Uncertainty: the barrier to automate medicine

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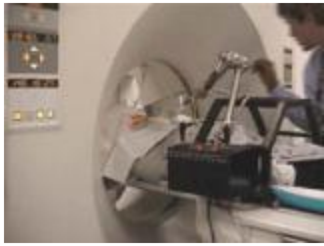
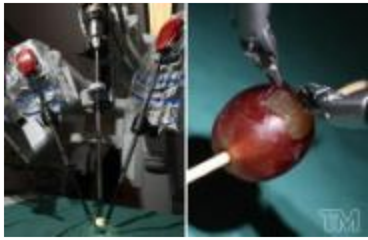
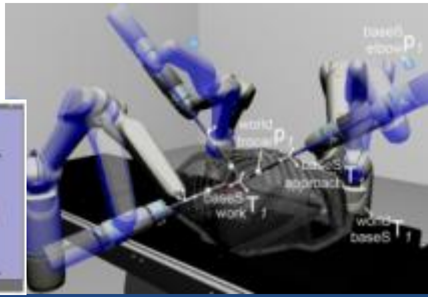
You name it!

- CIS: Computer-Integrated Surgery
- CIIM: Computer-Integrated Interventional Medicine
- CAS: Computer-Assisted Surgery
  Computer-Aided Surgery
- IGS(T): Image-Guided Surgery (Therapy)
- MIS: Minimally Invasive Surgery

- Surgical CAD/CAM
  - CASD Computer Aided Surgical Design
  - CASM Computer Aided Surgical Manufacturing
- Surgical Total Quality Management

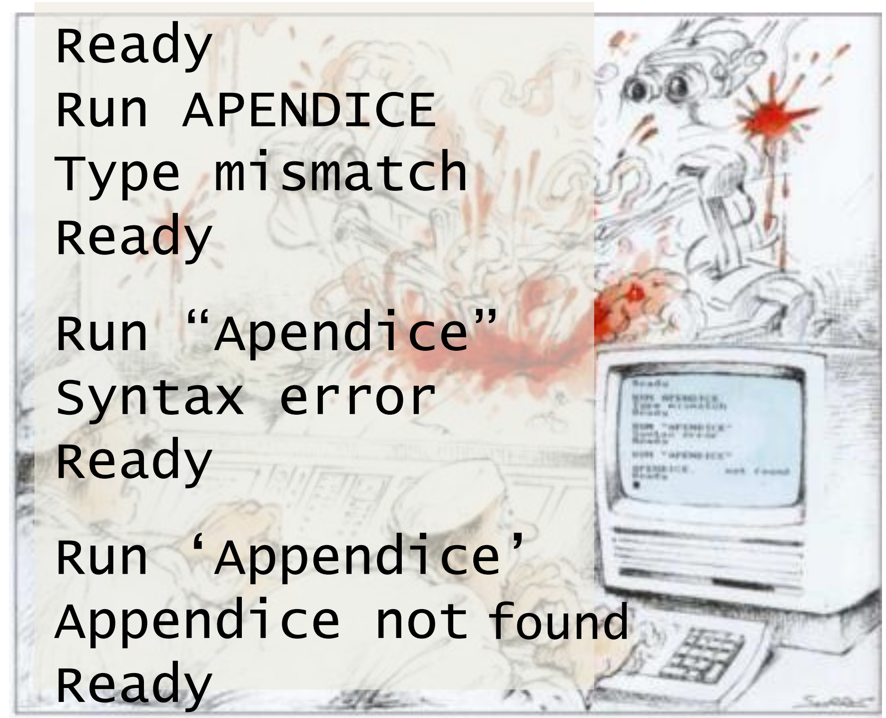

Patient treatment

Errors mean risk and danger

No routine operation

Inherent danger originating form HW&SW

- Robot structure
- End effectors
- Sterility
- Software bug
- Interference of devices
- etc.



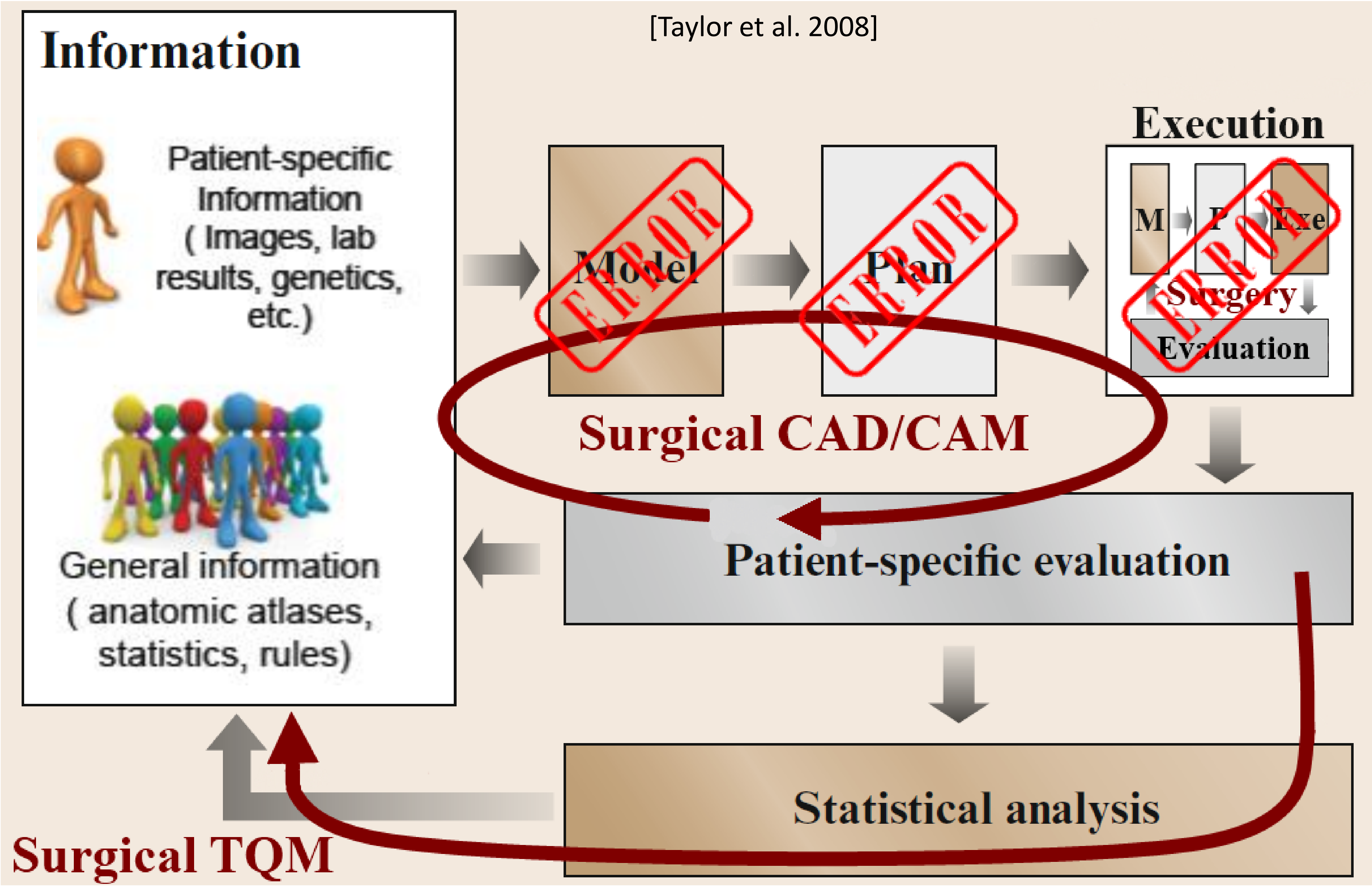
```
Ready
Run APENDICE
Type mismatch
Ready

Run "Apendice"
Syntax error
Ready

Run 'Appendice'
Appendice not found
Ready
```

Sources of errors

- Imaging errors
- Volume model generation errors
- Treatment planning errors
- **Registration errors**
- **Errors introduced by hardware fixturing**
- **Intra-operative data noise**
- **Inherent inaccuracies of surgical tools and actions**
- **System components' integration**
- Patient motion
- Physiological tissue motion

Credit: Renishaw plc

Concept of CIS



Facing the challenges in CIS

Different approaches

Investigating methods to improve the accuracy of treatment delivery

- Human-in-the-loop control
  - Leave the mapping to the surgeon

- Registration (image) based
  - Human oversight

Credit: CUREXO Inc.

Accuracy metrics

Originating from the industry

Inherent accuracy of system components

- Accuracy vs. repeatability

Use of phantoms (artifacts) for testing

From medical imaging (point-based registration)

FRE, FLE, TRE and similars

Problems with measurements

Accuracy of *treatment delivery* is important

- Difficult to measure routinely
- Single numbers are not meaningful

Ultimate goal

task specific measurement of uncertainty

Accuracy numbers

Robot	Company	Intrinsic accuracy	Repeat.	Application accuracy
Puma 200	Memorial Medical Center		**0.05**	**2**
ROBODOC	Int. Surgical Systems Inc. Curexo Tech. Corporation	**0.5 – 1.0**		**1.0 – 2.0**
NeuroMate	Inn. Medical Machines Int. Int. Surgical Systems Inc. Renishaw plc	**0.75 / 0.6** **0.36 ± 0.17**	**0.15**	**0.86 ± 0.32** **1.95 ± 0.44**
da Vinci	Intuitive Surgical Inc.	**1.35** **1.02 ± 0.58**		
da Vinci S	Intuitive Surgical Inc.	**1.05 ± 0.24**		
CyberKnife	Accuray Inc.			**0.42 ± 0.4** **0.93±0.29**
B-Rob I	ARC GmbH, Seibersdorf			**1.48 ± 0.62**
B-Rob II	ACMIT (ARC GmbH)			**0.66 ± 0.27** **1.1 ± 0.8**
SpineAssist	Mazor Surgical Technologies			**0.87 ± 0.63**

All values are in mm

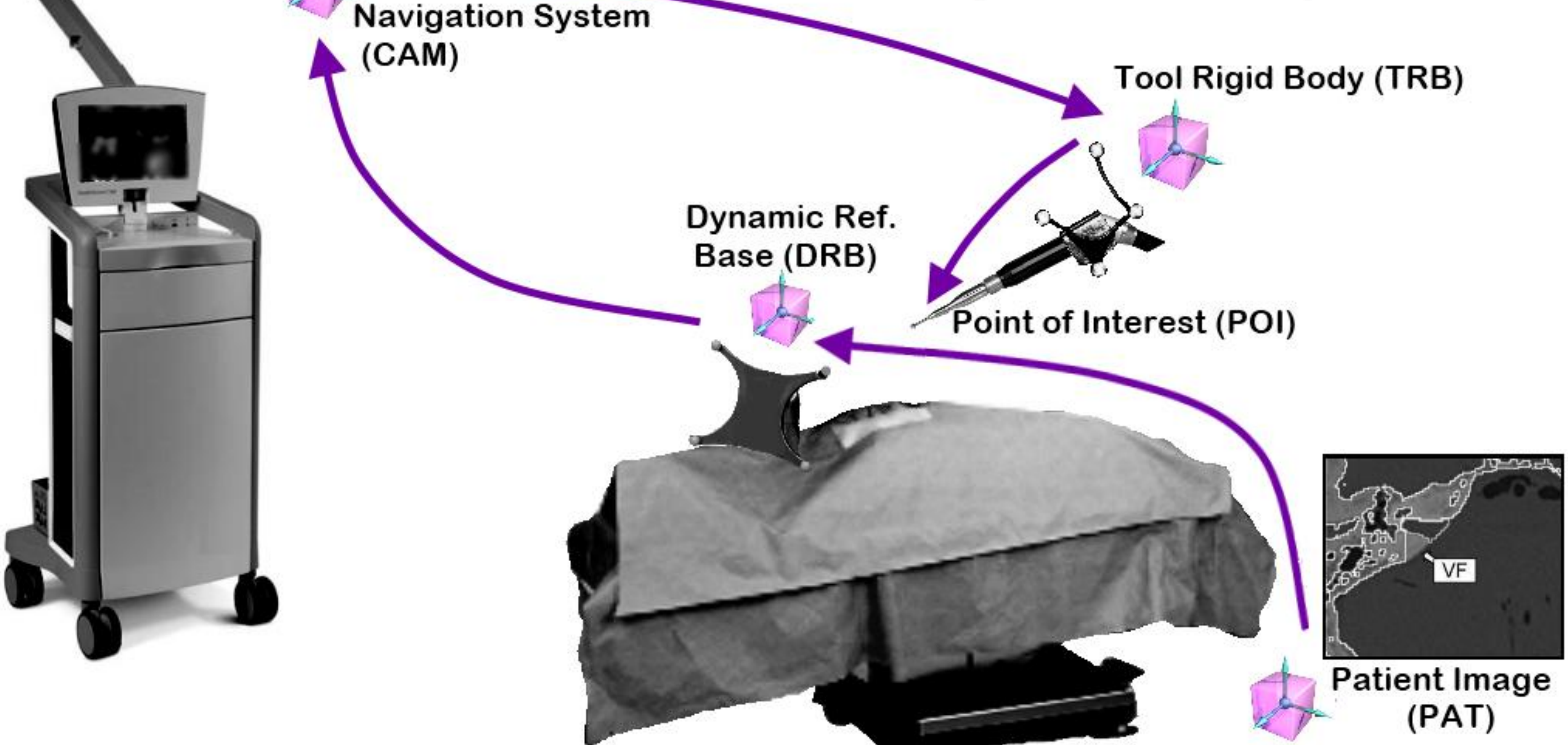
Error in integrated systems

Integrated IGS setups

$$ {}^{PAT}_{POI}\mathbf{T} = {}^{TRB}_{POI}\mathbf{T} \cdot {}^{CAM}_{TRB}\mathbf{T} \cdot {}^{DRB}_{CAM}\mathbf{T} \cdot {}^{PAT}_{DRB}\mathbf{T} $$

$$ {}^{PAT}_{POI}\mathbf{T} = f(\mathbf{t}) + f(\Delta\mathbf{t}) $$

$$ {}^{A}_{B}\mathbf{T} \xrightarrow{\text{Rot2Euler}} \mathbf{t} = [x, y, z, \phi, \theta, \psi] $$



Erroneous transformation matrix calculation

$$ {}_{\mathrm{B}}^{\mathrm{A}}\widetilde{\mathbf{T}} = {}_{\mathrm{B}}^{\mathrm{A}}\mathbf{T} \cdot \Delta {}_{\mathrm{B}}^{\mathrm{A}}\mathbf{T} \text{ and } \Delta {}_{\mathrm{B}}^{\mathrm{A}}\mathbf{T}_{\mathrm{Rot}} \approx \mathbf{I} + \theta \mathbf{N} $$

$$ {}_{\mathrm{B}}^{\mathrm{A}}\mathbf{T}_{\mathrm{Rot}}(\mathbf{n}, \theta) = e^{\theta \mathbf{N}}, \text{ where } \mathbf{N} = \begin{bmatrix} 0 & -n_z & n_y \\ n_z & 0 & -n_x \\ -n_y & n_x & 0 \end{bmatrix} $$

$$ \Delta {}_{\mathrm{B}}^{\mathrm{A}}\mathbf{T}_{\mathrm{Rot}} \cdot \Delta {}_{\mathrm{B}}^{\mathrm{A}}\mathbf{T}_{\mathrm{Trans}} \approx \Delta {}_{\mathrm{B}}^{\mathrm{A}}\mathbf{T}_{\mathrm{Trans}} $$

$$ \tilde{\mathbf{x}}_A = \mathbf{x}_A + \Delta \mathbf{x}_A $$

$$ \tilde{\mathbf{x}}_B = {}_{\mathrm{B}}^{\mathrm{A}}\widetilde{\mathbf{T}} \mathbf{x}_A = \mathbf{x}_B + \Delta \mathbf{x}_B $$

$$ \Delta \mathbf{x}_B = {}_{\mathrm{B}}^{\mathrm{A}}\mathbf{T}_{\mathrm{Rot}} \left(\theta \mathbf{N} \mathbf{x}_A + \Delta \mathbf{x}_A + \Delta {}_{\mathrm{B}}^{\mathrm{A}}\mathbf{T}_{\mathrm{Trans}} \right) $$

where **X** is a 3D point and *Θ* is an angle of rotation.

Propagation of errors II

Covariance matrix based approximation

$$\mathbf{\Sigma}_{\mathbf{x}_i} = \mathbf{E}\{\Delta\mathbf{x}_i\Delta\mathbf{x}_i^{\mathrm{T}}\} = \mathbf{E}\{(\mathbf{x}_i - \tilde{\mathbf{x}}_i)(\mathbf{x}_i - \tilde{\mathbf{x}}_i)^{\mathrm{T}}\}$$

$$\mathbf{x}_B = f(\mathbf{x}_A, \mathbf{t})$$

$$\Delta\mathbf{x}_B = \left.\frac{\partial f(\mathbf{x}_A, \mathbf{t})}{\partial \mathbf{t}}\right|_{\mathbf{t}=\tilde{\mathbf{t}}} = \mathbf{J}_f \Delta\mathbf{t}$$

$$\Delta\mathbf{t} = (\mathbf{J}_f^{\mathrm{T}}\mathbf{J}_f)^{-1}\mathbf{J}_f^{\mathrm{T}}\Delta\mathbf{x}_B$$

Error covariance:

$$\mathbf{\Sigma}_{\mathbf{t}} = \mathbf{E}\{\Delta\mathbf{t}\Delta\mathbf{t}^{\mathrm{T}}\} = (\mathbf{J}_f^{\mathrm{T}}\mathbf{J}_f)^{-1}\mathbf{J}_f^{\mathrm{T}} \overbrace{\begin{bmatrix} \mathbf{\Sigma}_{\mathbf{x}_B} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \mathbf{\Sigma}_{\mathbf{x}_B} \end{bmatrix}}^{\bar{\mathbf{\Sigma}}_{\mathbf{x}_B}} ((\mathbf{J}_f^{\mathrm{T}}\mathbf{J}_f)^{-1}\mathbf{J}_f^{\mathrm{T}})^{\mathrm{T}}$$

Propagation:

$$\mathbf{\Sigma}_f = \mathbf{E}\{(\mathbf{J}_f\Delta\mathbf{x}_A)(\mathbf{J}_f\Delta\mathbf{x}_A)^{\mathrm{T}}\} = \mathbf{J}_f\mathbf{\Sigma}_{\mathbf{x}_A}\mathbf{J}_f^{\mathrm{T}}$$

$$\mathbf{\Sigma}_{f^{-1}} = \mathbf{J}_{f^{-1}}\mathbf{\Sigma}_{\mathbf{x}_A}\mathbf{J}_{f^{-1}}^{\mathrm{T}} = (\mathbf{J}_f^{\mathrm{T}}\mathbf{\Sigma}_{\mathbf{x}_A}^{-1}\mathbf{J}_f)^{-1}$$

$$\mathbf{t} = [x, y, z, \phi, \theta, \psi]$$

[Bauer et al. 2006]

Stochastic approach to CIS

Modeling for complex system noise

$$ {}^{\mathrm{PAT}}_{\mathrm{POI}}\mathbf{T} = f(\mathbf{t}) + f(\Delta\mathbf{t}) $$

Calculate the integral of the probability distribution function over the unsafe region (e.g., out of a Virtual Fixture):

$$ \mathbf{P}(\mathrm{POI} \notin \mathrm{VF}) = \int_{\mathbf{t} \notin \mathrm{VF}} f(\mathbf{t})\,\mathrm{d}\mathbf{t} $$

Scaling for safety features to critical locations:

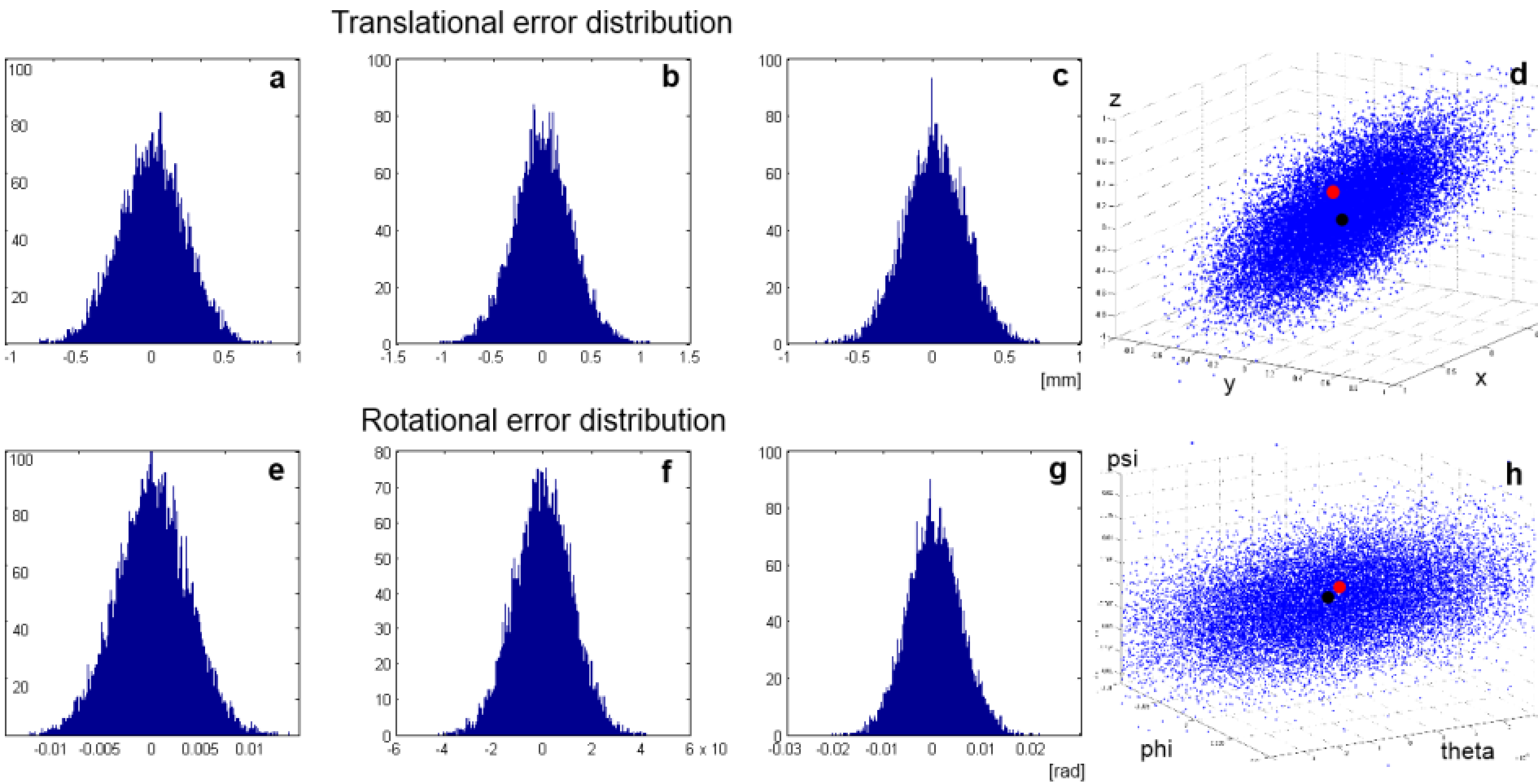
$$ \eta = w_1 \mathbf{P}(\mathrm{POI} \notin \mathrm{VF}_1) + w_2 \mathbf{P}(\mathrm{POI} \notin \mathrm{VF}_2) + \ldots $$

Stochastic approach allows to derive the distribution of the erroneous POI

Application to integrated systems

Modeling for complex system noise

STD: [0.32, 0.28, 0.30, 0.002, 0.003, 0,005] along $[x, y, z, \phi, \theta, \psi]$

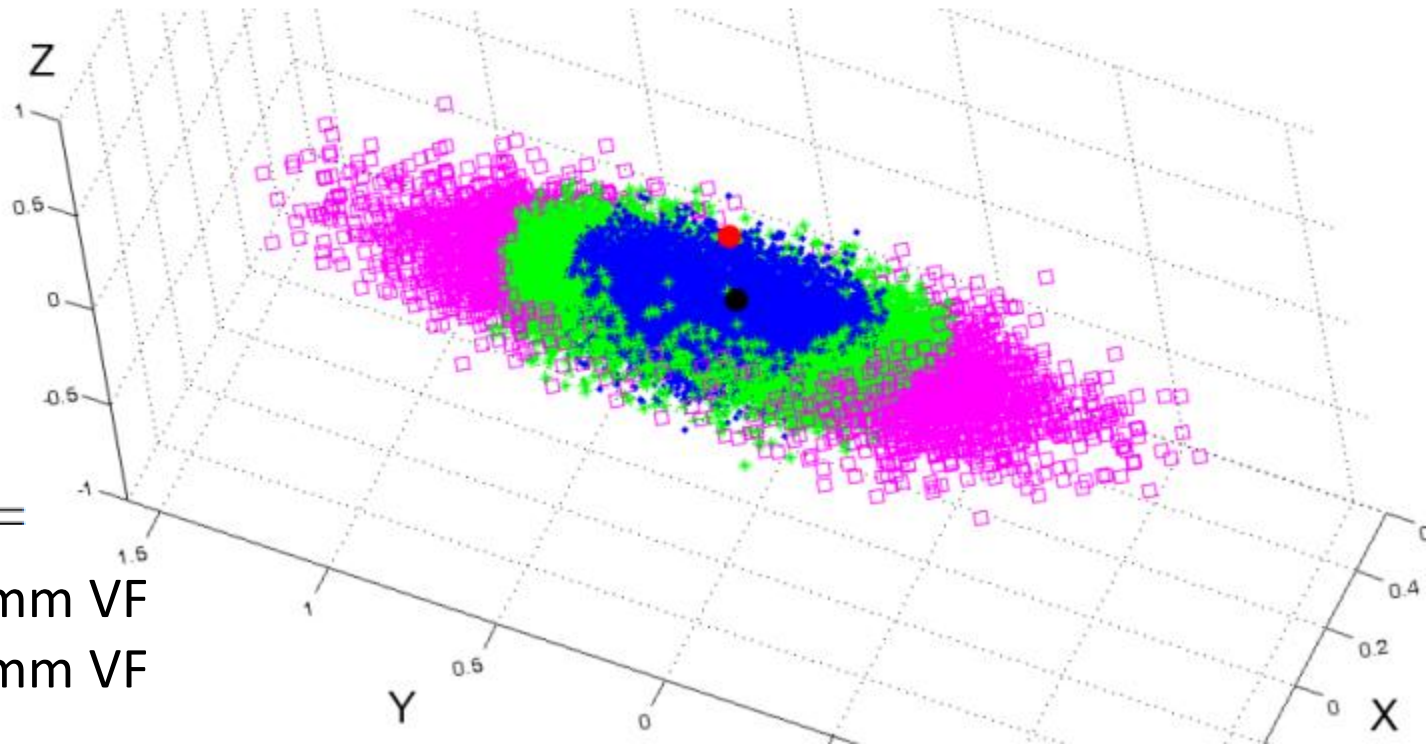


Application to integrated systems

Modeling for complex system noise

Pre-operation simulation

- Allows for estimation of real accuracy
- Notification of error distribution
- Optimal positioning of the devices



$$\mathbf{P}(\mathrm{POI} \notin \mathrm{VF}) =$$

0.438 for the 0.2 mm VF

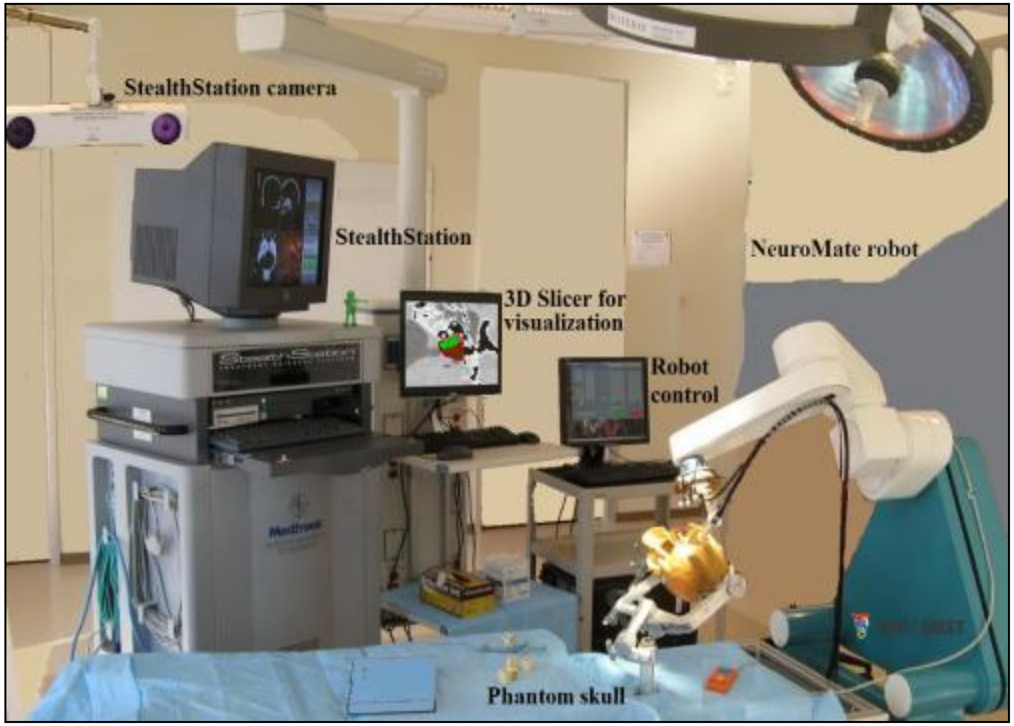
0.214 for the 0.4 mm VF

Application

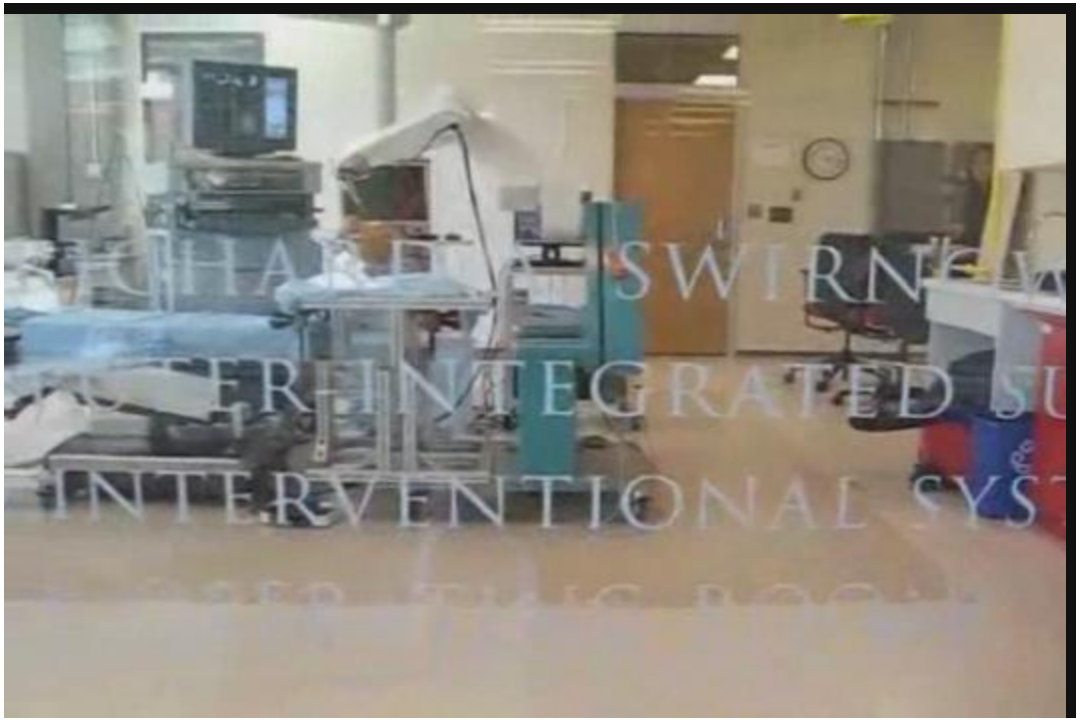
Skull base drilling robot at CISST ERC

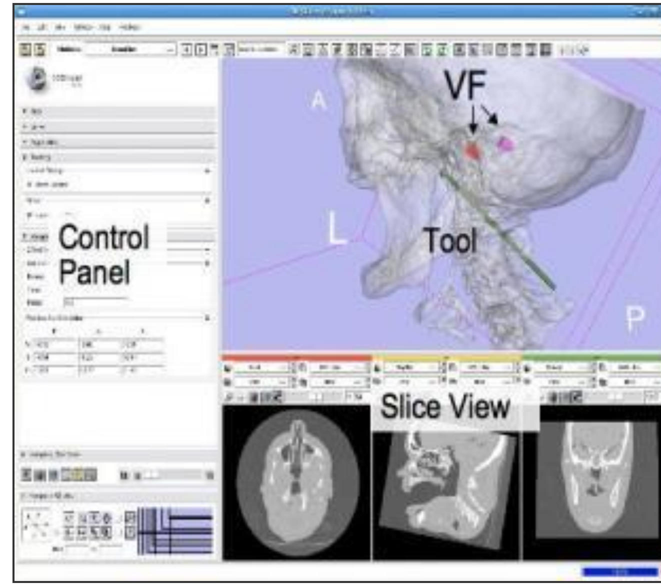
PI: Dr. Peter Kazanzides

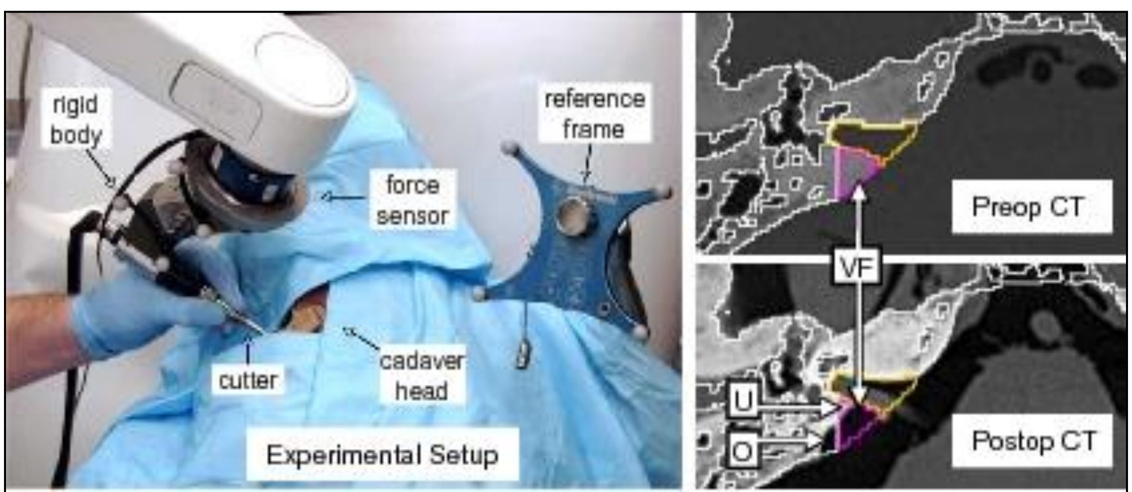
- NeuroMate robot (Integrated Surgical Systems Inc.)
  - 5 DOF serial, FDA cleared
- StealthStation surgical navigator (Medtronic Navigation Inc.)
  - FDA cleared
- 6DOF force sensor (JR3 Inc.)
- Surgical bone drill (Anspach Co.)
- Slicer 3D
- Control PC

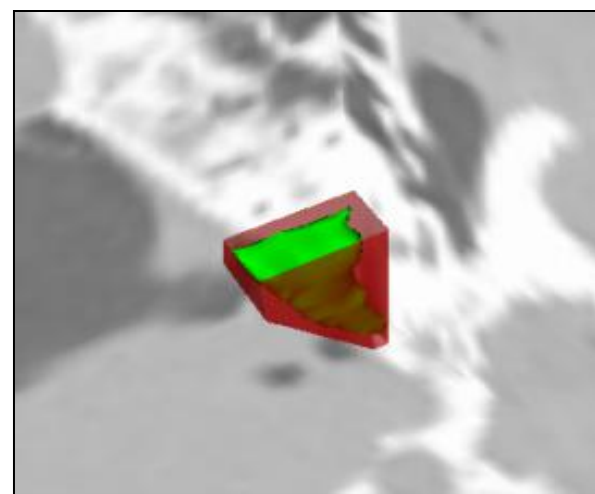


The JHU neurosurgery robot system

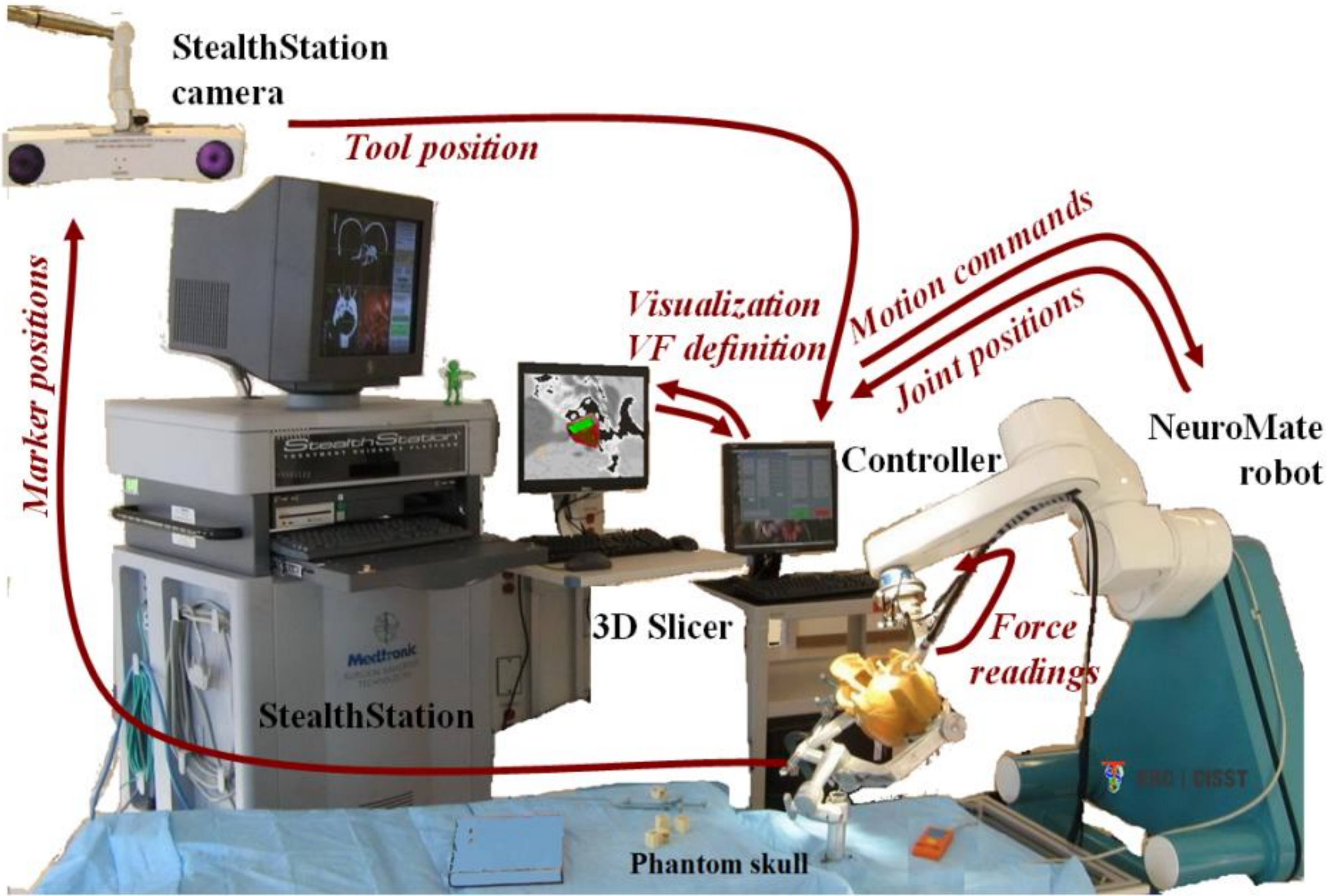






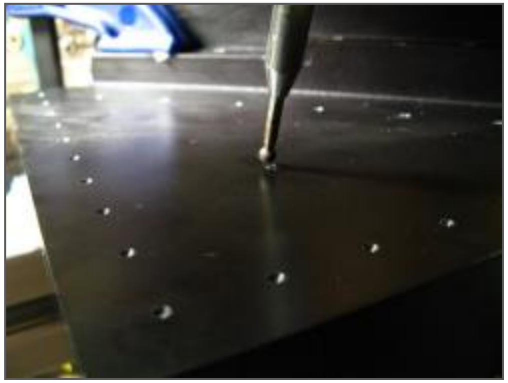


System operations

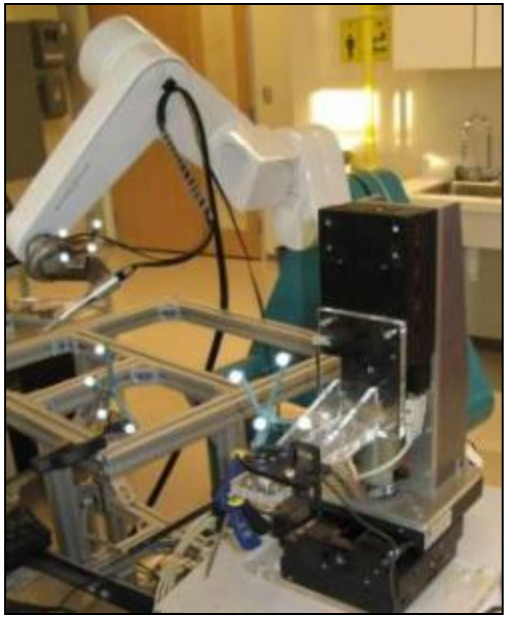


Accuracy measurements I

Using the Nebraska phantom
(draft ASTM standard)

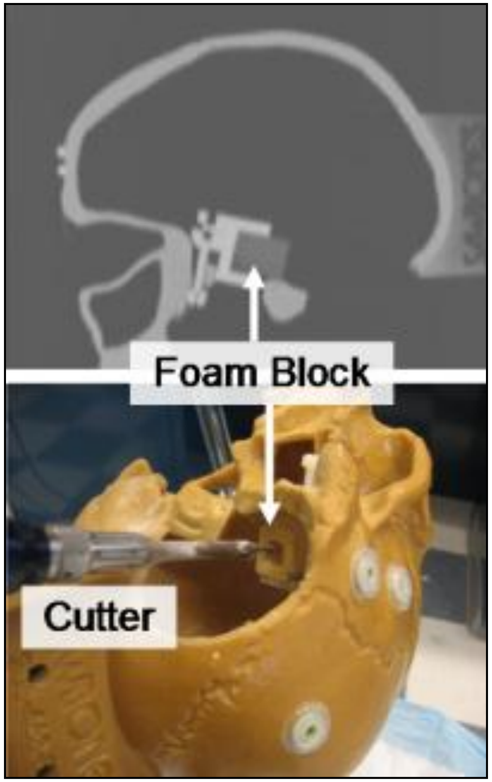


- NeuroMate robot
  - 0.36 mm FRE
  - 0.34 ± 0.17 mm TRE



- StealthStation navigation system
  - With hand-held probe
    - » 0.51 ± 0.42 mm TRE (FRE: 0.52 mm)
  - With the Robot Rigid Body
    - » 0.49 ± 0.22 mm TRE (FRE: 0.49 mm)

Accuracy measurements II

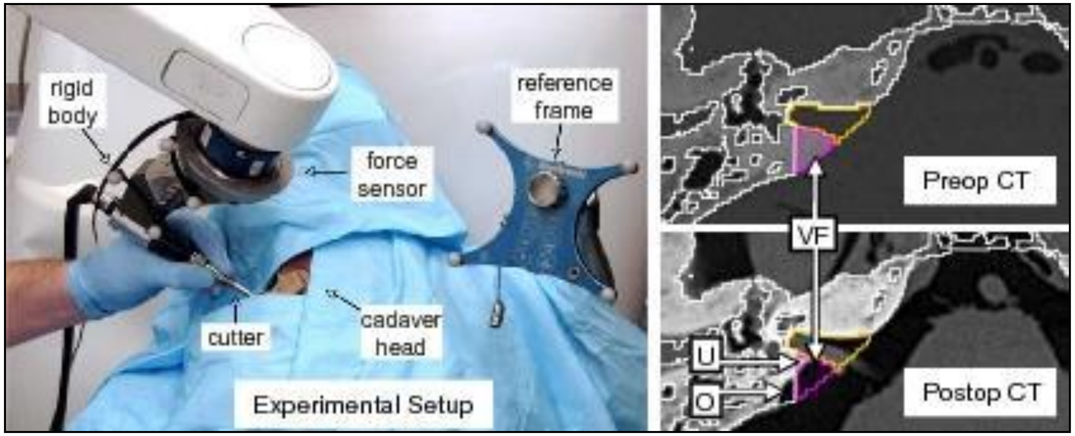


Determining application accuracy

- Foam block cutting
  - Overall accuracy: 0.79 ± 0.82 mm

- Cadaver tests
  - Application accuracy: average Ø 1 mm
  - Maximum overcut 2.5–3 mm

[Xia et al. 2008]



Stochastic approach to error estimation

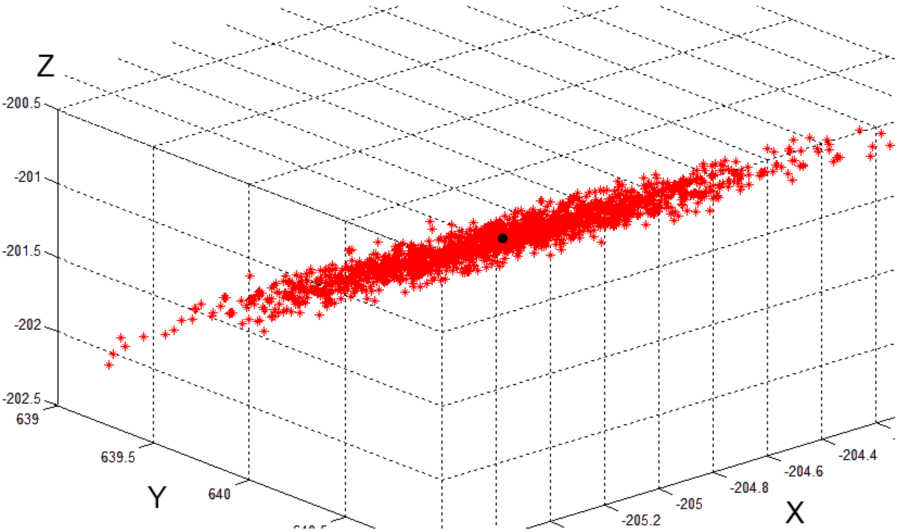
Results for the JHU system

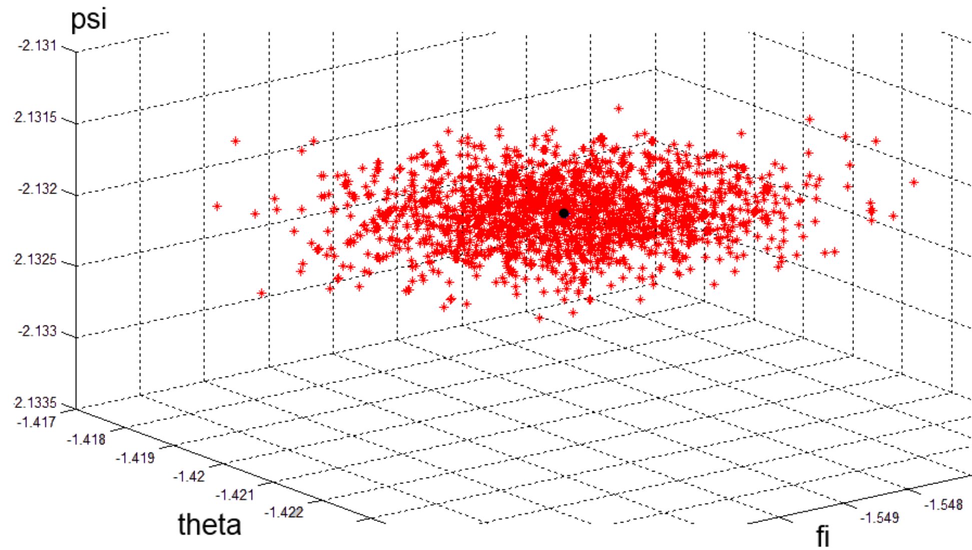
PCA showed that 2 axes account for :

99.7% of the variance along one plane

98.6% of the variance in rotations along one plane

This is due to the anisotropic arrangement of the devices





Pre-operative simulation should allow for optimal positioning of the devices

Conclusion

Uncertainty in CIS can cause significant problems

Integrated systems have complex theory for error propagation

Current hardware allows for on-site simulation:

- Provided inherent error statistics have been derived
- Better understanding of error distribution
- Specific handling of critical anatomy
- Proper risk assessment
- Understanding the OR conditions
- Optimal positioning of the devices, provide practical information in the user manual based on prior experience

Safer operation with intelligent surgical tools is the future!

Acknowledgment

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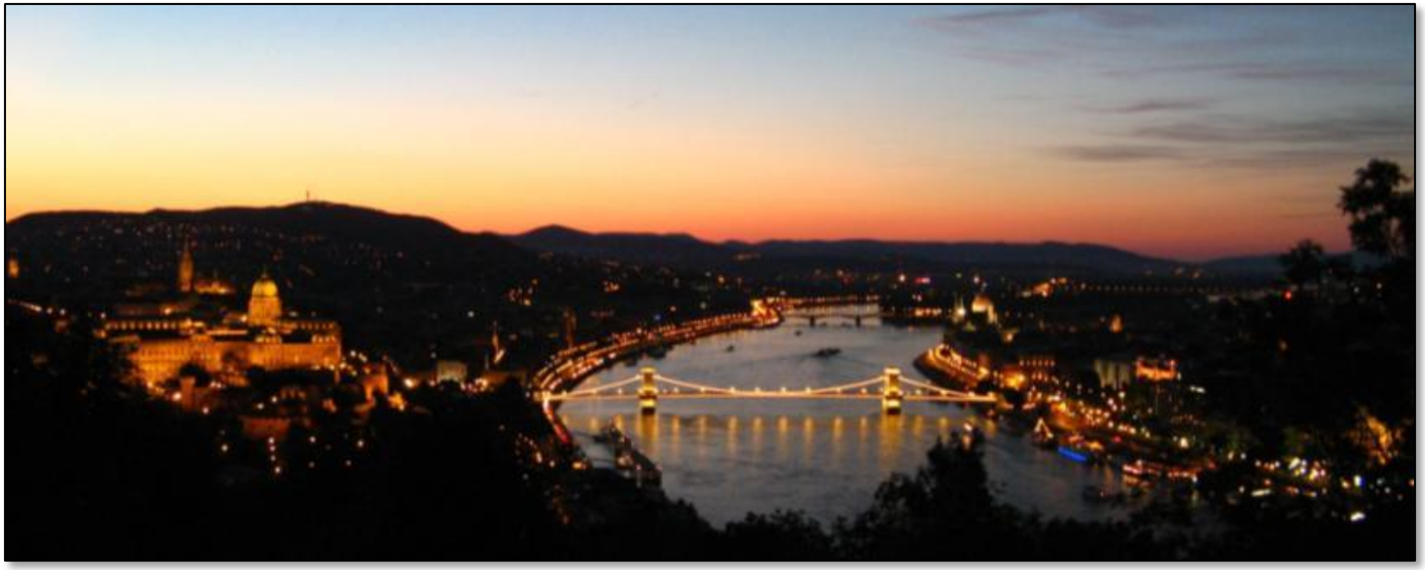
Center for Computer Integrated Surgical Systems and Technology (CISST ERC) – Baltimore, MD, USA



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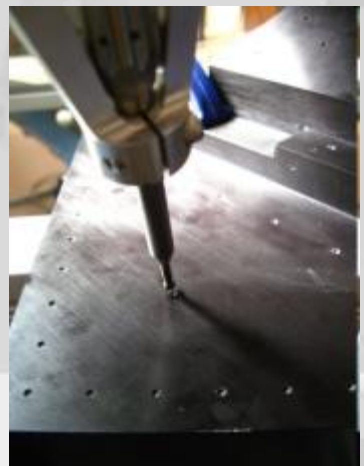

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