Biomechanical studies of the knee for medical robotics applications, and review on other medical robotics systems and activities

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What's in my talk and on our lab's agenda

- Knee kinematic
  - Pathology classification
- Parallel robots for MEMS fabrication
- reciprocal figure and Maxwell theorem
- MBARS: Mini Bone Attached Robotic System
- Medical Cardiac Snake
- A Robotic System for MIS
  Ultrasound-Guided Prostate Brachytherapy

Major Components in a Medical Robotics Systems

Pre/Intra-operative Planning

Intraoperative robotic system

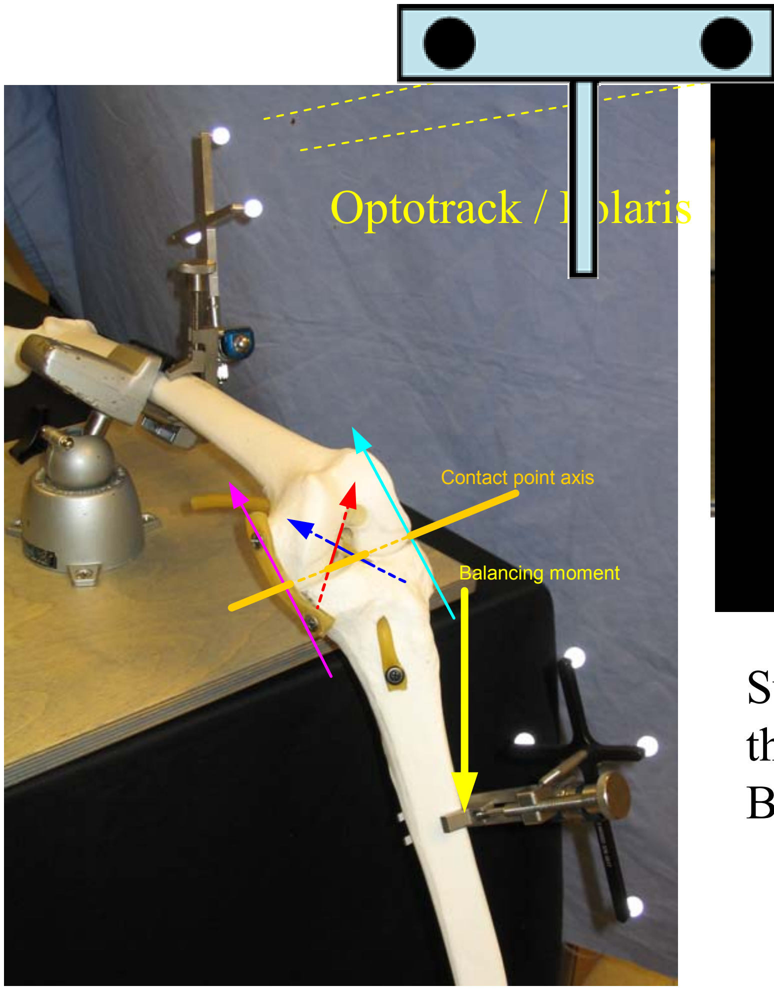
Post-operative Evaluation

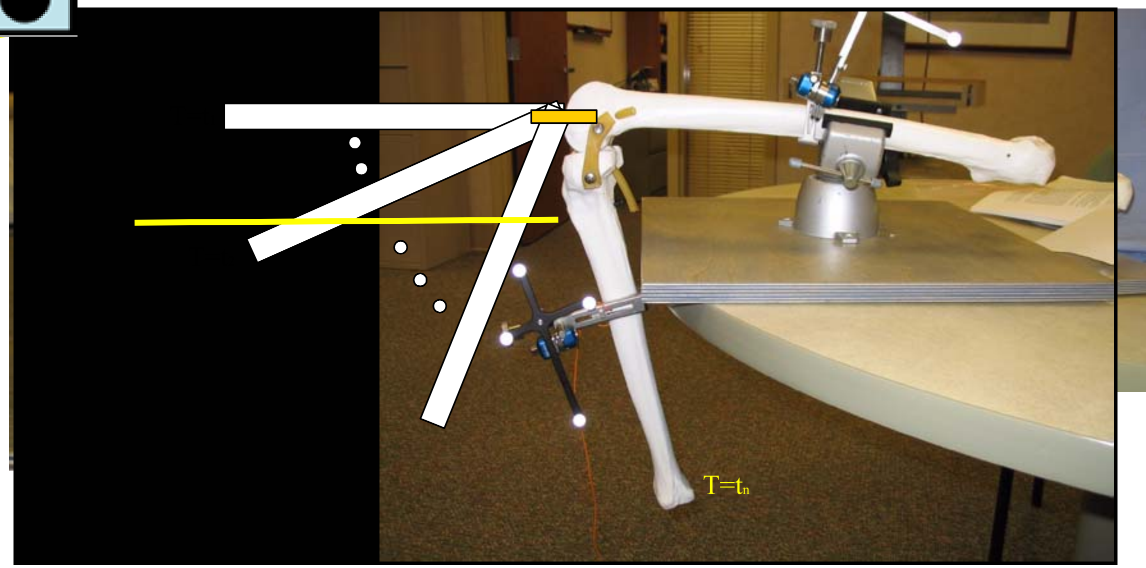
Knee kinematics

- Given geometry and observations of knee motion, extract the mechanical properties of the knee (soft and hard tissues).

- Given knee geometry and mechanical properties, generate knee motion.

Experimental Setup





$$\sum F = 0$$

$$\sum M = 0$$

Sum of the reciprocal product of the twist along the contact point axis and the wrenches applied By the ligaments and balancing moment should be zero

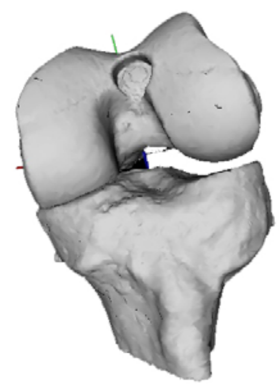
Mechanical properties of soft tissues $k_i, l_{0,i}$

Calculating Contact Path

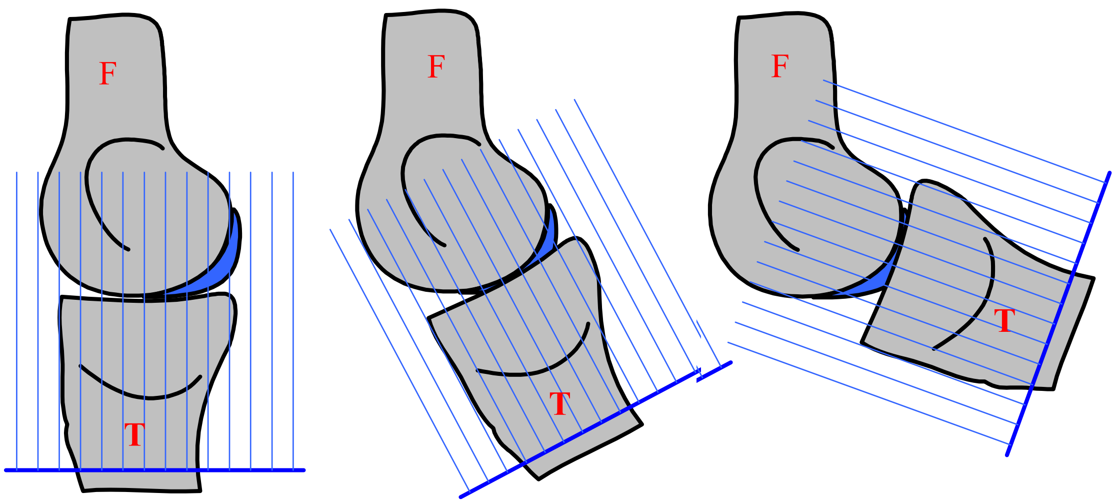
- Given surface models of both the femur, M_F, and the tibia, M_T, which are given as triangulated meshes of n_F and n_T triangles respectively, such that:

$$\mathcal{M}_{\mathrm{F}}\,(\mathcal{V}_F, \mathcal{T}_T) = \bigcup_{i=1}^{n_F} \mathcal{T}_{\mathrm{F,i}}$$

$$\mathcal{M}_{\mathrm{F}}\,(\mathcal{V}_F, \mathcal{T}_T) = \bigcup_{i=1}^{n_F} \mathcal{T}_{\mathrm{F,i}}$$

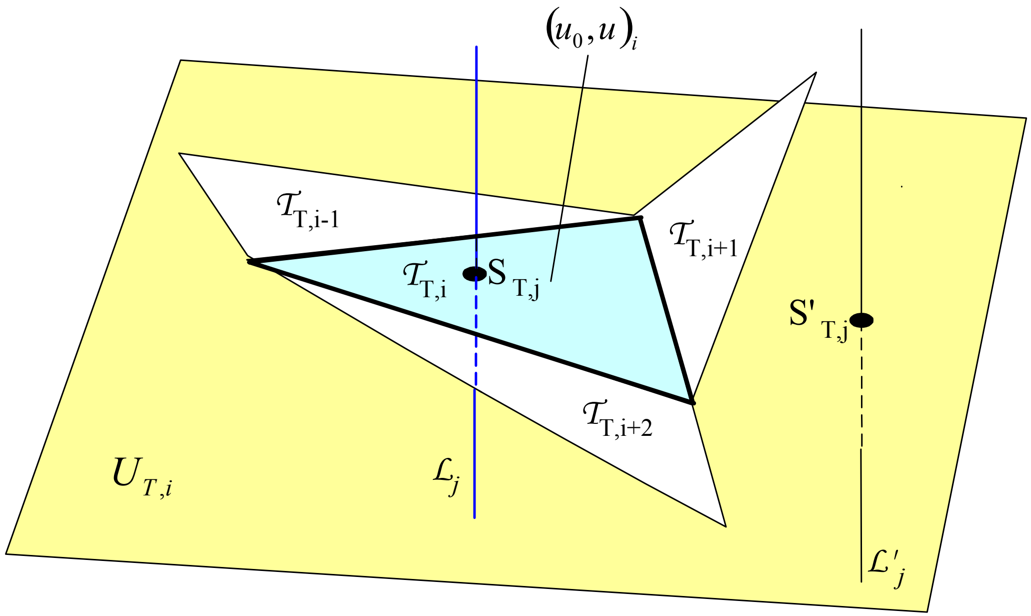


fix a sampling grid, $\mathcal{P}_G$, of m points to the tibia and attach a set of m parallel lines, $\mathcal{L}$, to the grid such that when the tibia moves through different flexion configurations both the sampling grid and the set of lines attached to it transform with it



$$\mathcal{L}_j = \left(\hat{z}_T , \mathcal{P}_{G,j} \times \hat{z}_T \right) = \left(l, \bar{l}\right)_i \quad , j = 1, \cdots m$$

Calculate the intersection point of each of the lines in $\mathcal{L}$ with both surface models $\mathcal{M}_F$ and $\mathcal{M}_T$

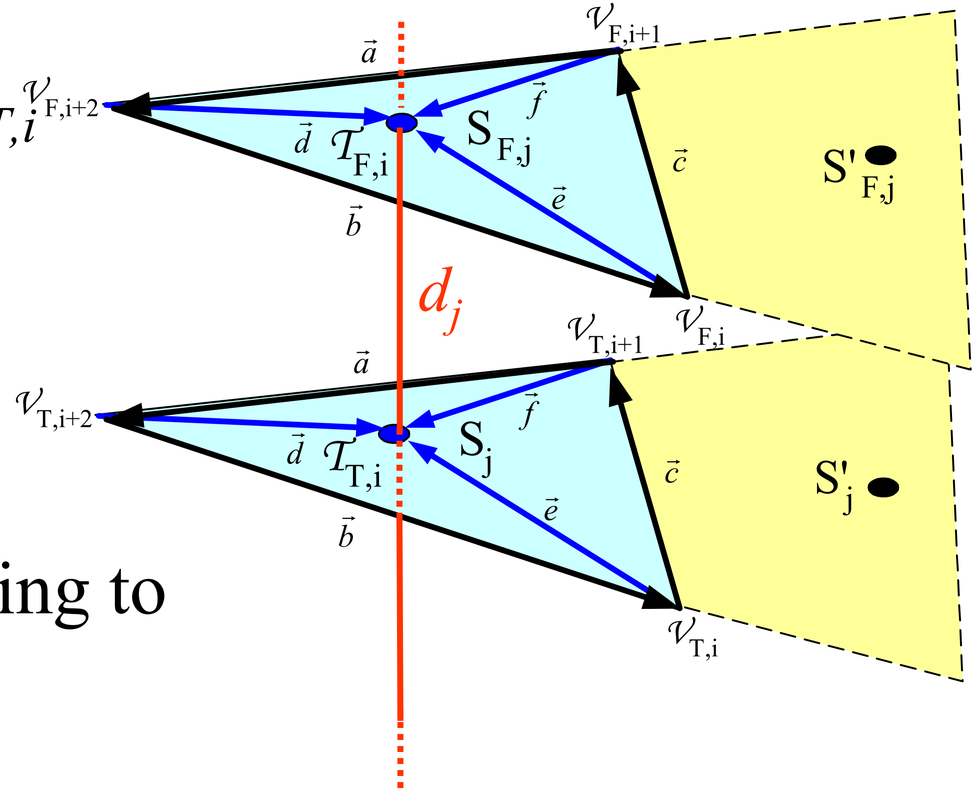


$$S_{T,j} = (s_0, s)_{T,j} = \left(u_i \cdot l_j, -u_{0,i} l_j + u_i \times \bar{l}_j\right) \qquad j = 1, \cdots, m \quad i = 1, \cdots, n_F, or\ n_T$$

$$S_{T,j}\Re = (s_0, s)\Re \qquad\qquad \Re U_{T,i} = \Re(u_0, u)_{T,i}$$

Cartesian coordinates of a point — homogeneous plane coordinate vector of a plane verify that $S_{T,j}$ is inside $\mathcal{T}_{T,i}$

$$\left|\vec{a}\times\vec{b}\right| = \left|\vec{a}\times\vec{d}\right| + \left|\vec{b}\times\vec{e}\right| + \left|\vec{c}\times\vec{f}\right|$$



Check for distance according to

$$d_j = \left\| \mathcal{P}_{T,j} - \mathcal{P}_{F,j} \right\|_{j=1,\cdots,m}$$

Check for minimal distance and set contact points* to be $\mathcal{P}_{C.T,k}$, and $\mathcal{P}_{C.F,k}$ (k=1,…,w).

*In case of multiple potential contact points or overlapping surface models due to measurement error, the contact point is set to be the center of gravity of the contact region.

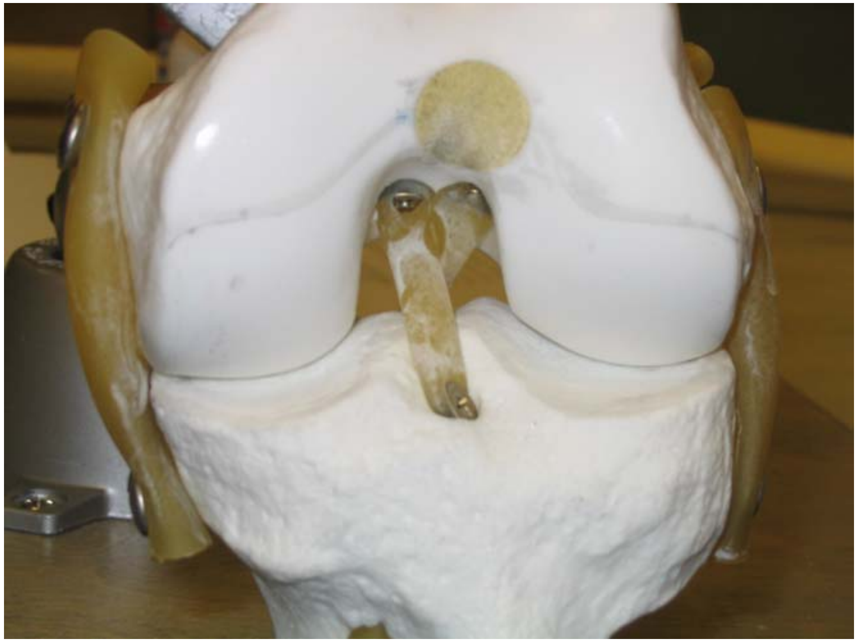
Transform the tibia surface model $\mathcal{M}_T$ and $\mathcal{L}$ to the next knee configuration such that

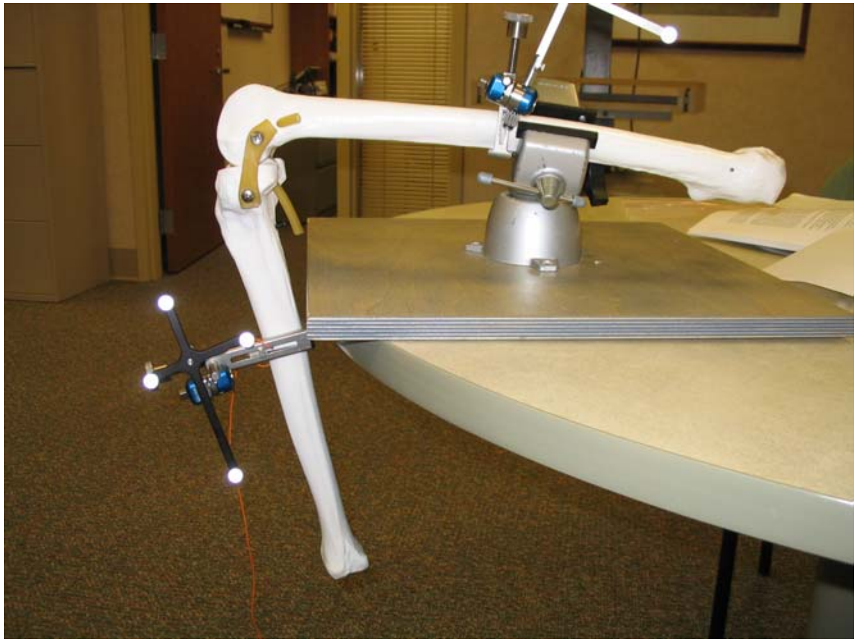
$$\mathcal{M}_{T,i+1} = {}^{F}T_{T,i}\mathcal{M}_{T,i}$$

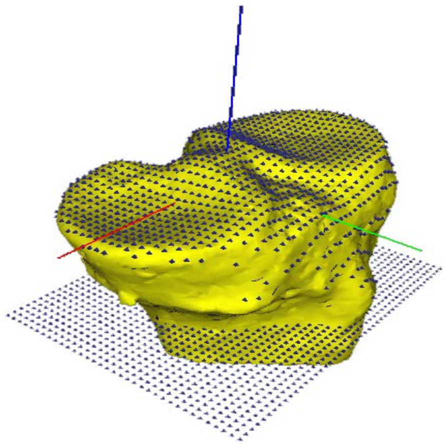
$$\mathcal{L}_{i+1} = \begin{bmatrix} R & 0 \\ W \cdot R & R \end{bmatrix} \cdot \mathcal{L}^{\mathrm{T}}{}_{i} \qquad W = \begin{bmatrix} 0 & -t_z & t_y \\ t_z & 0 & -t_x \\ -t_y & t_x & 0 \end{bmatrix}$$

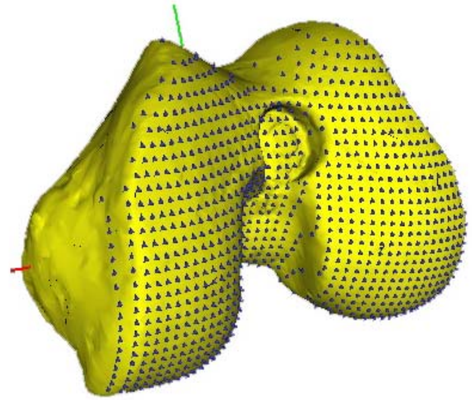
Repeat these steps for each of the *w* positions

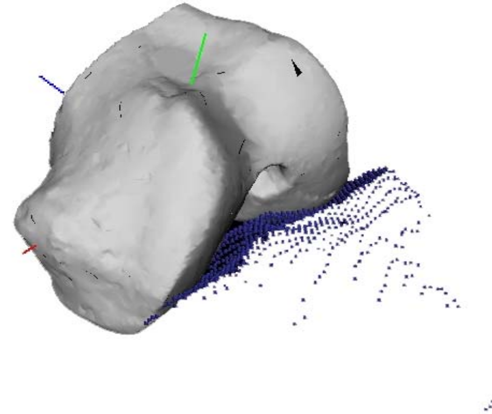
Experiment

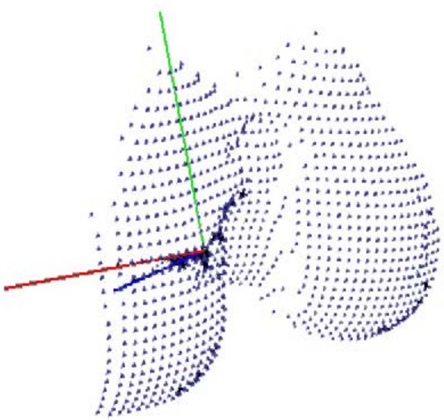


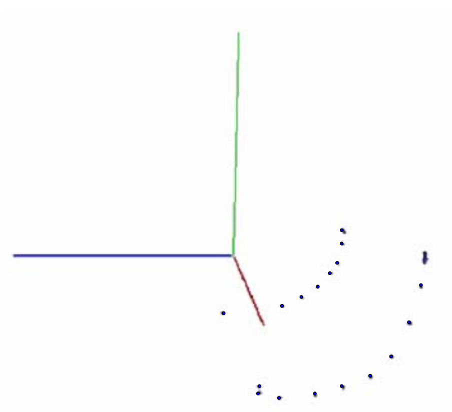


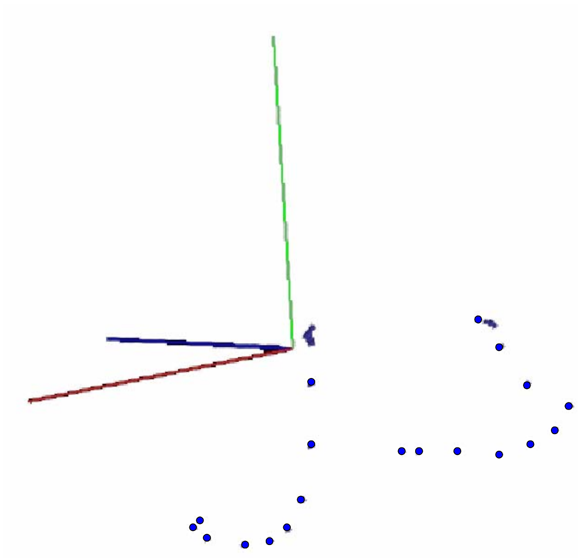


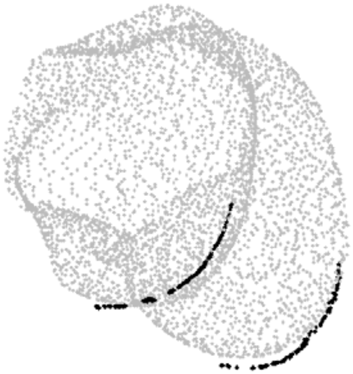


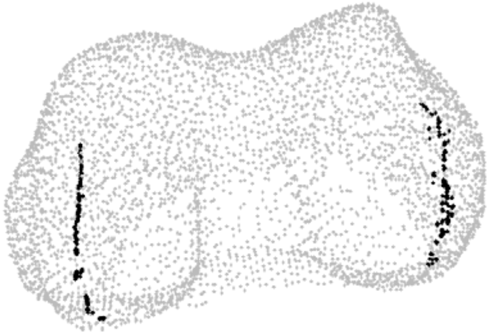


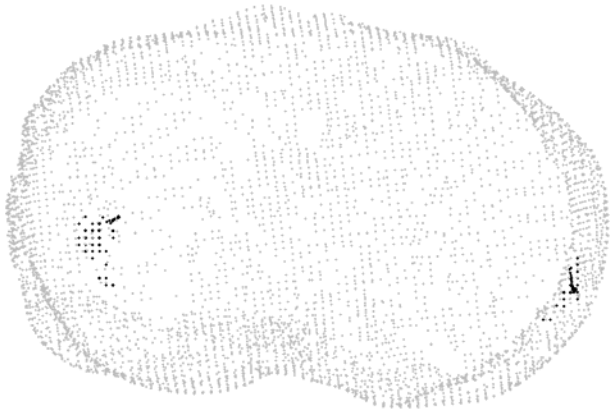






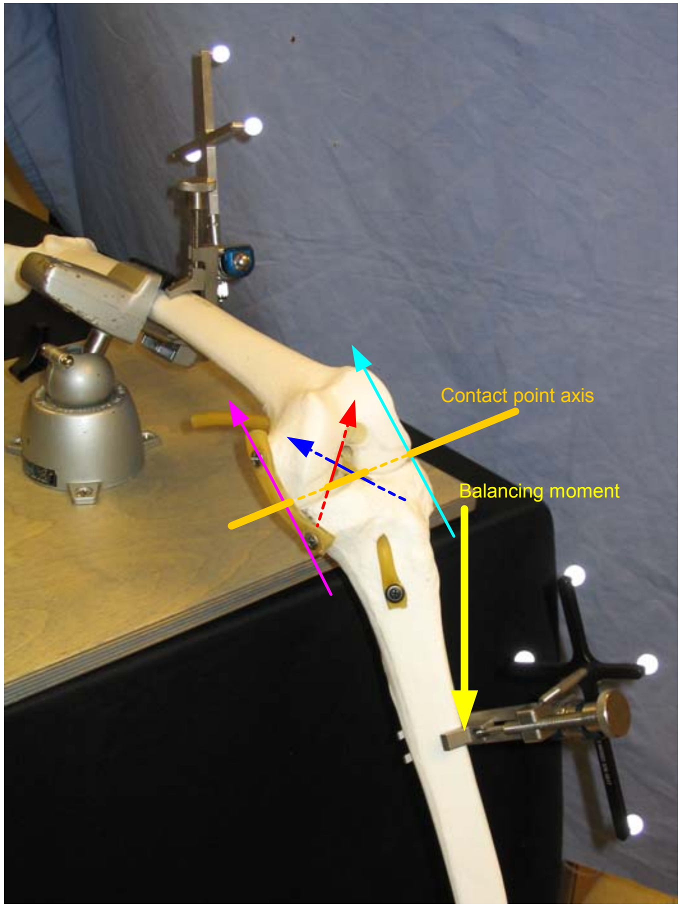






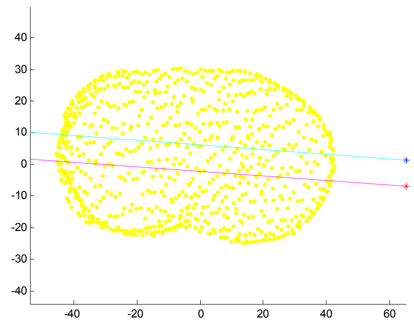
Contact points are shifted medially….

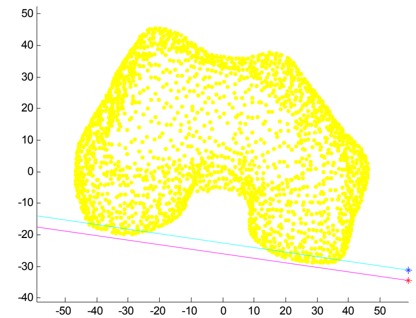
Calculation

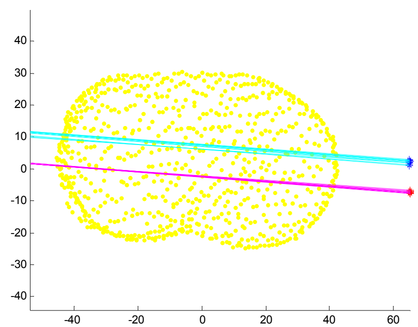


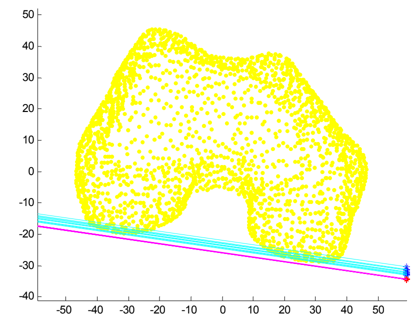
$$\sum M_L(l_0,k)_{i,j} = 0$$

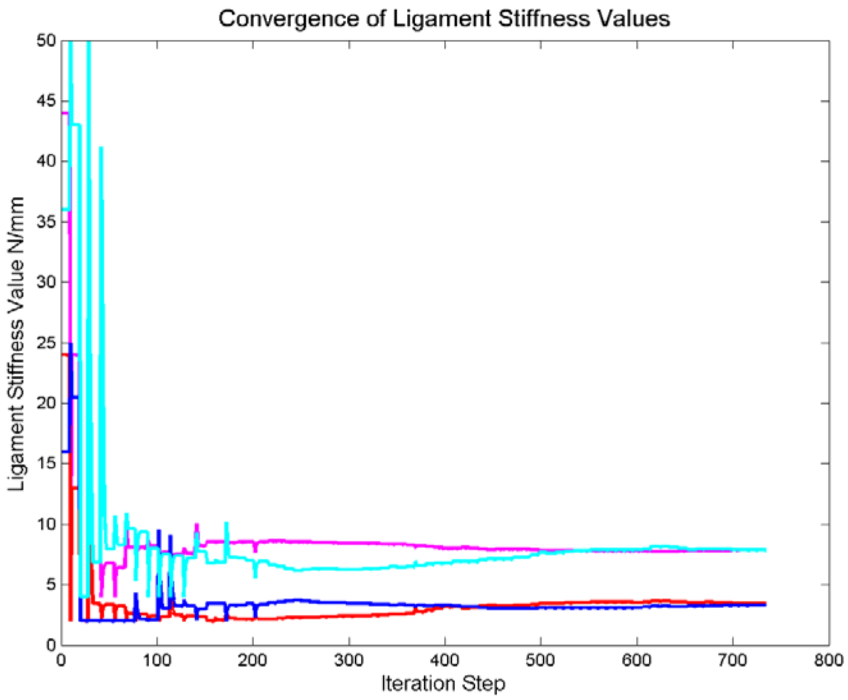
Offset of the results











Convergence of Ligament Stiffness Values
Ligament Stiffness Value N/mm
Iteration Step
0
5
10
15
20
25
30
35
40
45
50
0
100
200
300
400
500
600
700
800

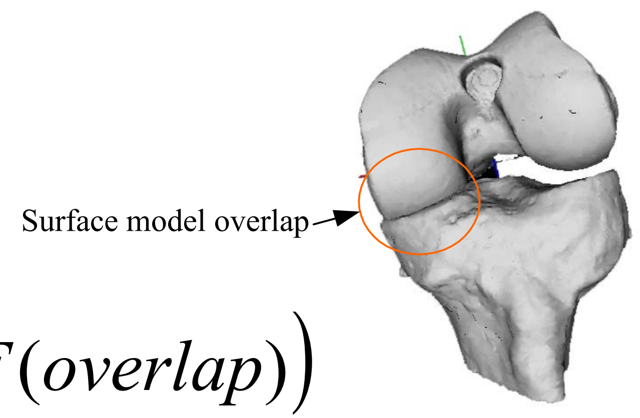
What we want to do next

- Eliminate friction/include in model
- More complex ligament model mechanical/geometrical
- Robust model
- Inverse solution
- Human trial

Inverse solution

- Given knee geometry (hard and soft tissues), mechanical properties of hard and soft tissue find knee configuration such that for configuration i:

$$F = \min\left(\sum Work({}^{F}T_{T,i})\right)$$



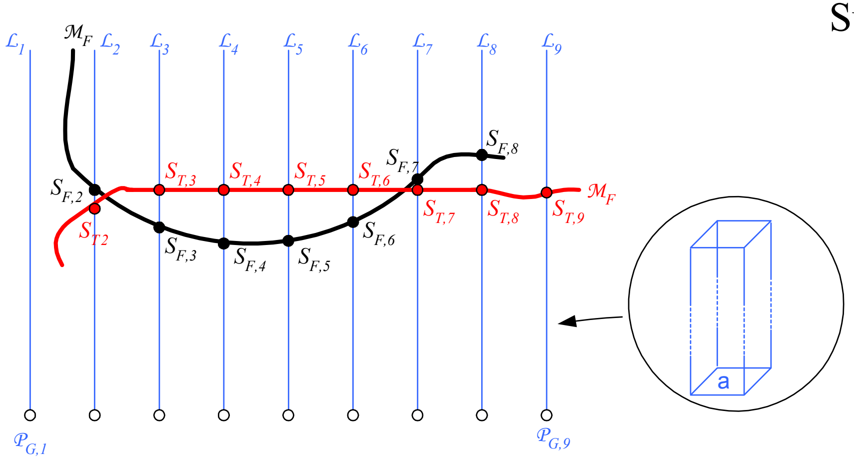
$$F = \min\left(\sum Work({}^{F}T_{T,i}) + P.F(overlap)\right)$$

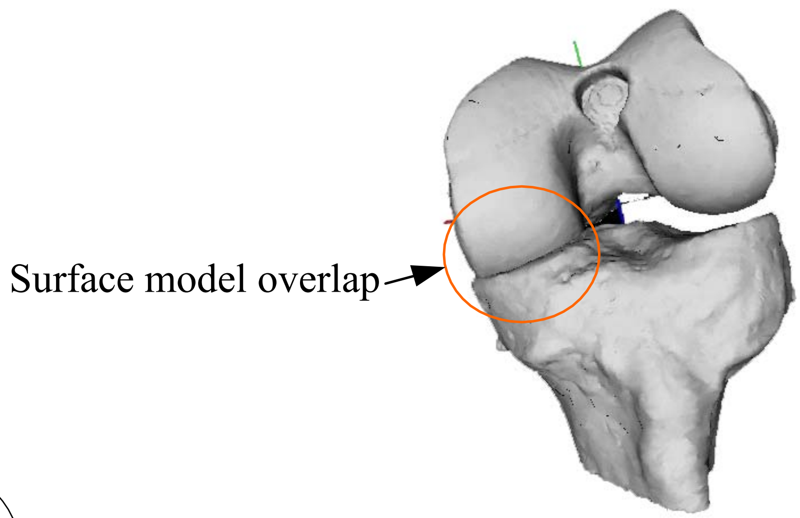
Calculating Contact Volume

For each line $\mathcal{L}_j$ calculate:

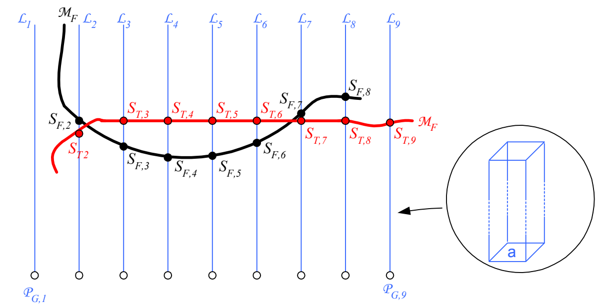
$$d_{T,j} = \left\| \mathcal{P}_{G,j} - S_{T,j} \right\|_{j=1,\cdots,m}$$

$$d_{F,j} = \left\| \mathcal{P}_{G,j} - S_{F,j} \right\|_{j=1,\cdots,m}$$

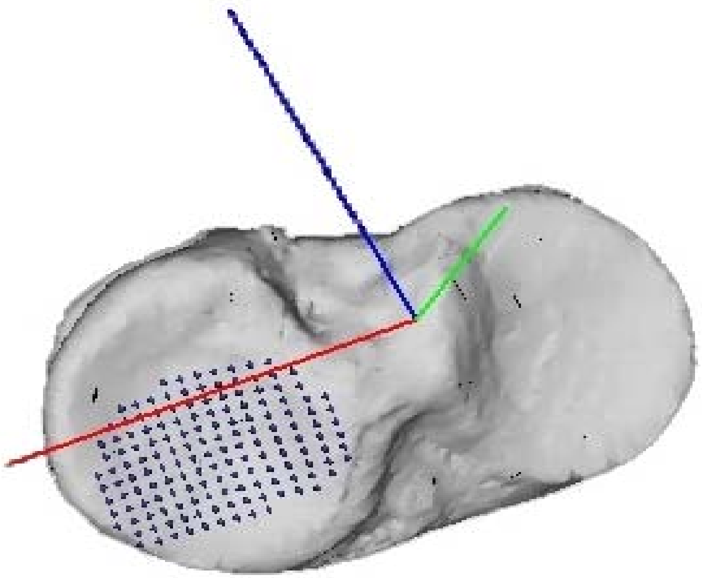


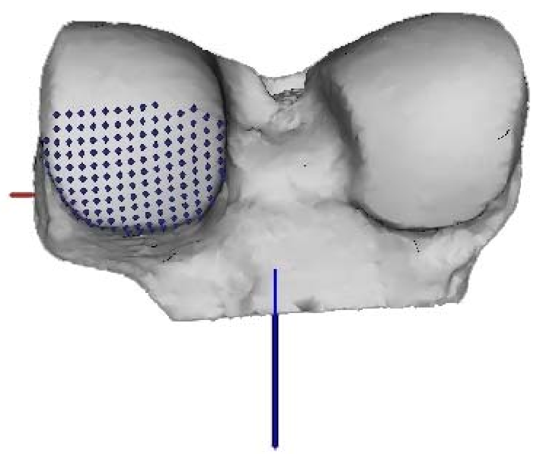


$$V_{total} = \sum_{j=1}^{m} v_j$$



$$v_j = \begin{cases} a \cdot \left(d_{T,j} - d_{F,j} \right) & d_{T,j} > d_{F,j} \\ 0 & d_{T,j} < d_{F,j} \end{cases}$$





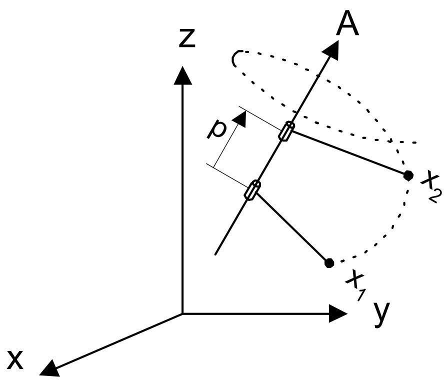
15.1 mm^3 for 1.5mm sampling grid

Pathology classification (Clustering)

Kinematics: The branch of mechanics that studies the motion of a body or a system of bodies without consideration given to its mass or the forces acting on it.

$$ {}^{a}T_{b} = \begin{bmatrix} R_{3\times 3} & P^{T} \\ 0_{1\times 3} & 1 \end{bmatrix} $$

Classical transformation matrix

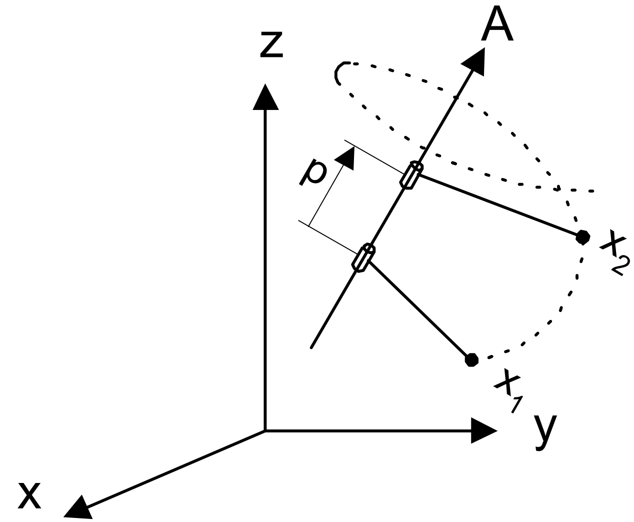


Screw motion

Screw

- "*Any given displacement of a rigid body can be effected by a rotation about an axis combined with a translation parallel to that axis*". [Ball, 1900]

- Screw: " *A Screw is a straight line with which a definite linear magnitude termed the pitch is associated*". [Ball, 1900]

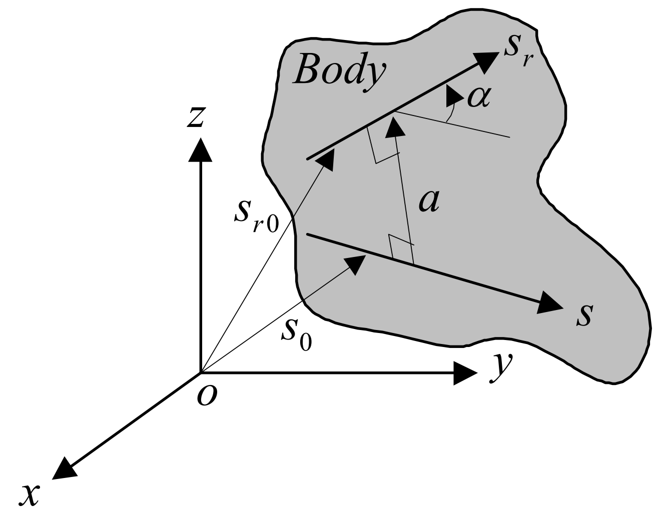


Screw motion (Helical)… mathematical definitions

angular

$$\hat{\$} = \begin{bmatrix} s \\ s_0 \times s + ps \end{bmatrix}$$

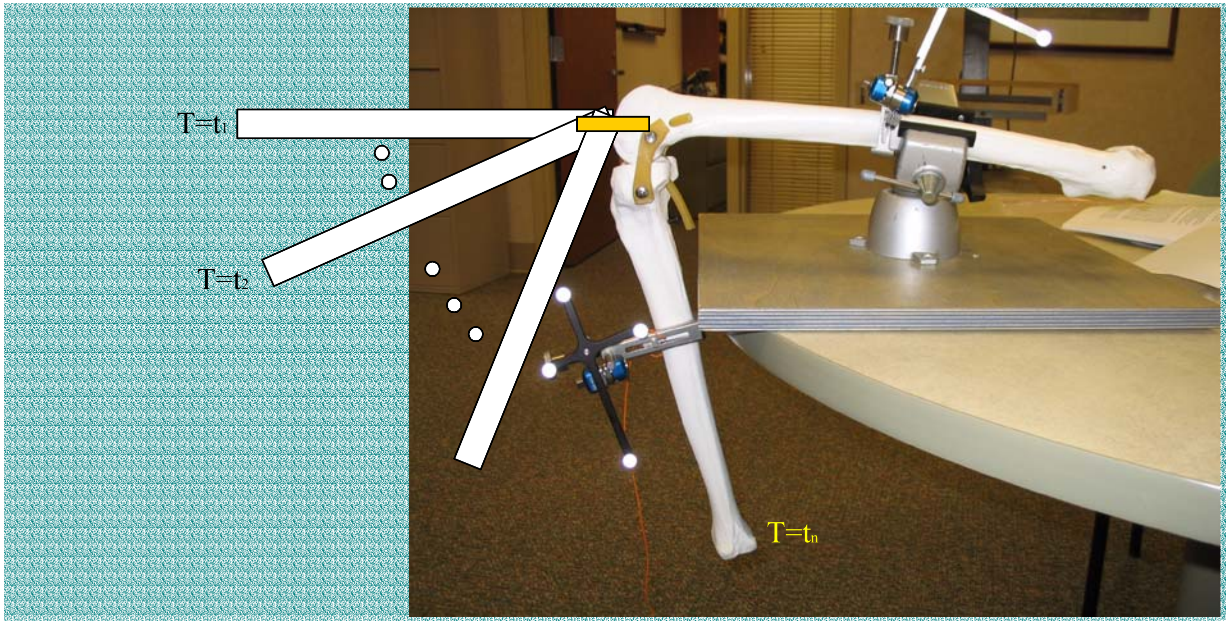
Linear



$$p_{\text{finite}} = d/\theta = \text{translation}/\text{rotation}$$

$$P = \infty \longrightarrow Linear\ \ motion$$

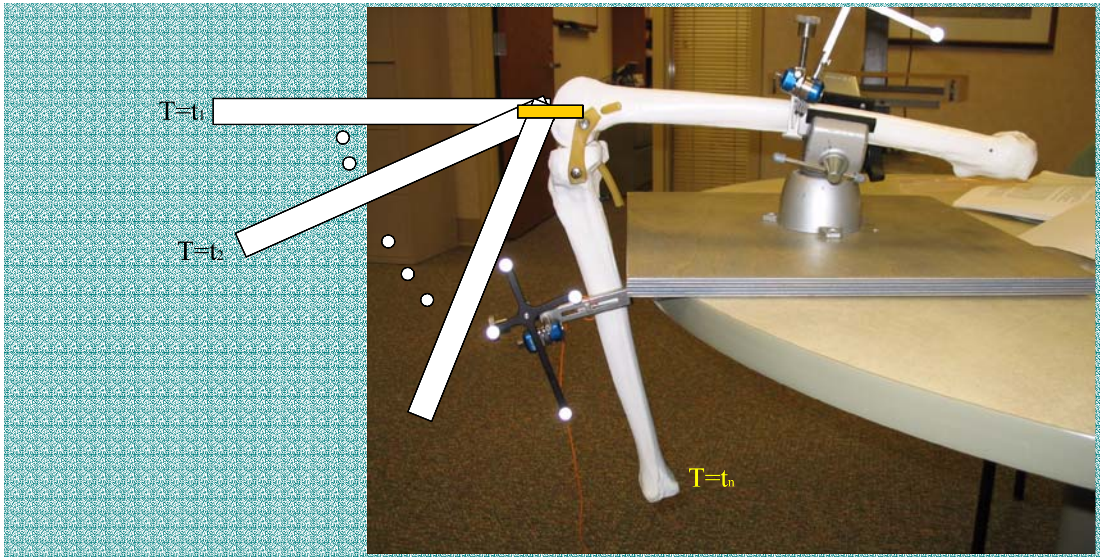
$$P = 0 \longrightarrow Rotational\ \ motion$$



Calculate the momentary screw coordinates of
Two successive observations and obtain:

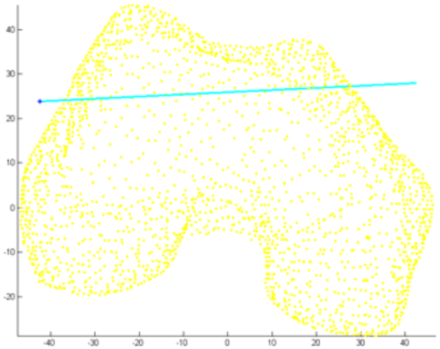
Screw coordinates
Screw axis
Pitch

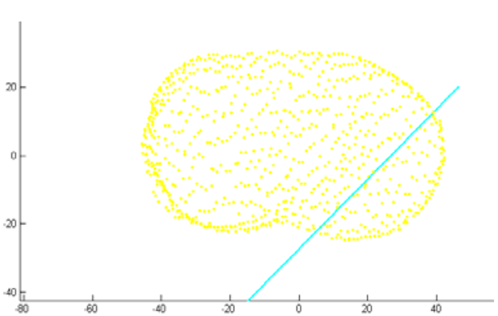
For each momentary change of flexion

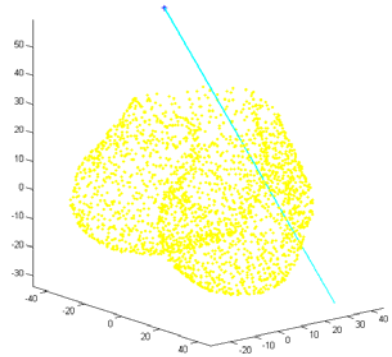


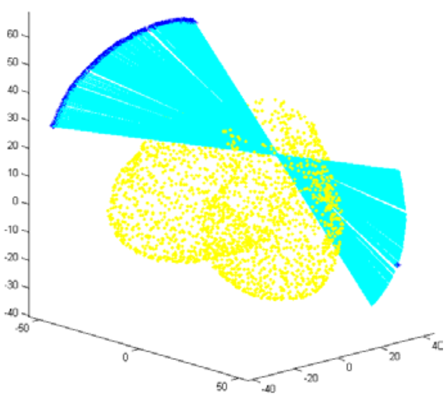
Jorge Angeles., 1986. Automatic Computation of the Screw Parameters of Rigid-Body Motion. Part I: Finitely Separated Positions, Journal of dynamic systems, measurements and control 108: 39-43

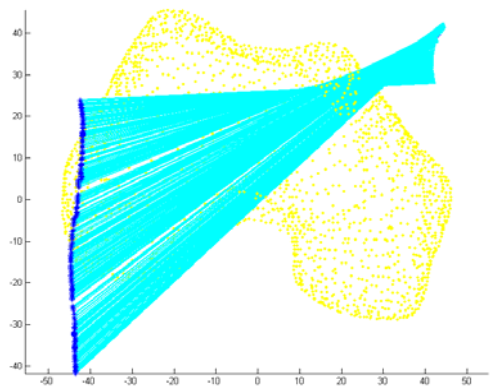
$$\hat{\$} = \begin{bmatrix} s \\ s_0 \times s + ps \end{bmatrix} = \left[\$_1, \$_2, \$_3, \$_4 \$_5, \$_6\right]^T$$

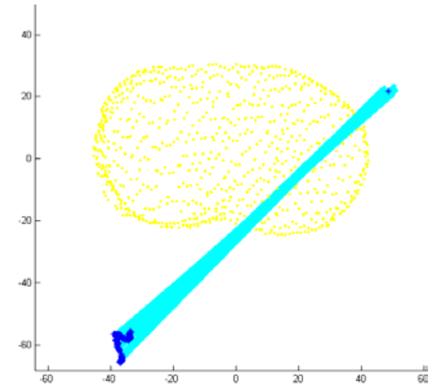




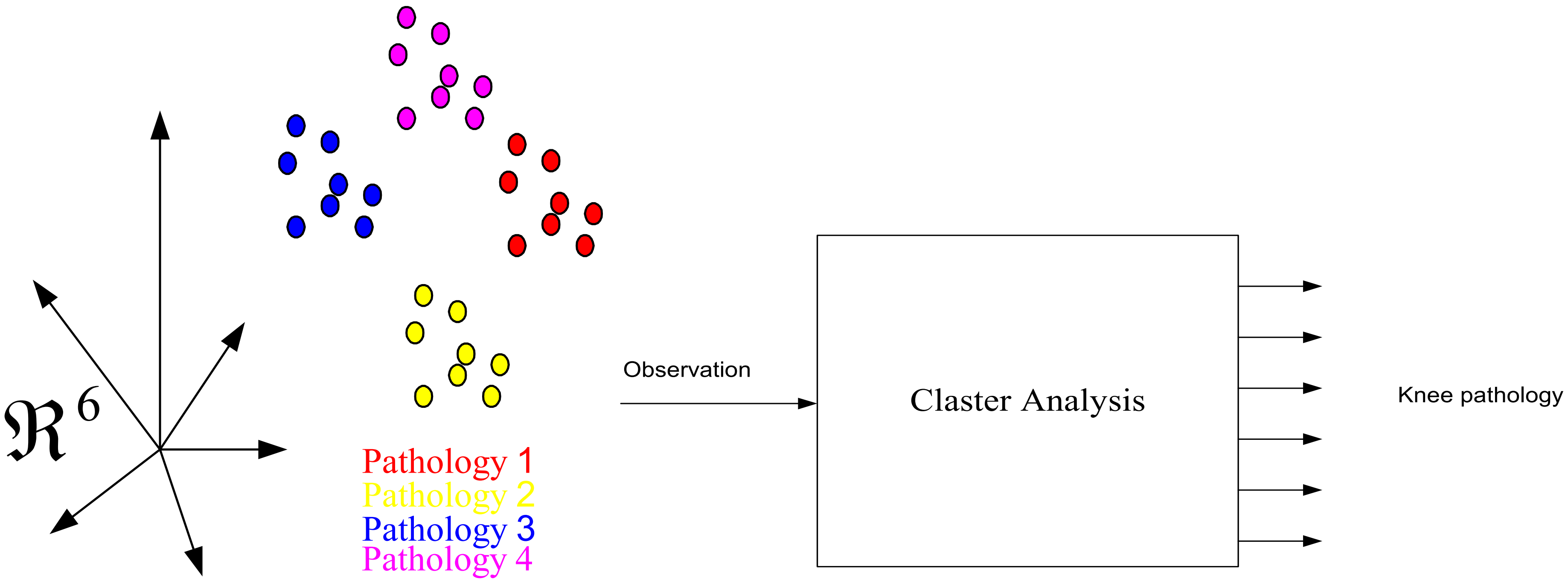








Clusters in R6



Questions

- Can we distinguish pathologies from observations: are there clusters?
- Are the clusters orthogonal?
- Can new observations be associated with the available clusters?

I don’t know

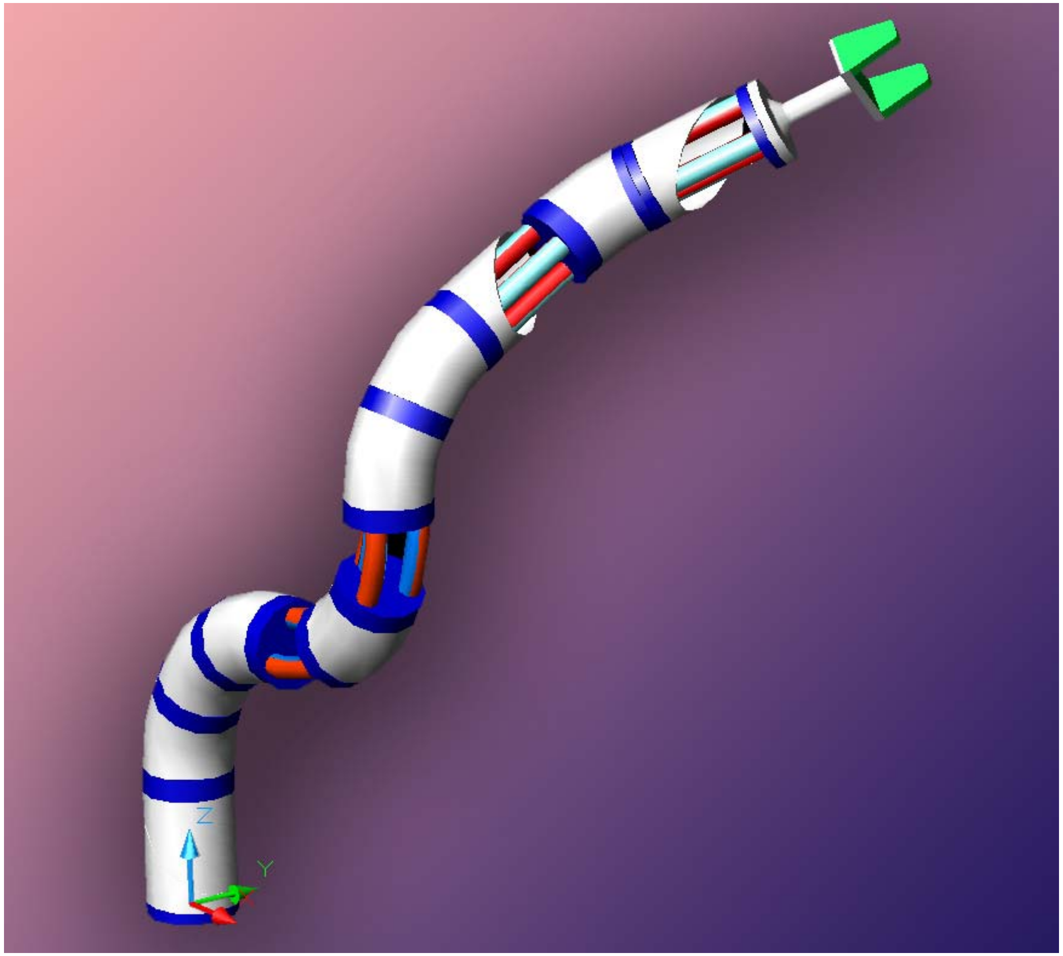
- Does it worth the efforts?

I think…yes

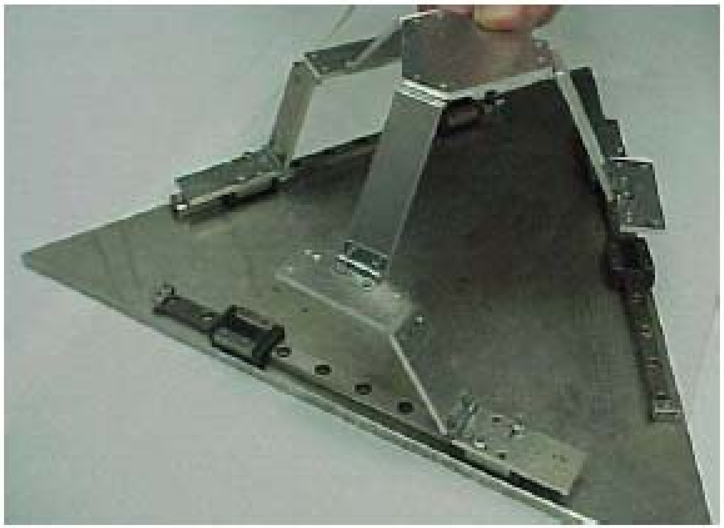
What we want to do next

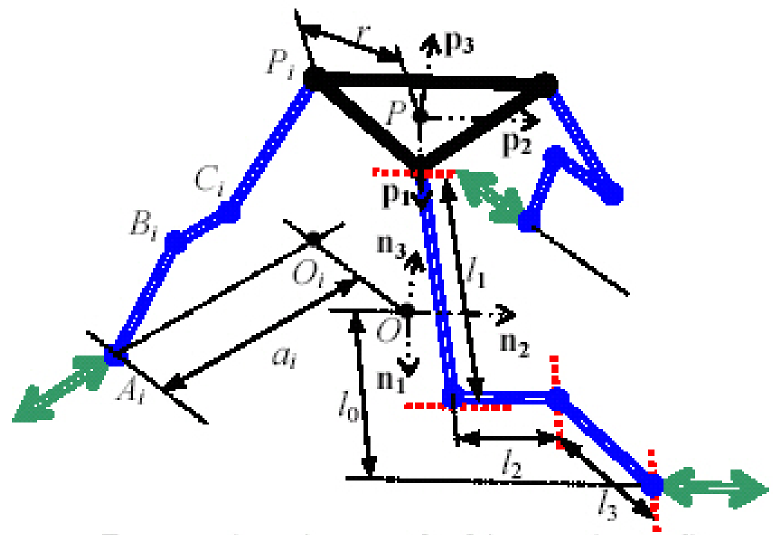
- Get more new data from Sawbones
- Principal components analysis/ Factor analysis
- Cluster analysis/ Functional data analysis.
- Human trials

Parallel robots for MEMS fabrication



The 3PRRRR robot



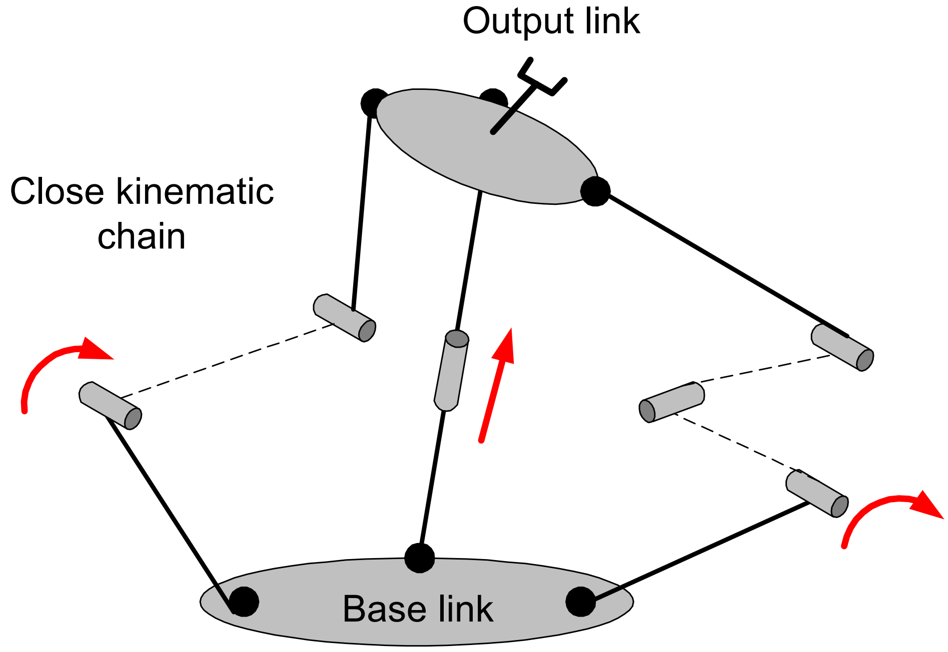


$$M_{active} = 6(14-15-1)+15\cdot 1 = 3\,DOF$$

$$M_{locked} = 6(11-12-1)+12\cdot 1 = 0\,DOF$$

Screw Based Jacobian of Limited-DOF Parallel Manipulator

- *General Purpose manipulator*
  6-DOF
- *Limited DOF manipulator*
  < 6-DOF



Parallel Manipulator

- Each limb can be considered as an open loop chain connecting a moving platform to a fixed base by l 1-DOF joints.
- The inst. twist, $\$_p$ of the moving platform is expressed as a linear combination of the l inst. twists [Mohamed and Duffy, 1985]

$$\$_p = \sum_{j=1}^{l} \dot{q}_{j,i} \hat{\$}_{j,i} \qquad for\ i = 1,\ldots,m\,\text{(limbs)}$$

$$\$_p = \sum_{j=1}^{l} \dot{q}_{j,i} \hat{\$}_{j,i} \qquad for\ i = 1,\ldots,m \,(\text{limbs})$$

- This equation contains many unactuated joint screws which can be eliminated applying the theory of reciprocal screws.
- Identify g unit screws $\hat{\$}_{r,6-l_i+1,i}$ each reciprocal to all the unactuated screws (motor is locked).
- Perform the reciprocal product of both side of $\$_p$ with each of the reciprocal screws which were found (g is the actuated joint).

$$\hat{\$}^T_{r,6-l_i+1,i} \cdot \$_p = \dot{q}_{j,i} \hat{\$}^T_{r,6-l_i+1,i} \cdot \hat{\$}_{g,i}$$

- Write in matrix form as:

$$J_x \$_p = J_q \dot{q}$$

- Where:

$$J_x = \begin{bmatrix} \hat{\$}^T_{r,6-l_i+1,1} \\ \hat{\$}^T_{r,6-l_i+1,2} \\ \vdots \\ \hat{\$}^T_{r,6-l_i+1,m} \end{bmatrix}$$

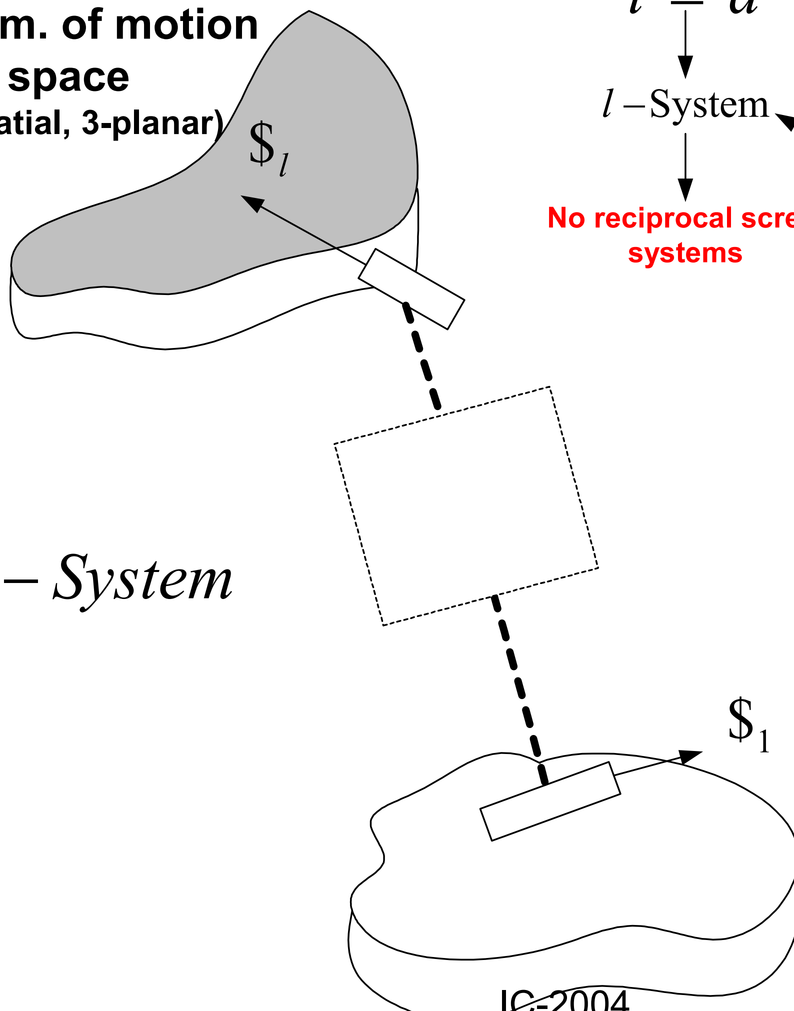
$$J_q = \begin{bmatrix} \hat{\$}^T_{r,6-l_i+1,i} \cdot \hat{\$}_{g,1} & 0 & \cdots & 0 \\ 0 & \hat{\$}^T_{r,6-l_i+1,i} \cdot \hat{\$}_{g,2} & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & \cdots & \hat{\$}^T_{r,6-l_i+1,i} \cdot \hat{\$}_{g,m} \end{bmatrix}$$

$$J_a \$_p = \dot{q} \qquad \text{where} \qquad J_a = J_q^{-1} J_x$$

Jacobian of actuation

Deep thoughts…

d = Dim. of motion space
(6-spatial, 3-planar)



$l-System$

$l = d \rightarrow l-\text{System} \rightarrow$ No reciprocal screw systems

$l < d \rightarrow d-l$ N.L.D.S $\rightarrow (d-l)-\text{System}$

$l-\text{System} \xleftrightarrow{R.R} (d-l)-\text{System}$

More deep thoughts…

Limb with l joints : k unactuated

$\downarrow$

$(d-k)$ N.L.D.S

$\downarrow$

$(d-k)$ - System

R.R

$\downarrow$

$(d-k)\text{- System} \subset (d-l)\text{- System}$

$\downarrow$

$\hat{\$}_{rj,i}$ Can be used as a reciprocal screw to calculate the Jacobian provided that: $(d-l)-\text{System} \not\subset \hat{\$}_{rj,i}$

Jacobian of constraints

- Screws that are R.R to all the joint screws in a link form a 6-l_i system: identify 6-l_i reciprocal basis screw of the ith *limb.*
- Perform the R.R product

$$\$_p = \sum_{j=1}^{l} \dot{q}_{j,i} \hat{\$}_{j,i} \qquad \textit{for } i = 1,\ldots,m \text{ (limbs)}$$

$$\hat{\$}^{T}_{r,k,i} \$_p = 0 \qquad \text{for } k = 1,2,\ldots..,6 - l_i$$

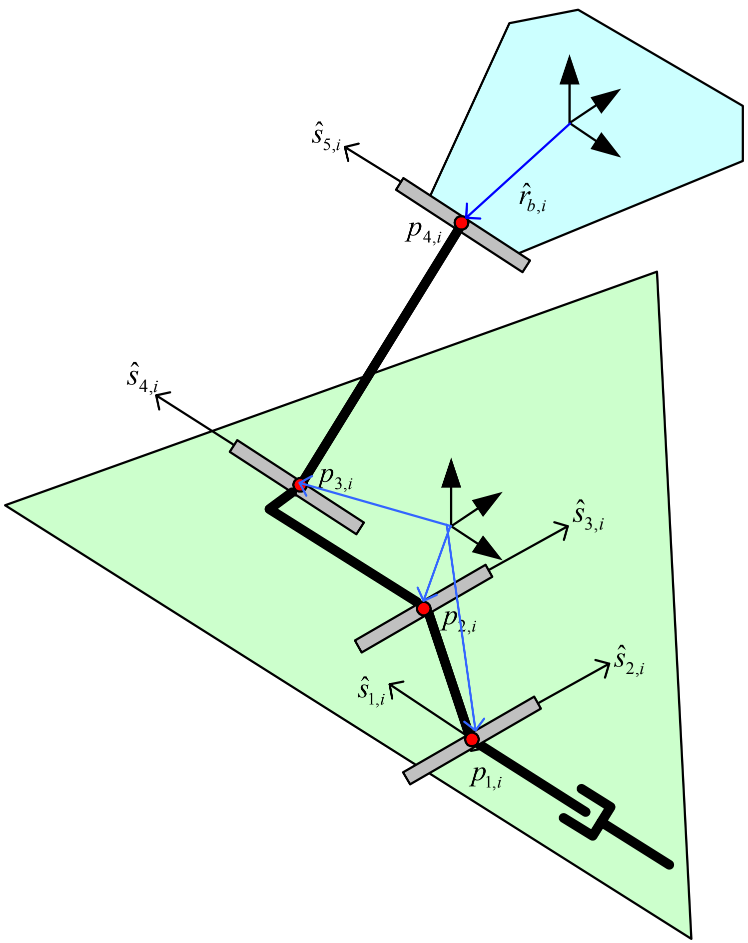
$$J_c \$_p = 0$$

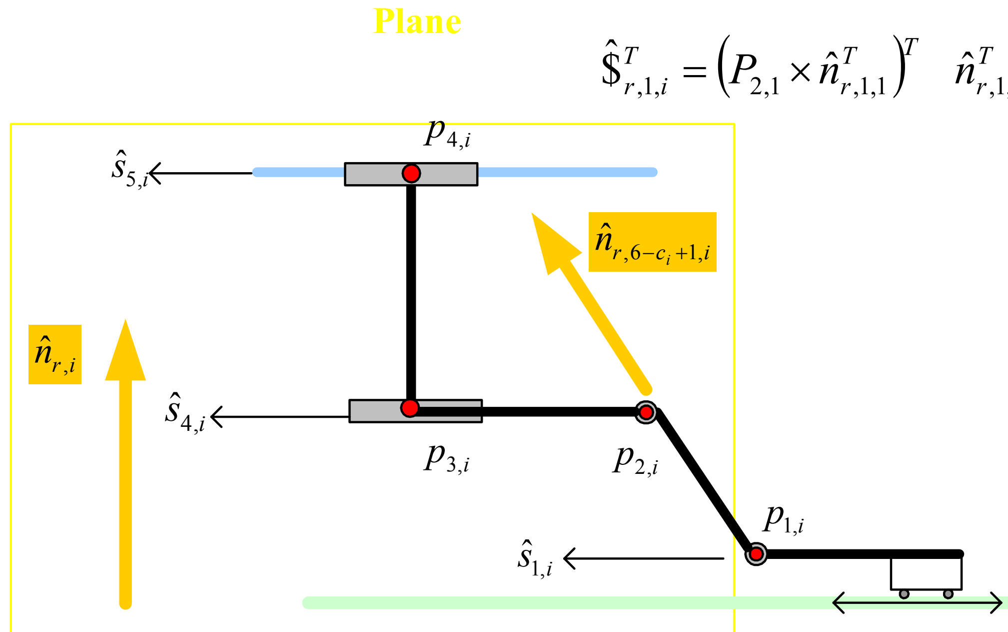
Jacobian of constraints

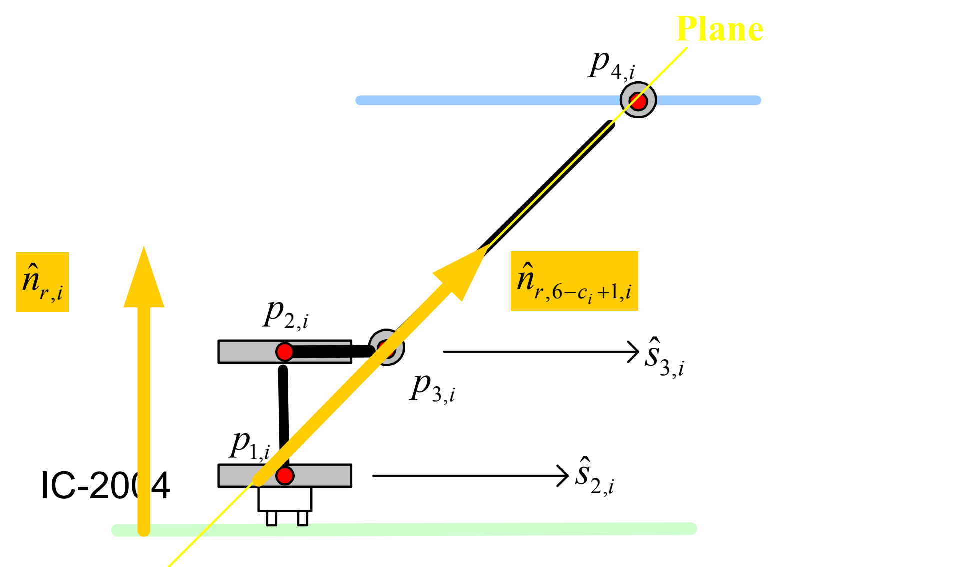
$$J = \begin{bmatrix} J_a \\ J_c \end{bmatrix}$$

Screw based Jacobian

$$\hat{\$}^T_{r,1,i} = \left(P_{2,1} \times \hat{n}^T_{r,1,1}\right)^T \quad \hat{n}^T_{r,1,1}$$







$$J = \begin{bmatrix} \hat{\$}^T_{r,1,1} / \hat{\$}^T_{r,1,1} \hat{\$}_{g,1,1} \\ \hat{\$}^T_{r,1,2} / \hat{\$}^T_{r,1,2} \hat{\$}_{g,1,2} \\ \hat{\$}^T_{r,1,3} / \hat{\$}^T_{r,1,3} \hat{\$}_{g,1,3} \\ 0^T \quad \hat{n}_1^T \\ 0^T \quad \hat{n}_2^T \\ 0^T \quad \hat{n}_3^T \end{bmatrix}$$

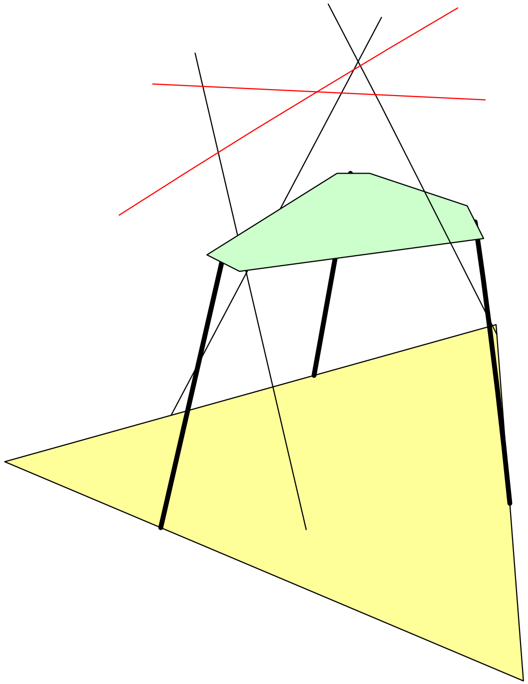
Actuation

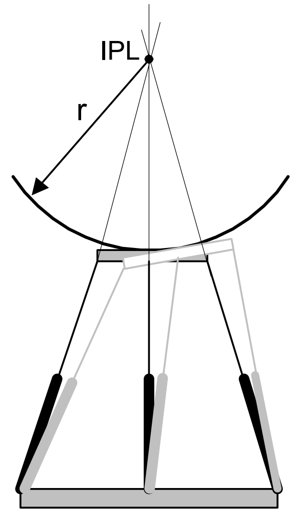
Constraints

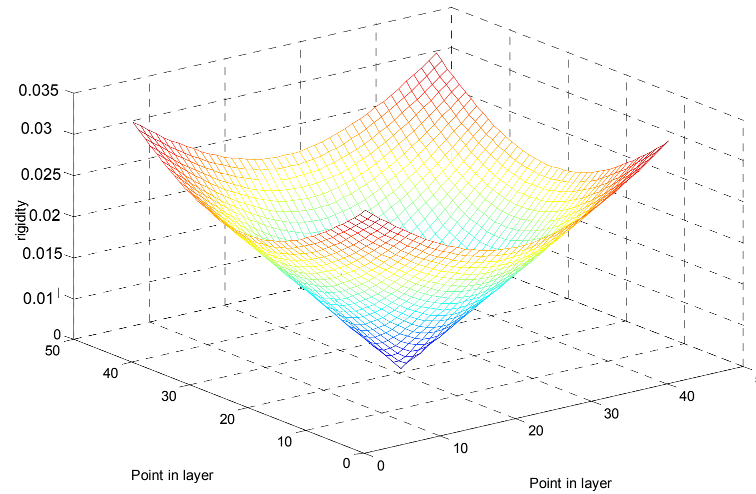
$$\dot{q} = \left[\dot{d}_{1,1}, \dot{d}_{1,2}, \dot{d}_{1,3}, 0,0,0\right]$$

$$\dot{q} = J\$_p$$

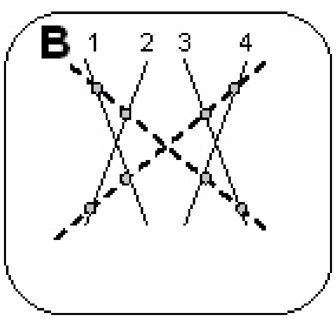
$$\hat{n}_i^T = [0,0,1]^T$$







Hyperbolic



$$J = \begin{bmatrix} \hat{\$}^T_{r,1,1} \big/ \hat{\$}^T_{r,1,1}\hat{\$}_{g,1,1} & \\ \hat{\$}^T_{r,1,2} \big/ \hat{\$}^T_{r,1,2}\hat{\$}_{g,1,2} & \\ \hat{\$}^T_{r,1,3} \big/ \hat{\$}^T_{r,1,3}\hat{\$}_{g,1,3} & \\ 0^T & \hat{n}_1^T \\ 0^T & \hat{n}_2^T \\ 0^T & \hat{n}_3^T \end{bmatrix}$$

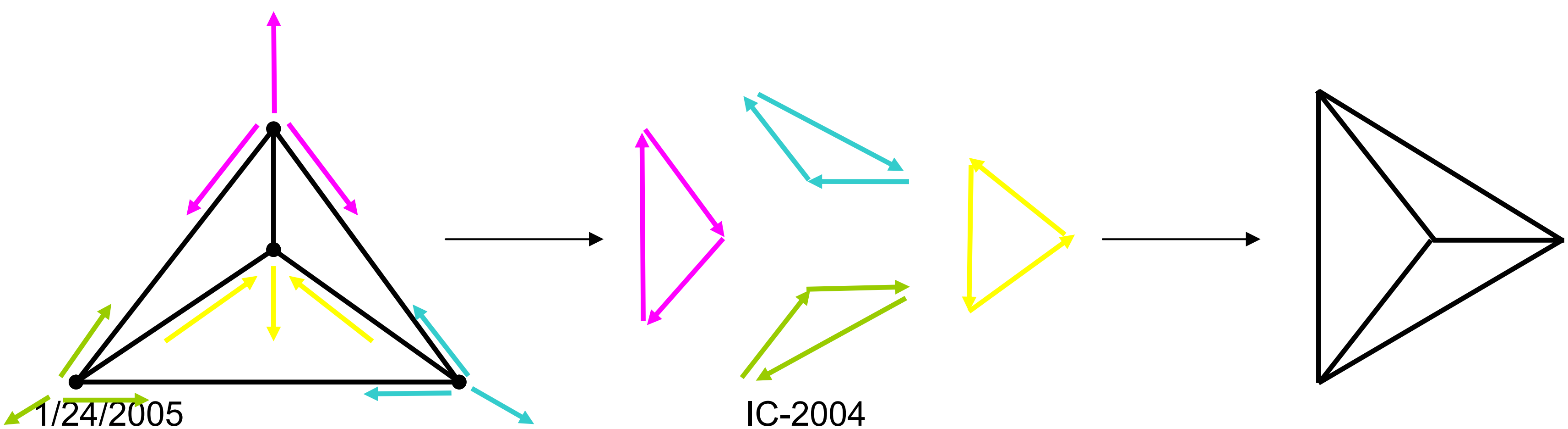
Hyperbolic Congruence

The reciprocal figure (Amir Degani)

- Definition: (Maxwell – 1864)

Two plane figures are reciprocal when they consist of an equal number of lines, so that corresponding lines in the two figures are perpendicular.

Corresponding line which converge to a point in one figure form a closed polygon in the other.



Maxwell Theorem

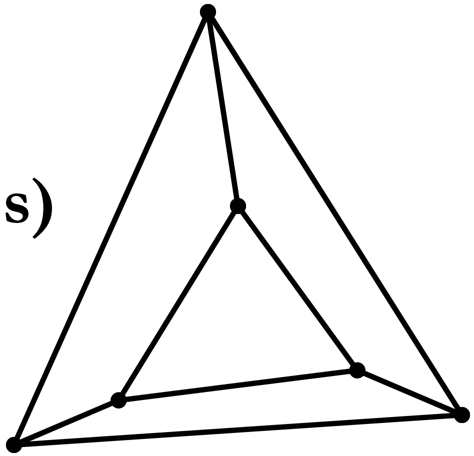
A drawing is the picture of a spherical polyhedron

⇕ IFF

The framework is rigid (supports a self stress)

⇕ IFF

Has a corresponding reciprocal figure



Duality: Singularities ←→ Reciprocal Figures

- ***Intuitive connection between Maxwell-Cremona Theorem and parallel mechanism singularity.***

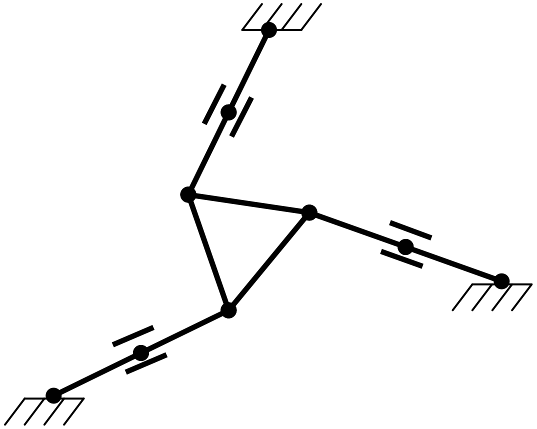
When there exists a reciprocal figure

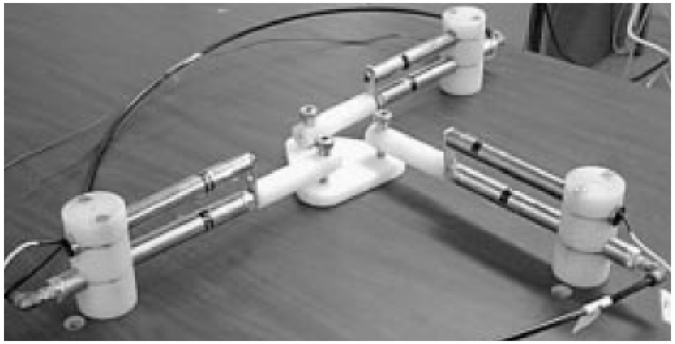
$\Updownarrow$

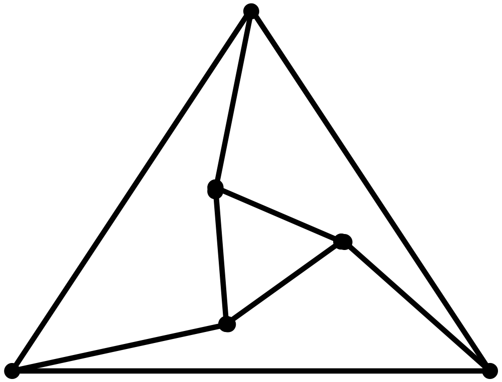
The planar framework is rigid

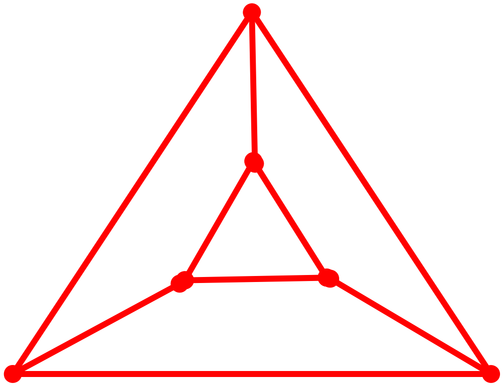
$\Updownarrow$

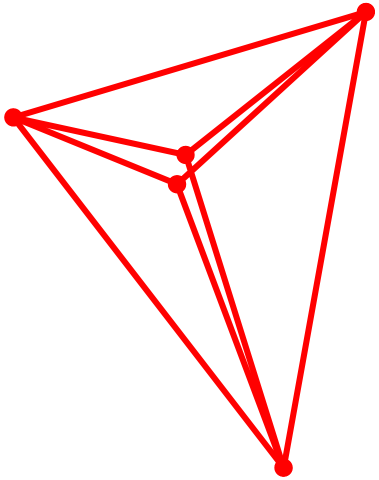
The mechanism looses a DOF







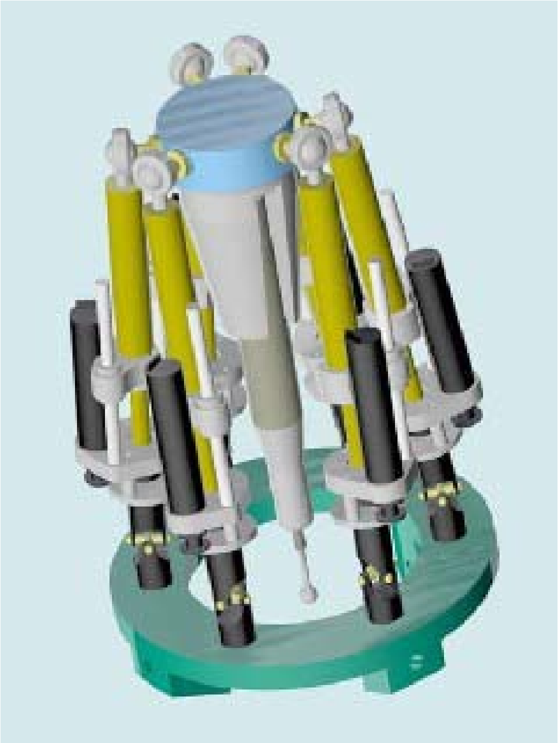


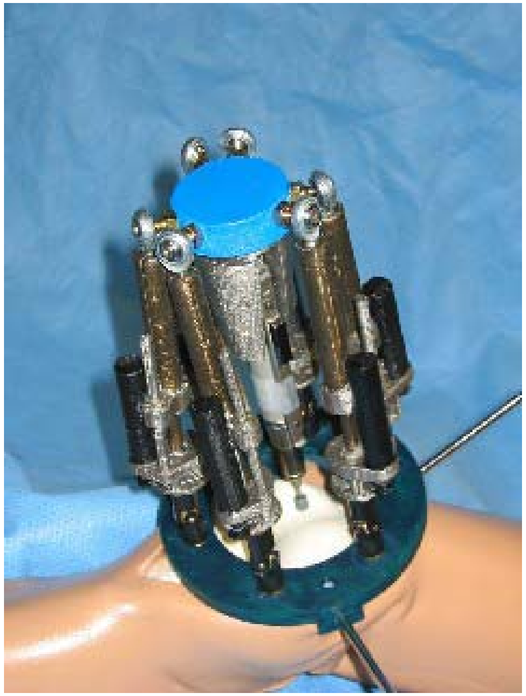


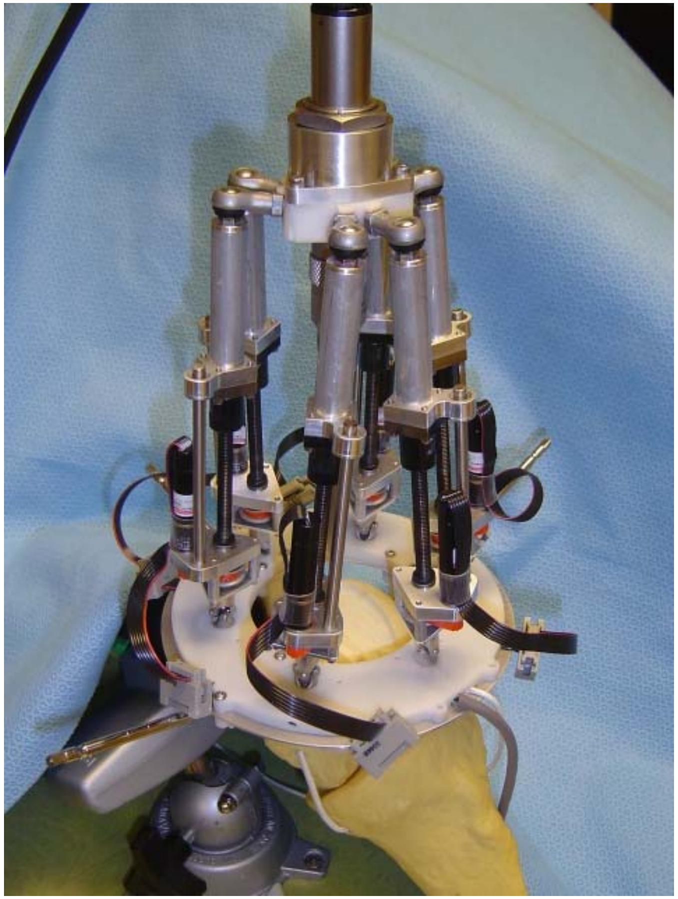
Future work

- Close mathematical formulation for 2D
- 3D

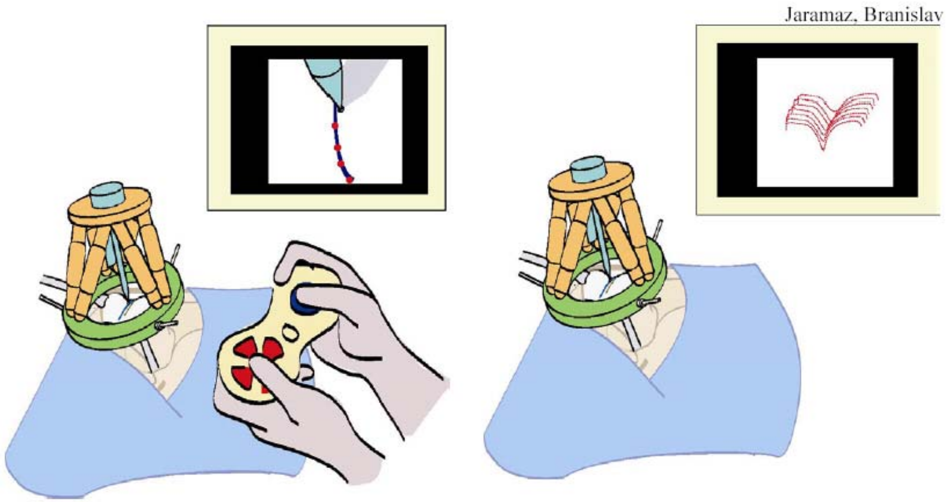
MBARS: Mini Bone Attached Robotic System



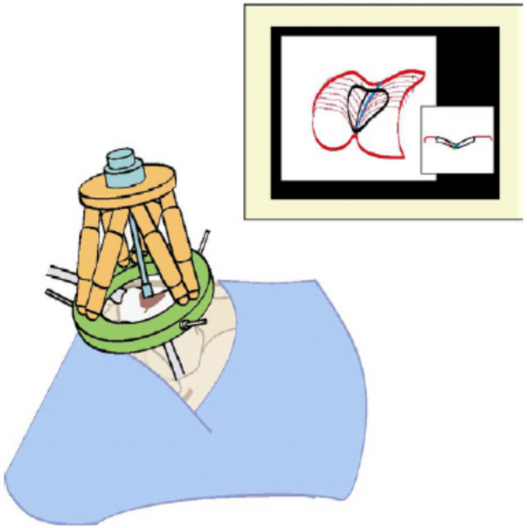




Imaged Free System



Cloud of points and Tracking the trochlear groove



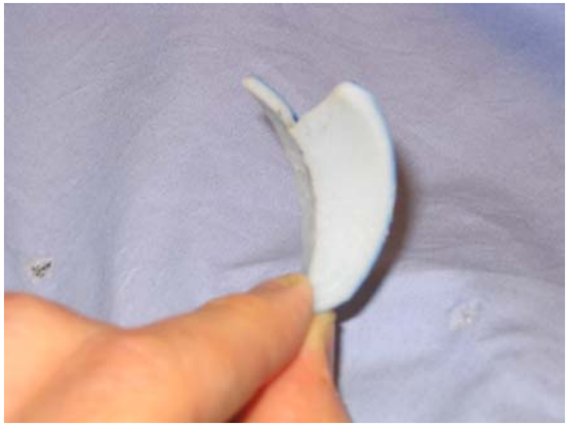
Intra-operative planning and bone shaping

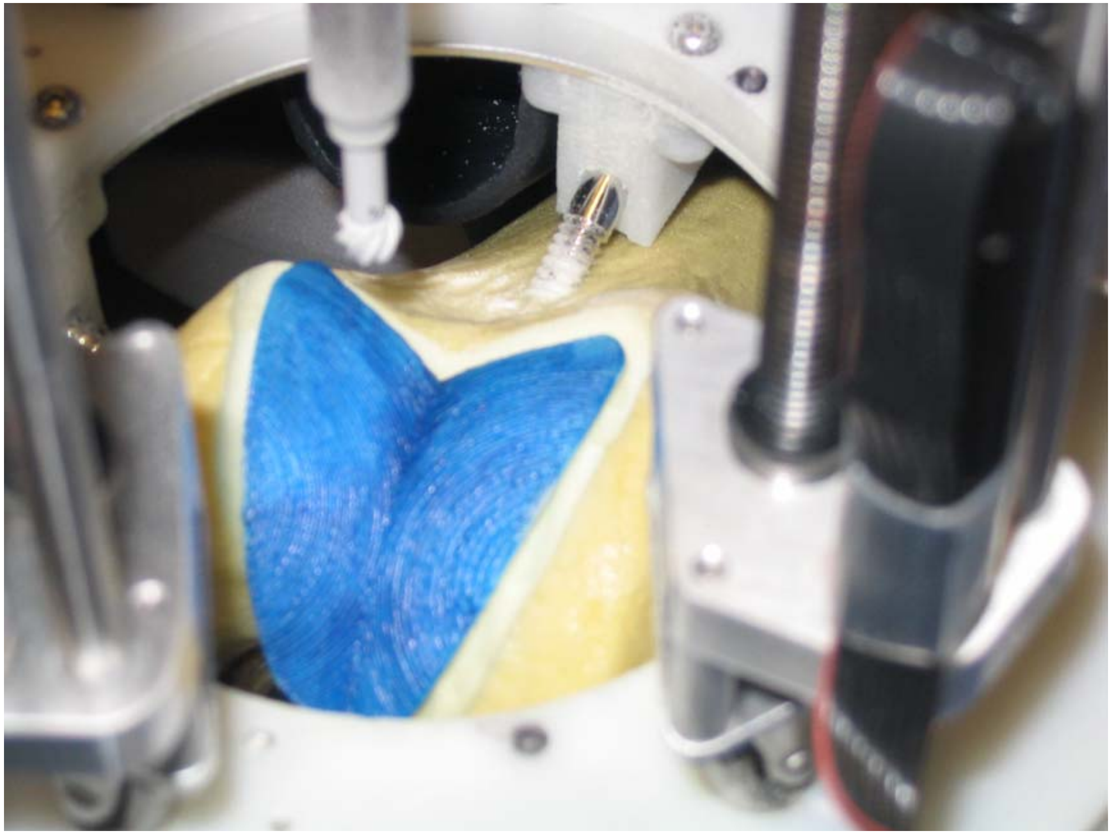
Haptic device

How does it being done today

- Surgeon traces (by hand & marker) template on to PF-surface
- Burr/chisle used to resect the trochlear groove
- Template is tried on knee; repeat 2 if necessary
- Secure final implant

First Prototype

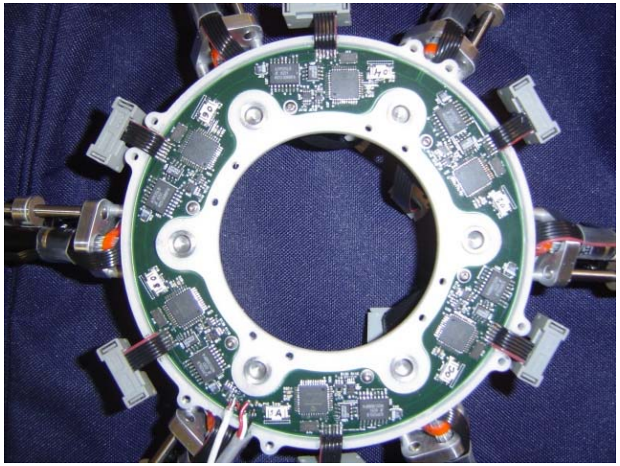


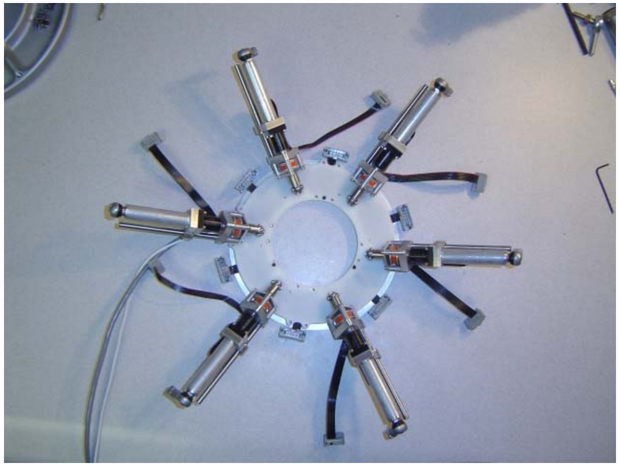


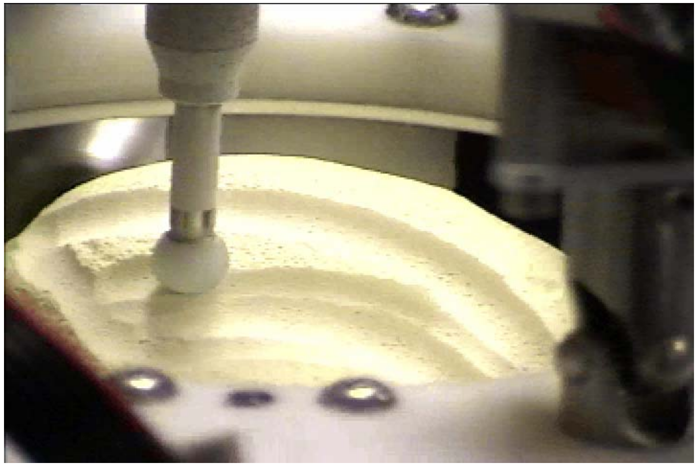
1/24/2005

IC-2004

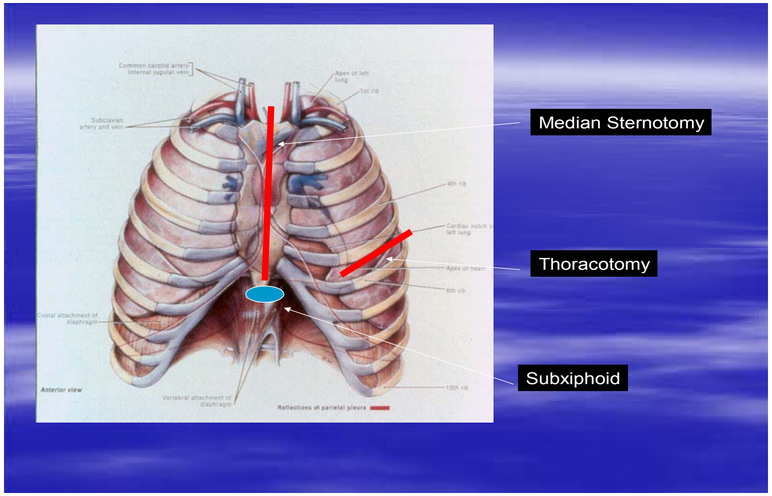
Low Level Control

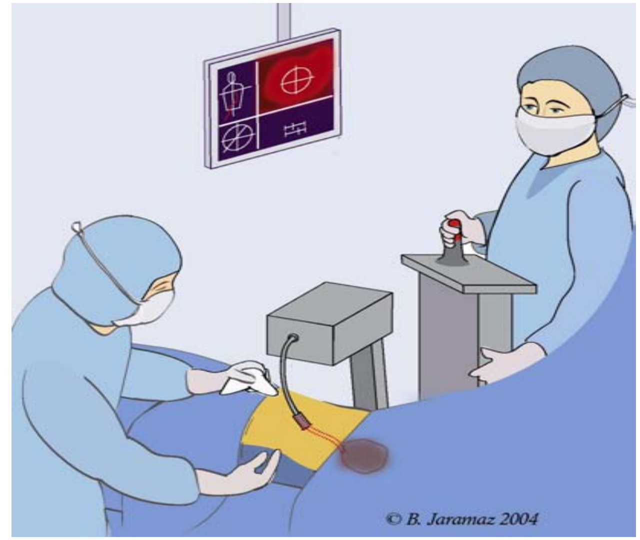




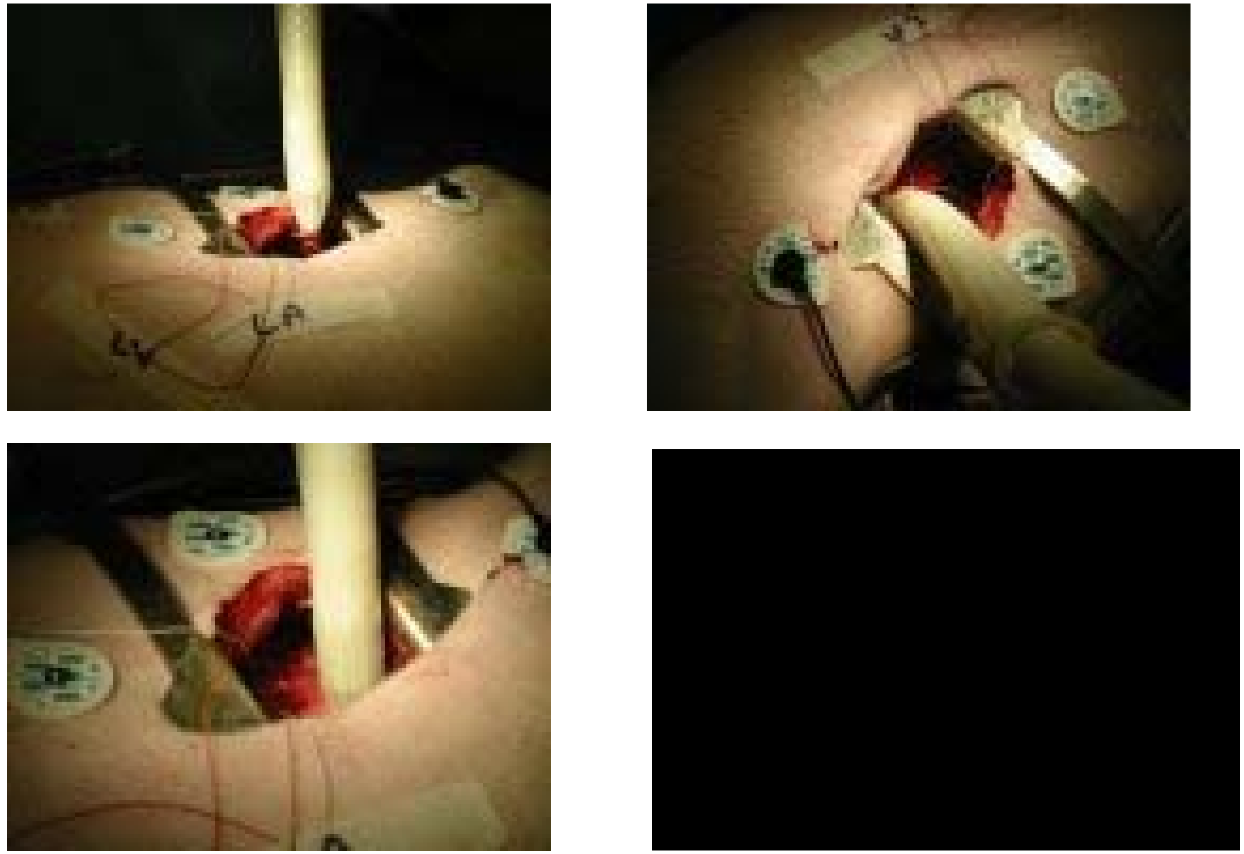


Medical Cardiac Snake

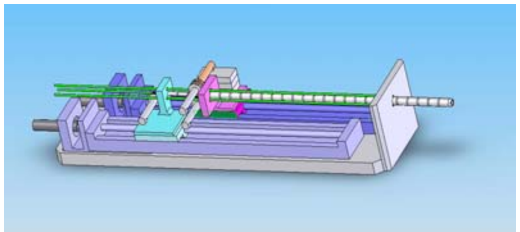


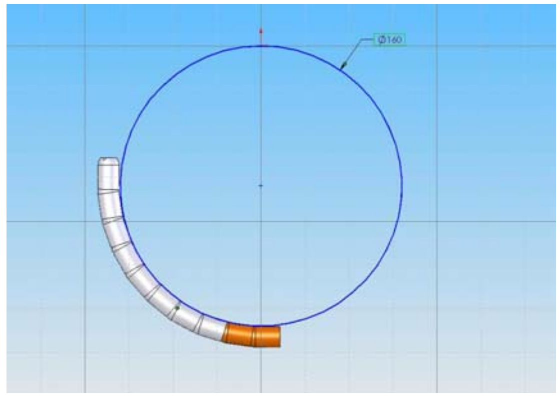


Medical Snake Robot for Cardiac Intervention



Once in operation theater,
6 mm working port running
through the snake

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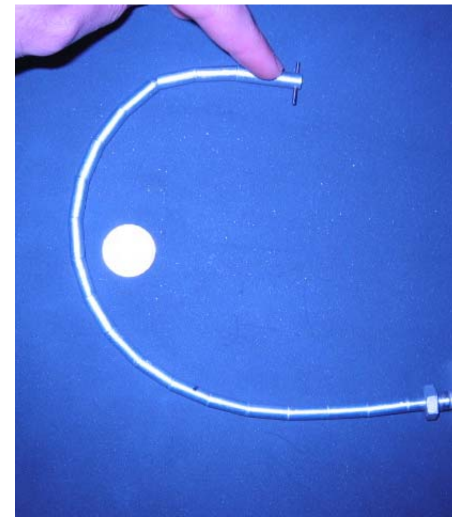
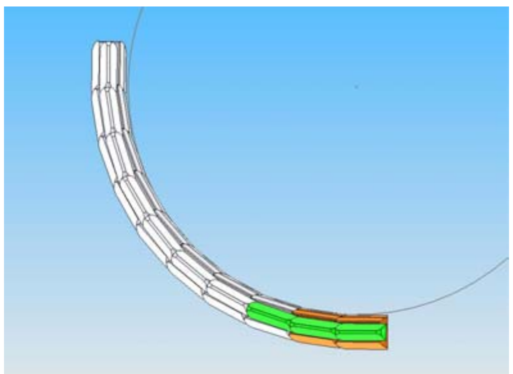
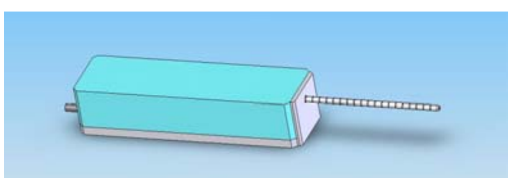




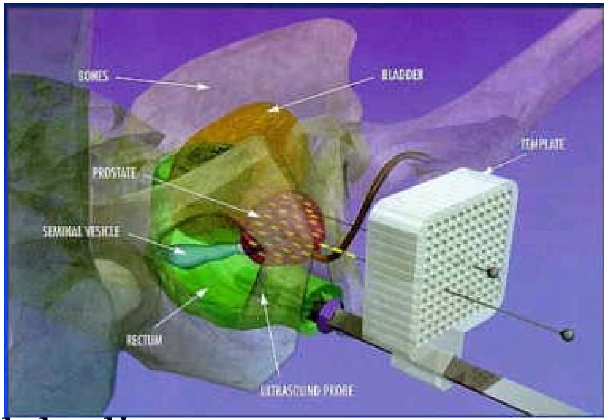


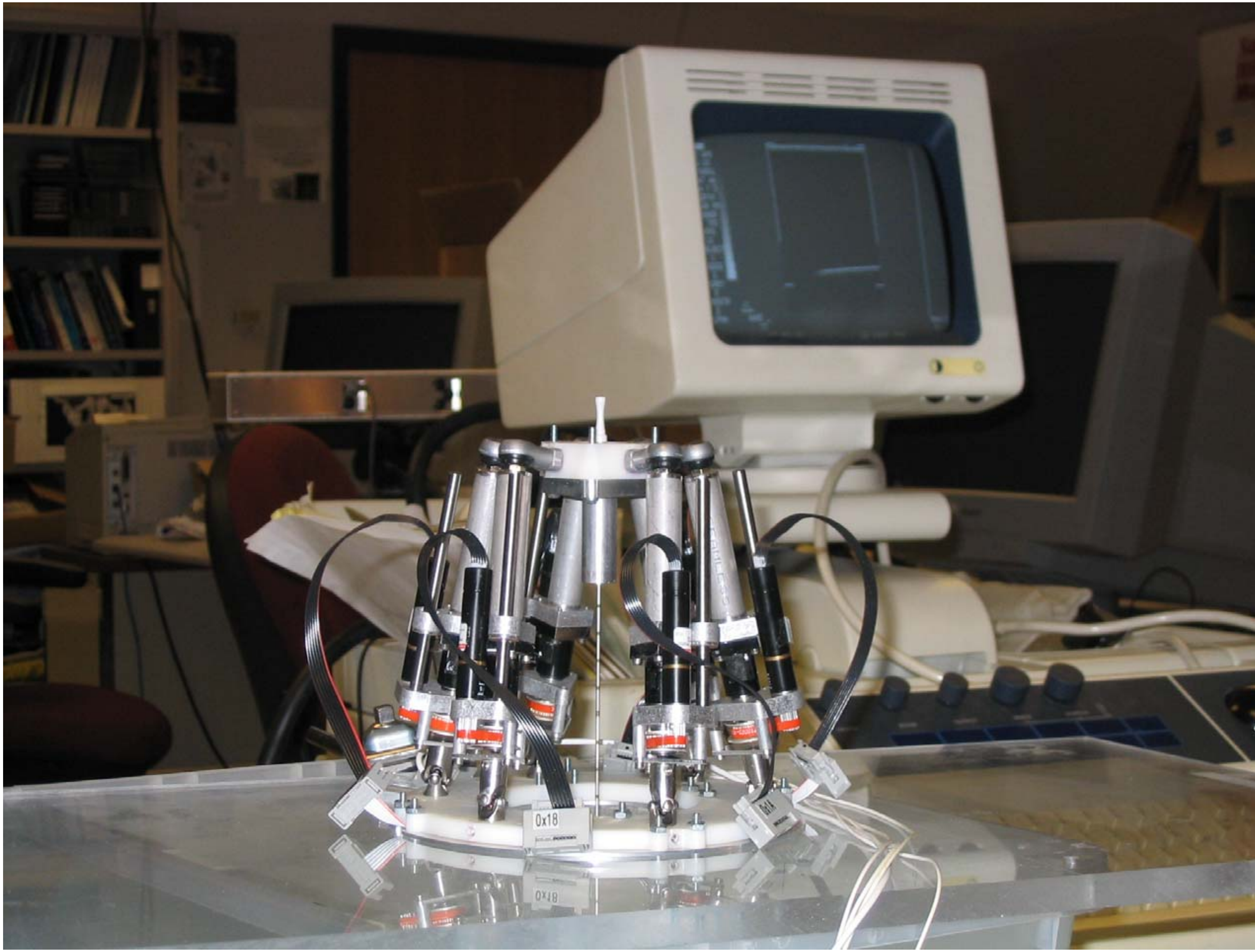
Application

- Drug delivery/inspection/intervention in the abdominal and thoracic area.
  - Cell transplantation
  - Gene therapy for angiogenesis
  - Epicardial electrode placement for resynchronization
  - Epicardial atrial ablation
  - Intrapericardial drug delivery
  - Ventricle-to-coronary artery bypass (VCAB)
  - Laparoscopic interventions.
- Laparoscopic tool of the next generation

A Robotic System for MIS ltrasound-Guided Prostate Brachytherapy

- Using radio active seeds for treatment of cancer.
- Robotics guided Needle insertion
  - Small/compact system based on high accuracy mini parallel robot.
  - No tracking system.
- Ultrasound based.
  - Ultrasound registration
  - Deformable model / Real time segmentation
  - Study on seeds motion due to deformation -> model adjustment
- Needle deflection/ robotic guided (other applications too)

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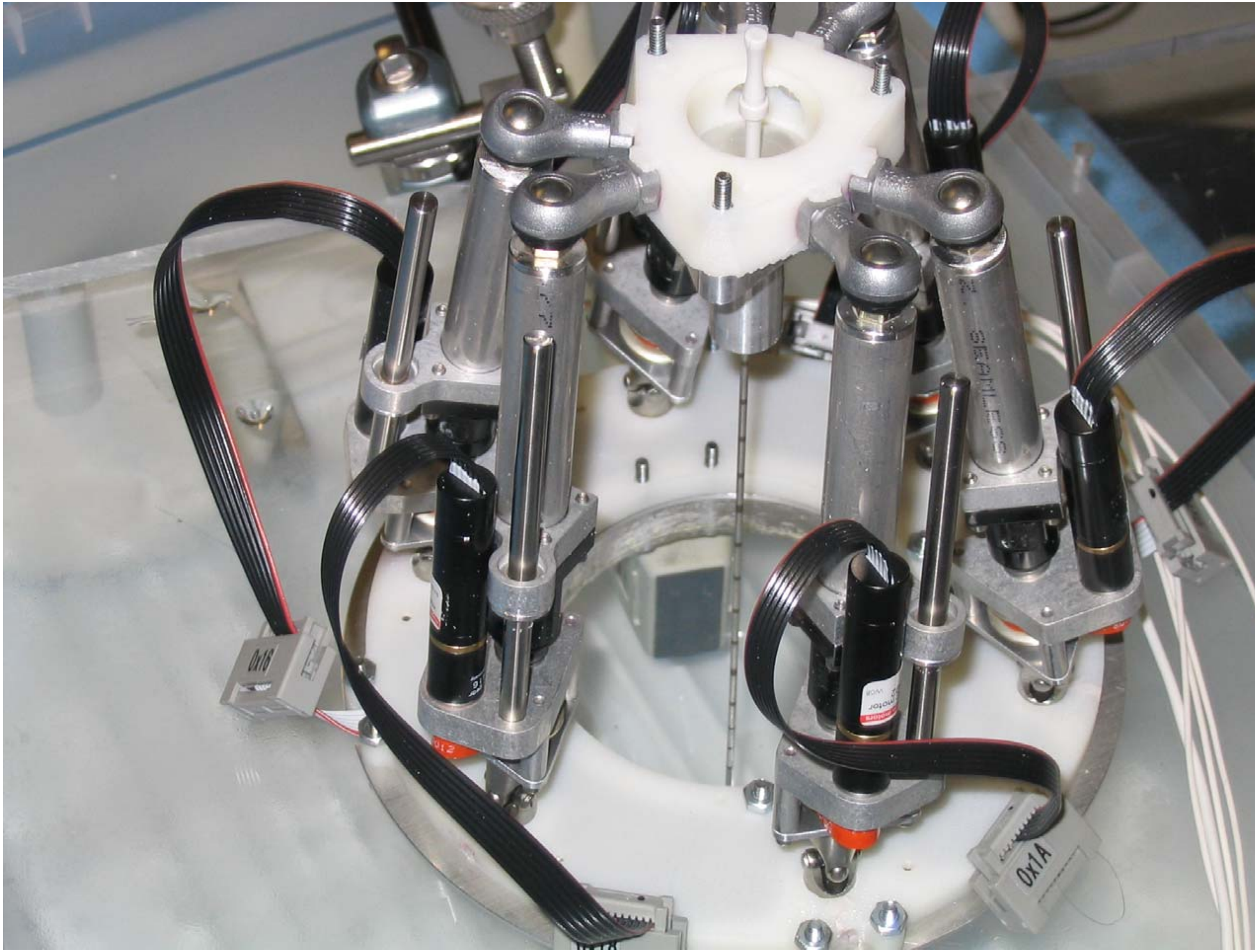
SEAMLESS
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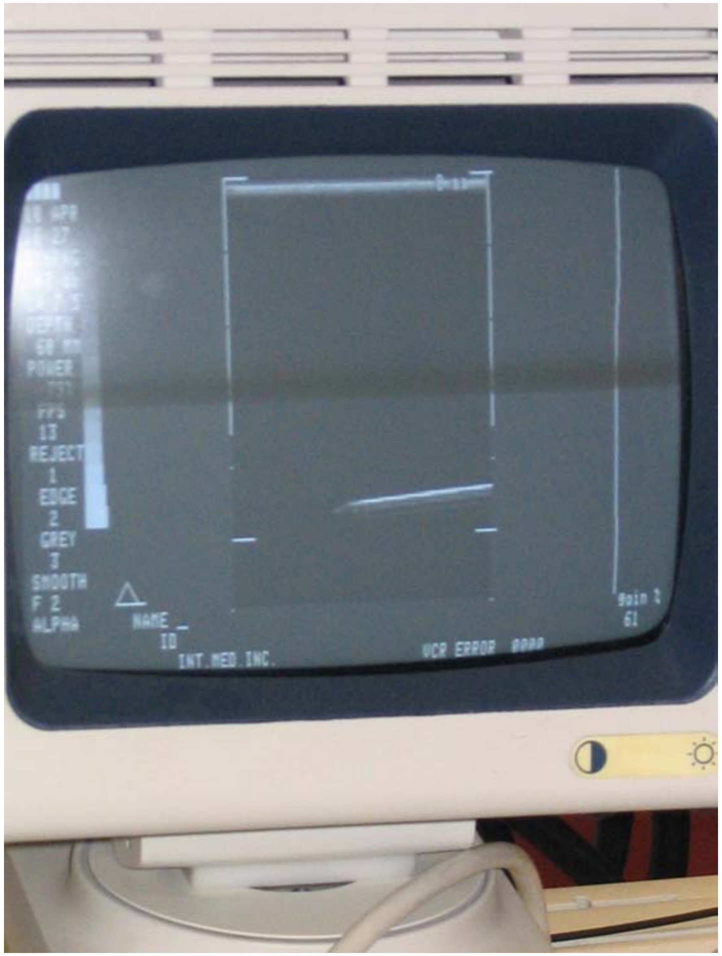
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POWER
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ID
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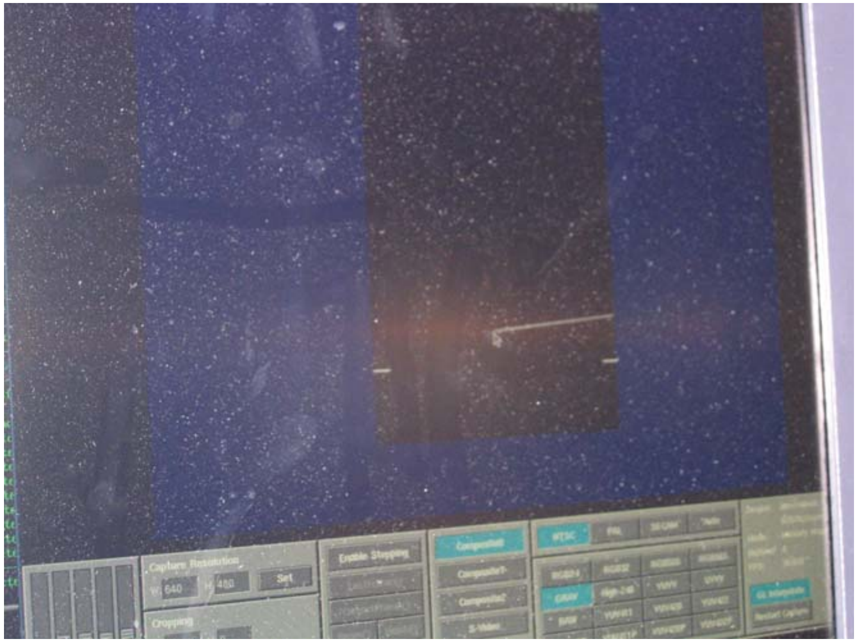
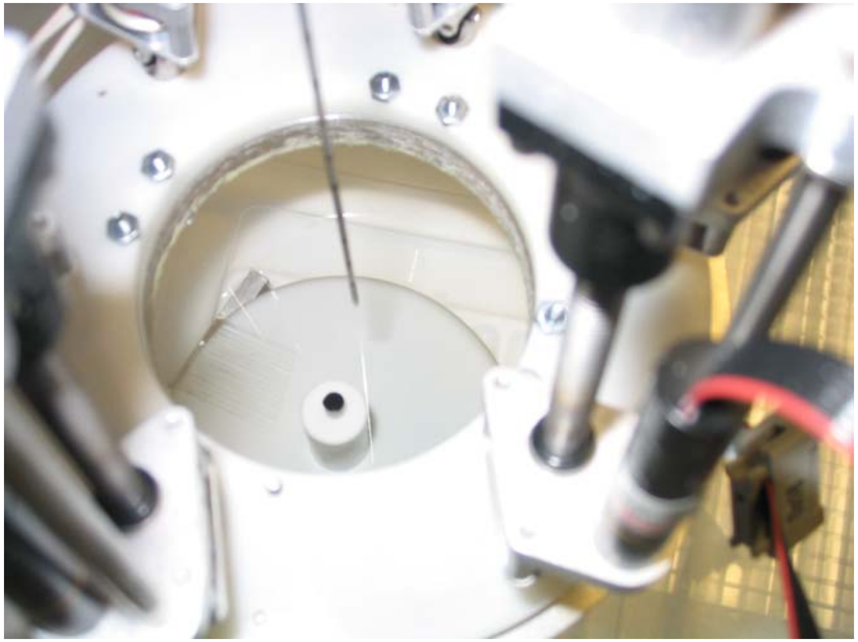
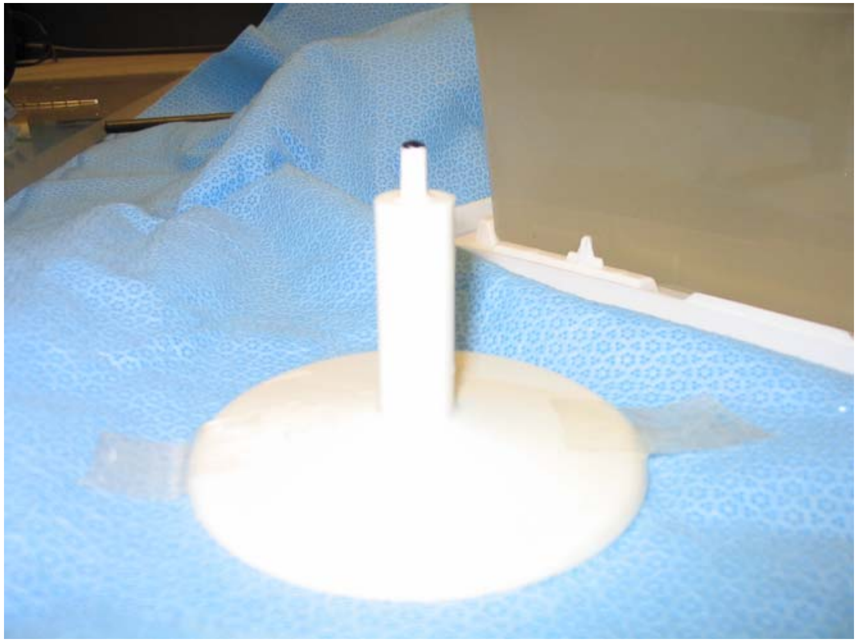
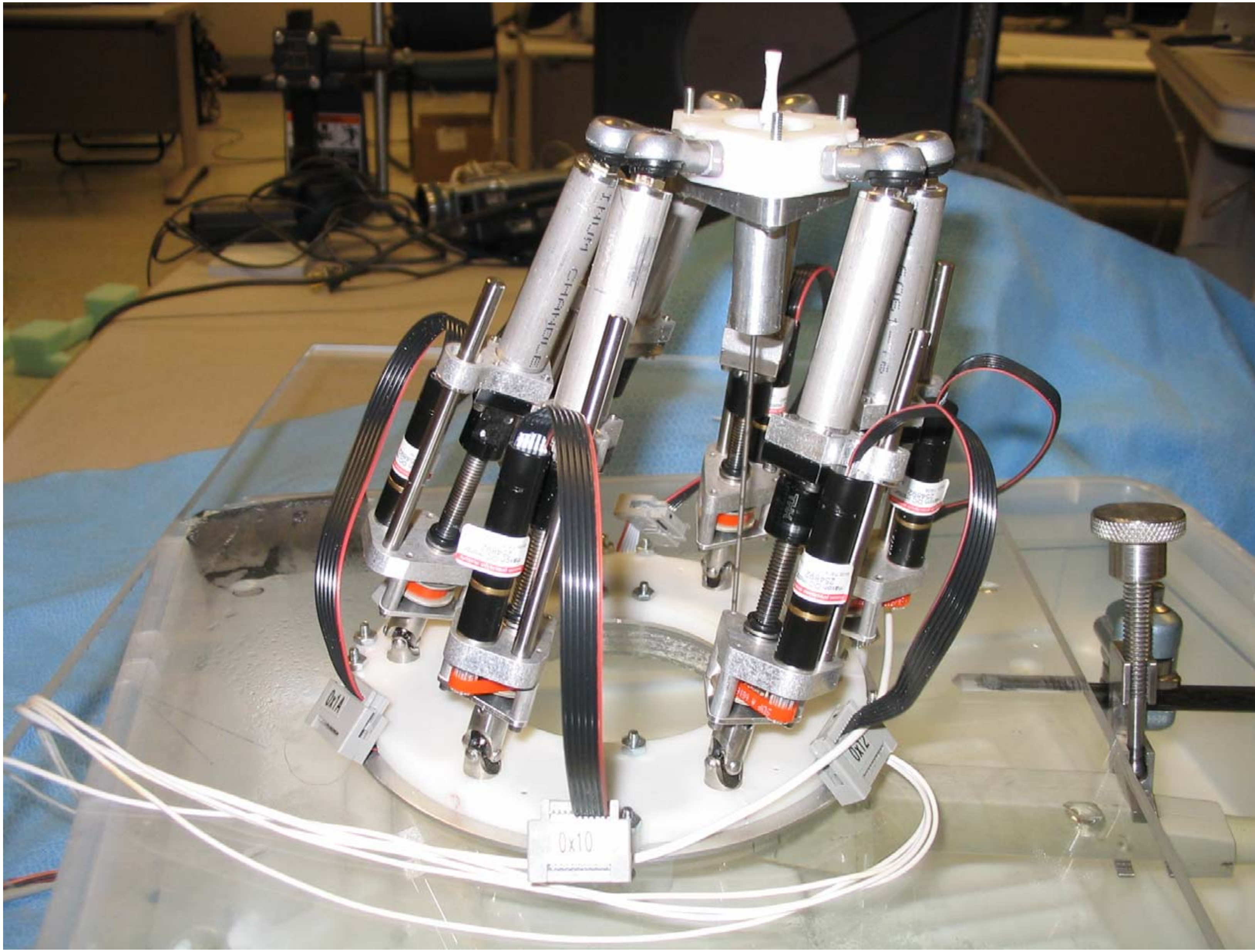
61


Capture Resolution
Set
Cropping



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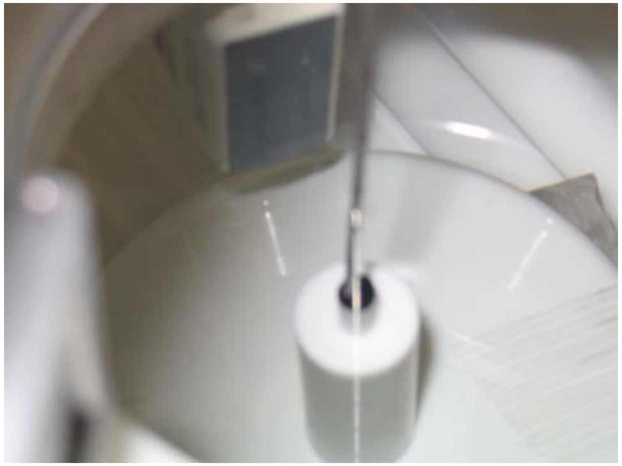
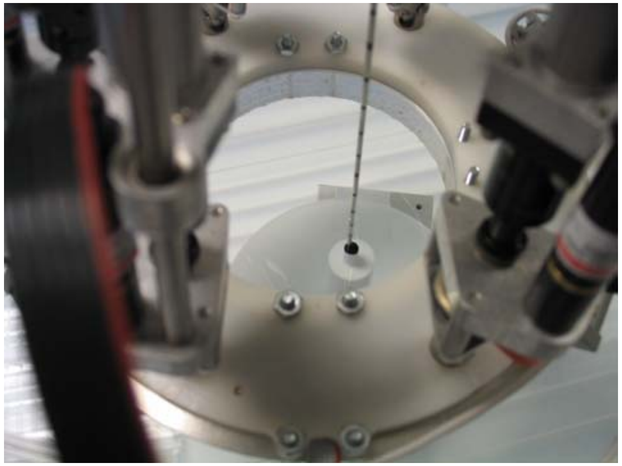

What we want to do

- Robot refinement and US mechanism
- Integrating US sensor with robotic platform
- Build 3D US model, and seeds tracking
- Real time simulation and real time update
- Elastic modeling of needle deflection in soft tissue and robotic compensation.

Thank you for your attention