Deformations

Georgia Tech College of Computing
Interactive & Intelligent Computing

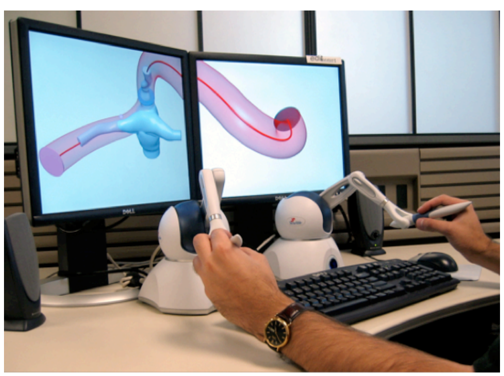
- Free-form deformations (FFD)
  - Parametric maps (Bezier, B-spline)
- Interpolating position constraints
  - Scodefs
  - Radial functions
- Interpolating position and orientation constraints
  - Twister (spatial and graph distance)
  - Bender
  - Laplace coordinates
- Deformation animation

Updated November 9, 2012

Bender: A Virtual Ribbon for Deforming 3D Shapes in Biomedical and Styling Applications

Ignacio Llamas, Alex Powell, Jarek Rossignac, Chris Shaw, Brian Whited

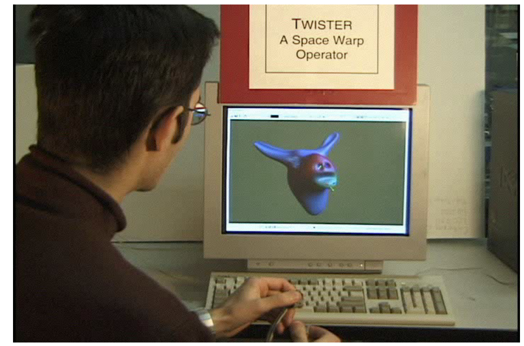
GVU Center and College of Computing
Georgia Tech, Atlanta, USA

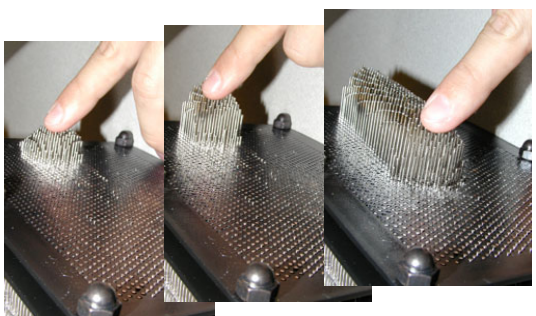


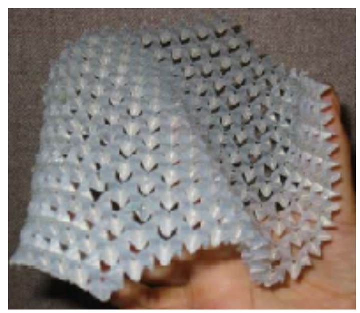
Digital Clay: A leap in human/shape interaction

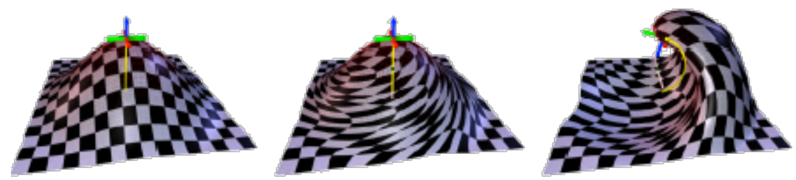
NSF-ITR/PE+SY project 0121663 at Georgia Tech. Allen, Book, Glezer, Ebert-Uphoff, Rosen, Rossignac, Shaw

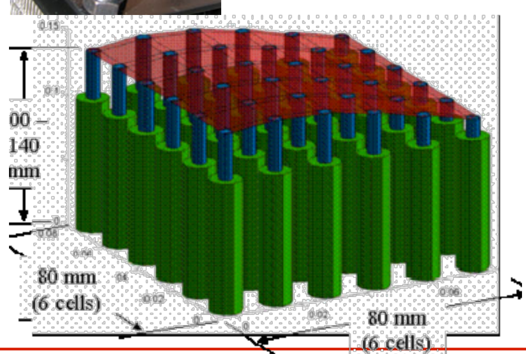
Two designs for a computer-controlled, physical surface that reacts to changes in 3D model and in pressure exerted by fingers

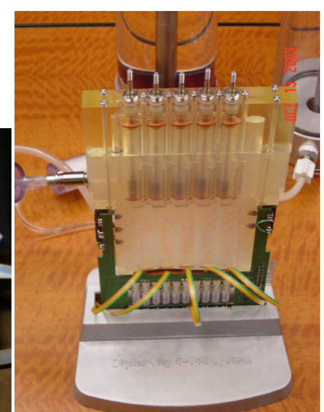


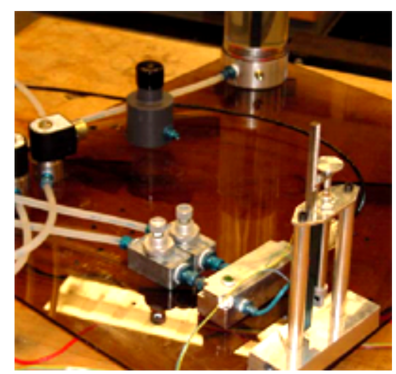




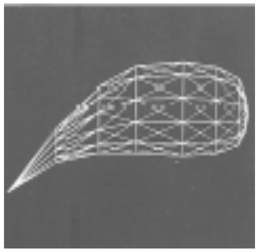


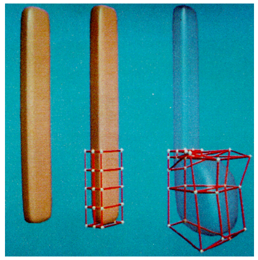






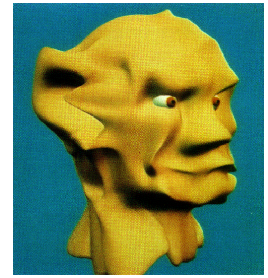
Examples of prior art

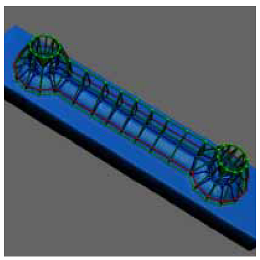

Parent77

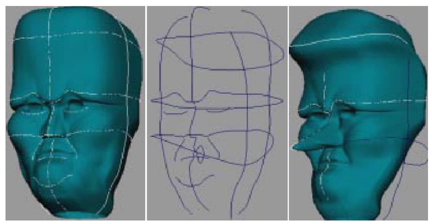

Sederberg86


Coquillart90

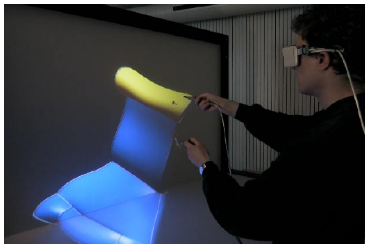

Borrel91

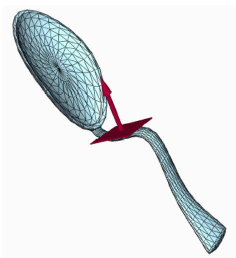

Hsu92


MacCracken96

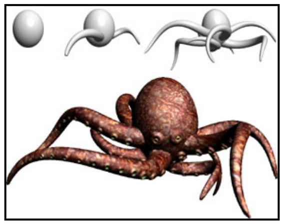

Sinh 98

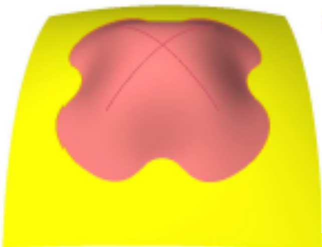

Schkolne01


Wesche01


Gain00


Jin00

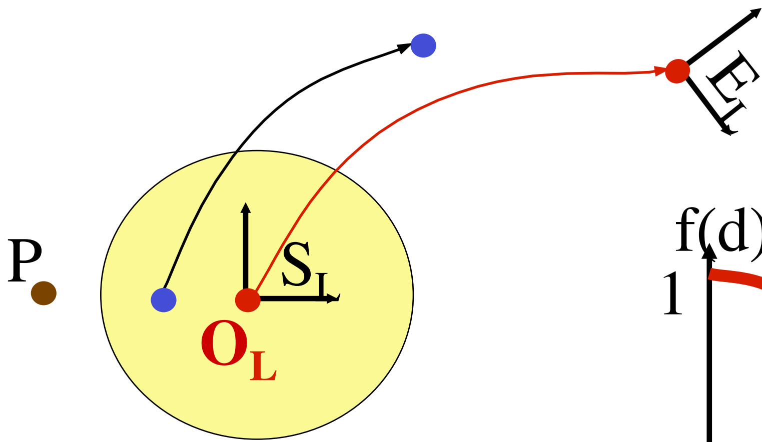

Pauly03

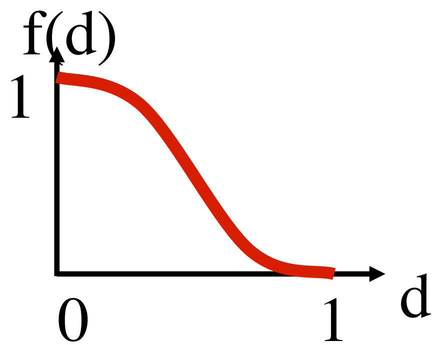

Pernot03


Yoshizawa03

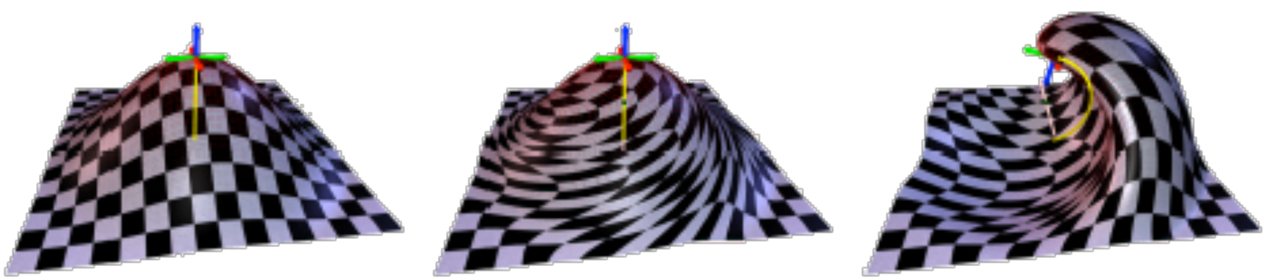
Space warp based on a screw motion

"Twister: A space-warp operator for the two-handed editing of 3D shapes", Llamas, Kim, Gargus, Rossignac, and Shaw. Proc. ACM SIGGRAPH**, July 2003.**



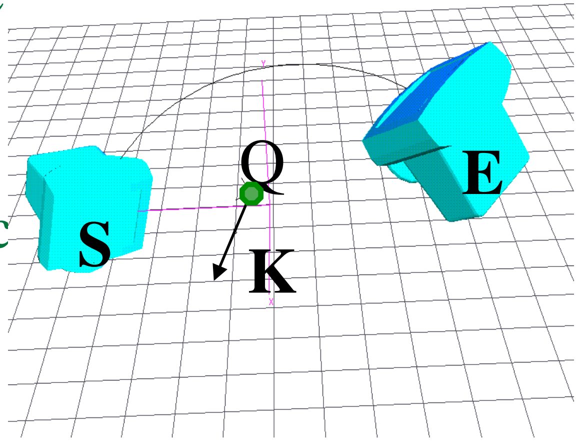


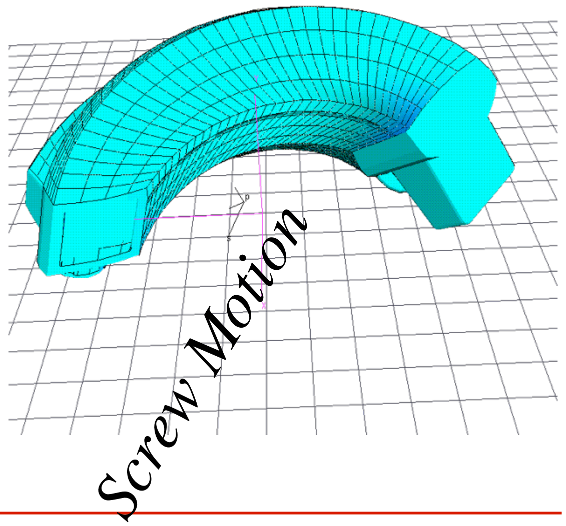
Decay function



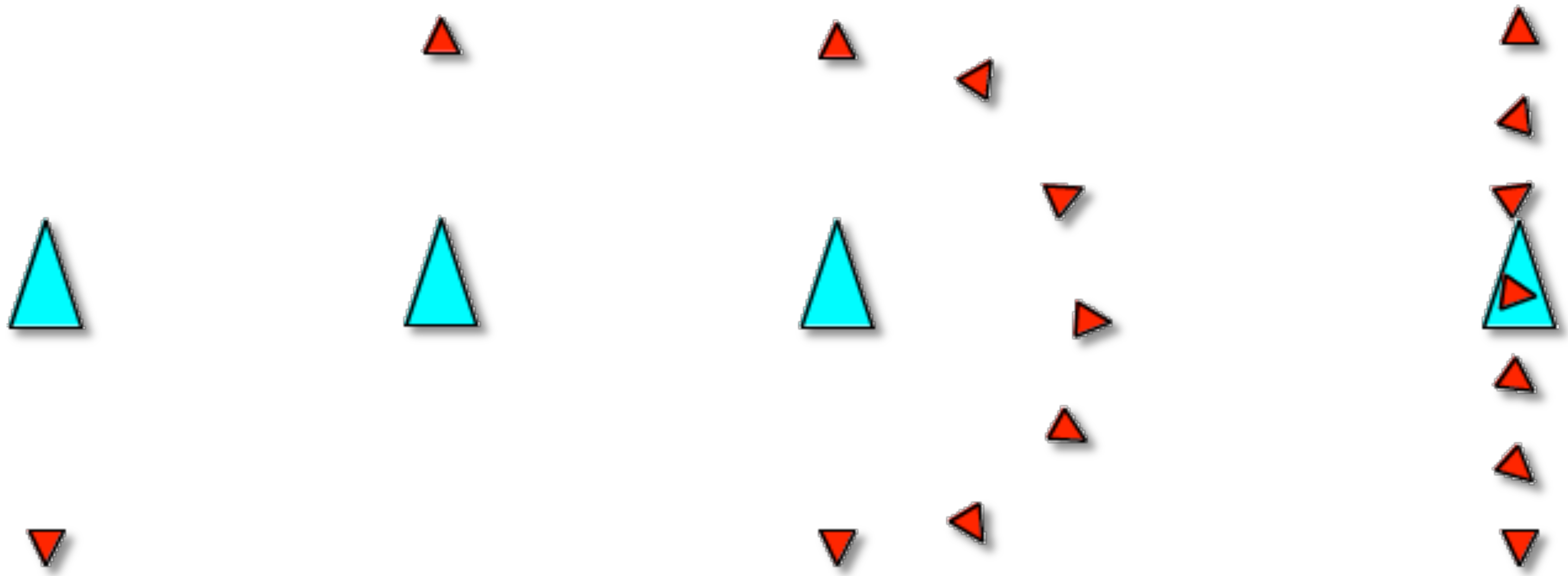
The universal screw-motion

- Screw motions are great!
  - Uniquely defined by start pose S and end pose
  - Independent of coordinate system
  - Subsumes pure rotations and translations
  - Minimizes rotation angle & translation distanc
  - Natural motions for many application
- Simple to apply for any value of t in [0,1]
  - Rotation by angle ***tb*** around axis Axis(**Q**,**K**)
  - Translation by distance ***td*** along Axis(**Q**,**K**)
  - Each point moves along a **helix**
- Simple to compute from poses S and E
  - Axis: point **Q** and direction **K**
  - Angle **b**
  - Distance **d**





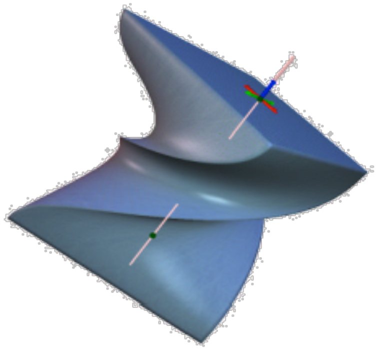
Motion independent of CS



Screw history

(Ceccarelli [2000] Detailed study of screw motion history)

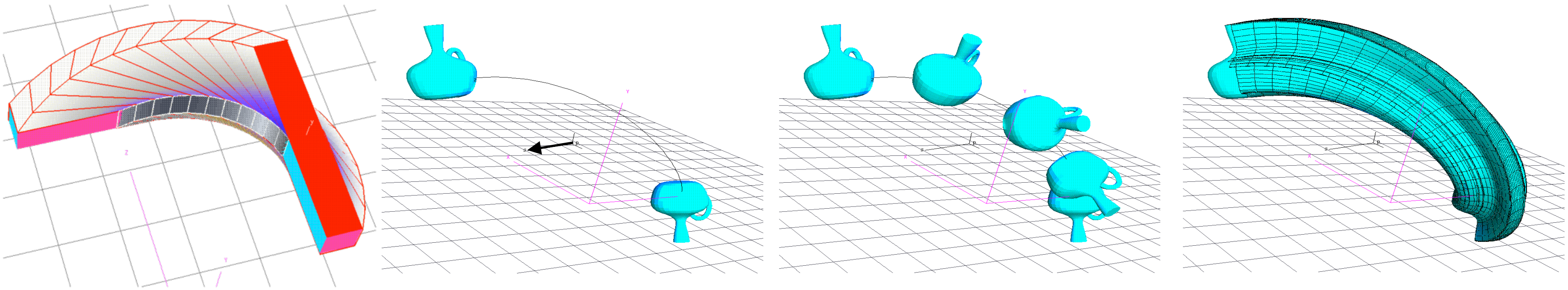
- Archimede (287–212 BC) designed helicoidal screw for water pumps
- Leonardo da Vinci (1452–1519) description of helicoidal motion
- Dal Monte (1545–1607) and Galileo (1564–1642) mechanical studies on helicoidal geometry
- Giulio Mozzi (1763) screw axis as the "spontaneous axis of rotation"
- L.B. Francoeur (1807) theorem of helicoidal motion
- Gaetano Giorgini (1830) analytical demonstration of the existence of the "axis of motion" (locus of minimum displacement points)
- Ball (1900) "*Theory of screws*"
- Rodrigues (1940) helicoidal motion as general motion
- ….
- Zefrant and Kumar (CAD 1998) Interpolating motions



Volume swept during screw motion

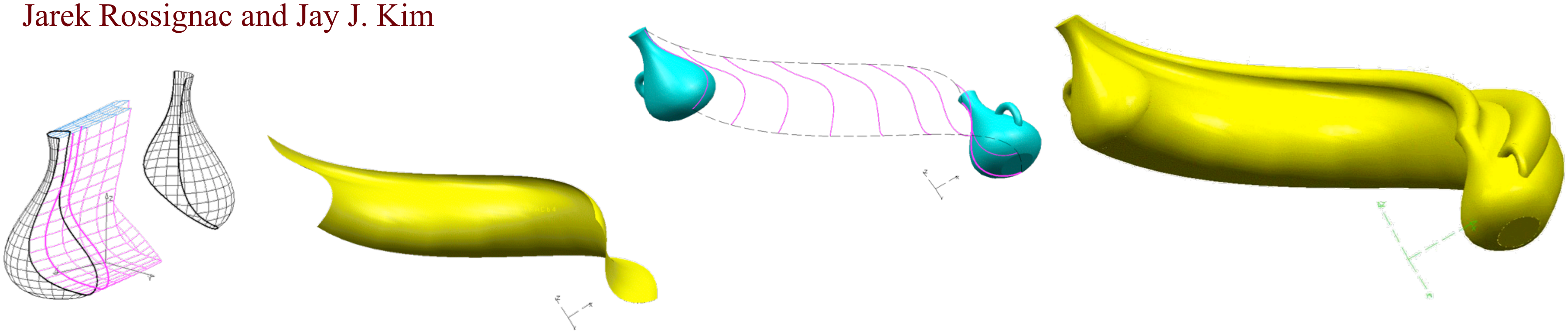
Computing and visualizing pose-interpolating 3D motions

Jarek Rossignac and Jay J. Kim, CAD, 33(4)279:291, April 2001.



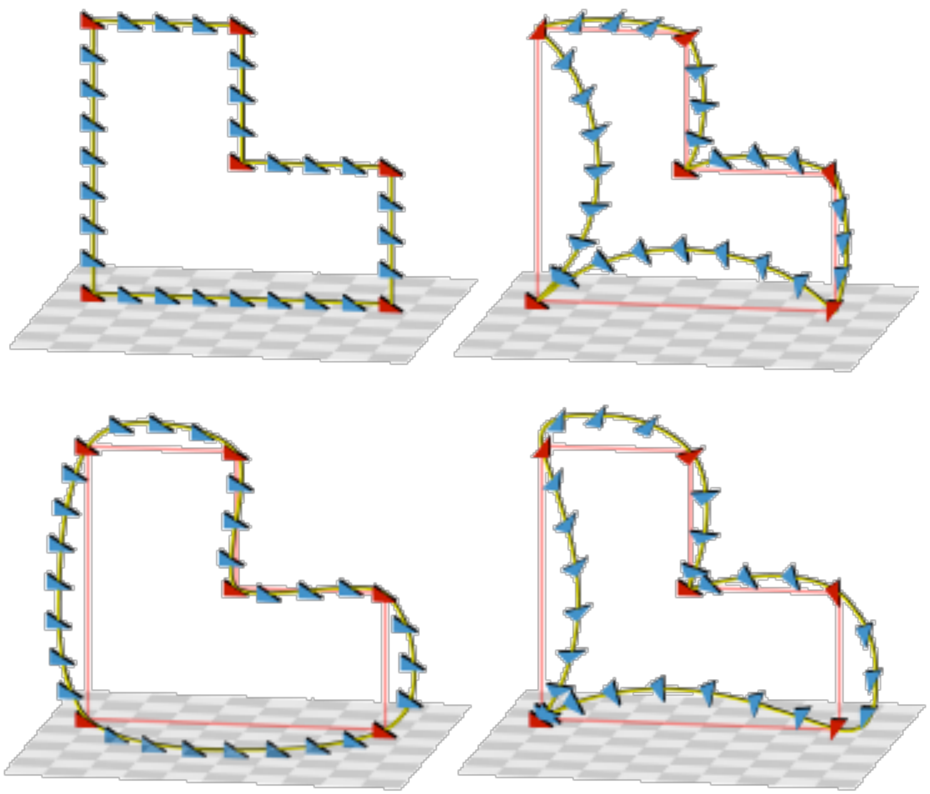
SweepTrimmer: Boundaries of regions swept by sculptured solids during a pose-interpolating screw motion

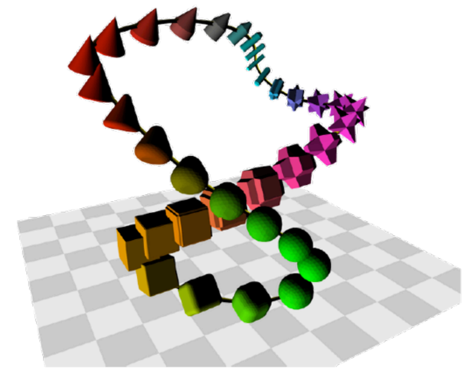
Jarek Rossignac and Jay J. Kim

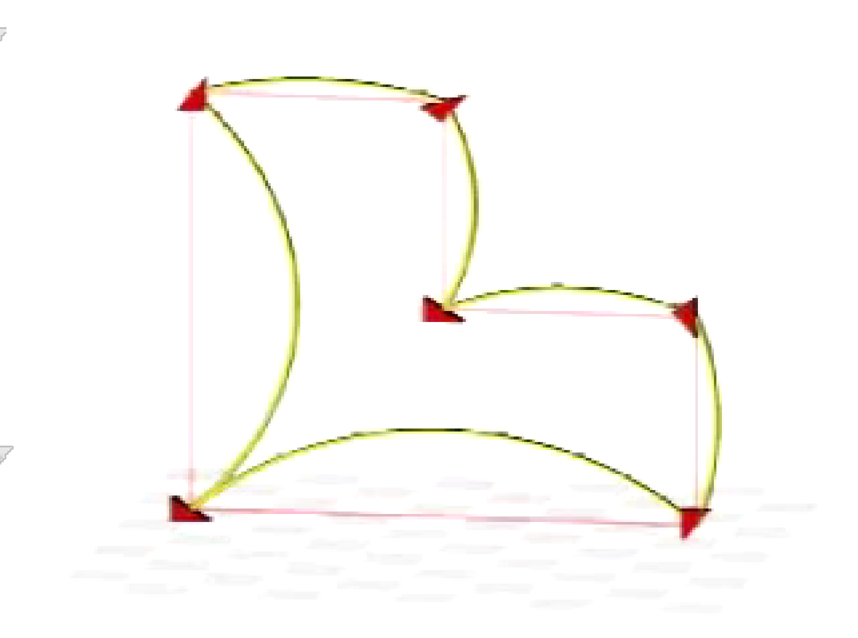


Smoothing piecewise-screw motions

"ScrewBender: Polyscrew Subdivision for Smoothing Interpolating Motions" A. Powell and J. Rossignac



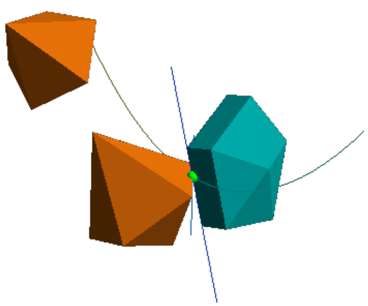
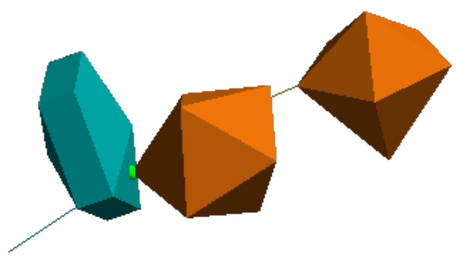
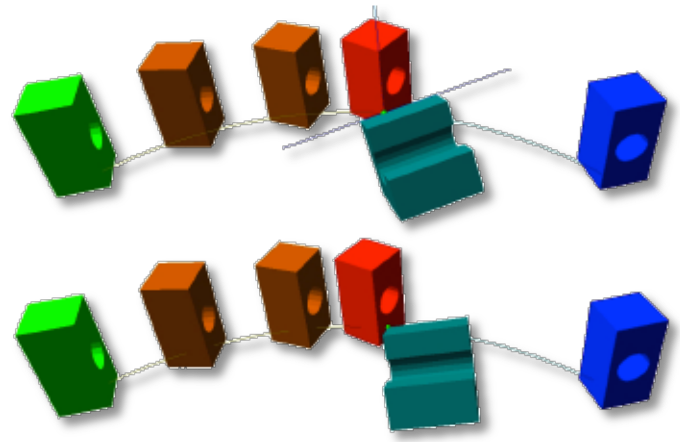


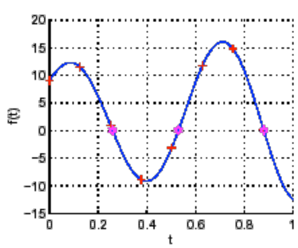


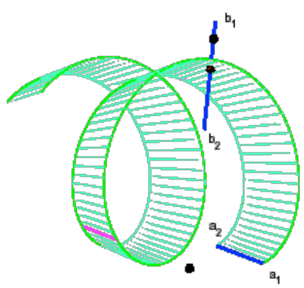
Collision during screw motions

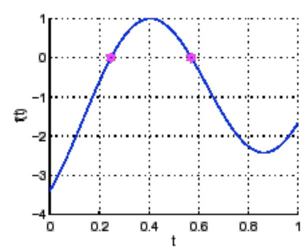
"Collision Prediction for Polyhedra under Screw Motions", BM Kim and J. Rossignac, ACM Symposium on Solid Modeling and Applications**, 2003.**

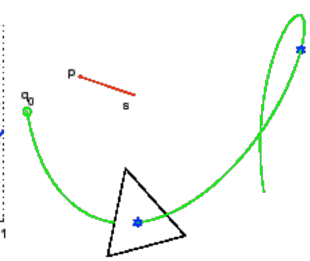
- **Helix is** $\mathrm{V}(t) = r\cos(tb)\mathrm{i} + r\sin(tb)\mathrm{j} + td\mathrm{k}$ **in screw coordinates**
- **The screw intersects plane** $d + \mathrm{V}(t) \bullet \mathrm{n} = 0$ **for values of** t **satisfying**









Computing the screw parameters

From initial and final poses:

M(0) and M(1)

K:=(U' –U)×(V' –V);

K:=K / ||K||;

b := 2 sin^{-1}(||U' –U|| / (2 ||K×U||));

d:=K•OO' ;

Q:=(O+O')/2 + (K×OO') / (2tan(b/2));

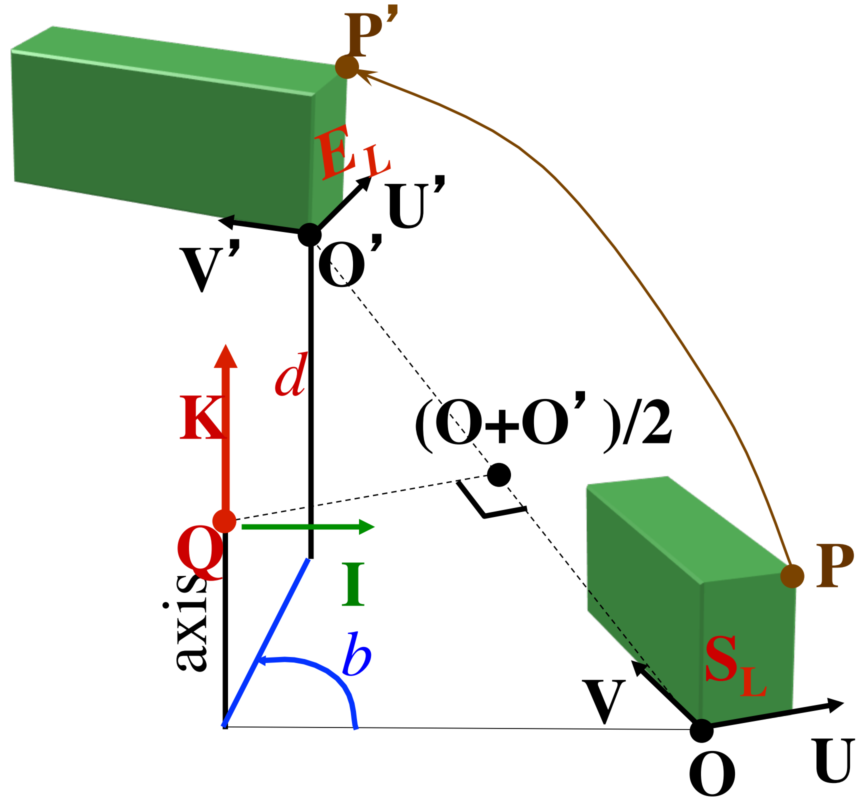
To apply a t-fraction of the screw:

Translate by –Q;

Rotate around K by tb;

Translate by (0,0,td);

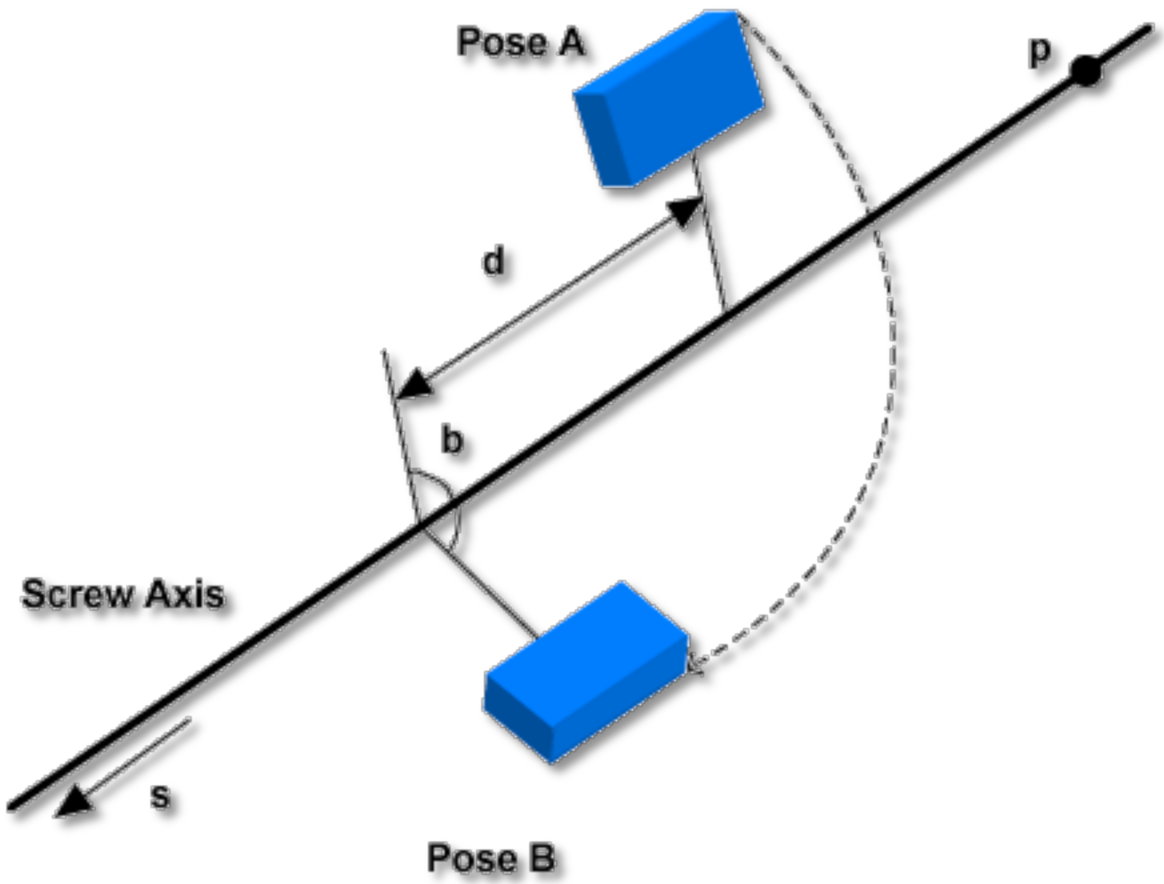
Translate by Q;



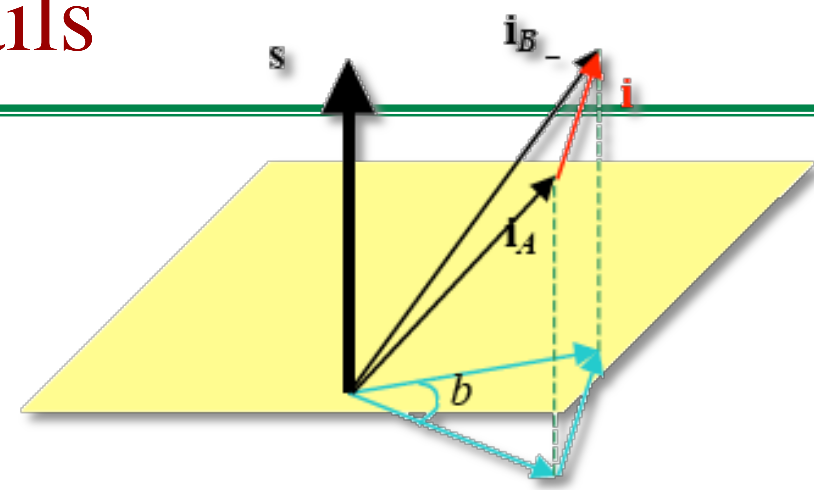
Details

s=K

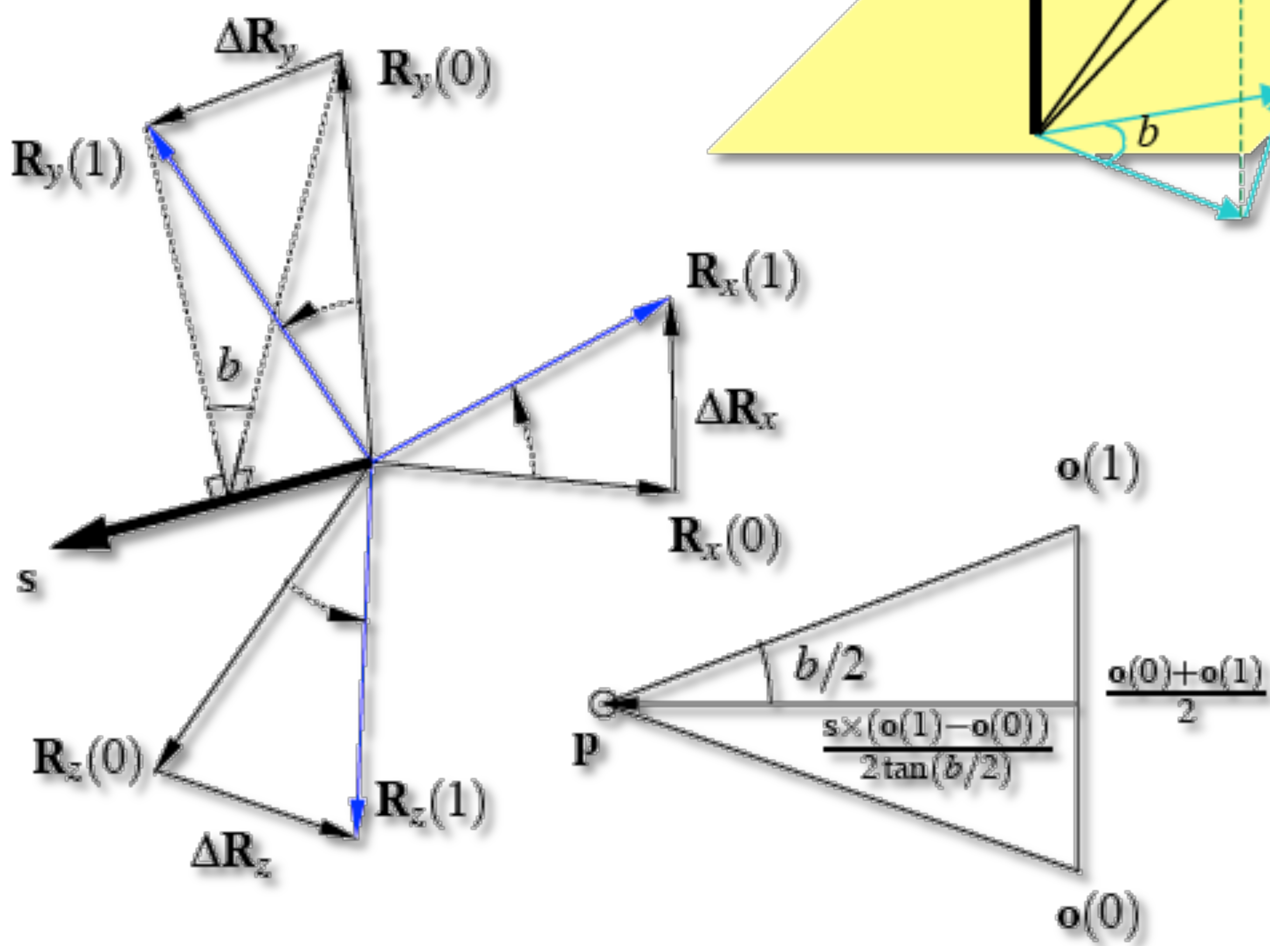
p=Q



Details

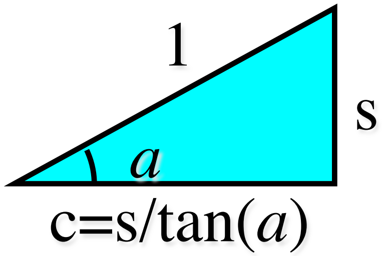


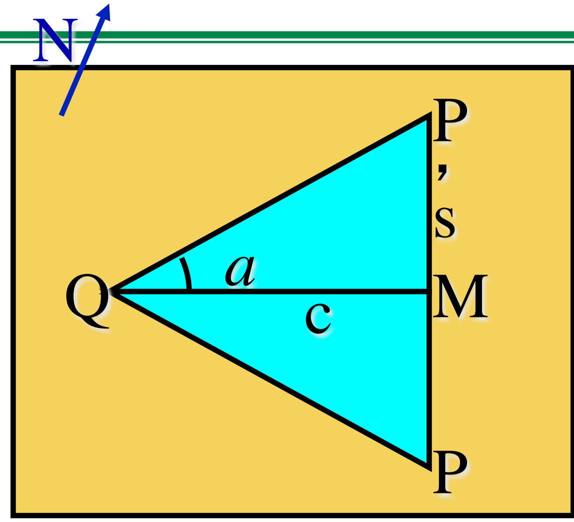
s
$\mathbf{i}_B$
$\mathbf{i}$
$\mathbf{i}_A$
b



$\Delta\mathbf{R}_y$
$\mathbf{R}_y(0)$
$\mathbf{R}_y(1)$
b
$\mathbf{R}_x(1)$
$\Delta\mathbf{R}_x$
$\mathbf{R}_x(0)$
s
$\mathbf{R}_z(0)$
$\mathbf{R}_z(1)$
$\Delta\mathbf{R}_z$
$\mathbf{o}(1)$
$b/2$
$\frac{\mathbf{o}(0)+\mathbf{o}(1)}{2}$
p
$\frac{\mathbf{s}\times(\mathbf{o}(1)-\mathbf{o}(0))}{2\tan(b/2)}$
$\mathbf{o}(0)$

Computing point Q on screw axis





Given P, P', and a, compute Q the center of rotation by angle $b=2a$ that brings P to P'

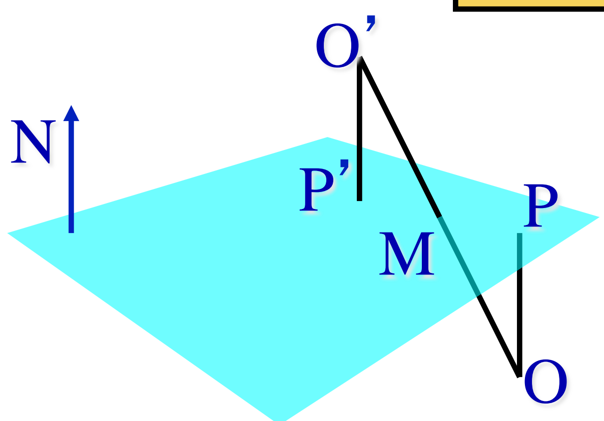
M=(P+P')/2

T=N×PP'/||PP'||

c=||PP'||/(2tan(a))

A=M+cT

=(P+P')/2+N×PP'/(2tan(a))



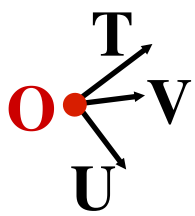
P=O+hN, P'=O'–hN (projections)

P+P'=O+O', PP'=OO'–2hN

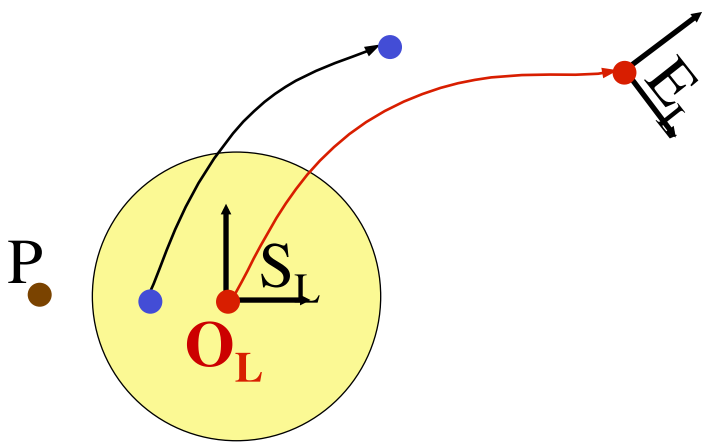
N×PP' = N×OO' – 2hN×N = N×OO'

A = (O+O')/2 + N×OO'/(2tan(b/2))

Mathematical model for the warp



- A pose is a 3D coordinate system: origin and basis
  - Can be represented by a vector and a rotation matrix (6 DoF)
  - Initial "grab" positions of the 2 trackers define **start poses**: S_L and S_R
  - Current positions of the trackers define **end poses**: E_L and E_R
  - End poses change during manipulation (until "release")
- We want a space warp W such that:
  - We meet the 12 **constraints**: $W(S_L)=E_L$, $W(S_R)=E_R$, (modulo scaling)
  - **Local** effect, $W(\mathbf{P})=\mathbf{P}$, when $d(||\mathbf{PO_L}||)>r$ and $d(||\mathbf{PO_R}||)>r$
  - The warp is **smooth** and **natural**
    - not surprising to the user
  - The user has fine control
    - Small changes to E_L and E_R produce small changes in the shape
- Upon release, E_L and E_R are frozen
  - The vertices of the mesh have new locations

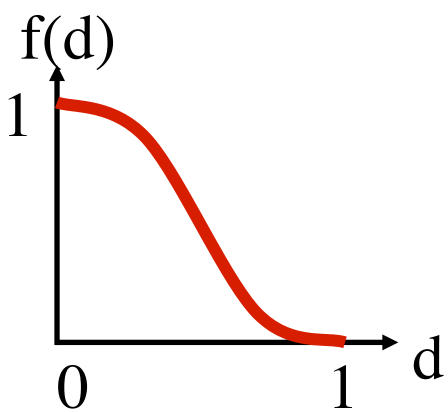


Single-hand warp and decay

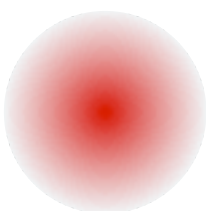
- S_L and E_L are interpolated by a screw motion L(t), t in [0,1]
- A point p moves by $L(f(\|PO_L\|/r))$,

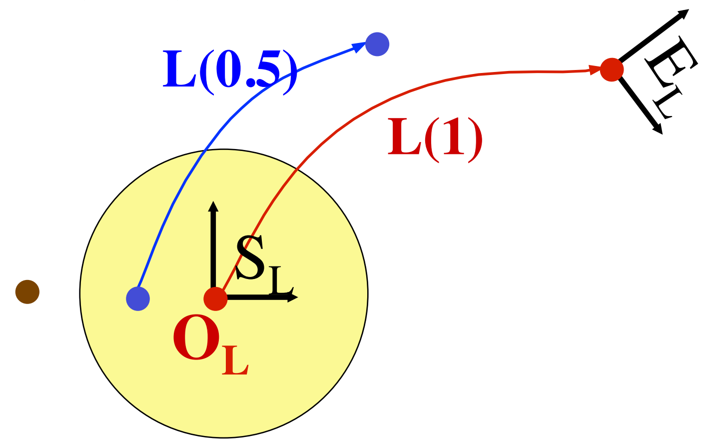
  $f(d)=\cos^2(d\pi/2)$ if $d<1$ and 0 otherwise

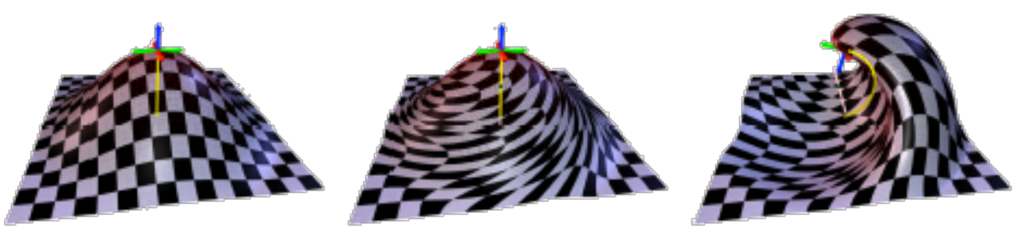
  – The grabbed point is subject to the whole motion L(1)
  – Points outside of the region of influence (RoI) don't move
  – The warp is smooth



3D radial decay profile

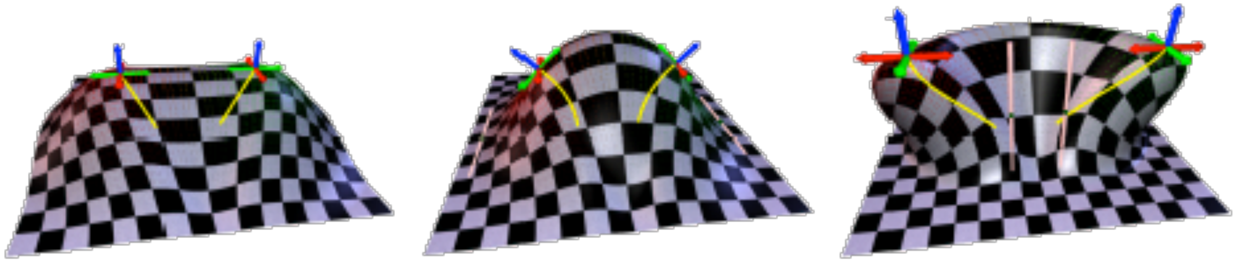




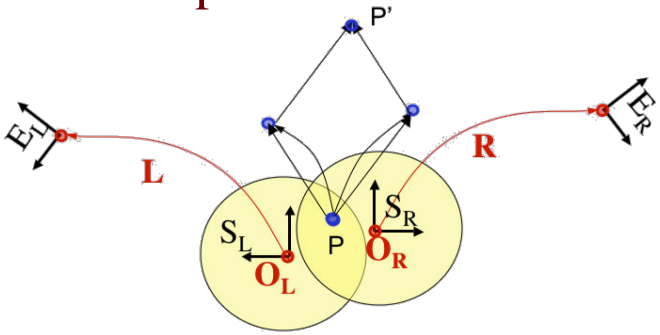


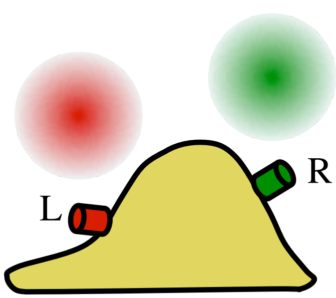
Two-hand warp

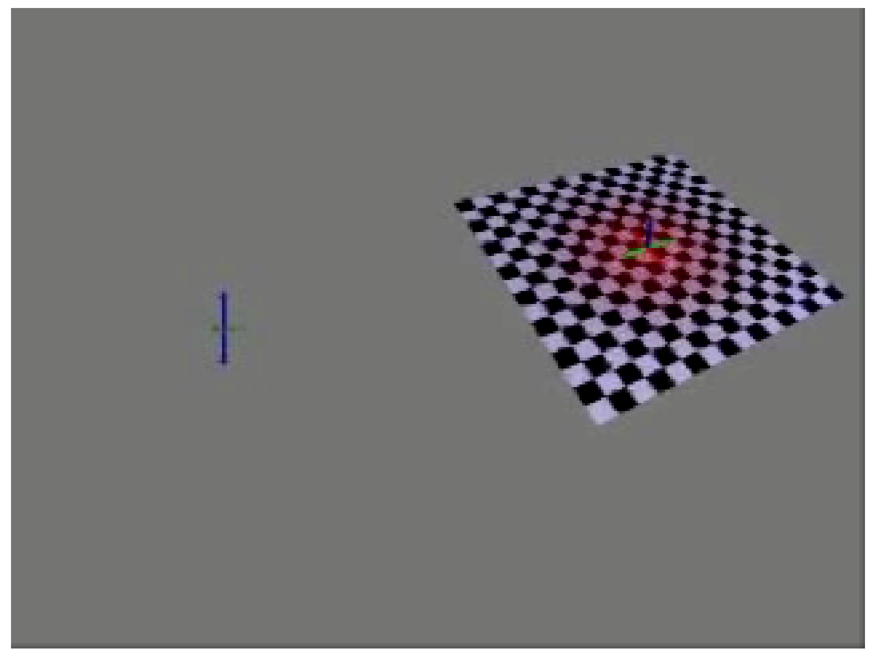
- Want to use two hands simultaneously to deform a shape



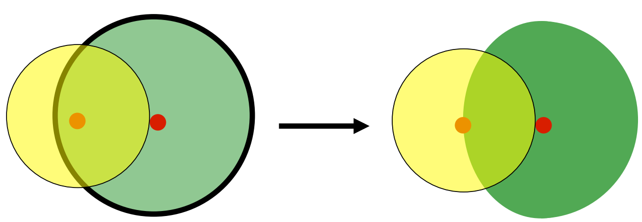
- A point P moves to $P + (L(f_L(P)) - P) + (R(f_R(P)) - P)$

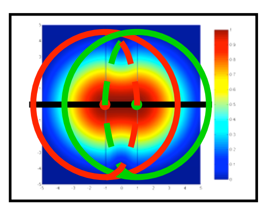






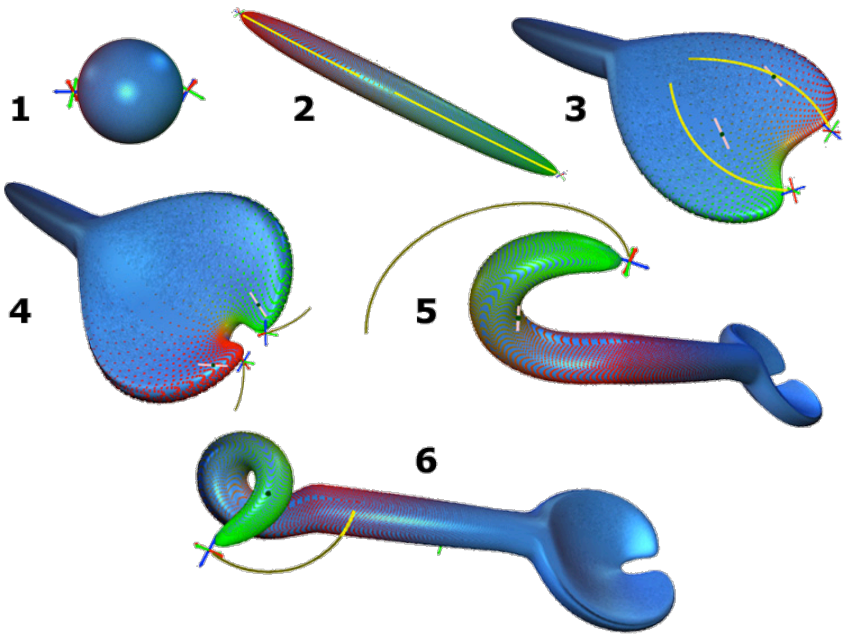
- Squash overlapping RoI

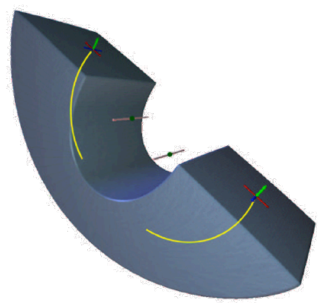


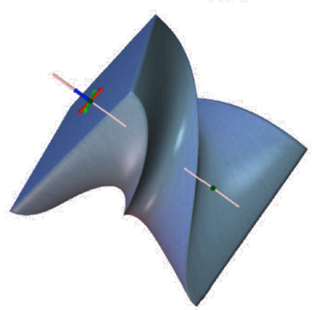


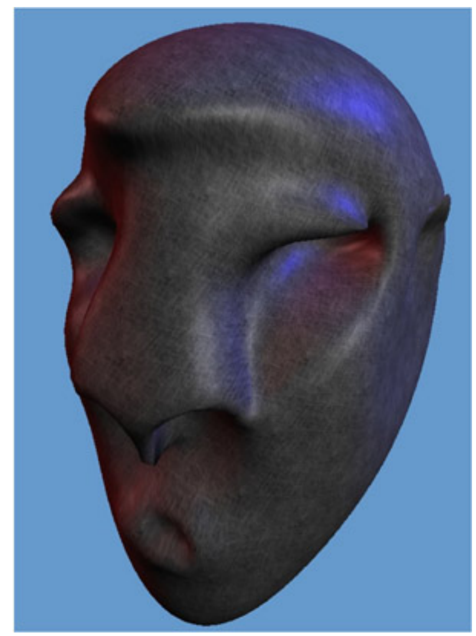
Some models designed in TWISTER

- **Implemented in C++, using OpenGL**
- **Realtime feedback (~20 fps with 30,000 vertices)**
  - Pentium III 866 Mhz, 256 MB RAM, NVIDIA Quadro 900 XGL
- **Adaptive subdivision**



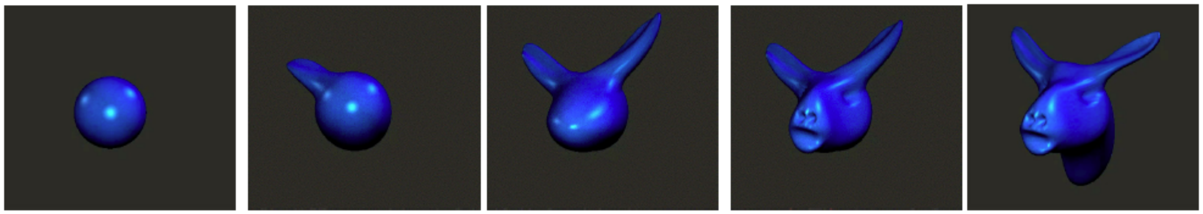




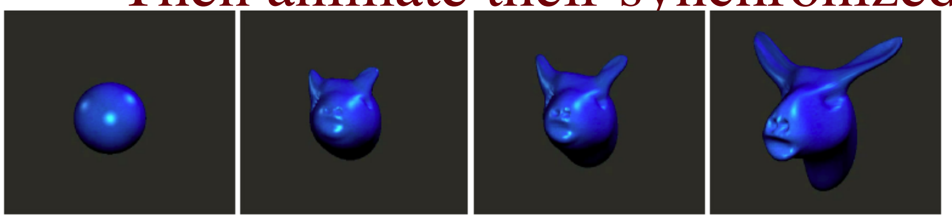


From design to animation

- Design one feature at a time

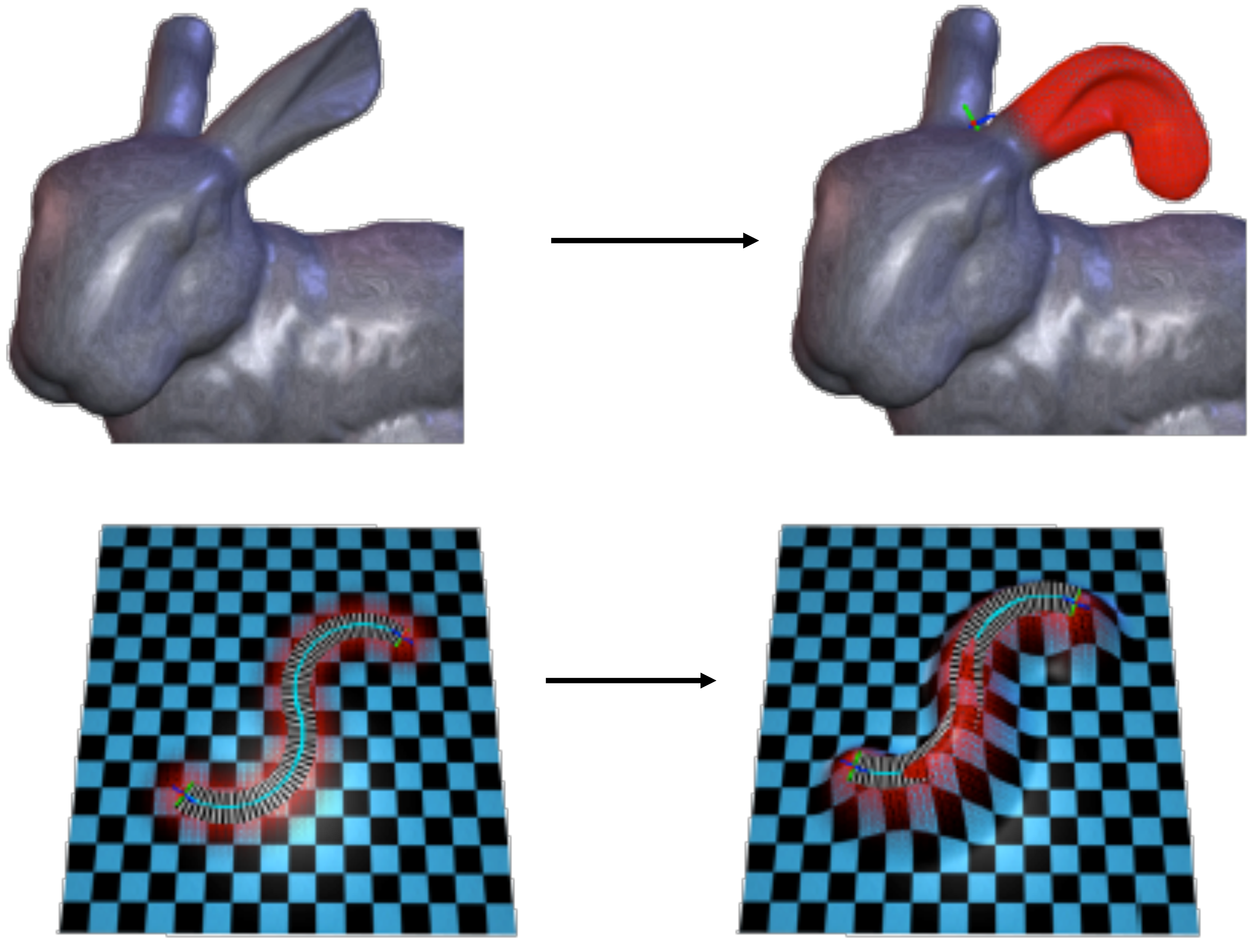


- Then animate their synchronized creation



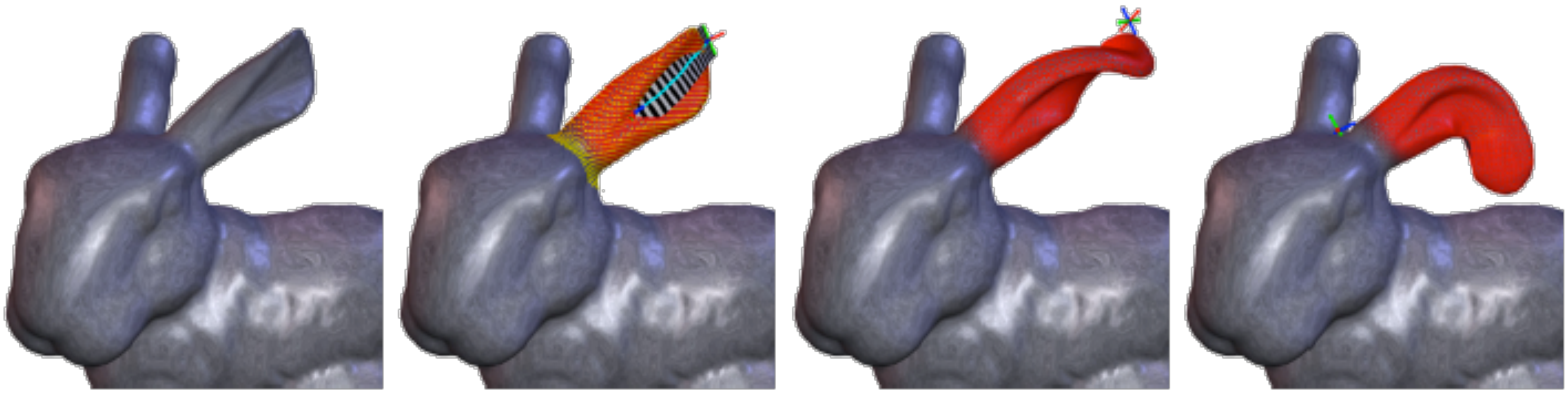
Limitations of TWISTER

Bends and extrusions are tedious with Twister



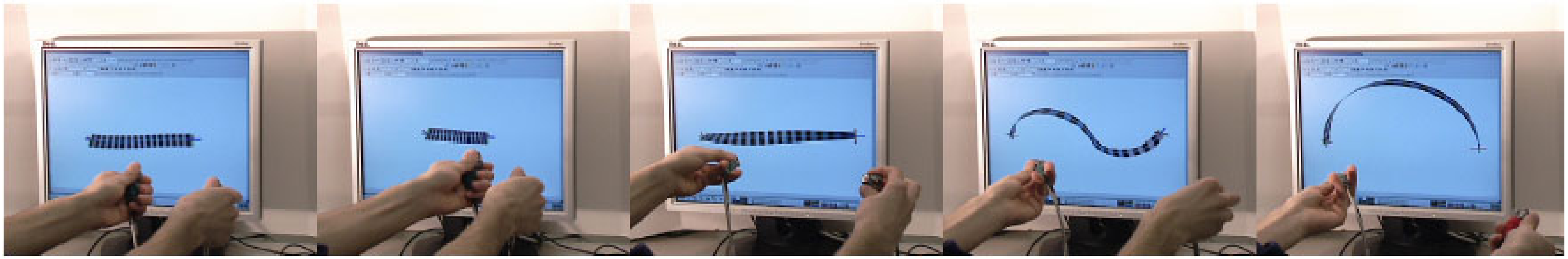
BENDER's Approach

- Artificial ribbon
- User controls its shape (wire) and twist with both hands
- Tube surrounding the ribbon is deformed (decay function)

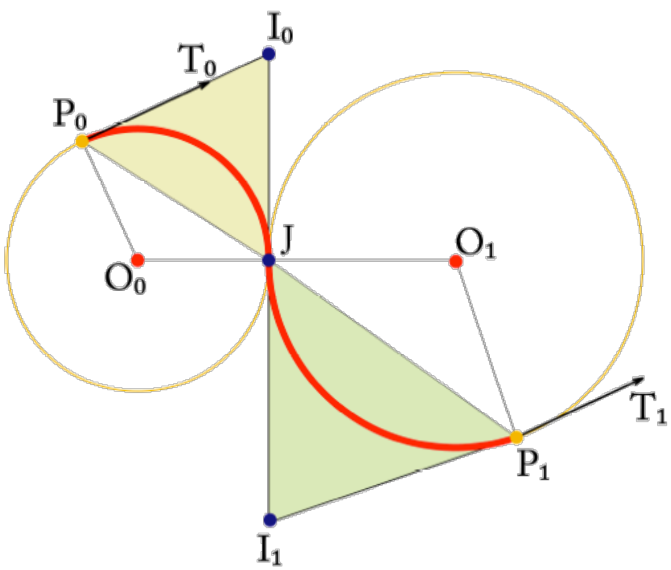


Controlling the ribbon with two hands

Each tracker controls one end of the ribbon



The central wire of the ribbon is a G^1 bi-arc curve



$I_0 = P_0 + aT_0$ $I_1 = P_1 - bT_1$

$||I_0 - I_1|| = a+b$

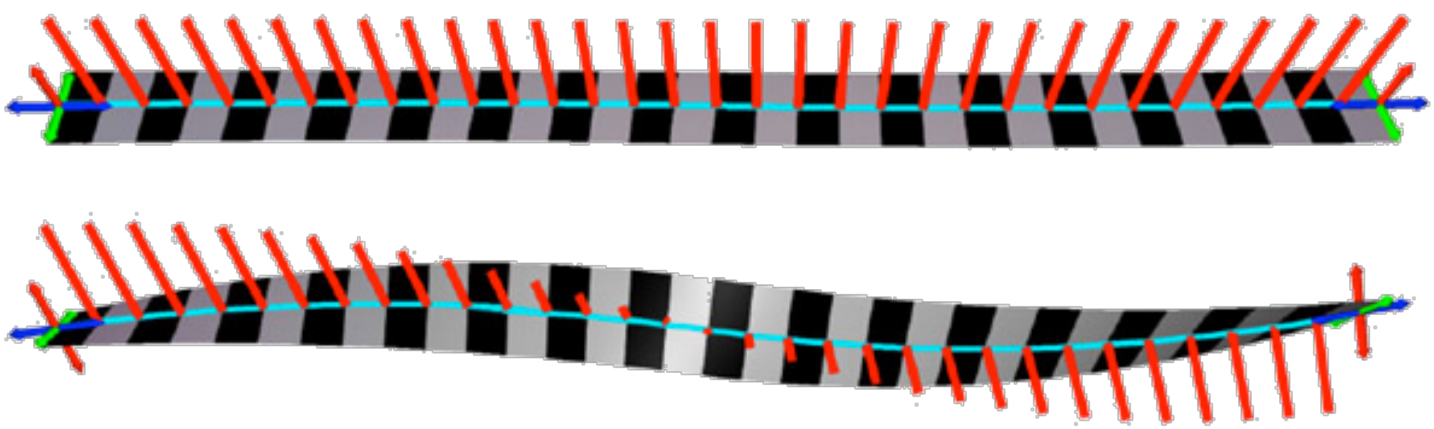
$J = (bI_0 + aI_1)/(a+b)$

Solve with a=b

"Piecewise-Circular Curves for Geometric Modeling", J. Rossignac and A. Requicha. **IBM Journal of Research and Development**, Vol. 13, pp. 296-313, 1987.

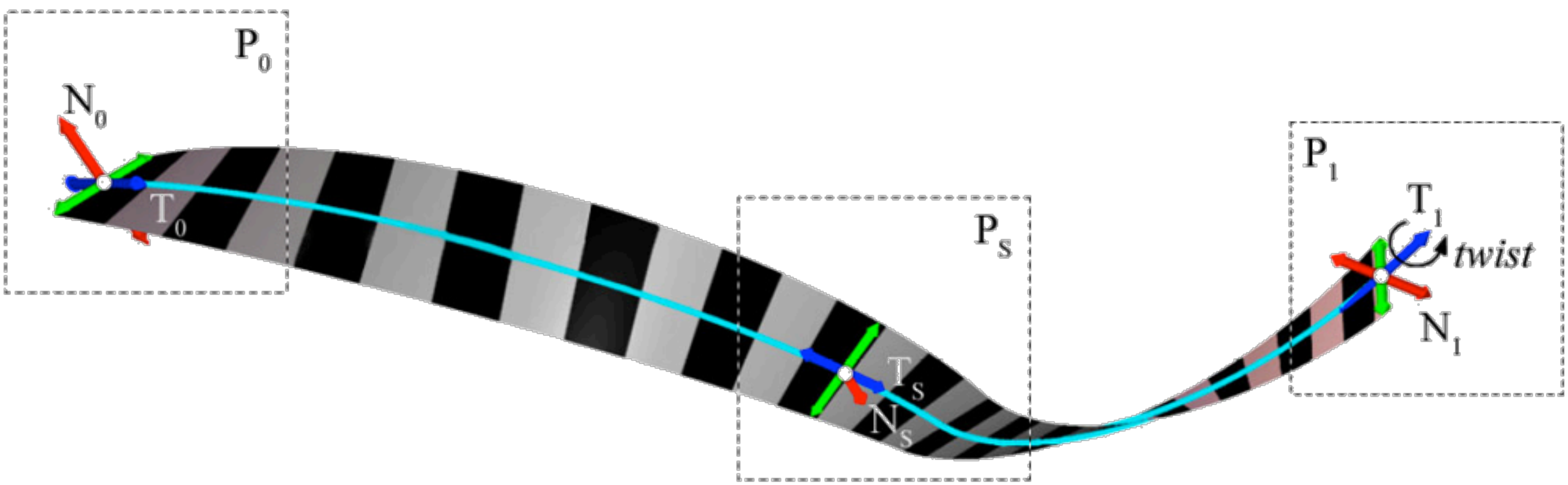
Twisting the ribbon

- Compute total twist
  - Use angle between P_0I_0J plane and tracker orientation at P0
  - Propagate it (pure rotation) to J
  - Compute total twist at J between the two arcs
- Distribute total twist evenly along the wire



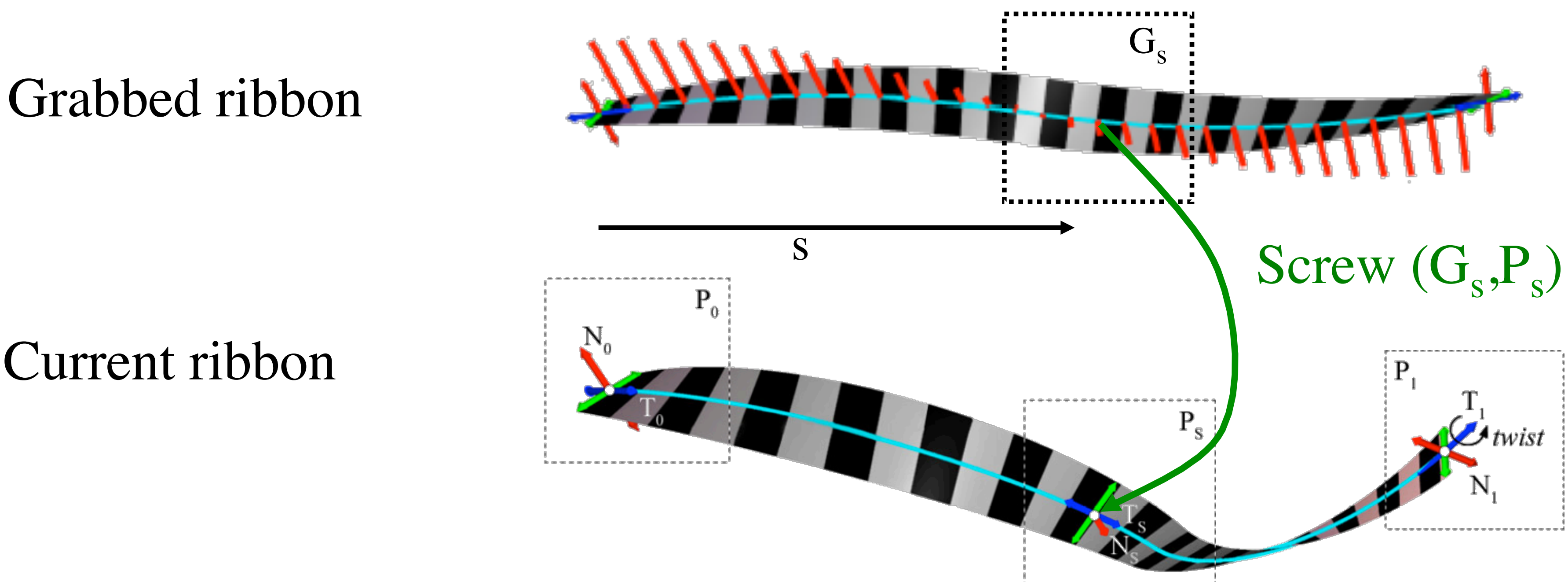
Parameterized pose along the ribbon

- Parameterise the wire: s in [0,1]
- Move the origin along the wire by an arc-length fraction s
- Get a Frenet trihedron (need only a rotation)
- Perform an fraction of the total twist around the tangent



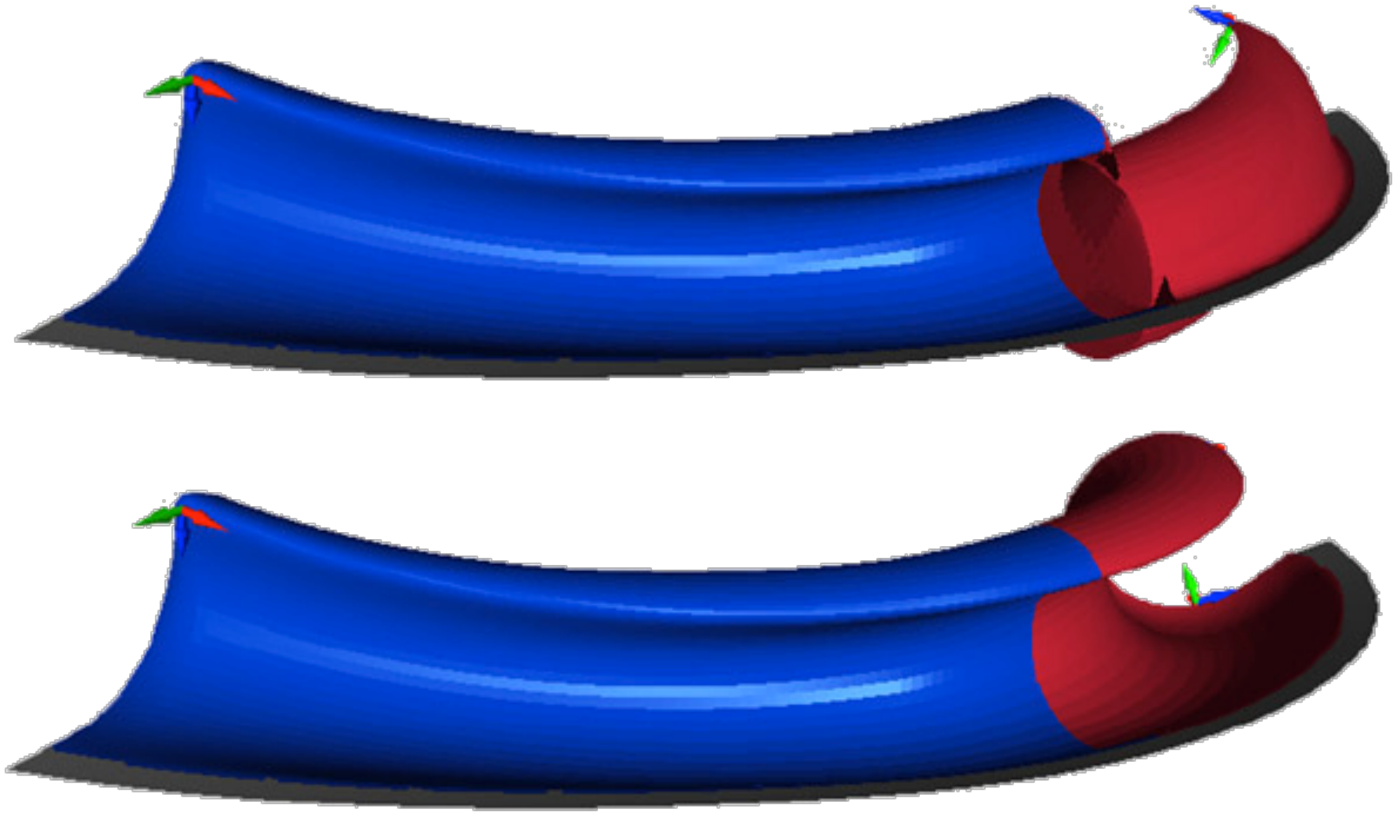
Interpolating two ribbons

- When a button is pressed, the grabbed ribbon is captured
- We compute a deformation that maps it into the current ribbon (during editing) or the final ribbon (upon release)
- The deformation maps each pose G_s of the grabbed ribbon into the corresponding pose P_s of the current ribbon
- The mapping is a screw motion!



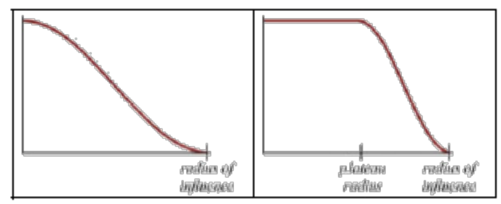
Preventing flips

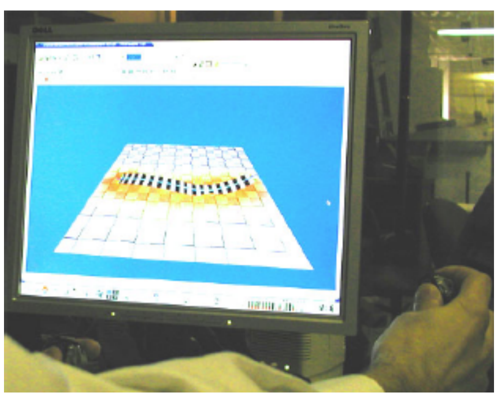
- The screw axis, K, may flip between consecutive values of s
- If so, we reverse it (which may lead to rotations >180^o)

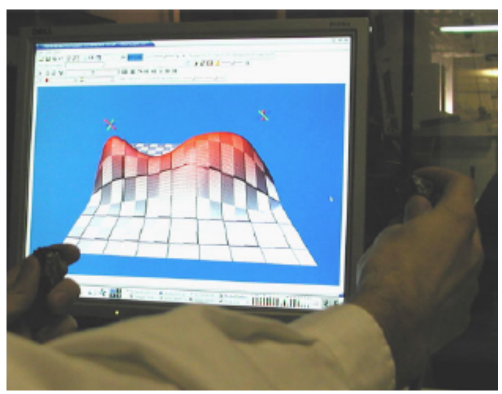


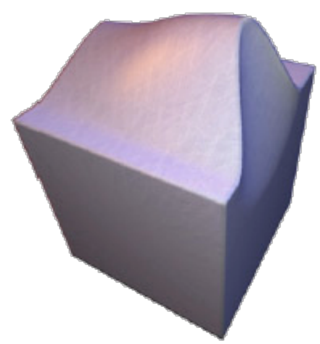
Warping space with a decay

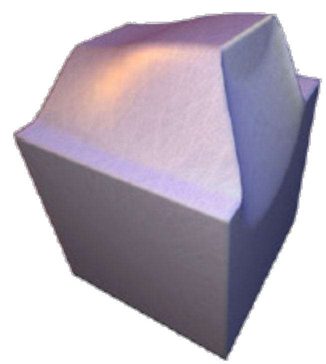
- To warp a point Q, we compute the parameter s of its closest projection(s) on the grab wire
- Then, we apply a fraction f of Screw(Gs,Ps)
- f depends on the distance from Q to the closest projection
  - Decay function
  - Plateau option





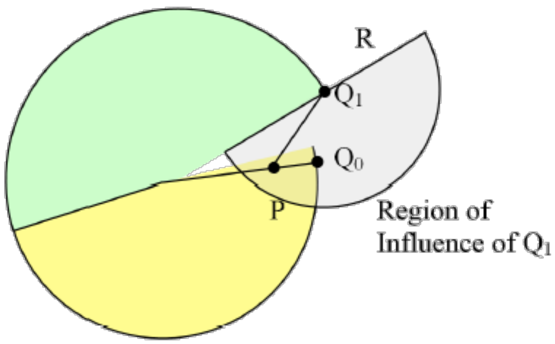


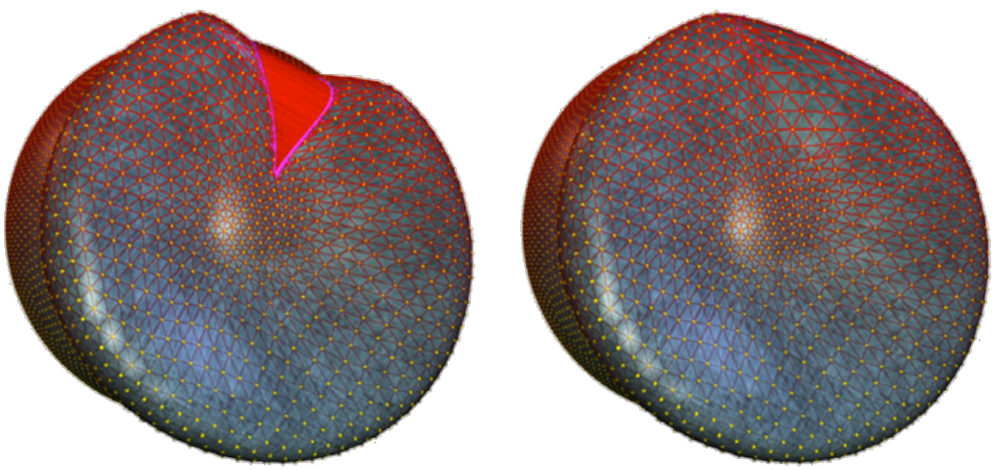


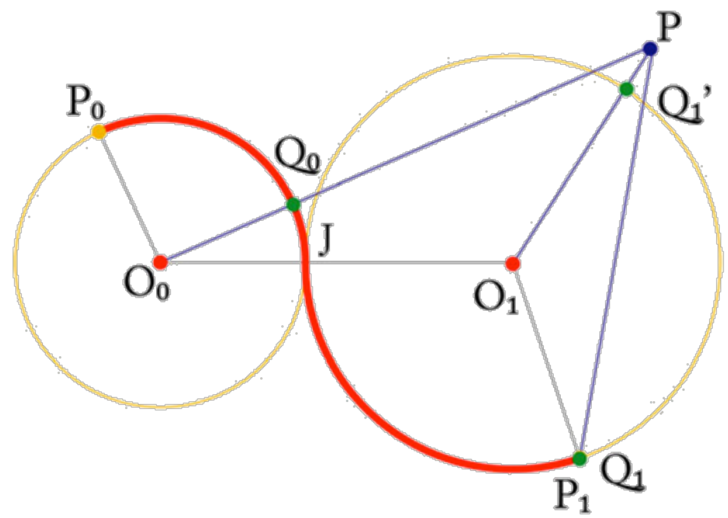


Avoiding tear (two-hand twister)

- Q may have one closest projection on each arc of the wire
- We use the two-hand version of Twister to blend the corresponding screw motions

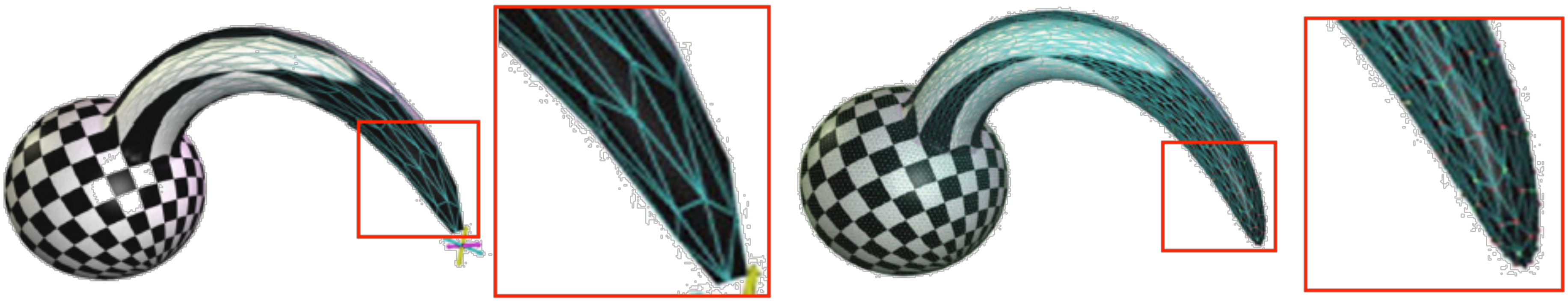


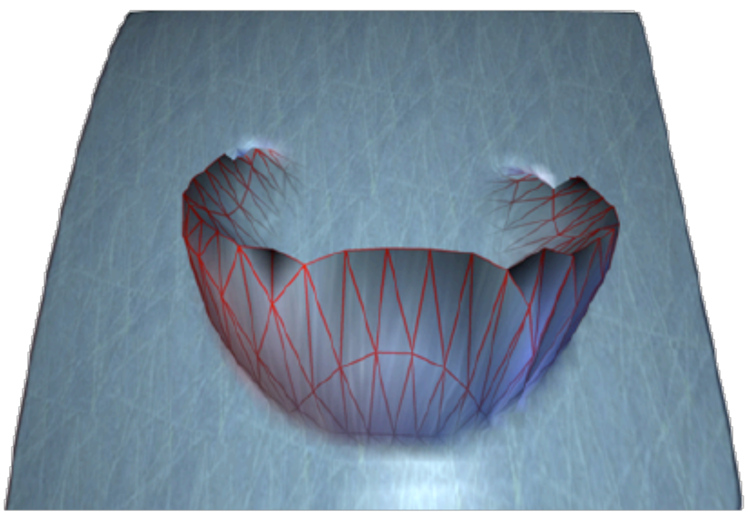




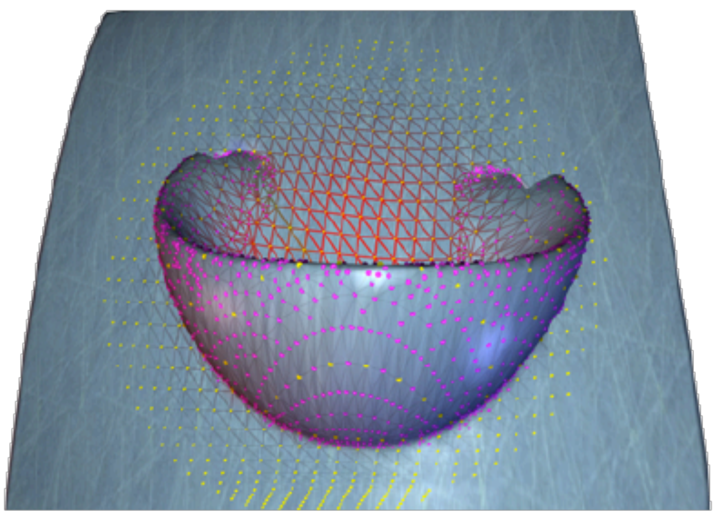
Adaptive subdivision

- The triangulation is automatically refined where needed



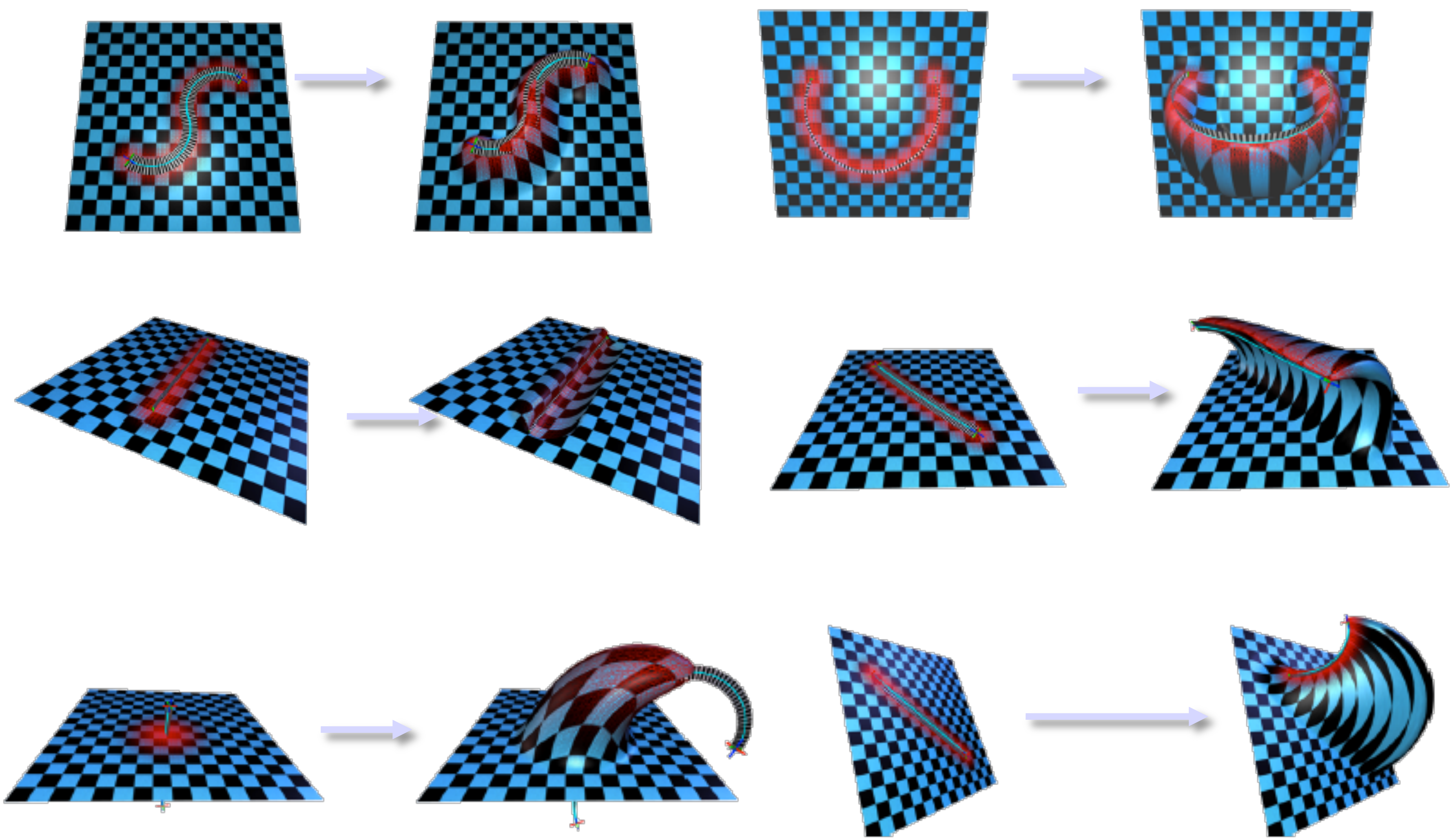


No subdivision

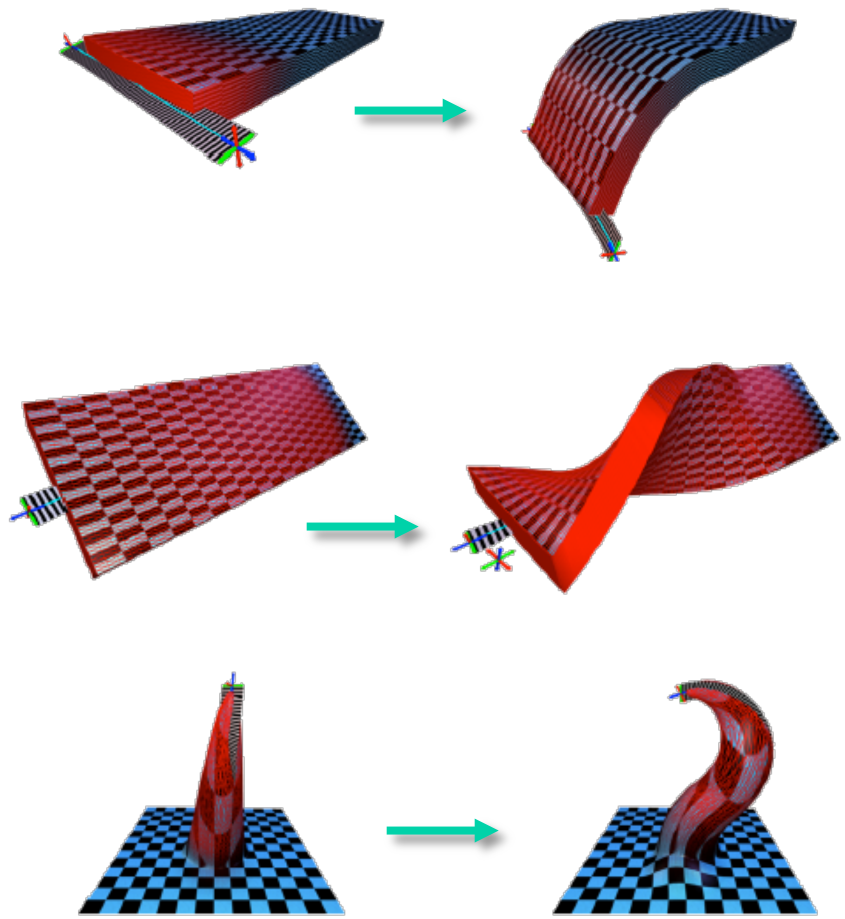


With subdivision

Creating features with BENDER

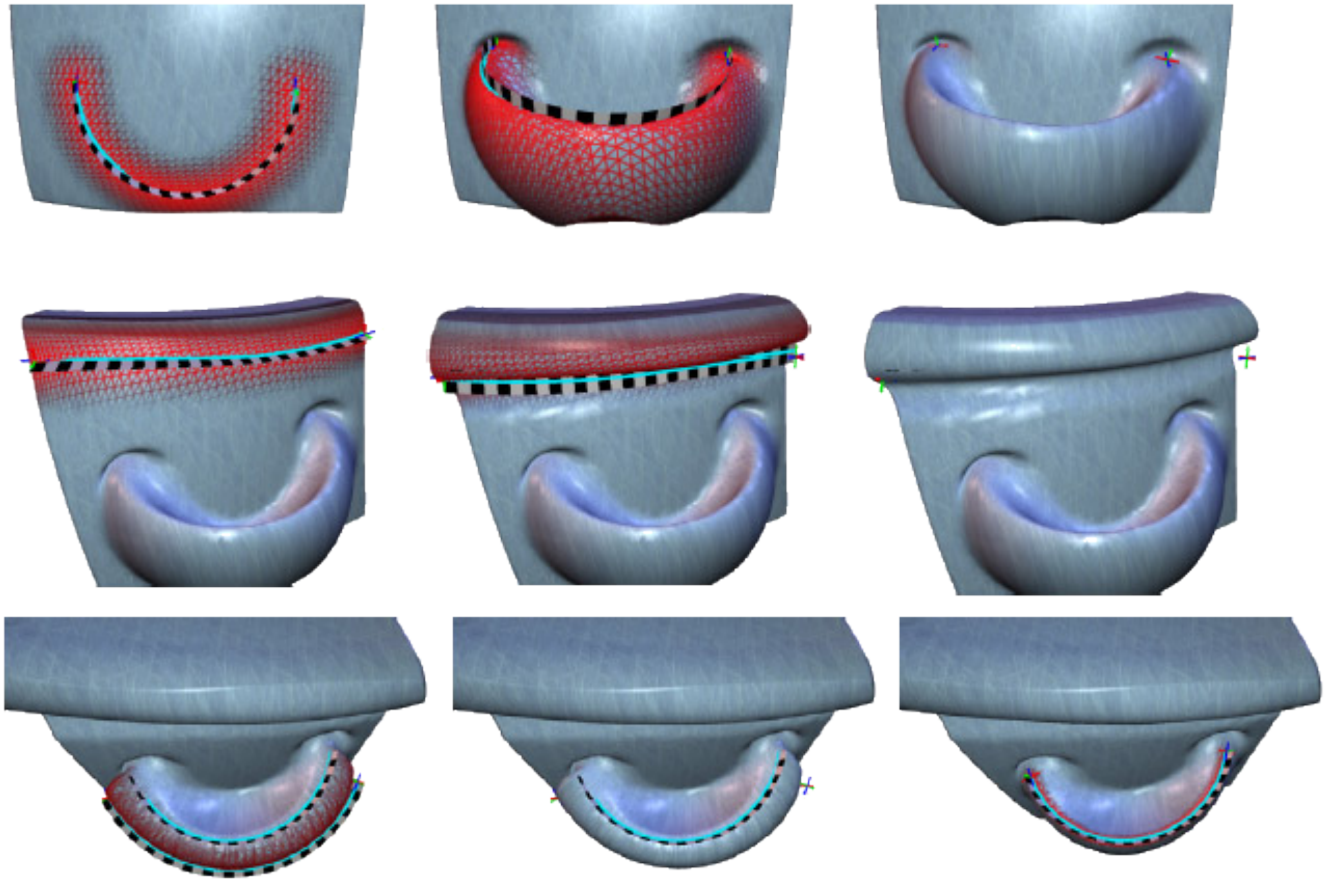


Deforming existing features



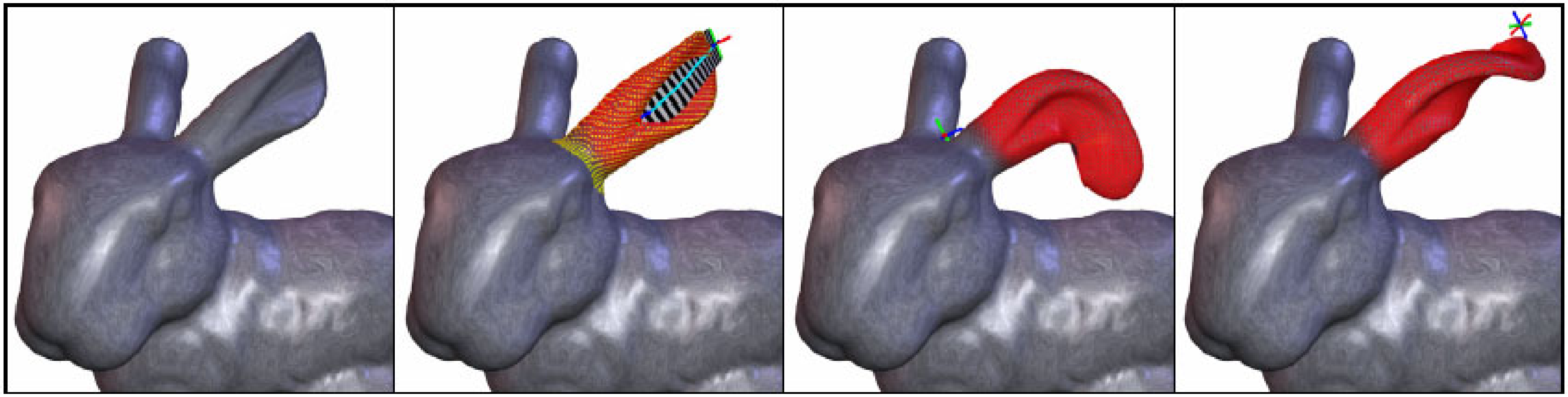
Making more complex features

- …with a few intuitive ribbon gestures

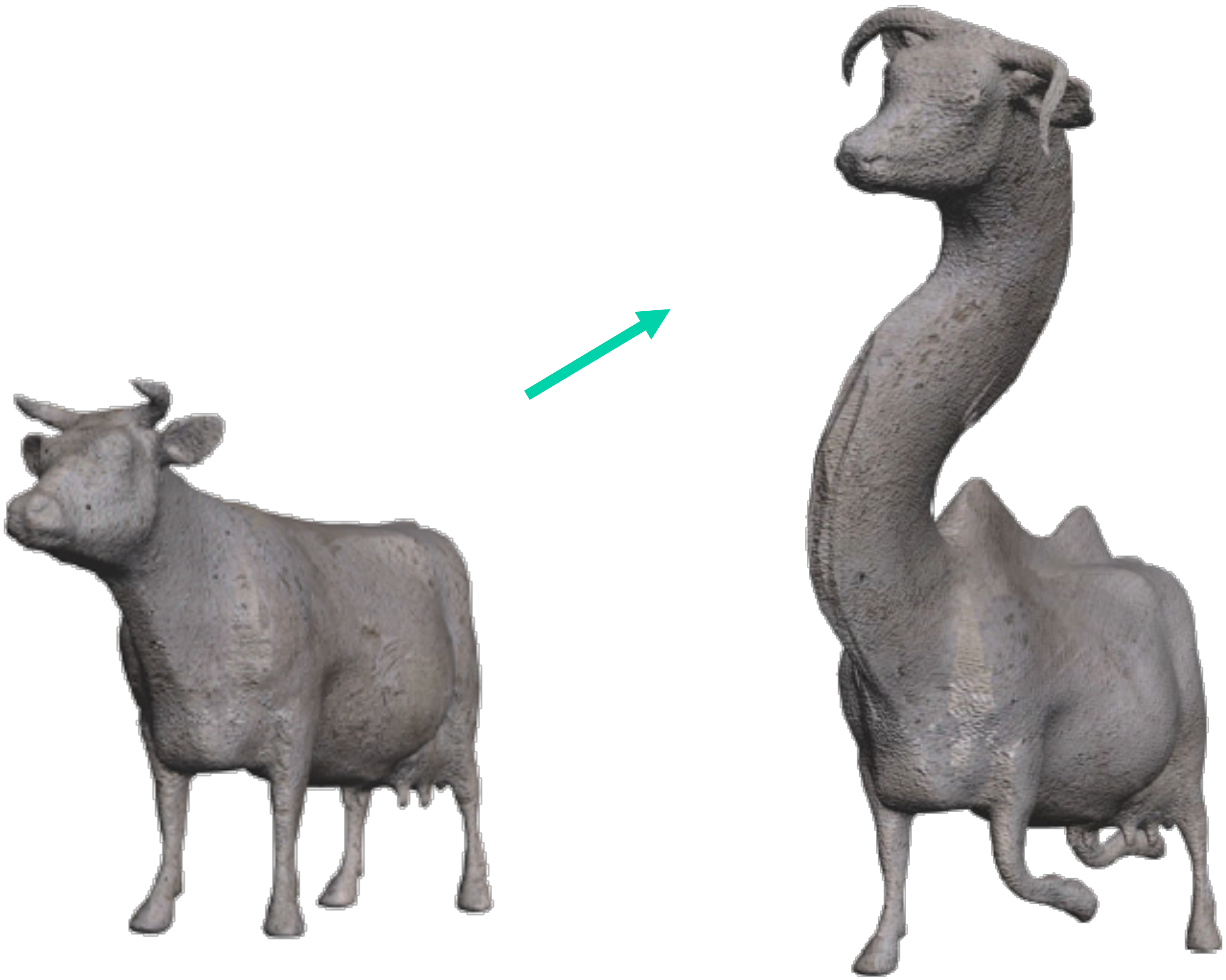


Twisting ears

- Position ribbon along the ear axis
- Grab and bend or twist
- Release



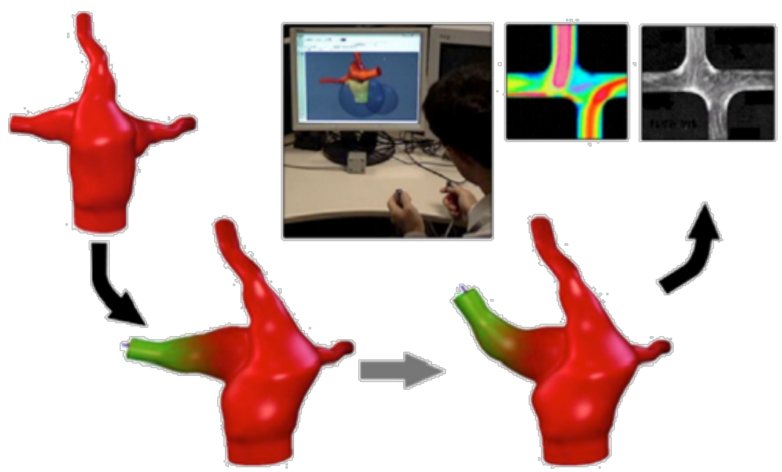
Genetic manipulation (?) with BENDER



SURGEM: Next Generation CAD Tools Targeting Anatomical Complexity for Patient-Specific Surgical Planning

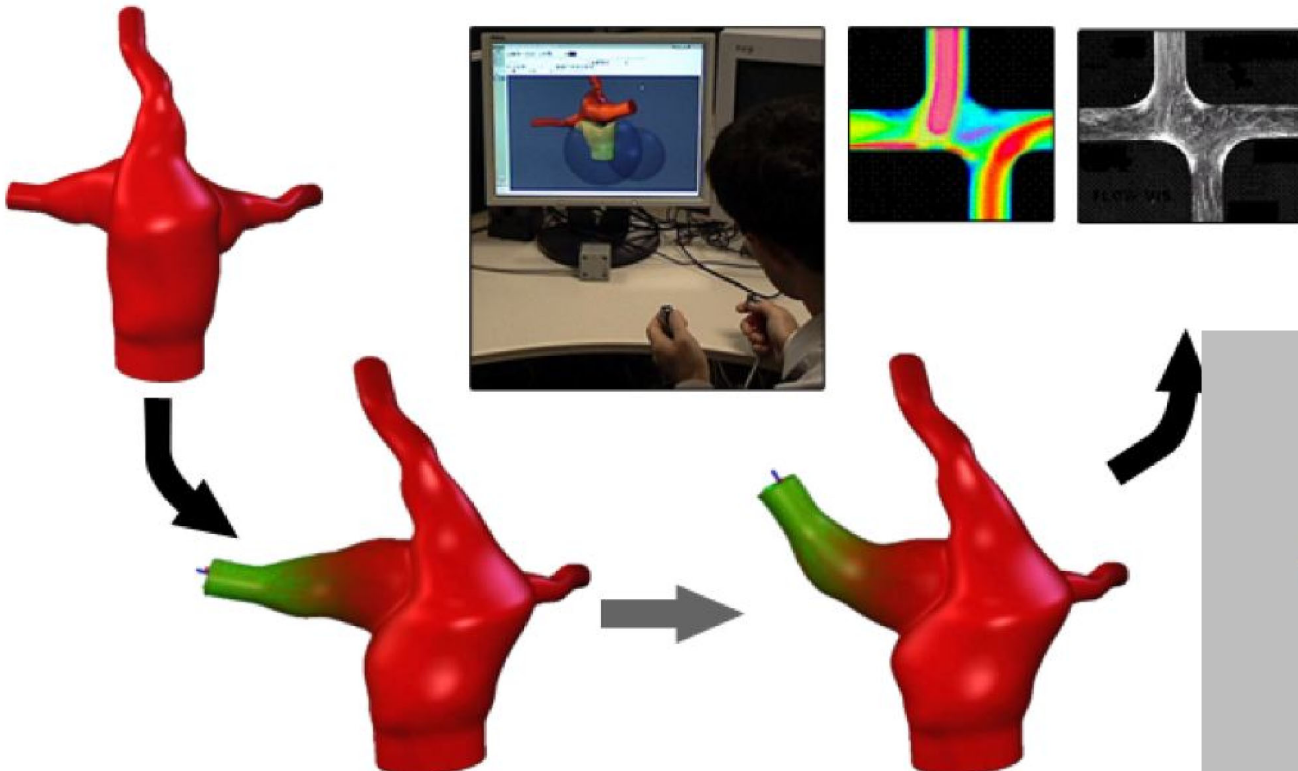
Jarek Rossignac[1], Kerem Pekkan[2], Brian Whited[1], Kirk Kanter[3], Ajit Yoganathan[1]

[1]College of Computing,
[2]Cardiovascular Fluid Mechanics Laboratory, [3]Emory University

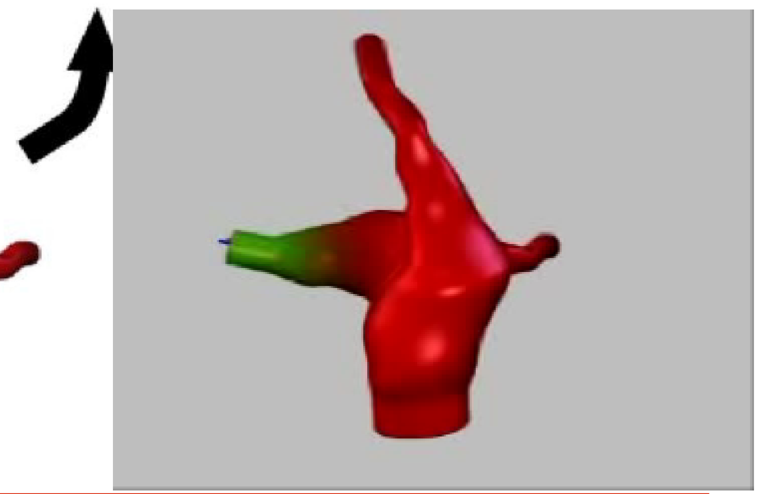


Supporting surgery planning

- **0.2% of babies in the US are born with a single ventricle.**
- **Surgeons want a tool to design the shape of the** Fontan repair **(cavopulmonary connection placing the pulmonary and systemic circuits in series with the univentricular heart).**



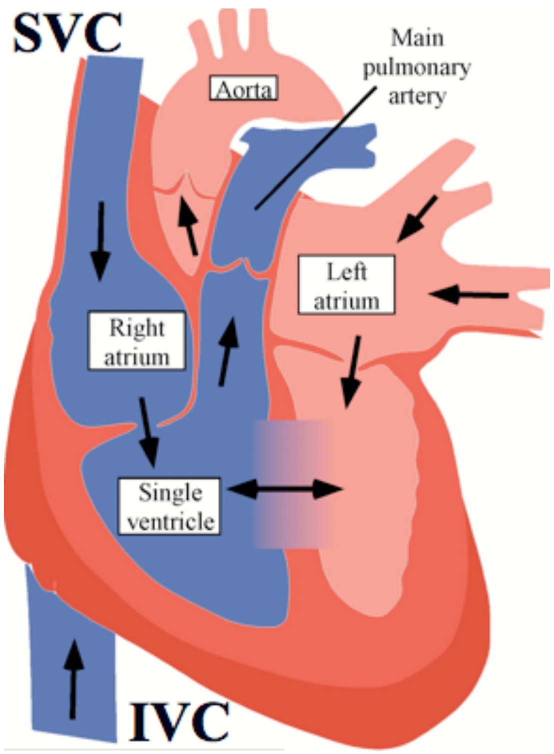
Collaboration with
Dr. Yoganathan
(GaTech/Emory)



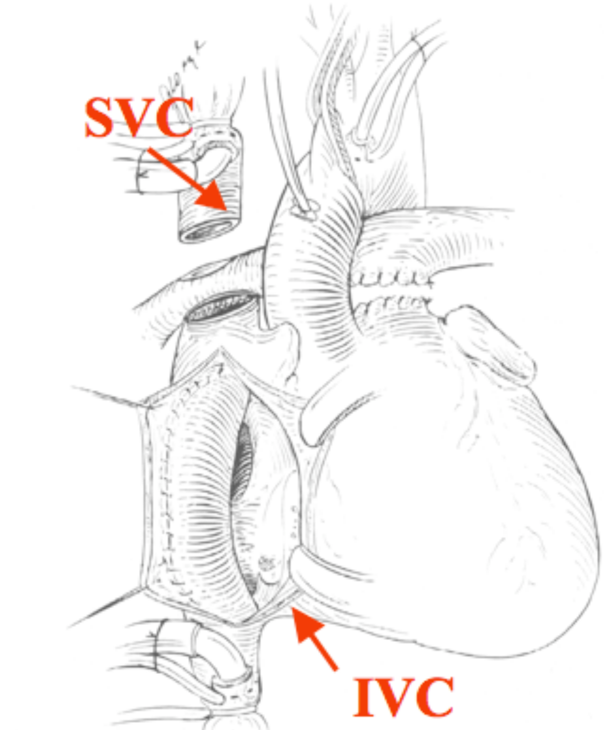
Total cavopulmonary connection

- **End-to-side anastomosis of the superior vena (SVC) to the unbranched RPA**
- **Connection of the inferior vena cava (IVC) to the RPA**

Single Ventricle

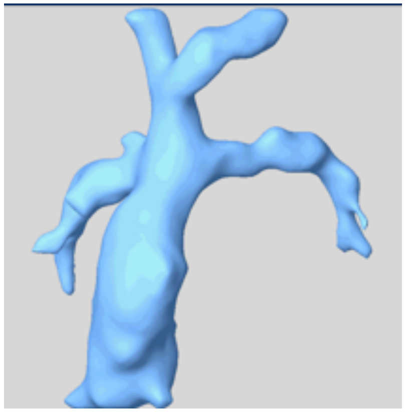


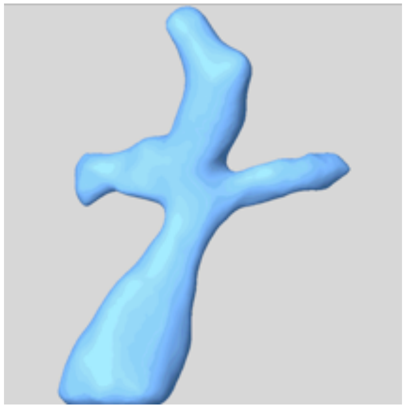
Lateral Tunnel



Surgical pathway optimizations

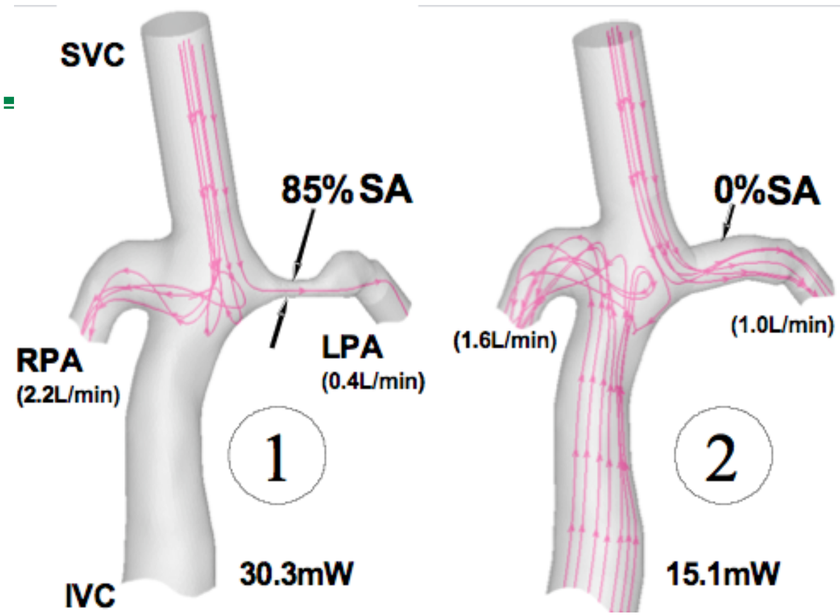
- Minimize Energy Losses
- Appropriately distribute flow to both lungs
- Appropriately distribute IVC flow to both lungs
- Plan for growth

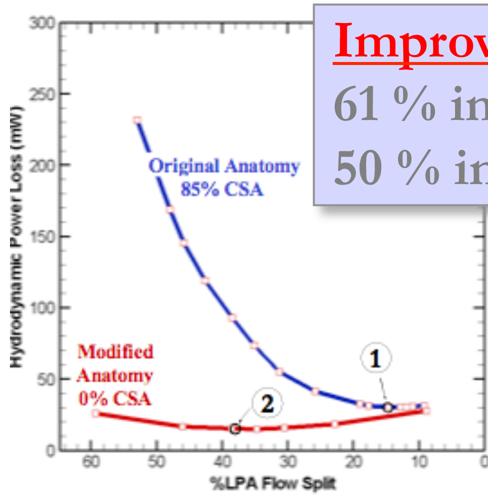




"+" shaped complex topologies

Pilot studies – Anatomy editing



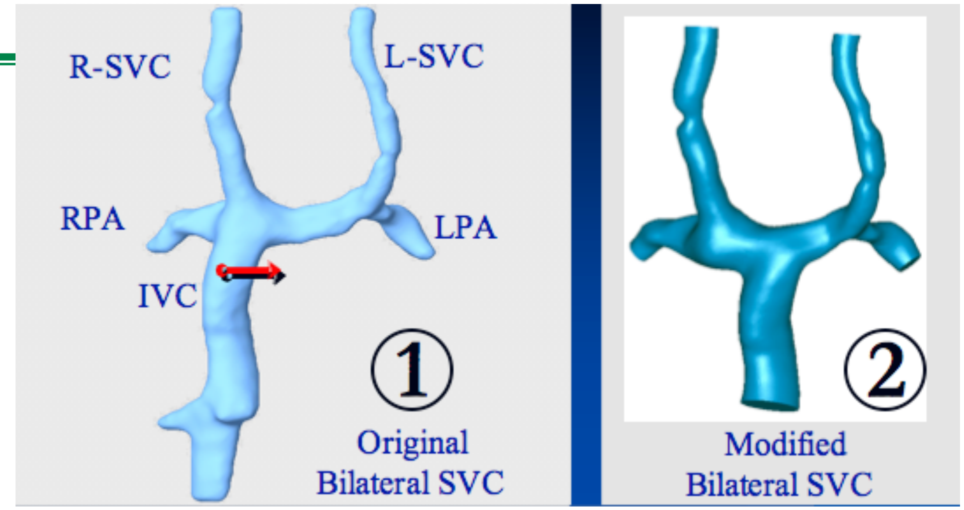


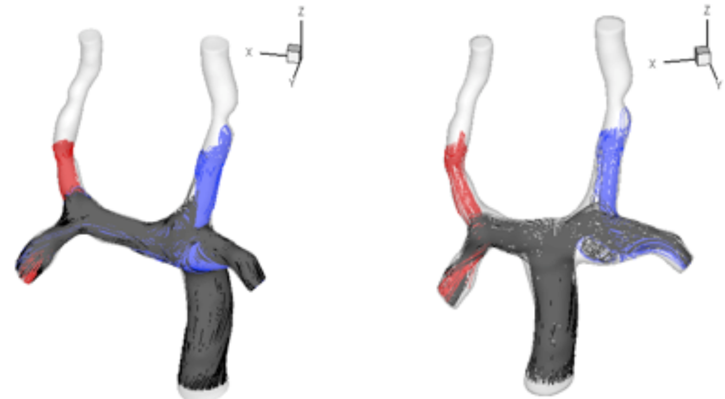
(Circulation 2005)

Improvements from 1 to 2:

61 % in LP perfusion

50 % in Power Loss





Original Modified

Improvements from 1 to 2:

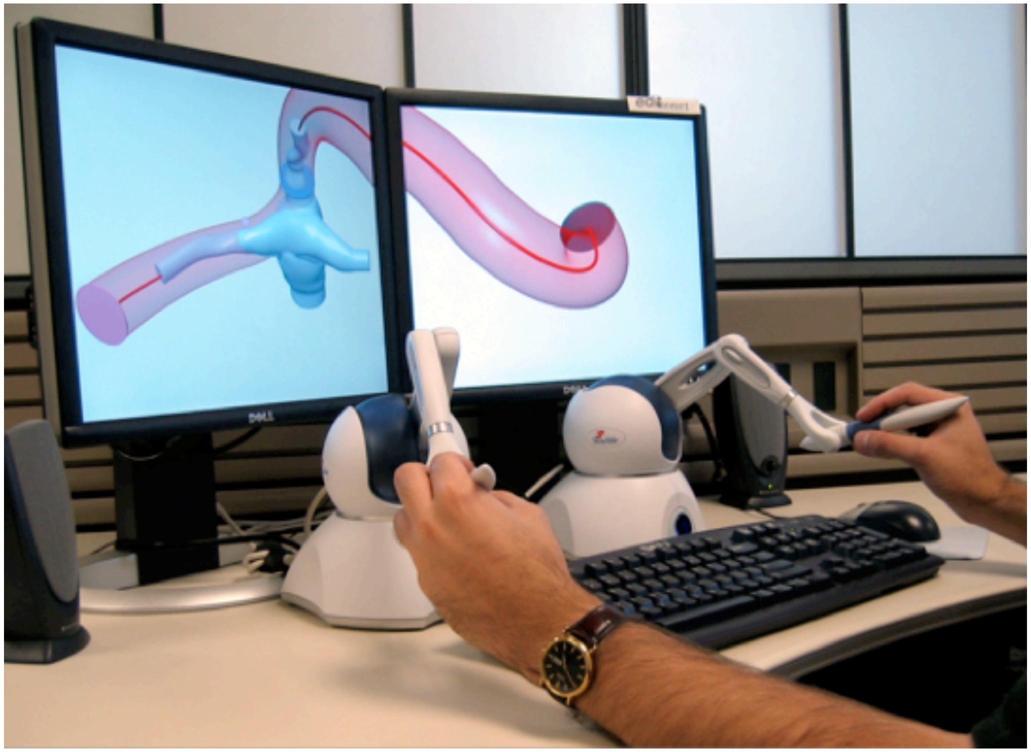
Less stasis in the MPA branch

10 % increase in Cardiac Output

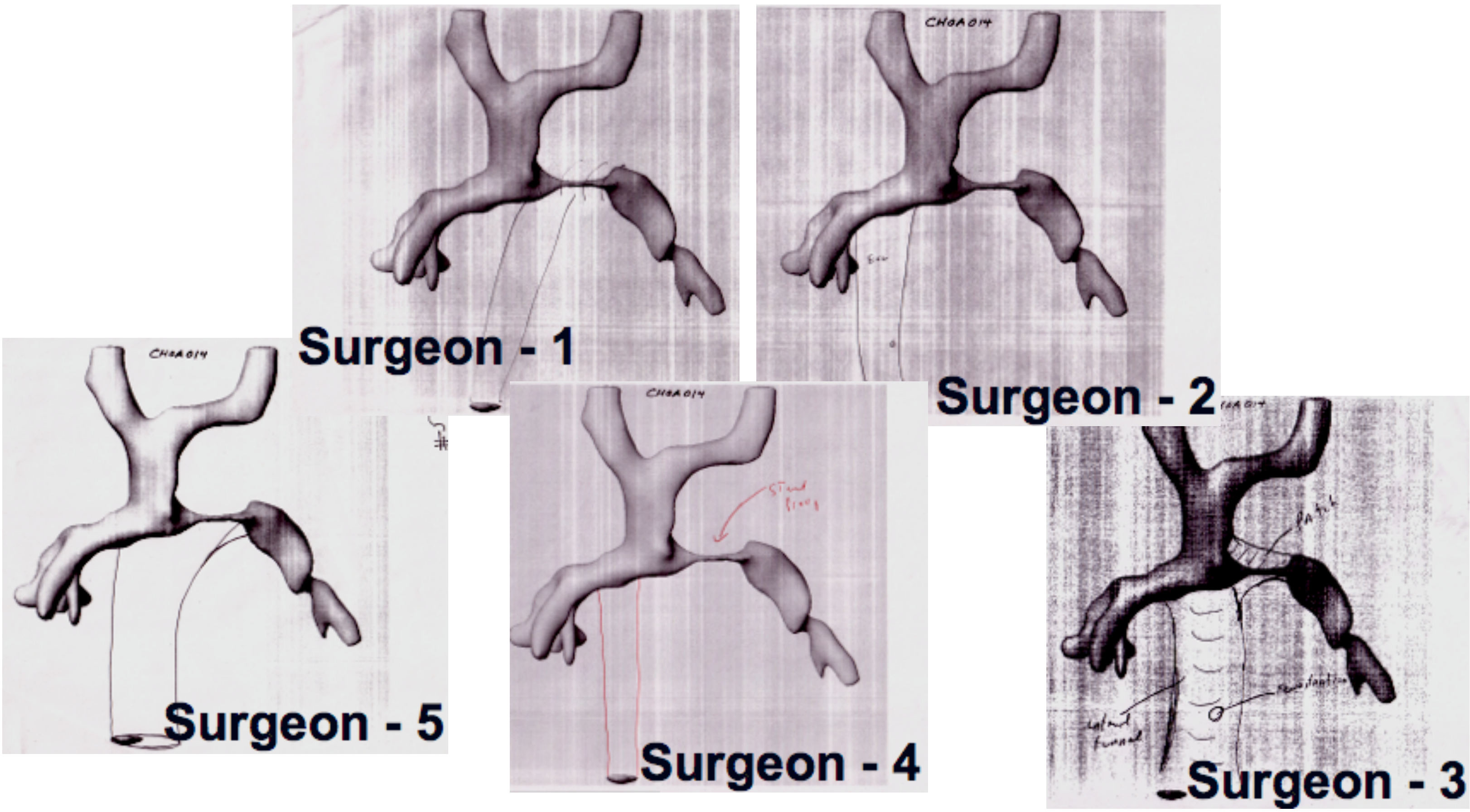
Better hepatic flow distribution

Surgem

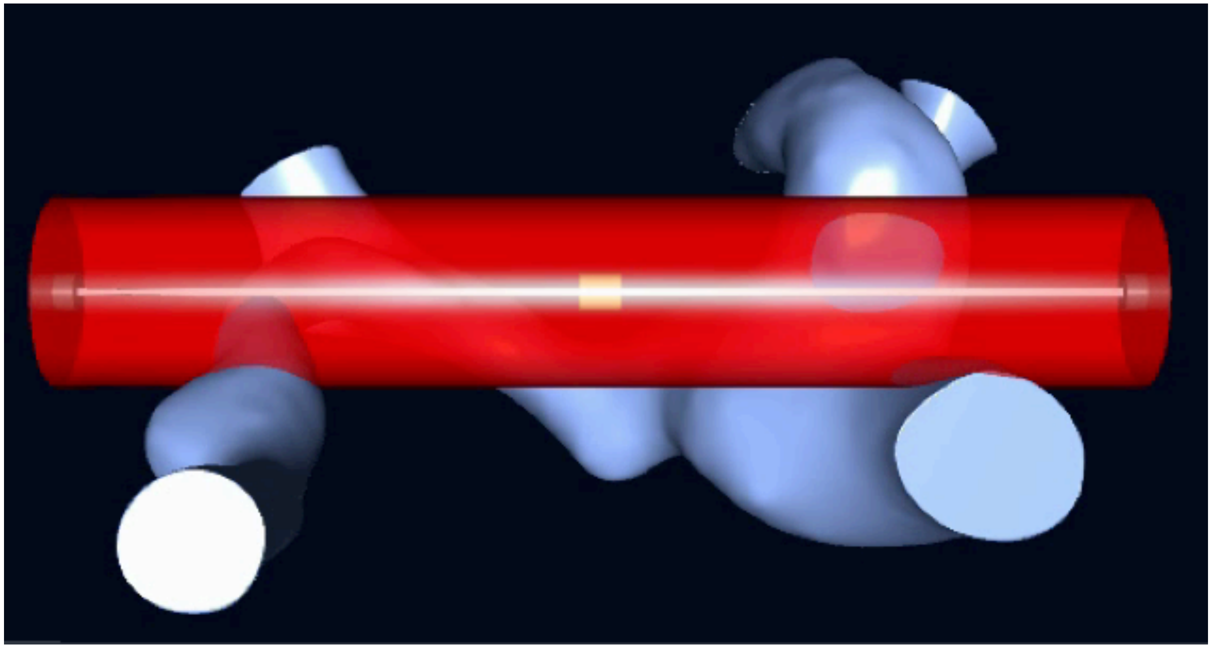
A shape interaction system based on haptic input devices that allows a surgeon to better plan the Fontan surgical operation on patient-specific geometry



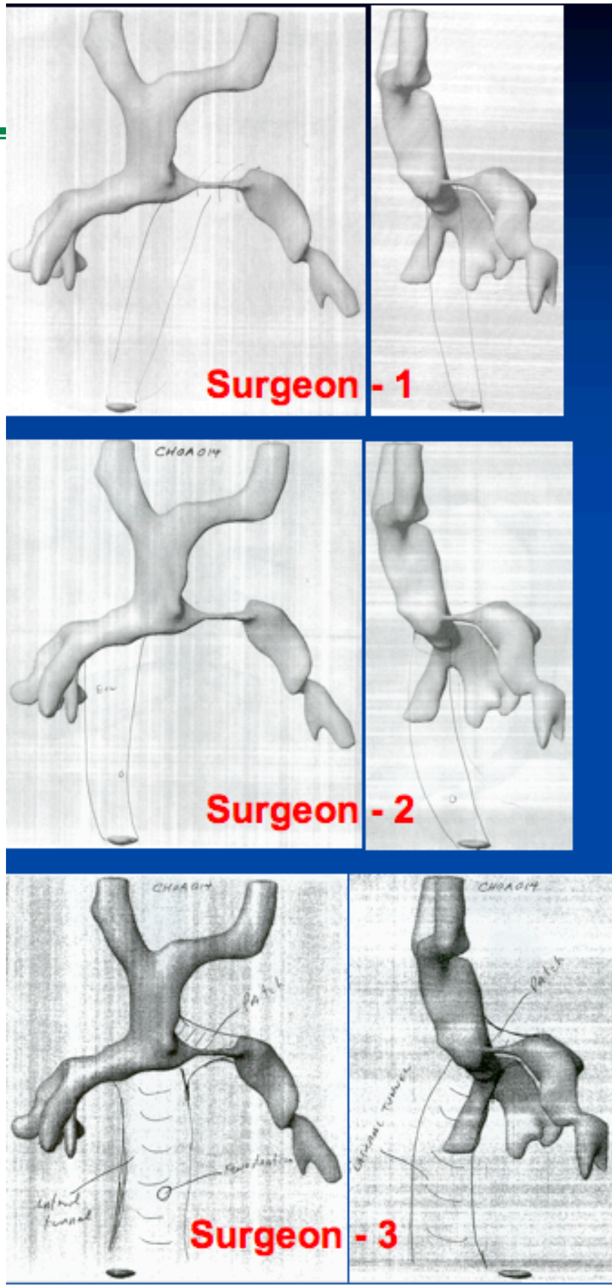
Surgeons sketches



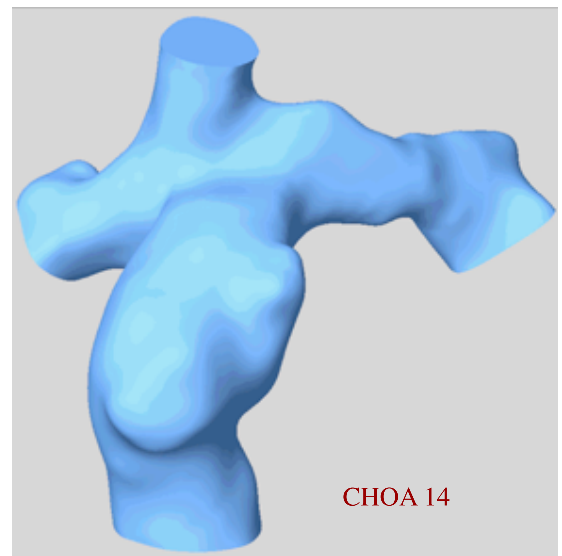
Interactive IVC baffle



Surgem – Surgical Planning Tool



Actual Post-Fontan



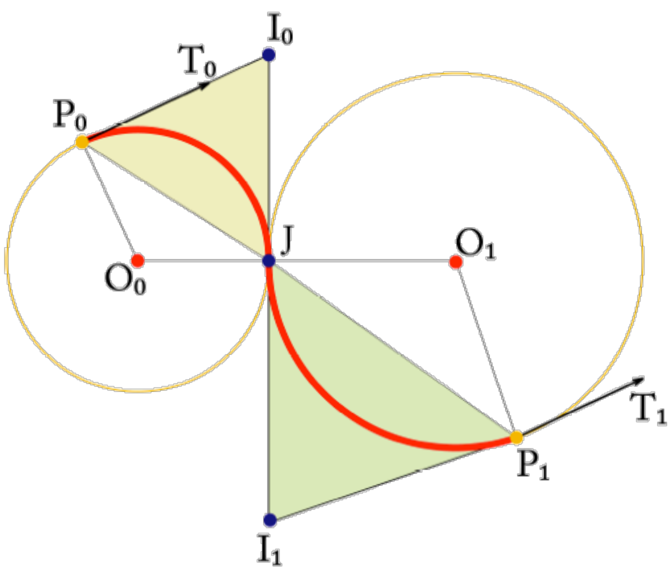
Artificial baffle

Each tracker controls the grabbed TCPC baffle

The central wire of the ribbon is a G1 bi-arc curve:

- given 2 control points/directions, 2 arcs can be fitted

Baffle contains 3 control points and 4 circular arcs



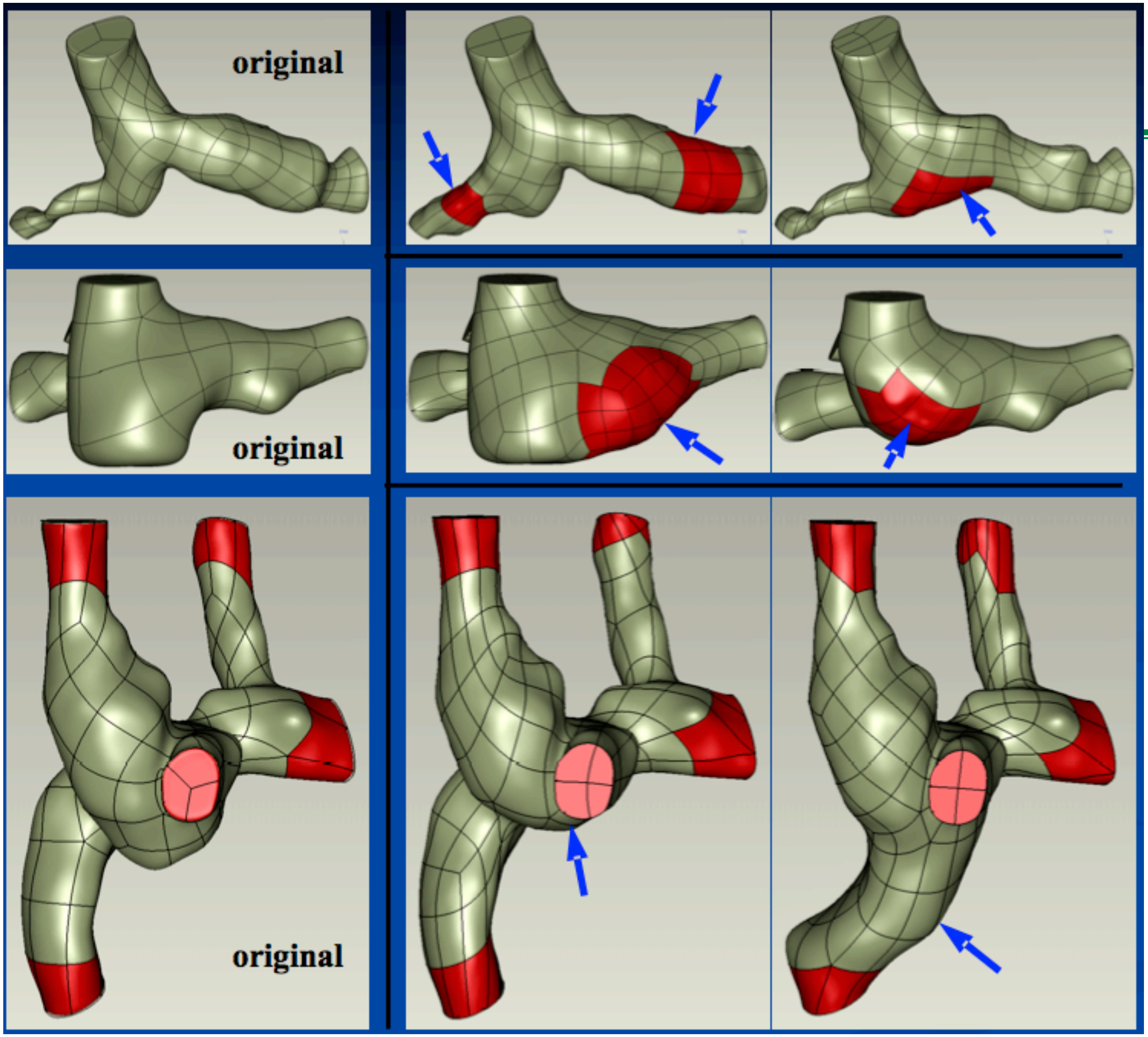
$I_0=P_0+aT_0$ $I_1=P_1-bT_1$

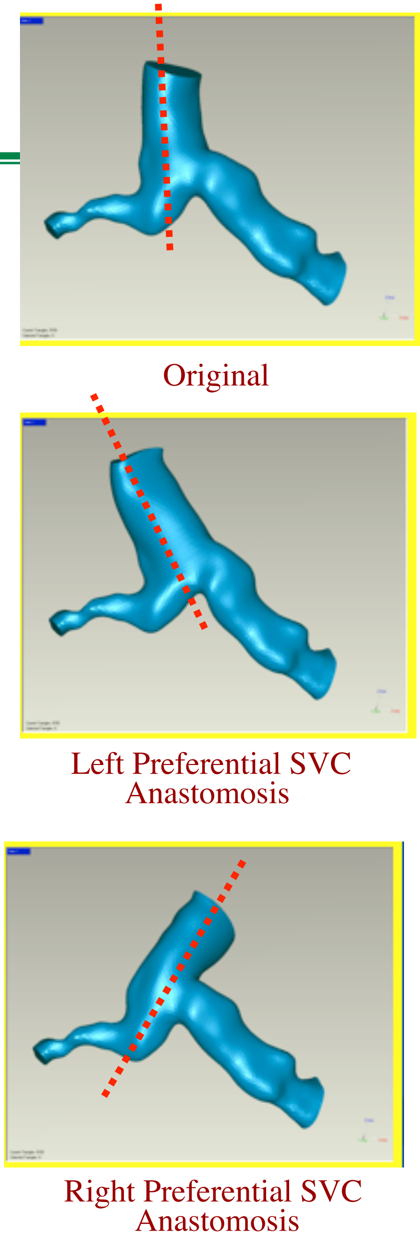
$||I_0-I_1||=a+b$

$J=(bI_0+aI_1)/(a+b)$

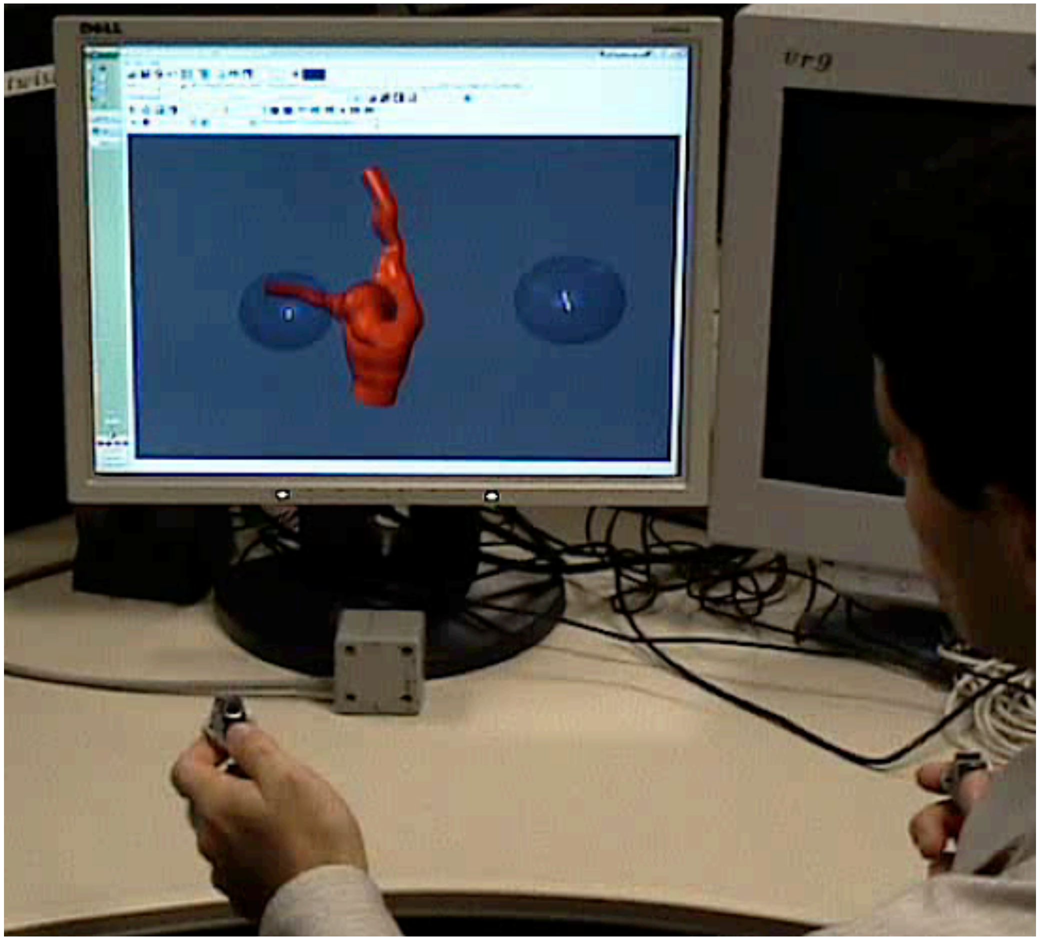
Solve with a=b

"Piecewise-Circular Curves for Geometric Modeling", J. Rossignac and A. Requicha. **IBM Journal of Research and Development**, Vol. 13, pp. 296-313, 1987.


original
original
original

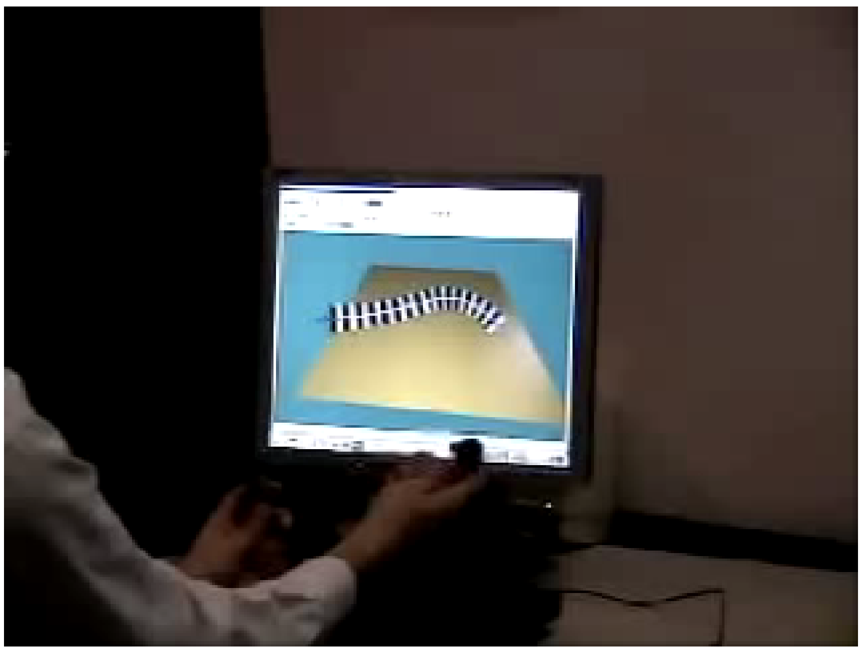

Original
Left Preferential SVC Anastomosis
Right Preferential SVC Anastomosis

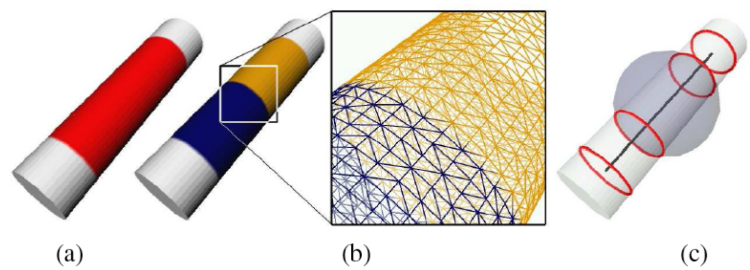
Preliminary surgical assessment



Conclusions and future work

- **Twister: effective and intuitive human/shape interaction,**
- **Bender: adds support for elongated features**
- What is missing:
  - Force feedback to align the cursors with a surface
  - Aligning the ribbon with a surface (automatic snap)
  - Automatic alignment of wire with centerline of tubes





“Plumber: a method for a multi-scale decomposition of 3D shapes into **tubular** primitives and bodies”
M. Mortara, G. Patanè, M. Spagnuolo, B. Falcidieno, J. Rossignac (ACM Solid Modeling’04)

Bender video