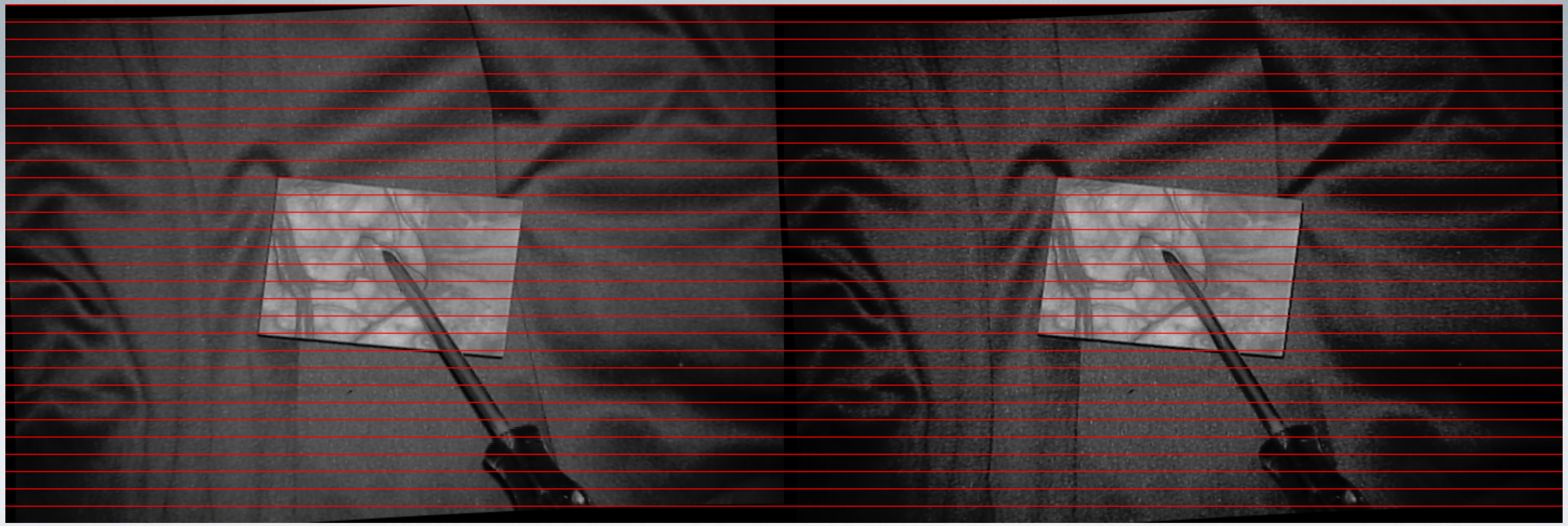
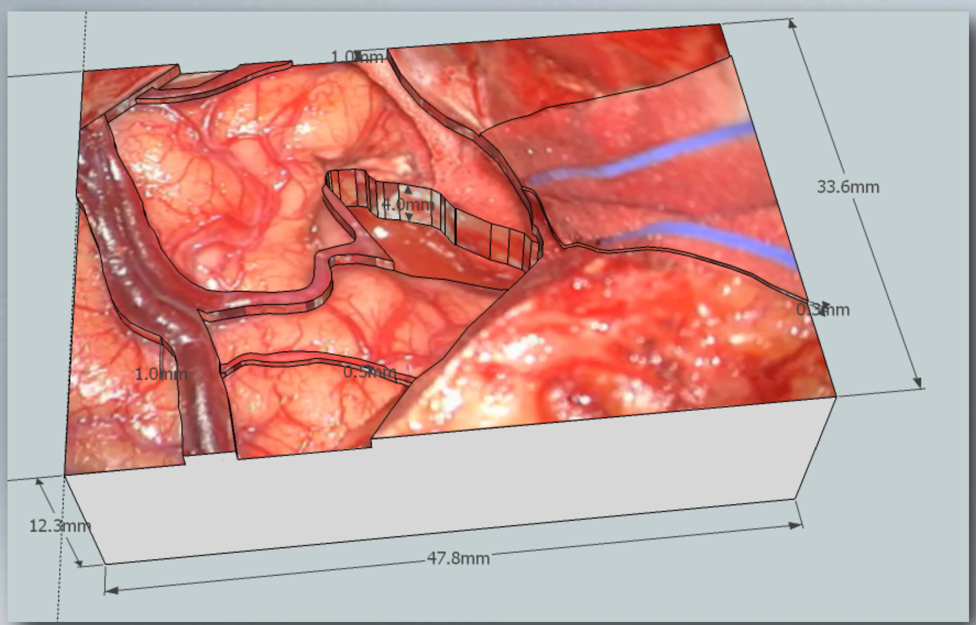
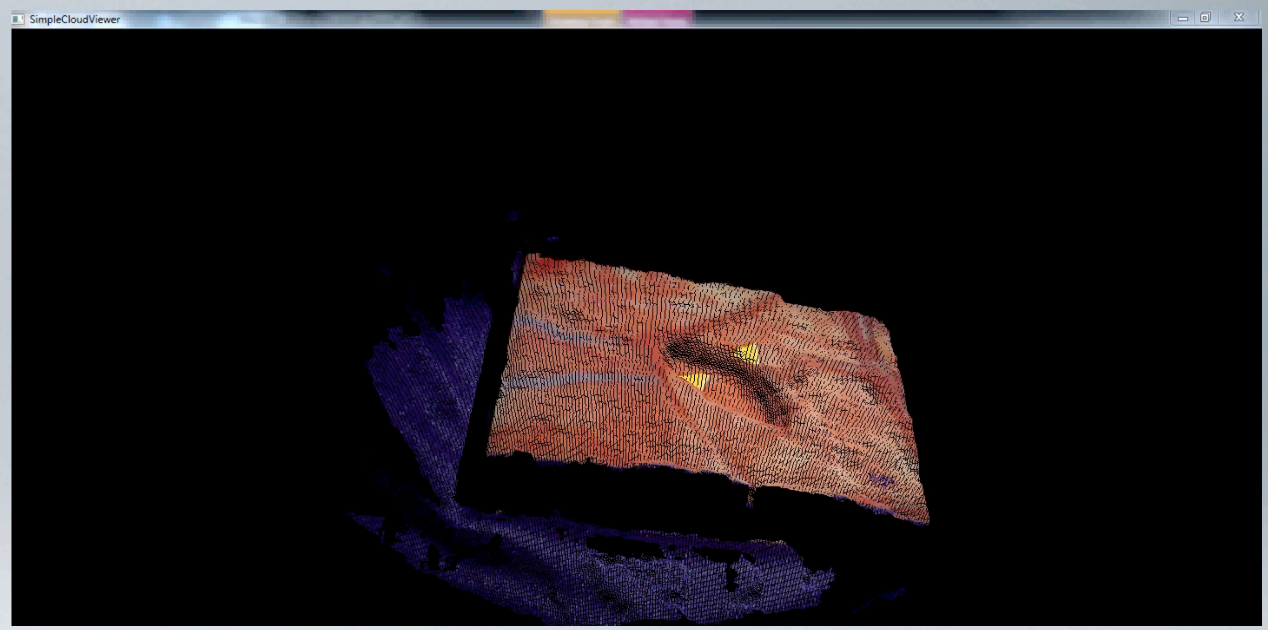


Image Source: Ankur Kumar

STEREO RECONSTRUCTION



Object



Reconstructed Point Cloud

Image Source: Ankur Kumar

IMAGING

- flat-panel C-arm operating room (Allura Xper FD20/20, Philips Medical Systems) in VUMC OR 10 (can only scan phantoms and cadaveric tissue due to possible contamination)

Allura C-arm

- Xoran xCAT portable CT

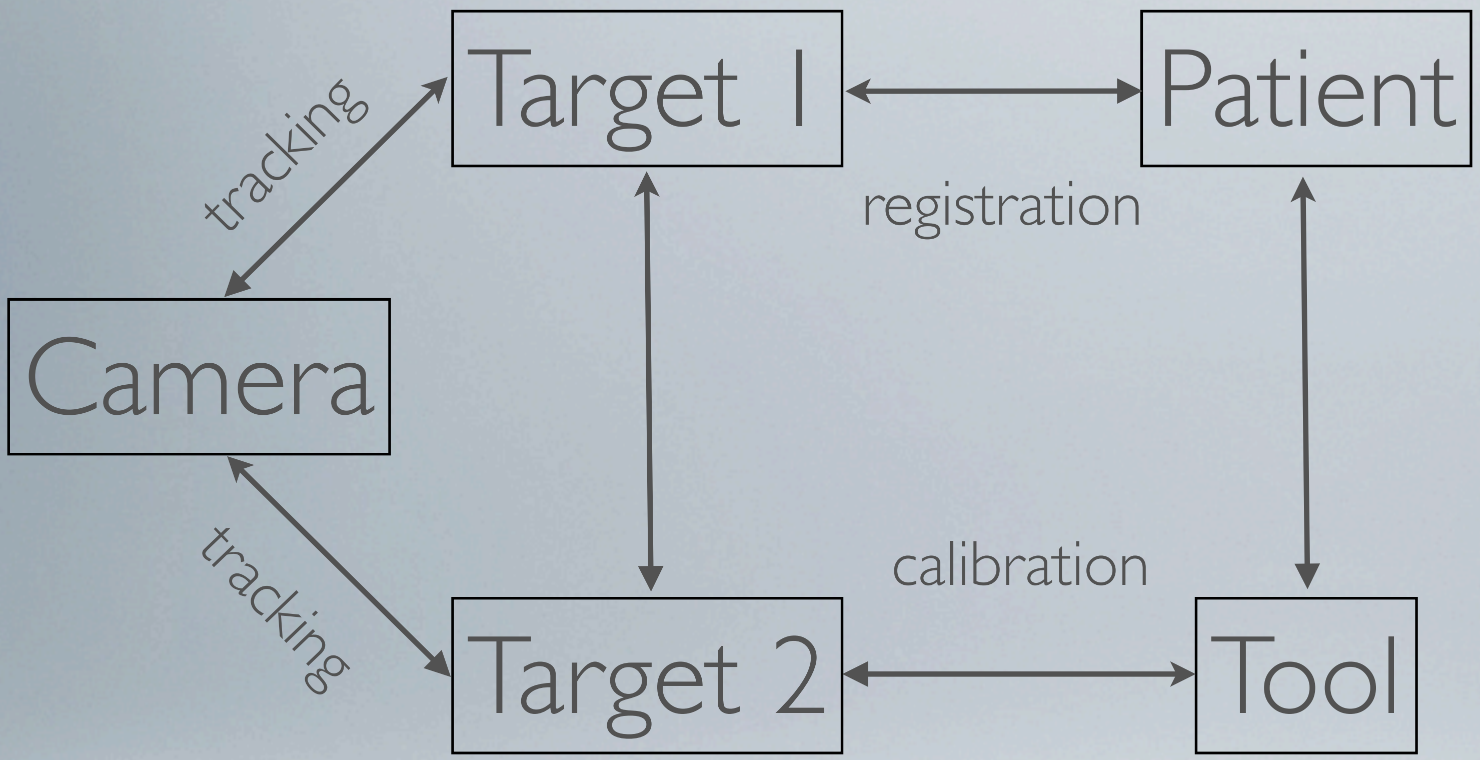
- CT in radiology (no animal tissue)

Xoran xCAT

- VUIIS (animal + cadaveric)

Image Sources: Ramya Balachandran and Jessica Burgner

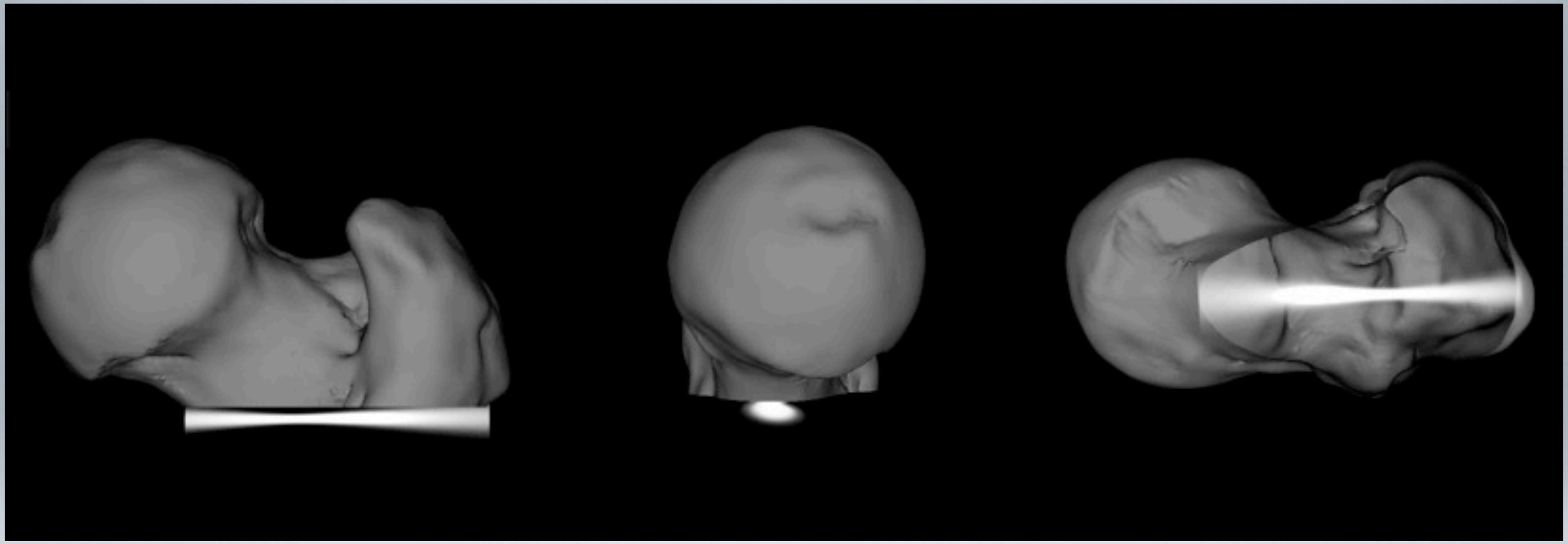
UNCERTAINTY PROPAGATION



SURGICAL NAVIGATION

A. L. Simpson, Computation and Visualization of Uncertainty in Computer-Assisted Surgery, PhD Thesis, School of Computing, Queen's University, Kingston, Ontario, Canada, 2010.

UNCERTAINTY VISUALIZATION



Model of the proximal femur showing the uncertainty visualization of the planned path between the lateral cortex and the target point (location of tumor) on the medial inferior neck.

A. L. Simpson, B. Ma, E. C. S. Chen, R. E. Ellis, and A. J. Stewart. Using Registration Uncertainty Visualization in a User Study of a Simple Surgical Task. In Medical Image Computing and Computer Assisted Intervention (MICCAI 2006), pages 397-404. Springer Lecture Notes in Computer Science 4191, 2006.

UNCERTAINTY PROPAGATION

- guidance display shows the CT and the tracked tool in CT coordinates so we transform:

$$\mathbf{T}_{tip}^{CT} = \mathbf{T}_{patient}^{CT} \, (\mathbf{T}_{patient}^{world})^{-1} \, \mathbf{T}_{tool}^{world} \, \mathbf{T}_{tip}^{tool}$$

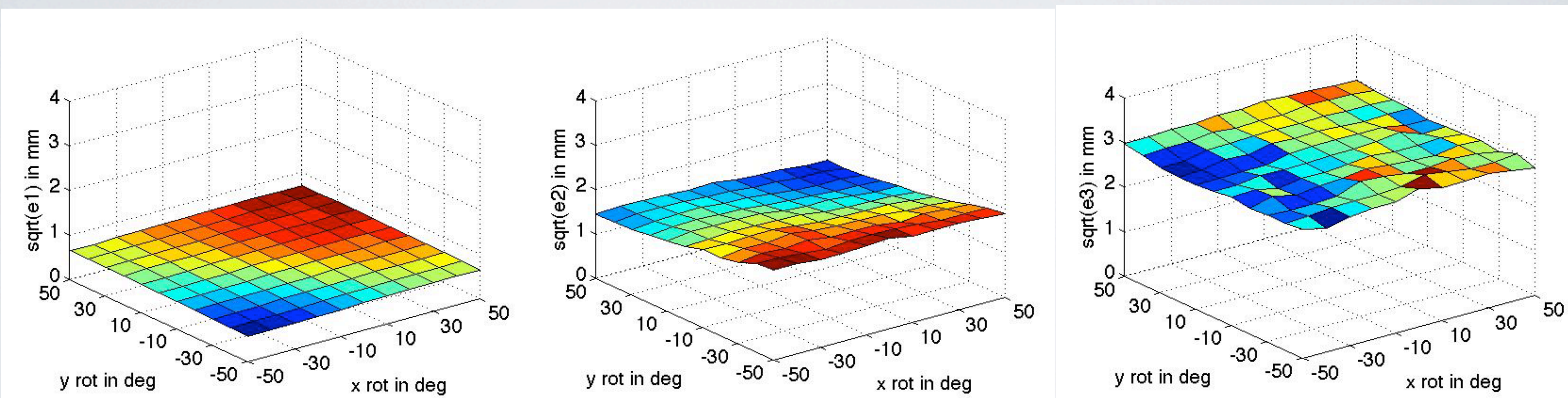
- each transformation has a covariance; we must propagate the uncertainties accordingly

- let $\mathbf{C_x}$ be the covariance of $\mathbf{x}$ and $\mathbf{C_w}$ be the covariance of $\mathbf{w}$, then the covariance of the combined transformation $\mathbf{C_y}$ is:

$$\mathbf{C_y} = \mathbf{J_x C_x J_x^{\mathit{T}}} + \mathbf{J_w C_w J_w^{\mathit{T}}}$$

where $\mathbf{J_x}$ is the Jacobian of $\mathbf{x}$ and $\mathbf{J_w}$ the Jacobian of $\mathbf{w}$

UNCERTAINTY MAGNITUDES

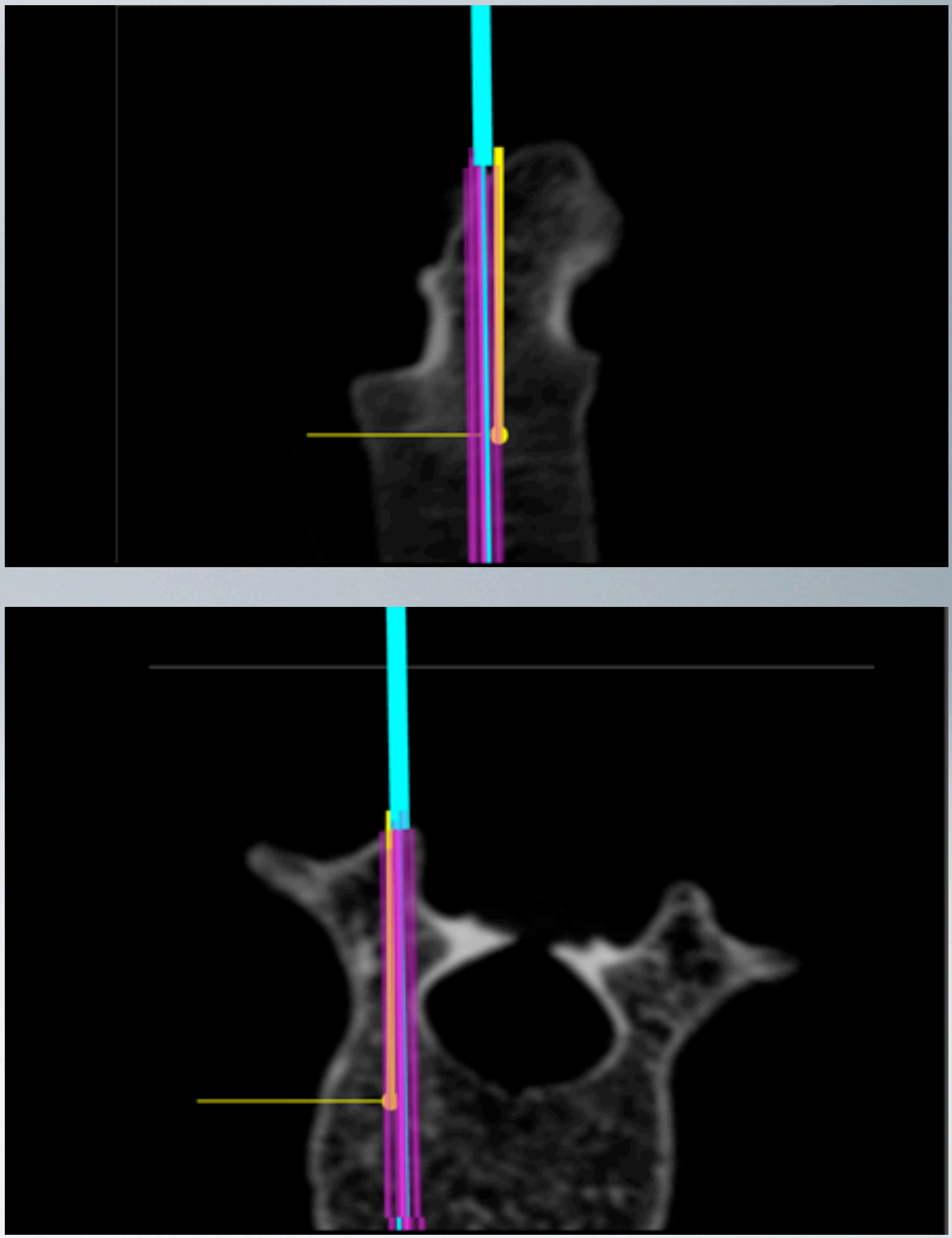


A sample covariance in tip position (x, y, z) measured by our model when registration and calibration covariance are factored in.

A. L. Simpson, B. Ma, R. E. Ellis, A. J. Stewart, and M. I. Miga, Uncertainty propagation and analysis of image-guided surgery, SPIE 2011 Medical Imaging: Visualization, Image-Guided Procedures, and Modeling Conference, Editors: K. H. Wong and D. R. Holmes III, Vol. 7964, 2011.

COVARIANCE PROPAGATION

Estimates of uncertainty from tracking, calibration, and registration can be propagated into the tip of a surgeon's tool, as the tool moves through space.



A. L. Simpson, E. M. Vasarhelyi, D. P. Borschneck, R. E. Ellis, B. Ma, and A. J. Stewart. Computation and Visualization of Uncertainty during Computer-Assisted Surgery, Submitted to IEEE Transactions on Visualization and Computer Graphics, 2012.