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

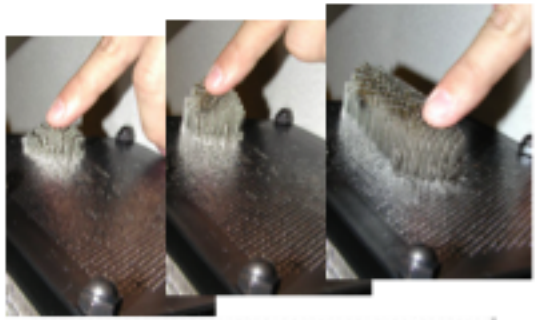
*Ignacio Llamas, Alex Powell, Jarek Rossignac, Chris Shaw*

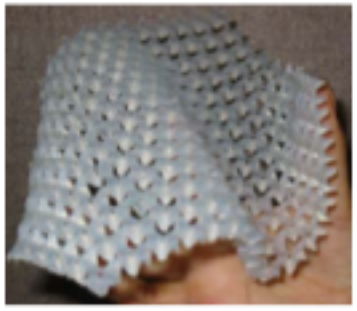
GVU Center and College of Computing
Georgia Tech, Atlanta, USA

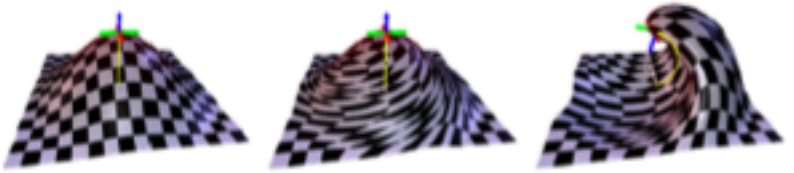
# Digital Clay: A leap in human/shape interaction

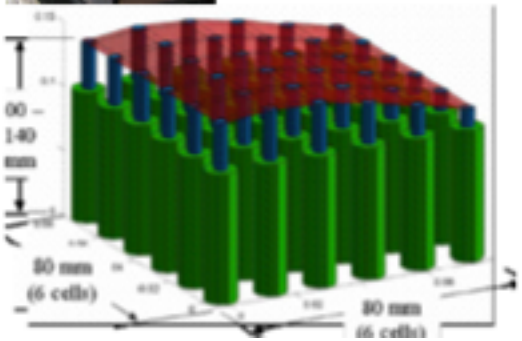
NSF-ITR/PE+SY project 0121663 at Georgia Tech. Allen, Book, Glezer, Ebert-Uphoff, Rosen, Rossignac, Shaw

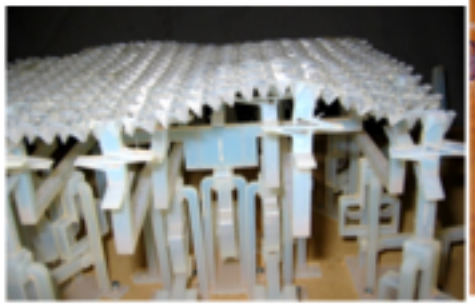
**Two designs for a computer-controlled, physical surface that reacts to changes in 3D model and in pressure exerted by fingers**

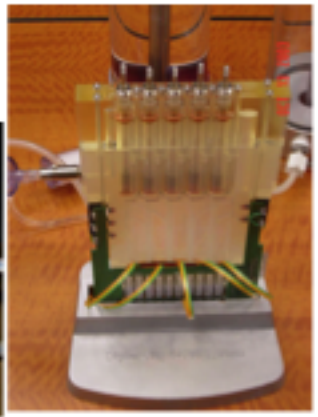



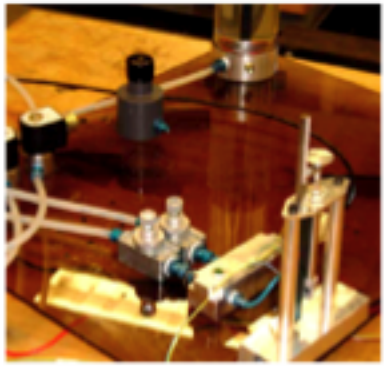




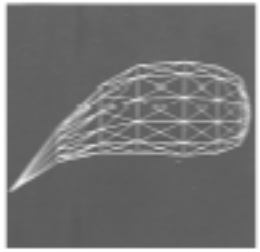


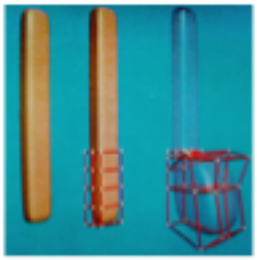




# Examples of prior art

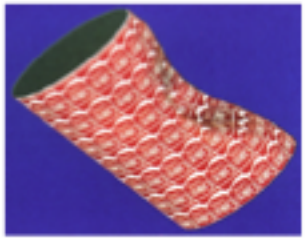


Parent77



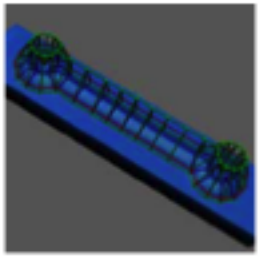
Sederberg86

Coquillart90

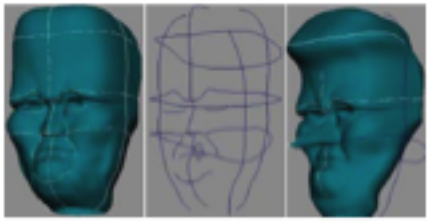


Borrel91

Hsu92

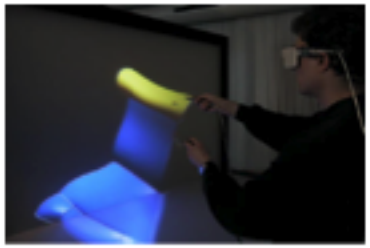


MacCracken96



Sinh 98

Schkolne01

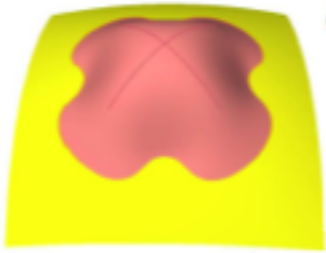


Wesche01

Gain00

Jin00

Pauly03

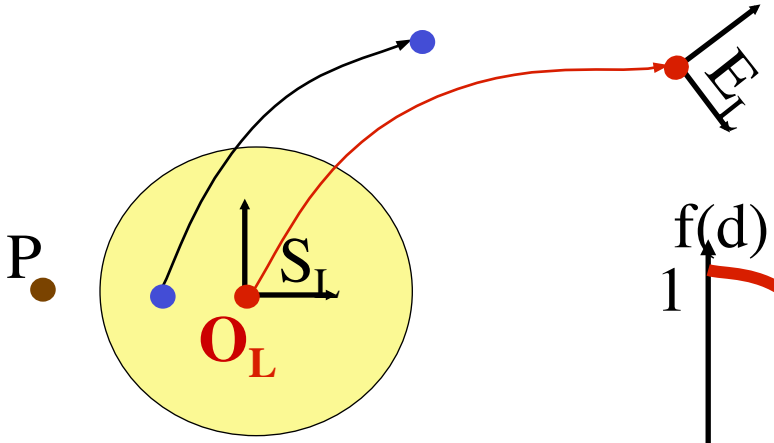


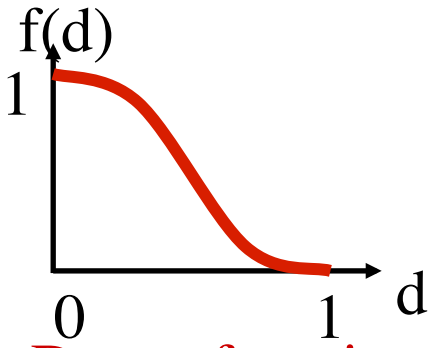
Pernot03

Yoshizawa03

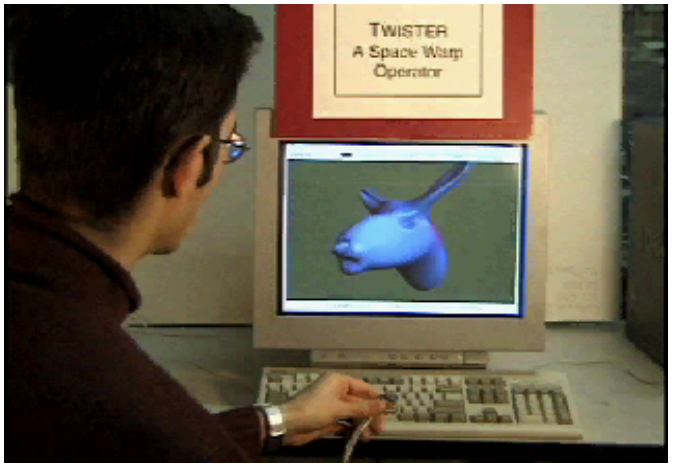
# Space warp based on a screw motion

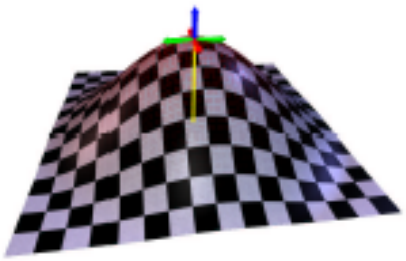
"Twister: A space-warp operator for the two-handed editing of 3D shapes", Llamas, Kim, Gargus, Rossignac, and Shaw. Proc. **ACM SIGGRAPH**, July 2003.

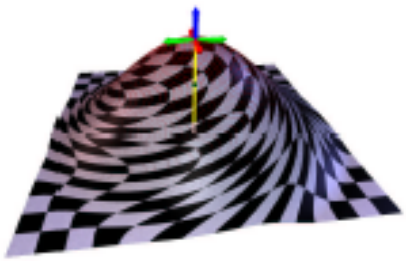


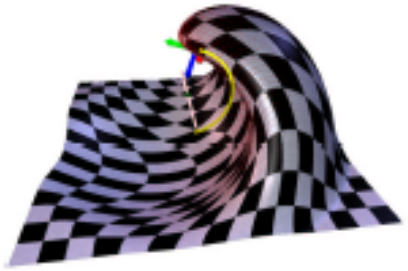




Decay function



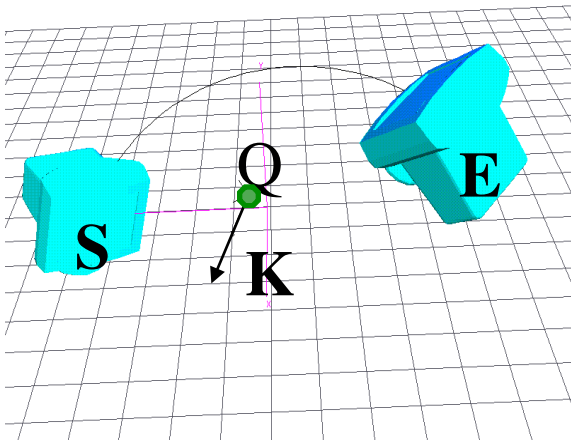



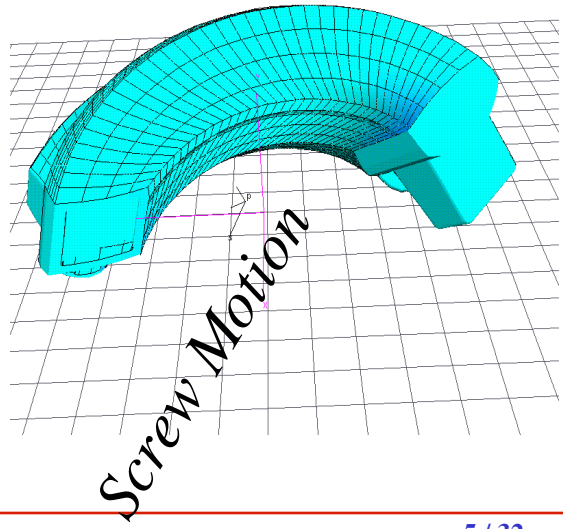




# The universal screw-motion

- **Screw motions are great!**
  - Uniquely defined by start pose S and end pose E
  - Independent of coordinate system
  - Subsumes pure rotations and translations
  - Minimizes rotation angle & translation distance
  - 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**

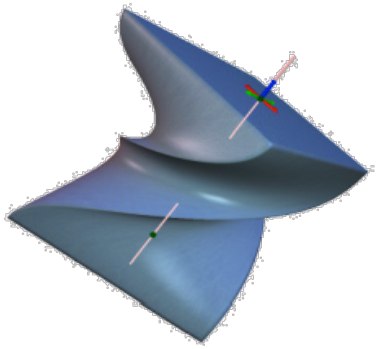


# Screw history

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

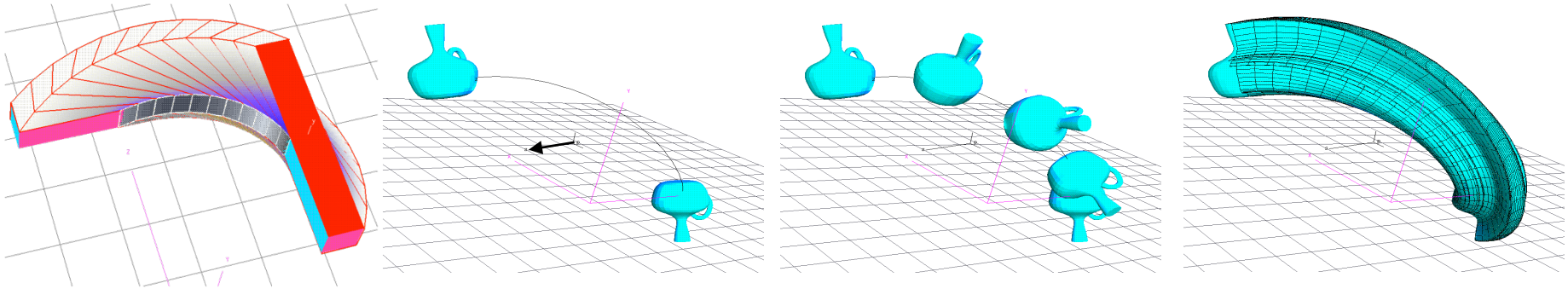
- **Archimede (287–212 BC) designed helicoidal screw for water pumps**
- **Leonardo da Vinci (1452–1519) description of helicoidal motion**
- **Dal Monte (1545–1607) and Galileo (1564–1642) mechanical studies on helicoidal geometry**
- **Giulio Mozzi (1763) screw axis as the "spontaneous axis of rotation"**
- **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

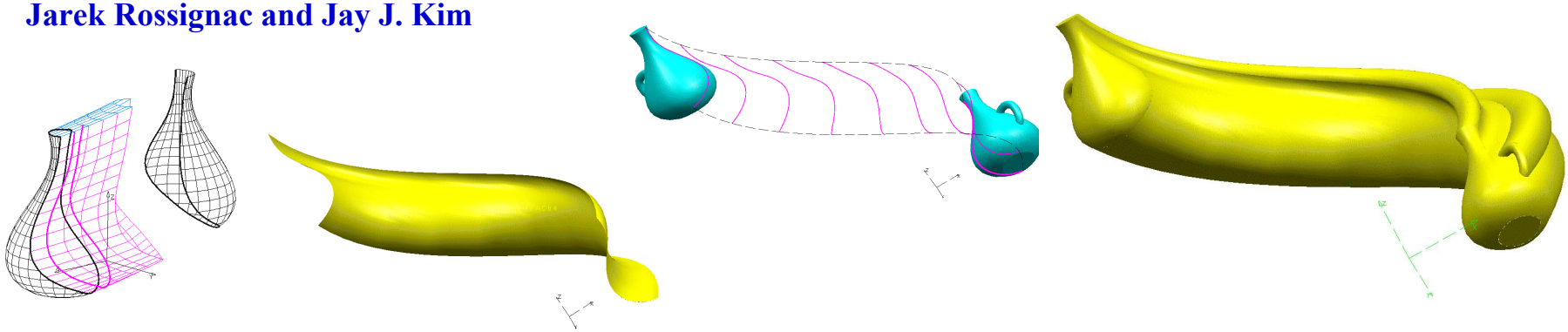
## Computing and visualizing pose-interpolating 3D motions

**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

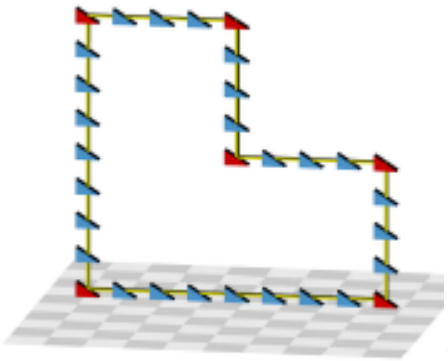
**Jarek Rossignac and Jay J. Kim**

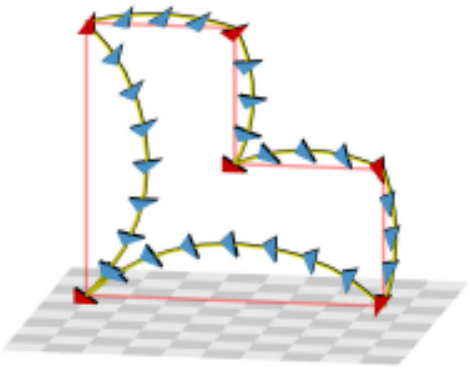


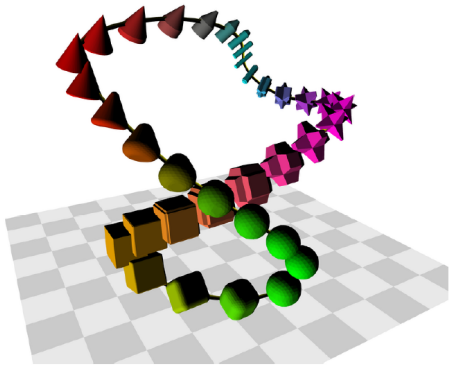
# Smoothing piecewise-screw motions

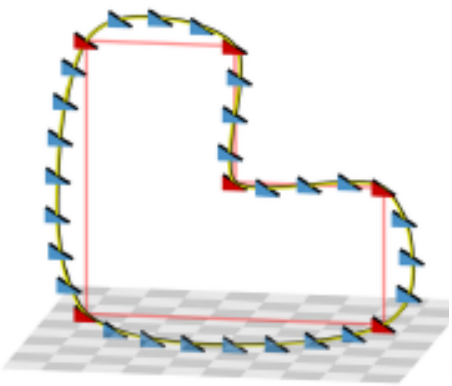
"ScrewBender: Polyscrew Subdivision for Smoothing Interpolating Motions" A. Powell

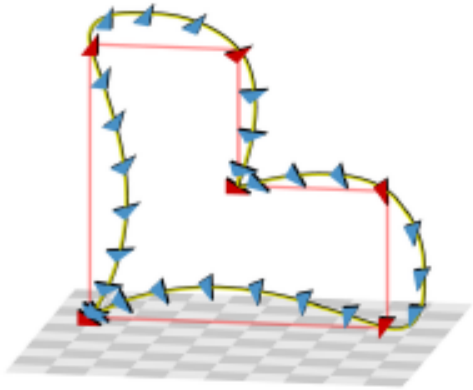
and J. Rossignac

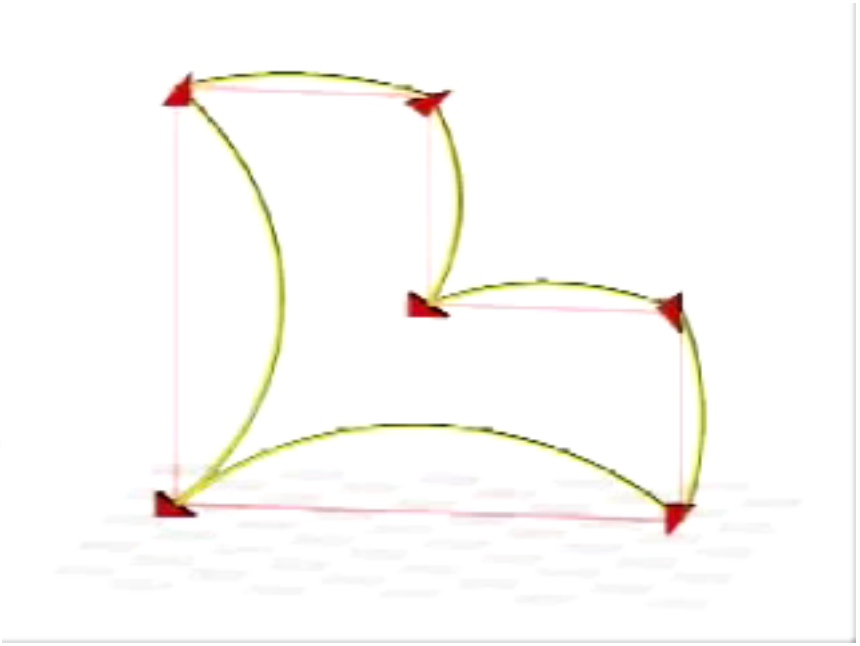








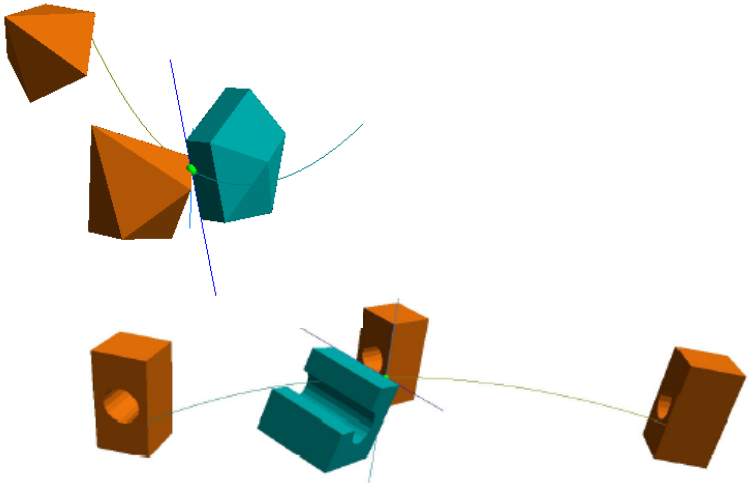


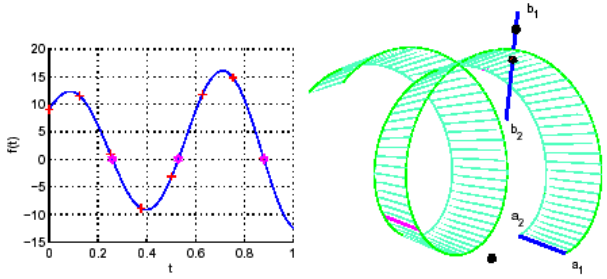


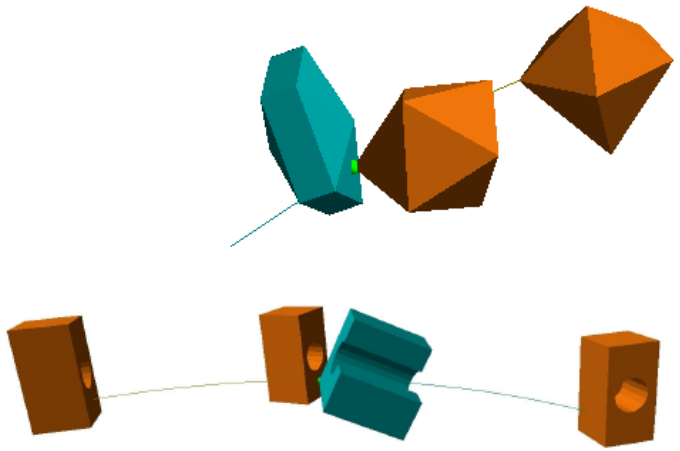
# Collision during screw motions

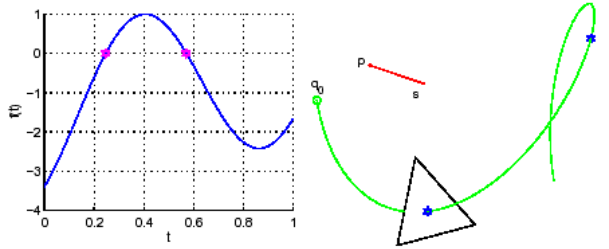
"Collision Prediction for Polyhedra under Screw Motions", BM Kim and J. Rossignac, ACM Symposium on **Solid Modeling and Applications**, 2003.

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







# Computing the screw parameters

From initial and final poses:

M(0) and M(1)

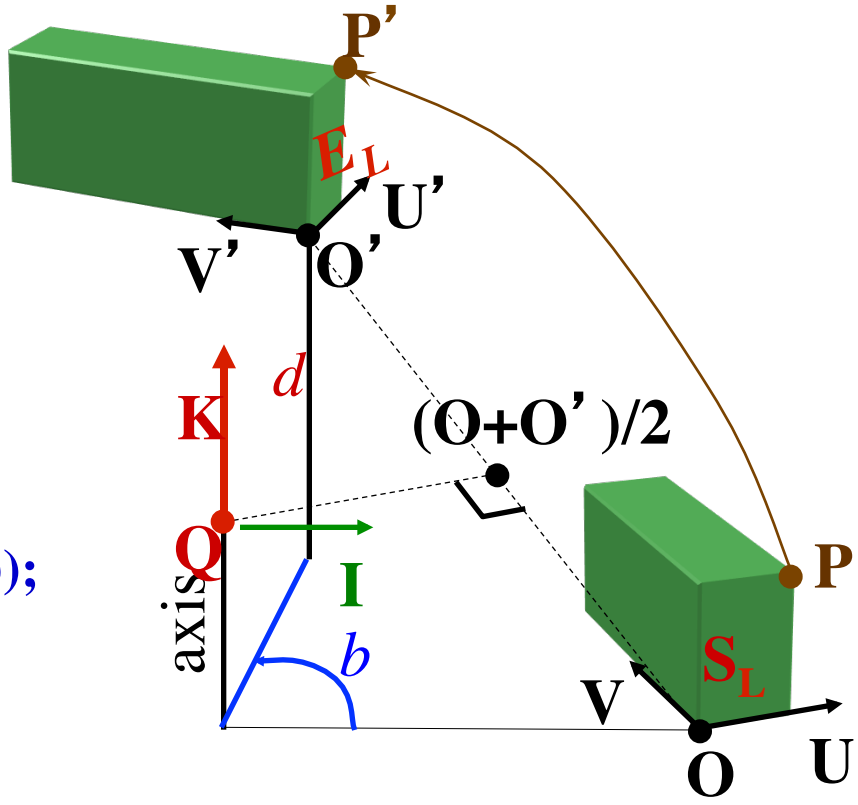
**K:=(U' –U)×(V' –V);**

**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;

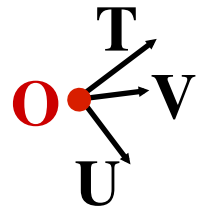
Rotate around K by *tb*;

Translate by (0,0,*td*);

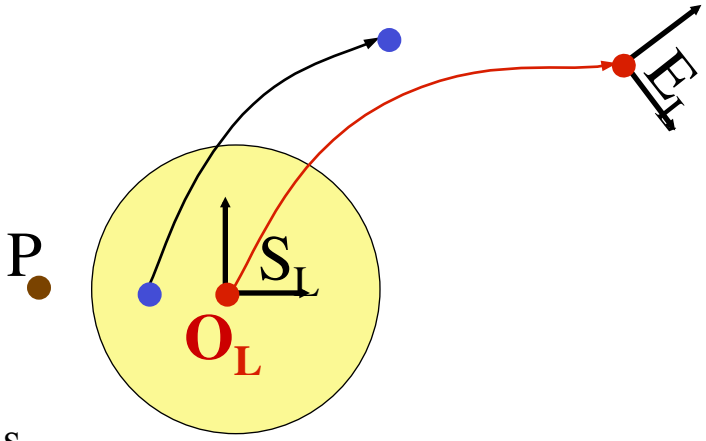
Translate by Q;

# 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

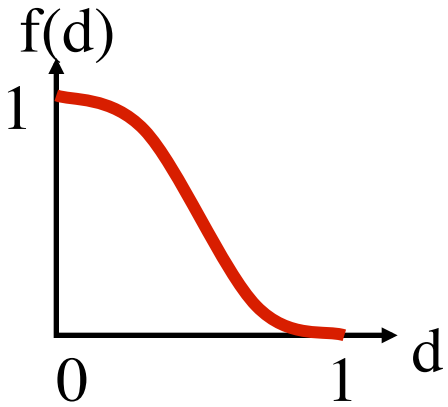



- **Upon release, $E_L$ and $E_R$ are frozen**
  - The vertices of the mesh have new locations

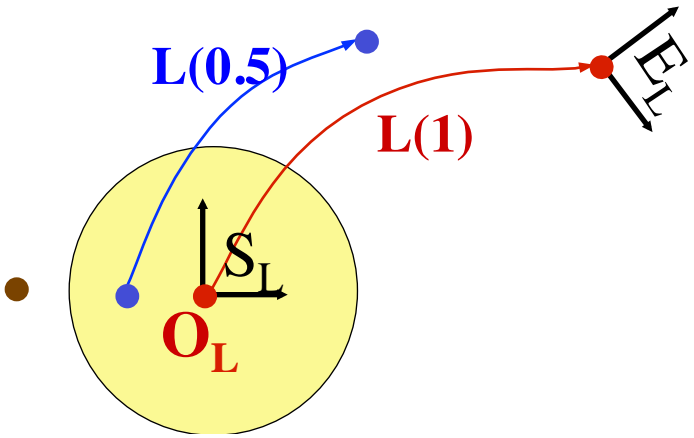
# Single-hand warp and decay

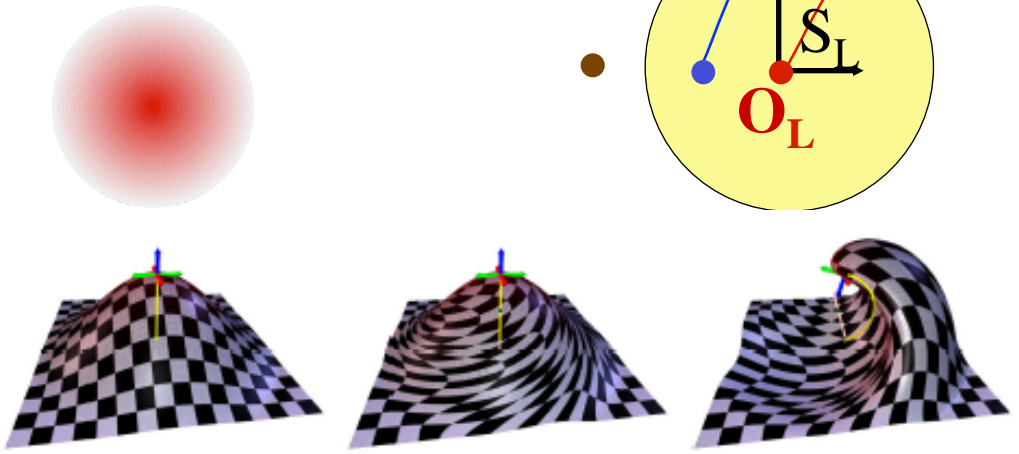
- **$S_L$ and $E_L$ are interpolated by a screw motion L(t), t in [0,1]**
- **A point p moves by $L(f(\|PO_L\|/r))$,**

  **$f(d)=\cos^2(d\pi/2)$ 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



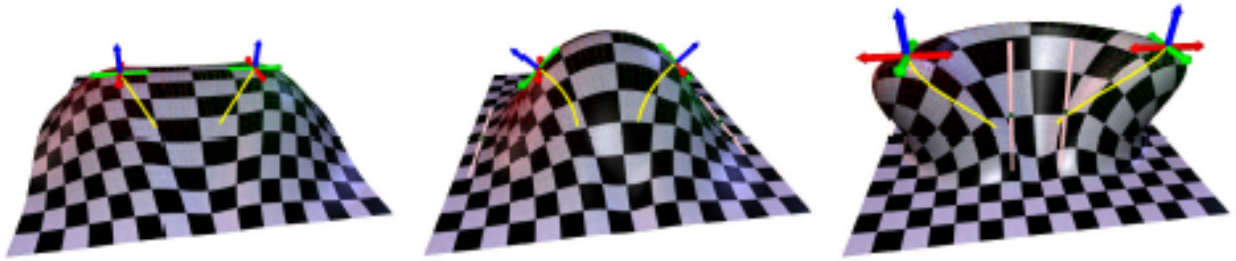

3D radial decay profile



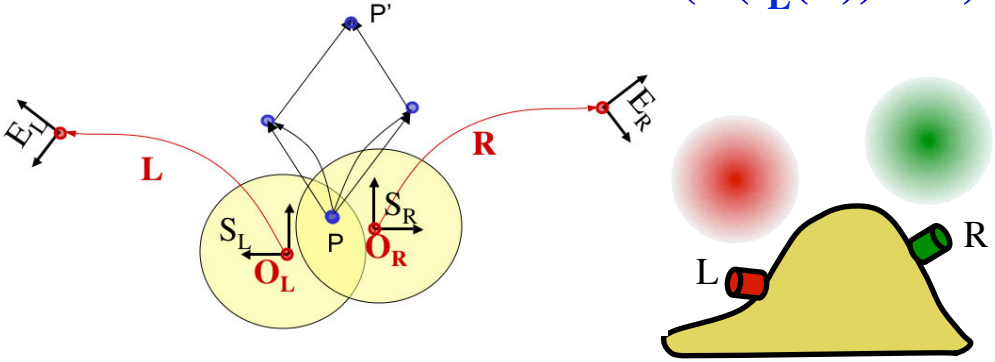



# Two-hand warp

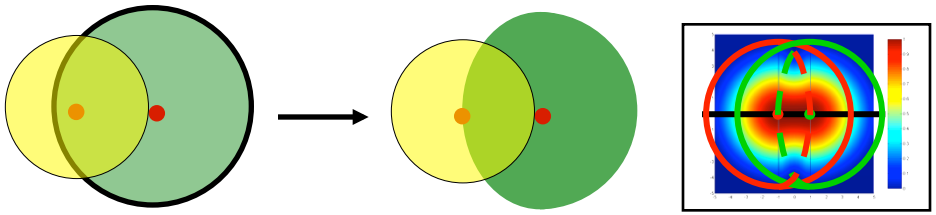
- **Want to use two hands simultaneouslv to deform a shape**



- **A point P moves to P + (L(f$_L$(P)) – P) + (R(f$_R$(P)) –P)**

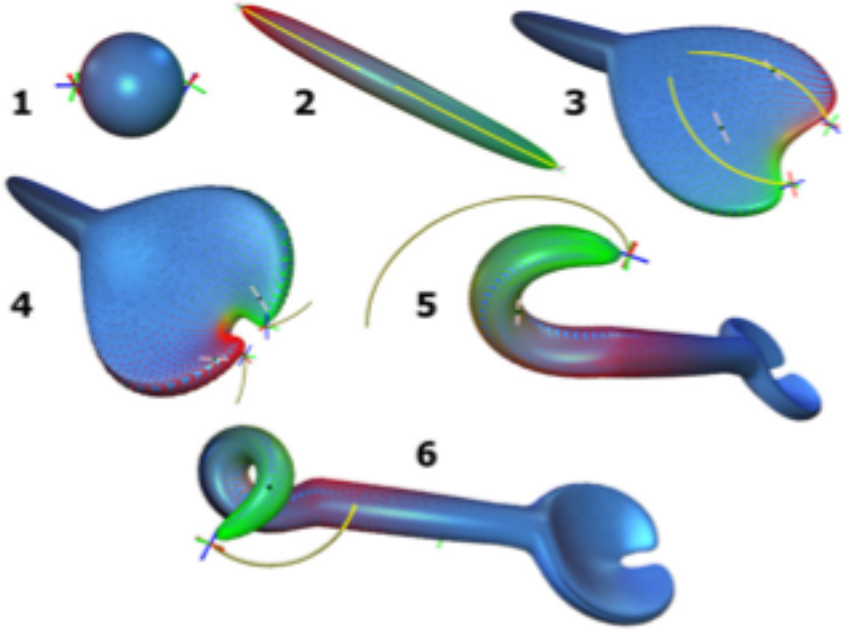


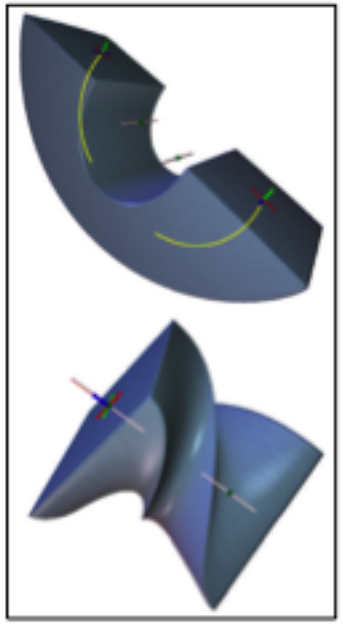

- **Squash overlapping RoI**

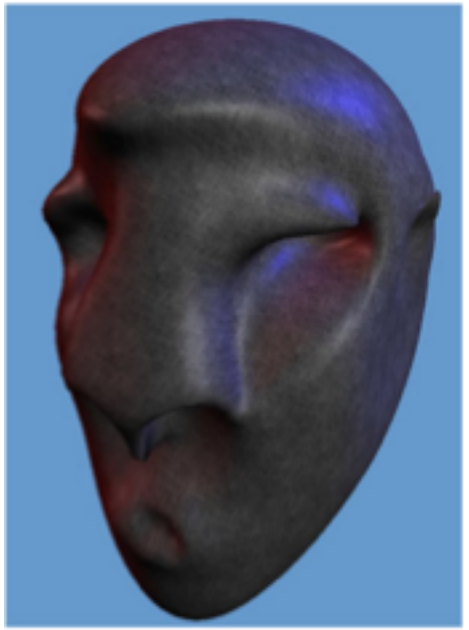


# Some models designed in TWISTER

- 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

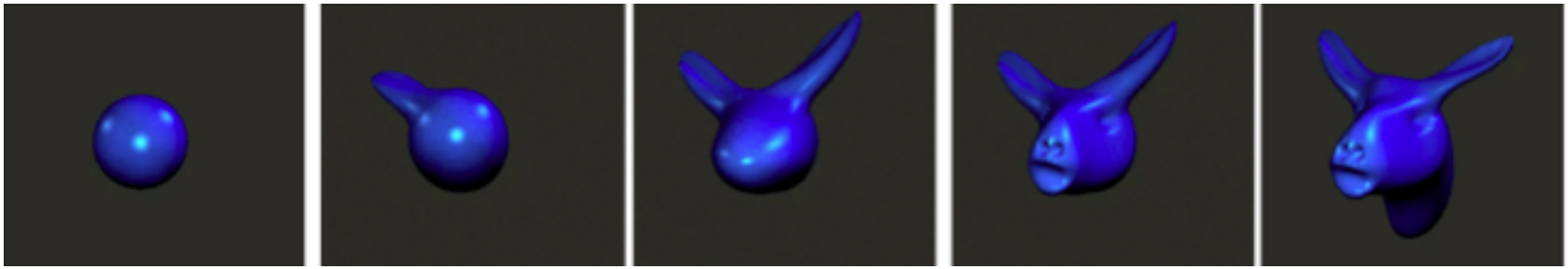


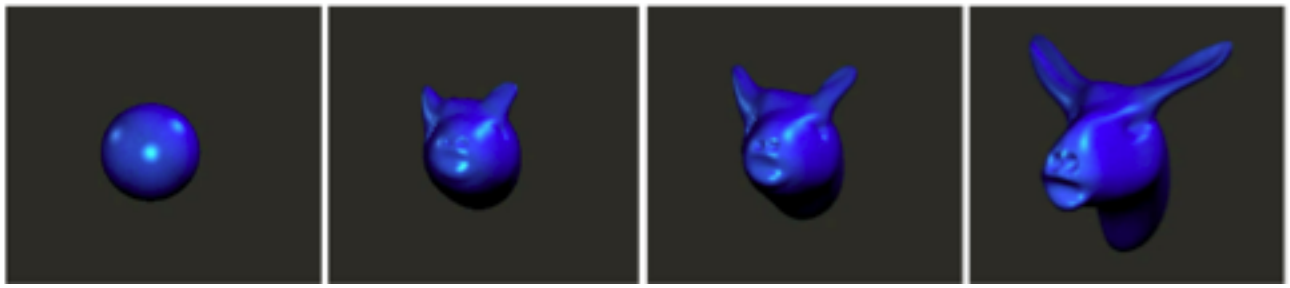


# From design to animation

- **Design one feature at a time**

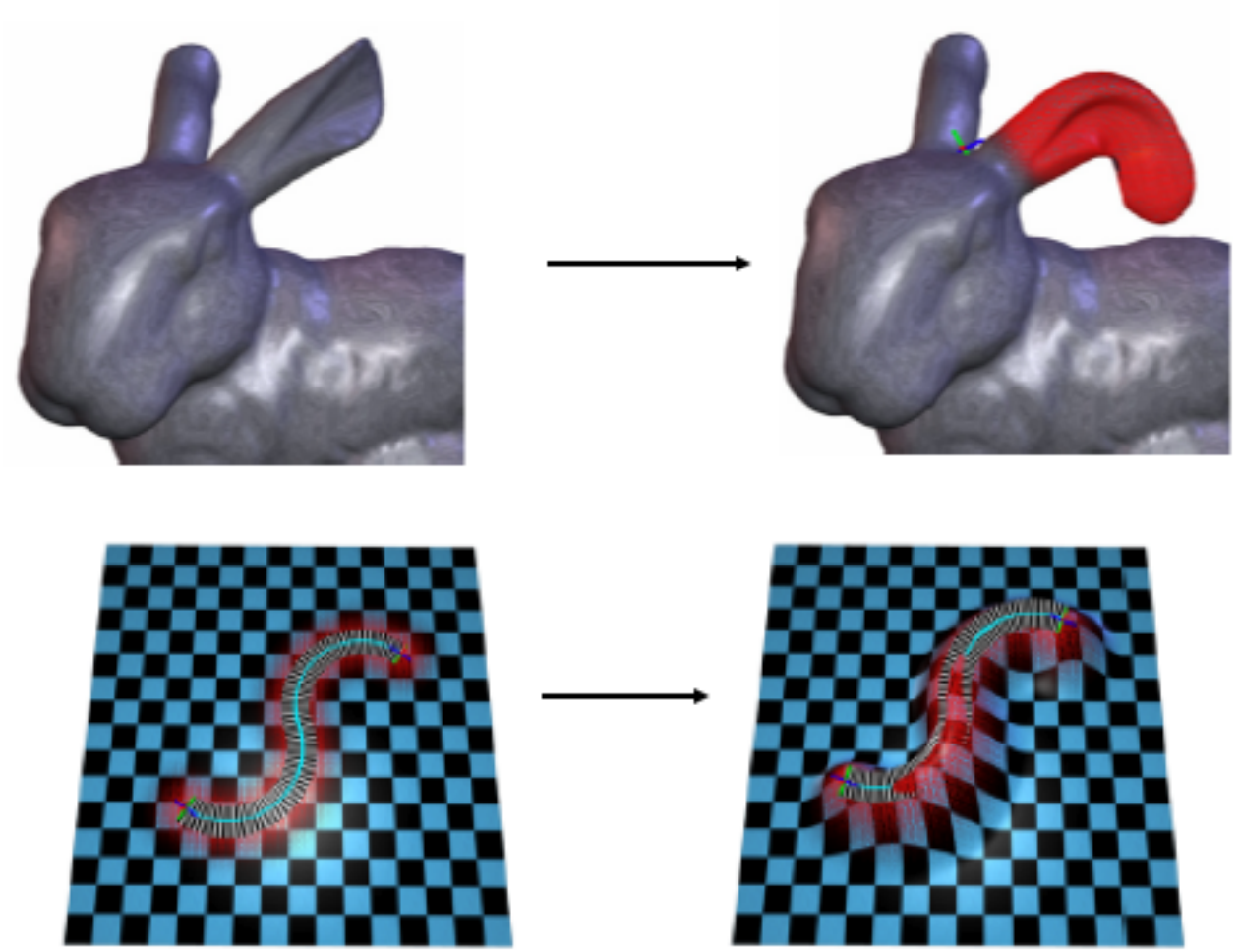


- **Then animate their synchronized creation**



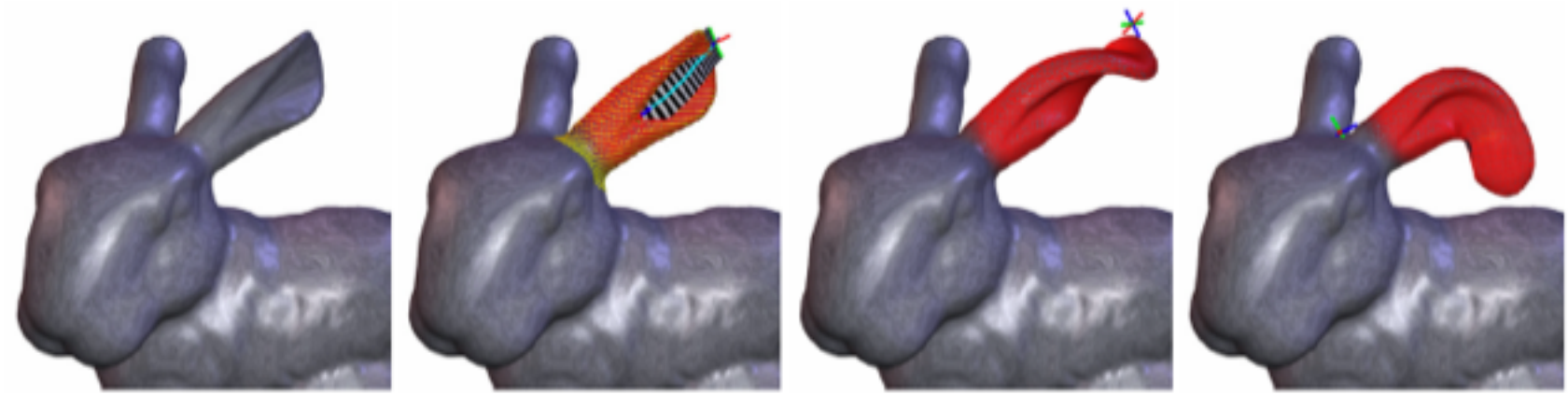
# Limitations of TWISTER

**Bends and extrusions are tedious with Twister**



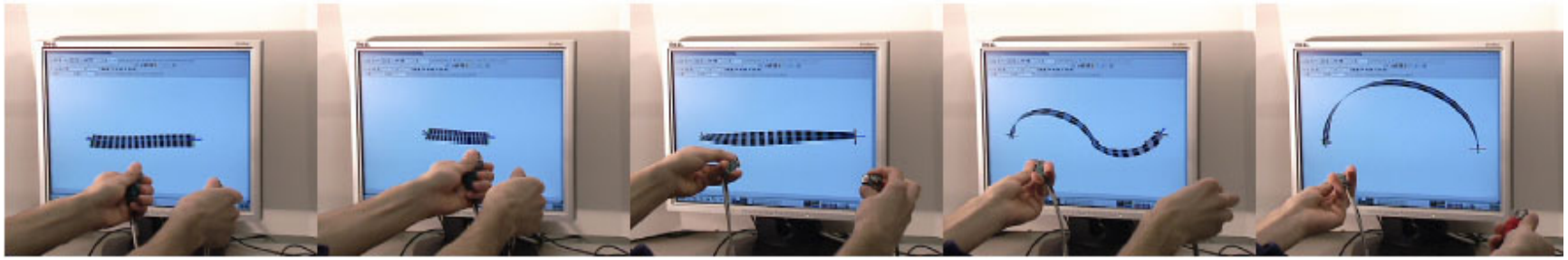
# BENDER's Approach

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

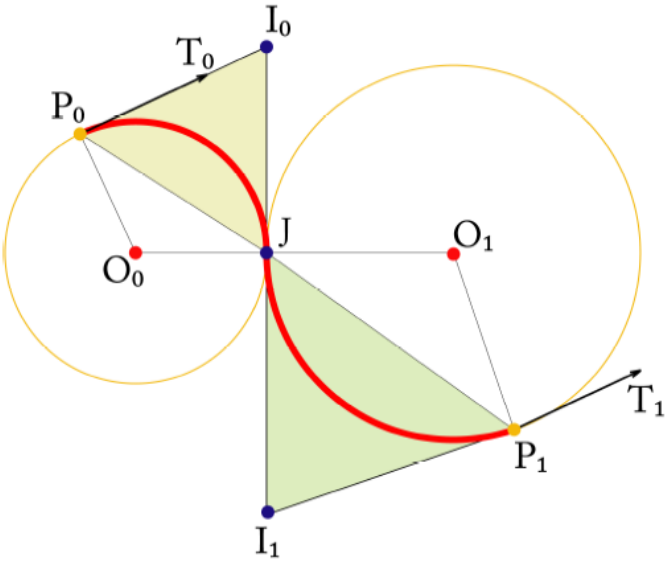


# Controlling the ribbon with two hands

## Each tracker controls one end of the ribbon



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




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

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

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

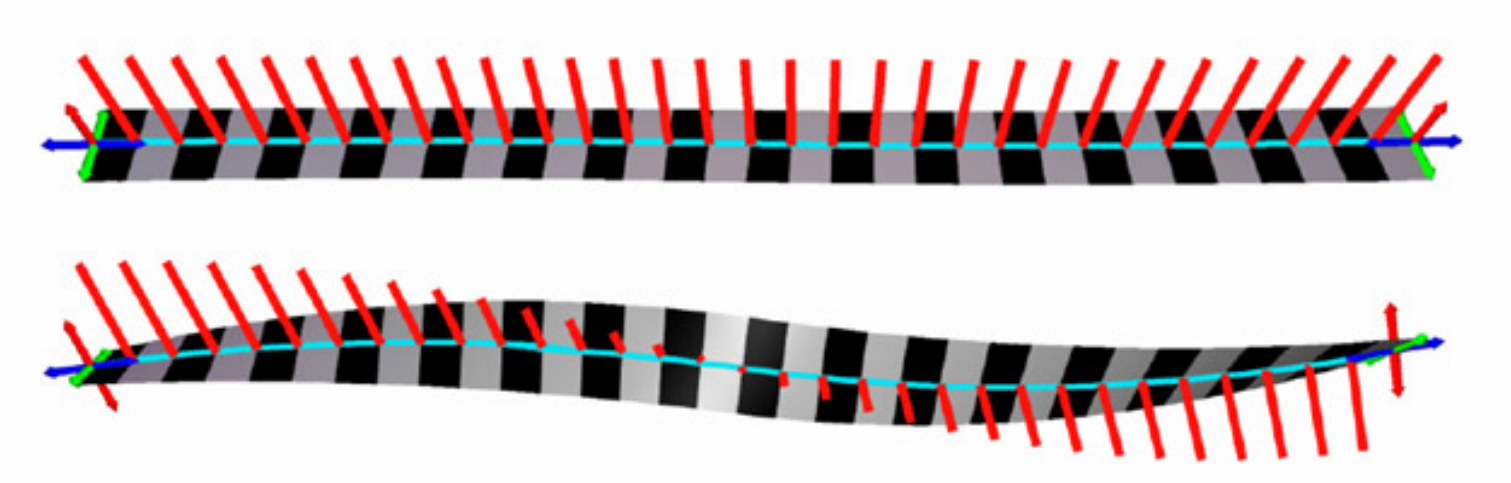
Solve with a=b

"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

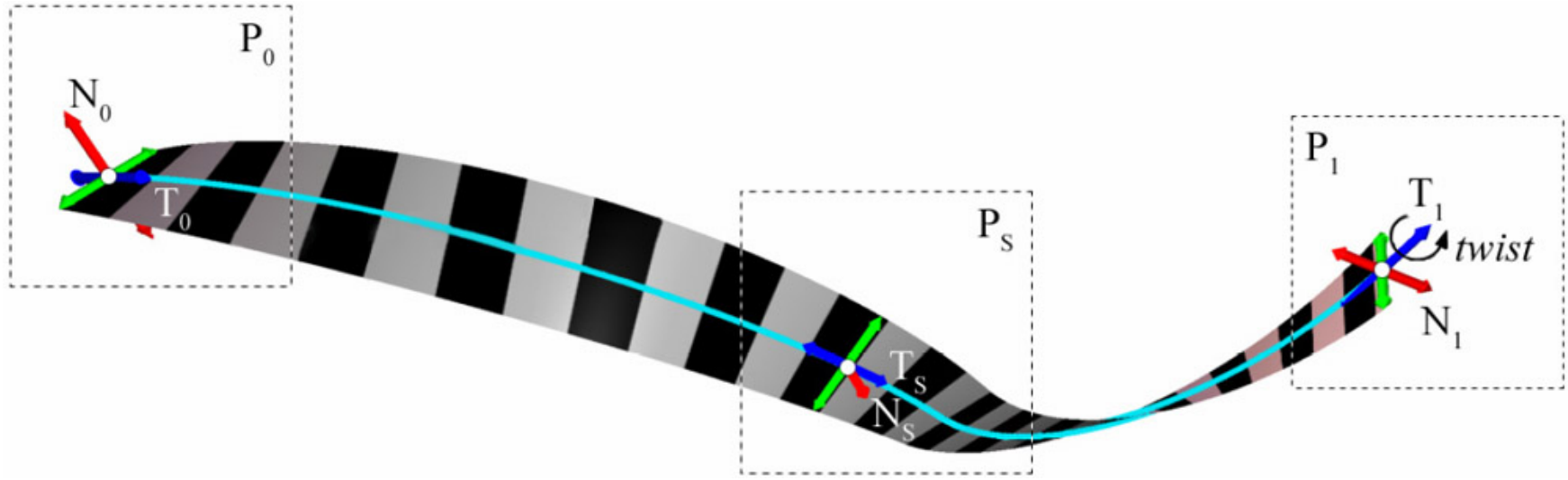
- **Compute total twist**
  - Use angle between $P_0I_0J$ plane and tracker orientation at P0
  - Propgate it (pure rotation) to J
  - Compute total twist at J between the two arcs

- **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**

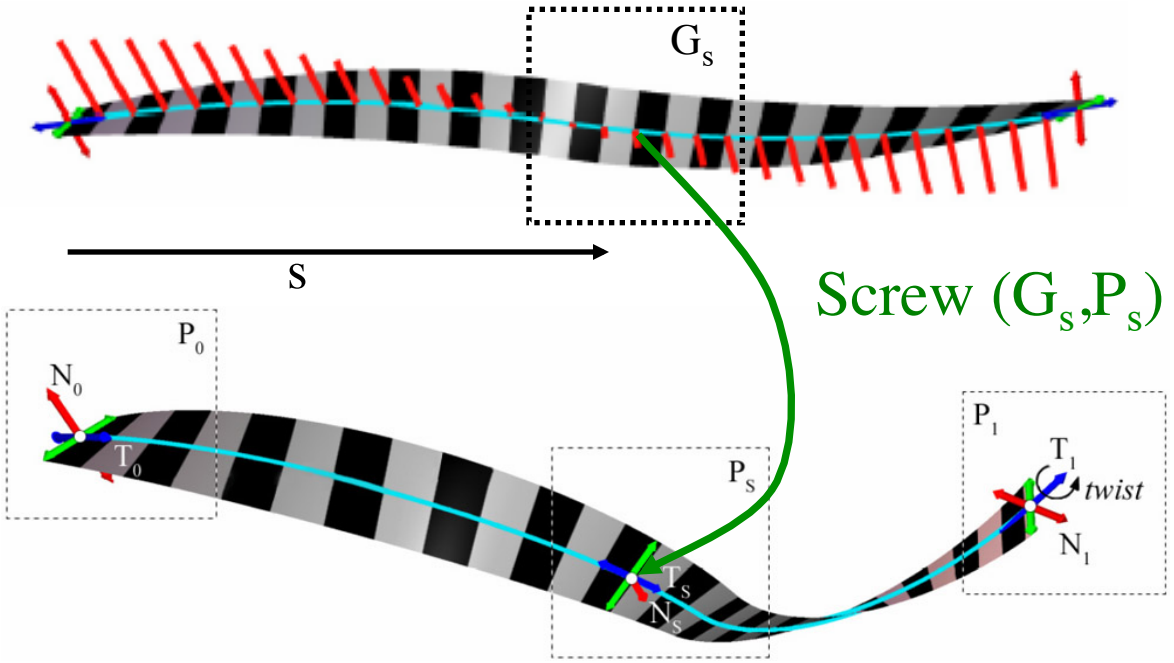


# Interpolating two ribbons

- **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!**

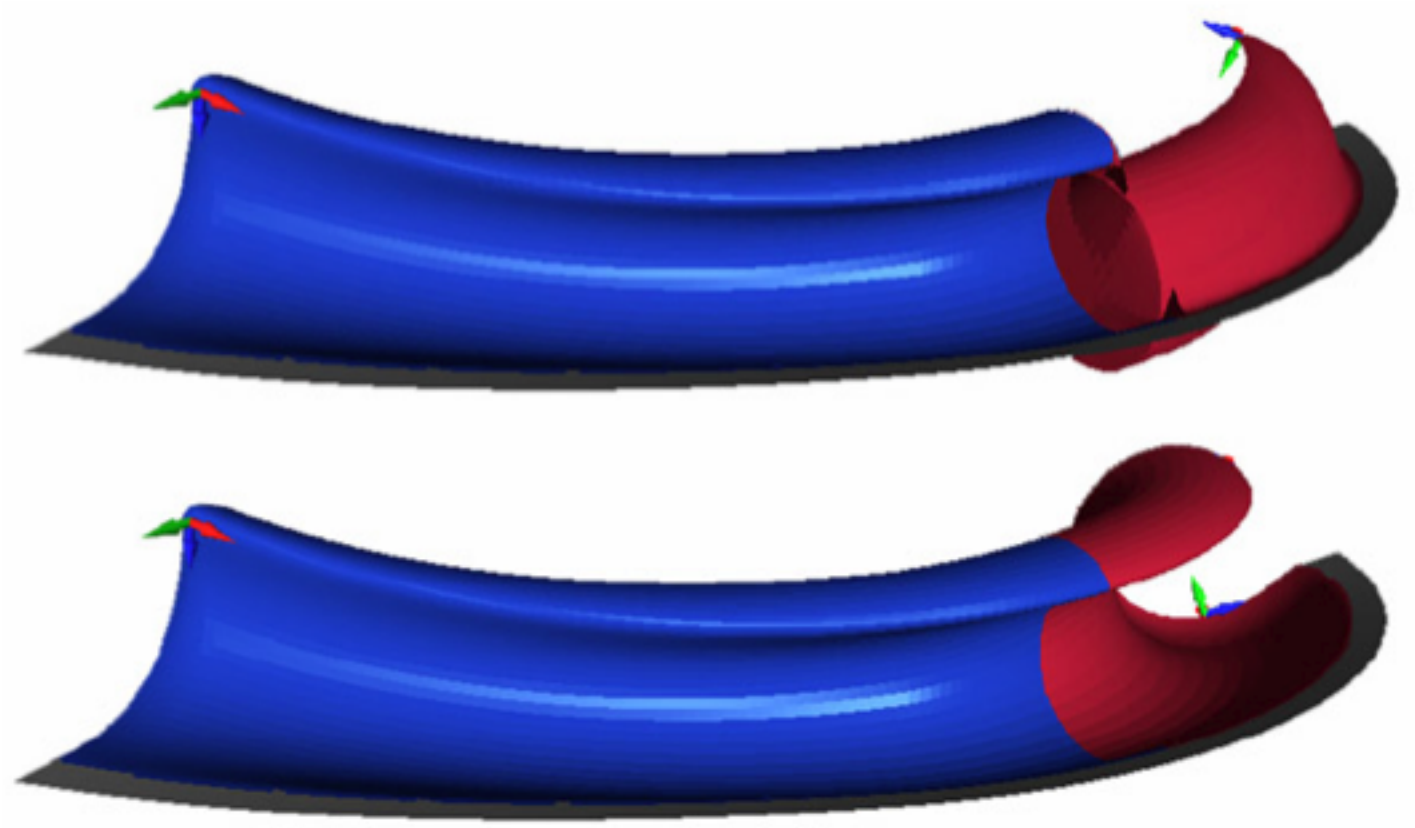
Grabbed ribbon

Current ribbon



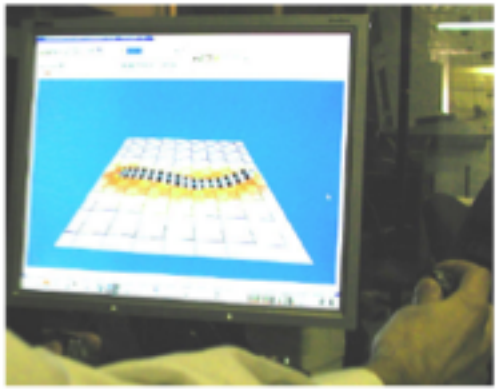
# Preventing flips

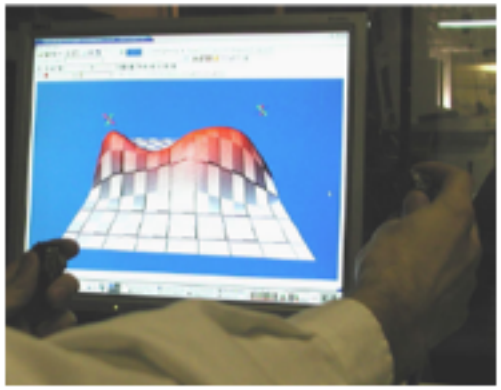
- **The screw axis, K, may flip between consecutive values of s**
- **If so, we reverse it (which may lead to rotations >180$^{o}$)**

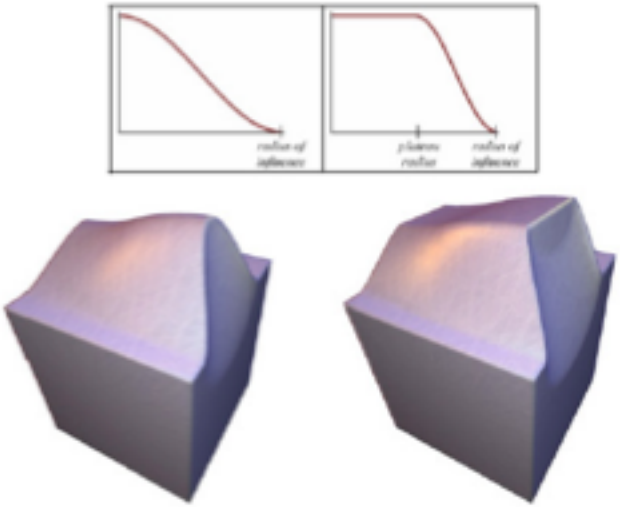


# Warping space with a decay

- **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

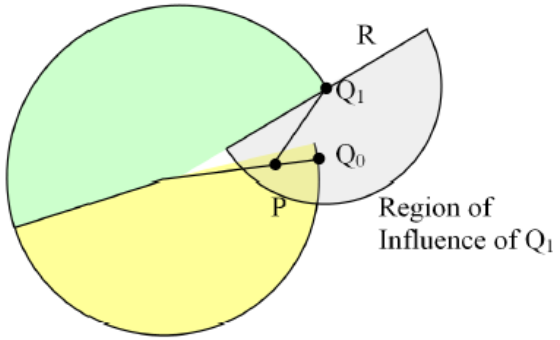


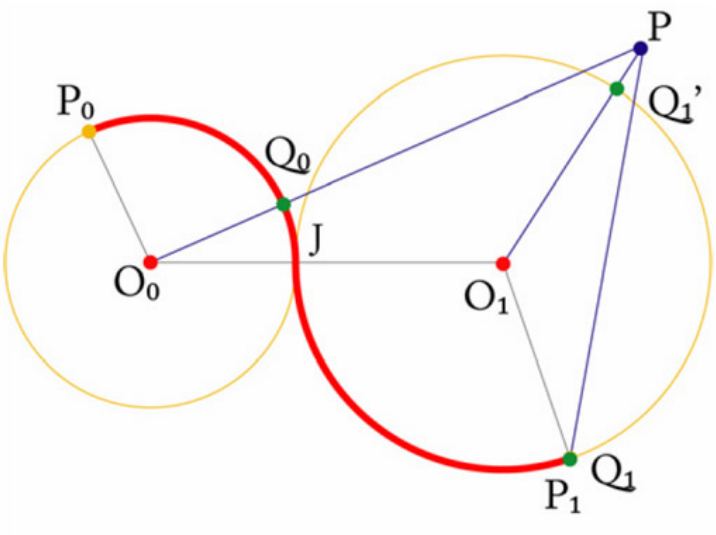


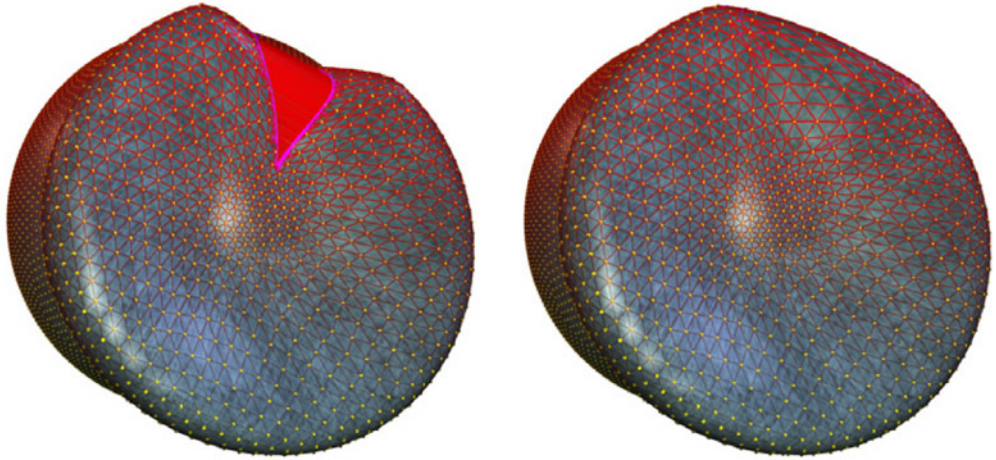


# Avoiding tear (two-hand twister)

- **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**

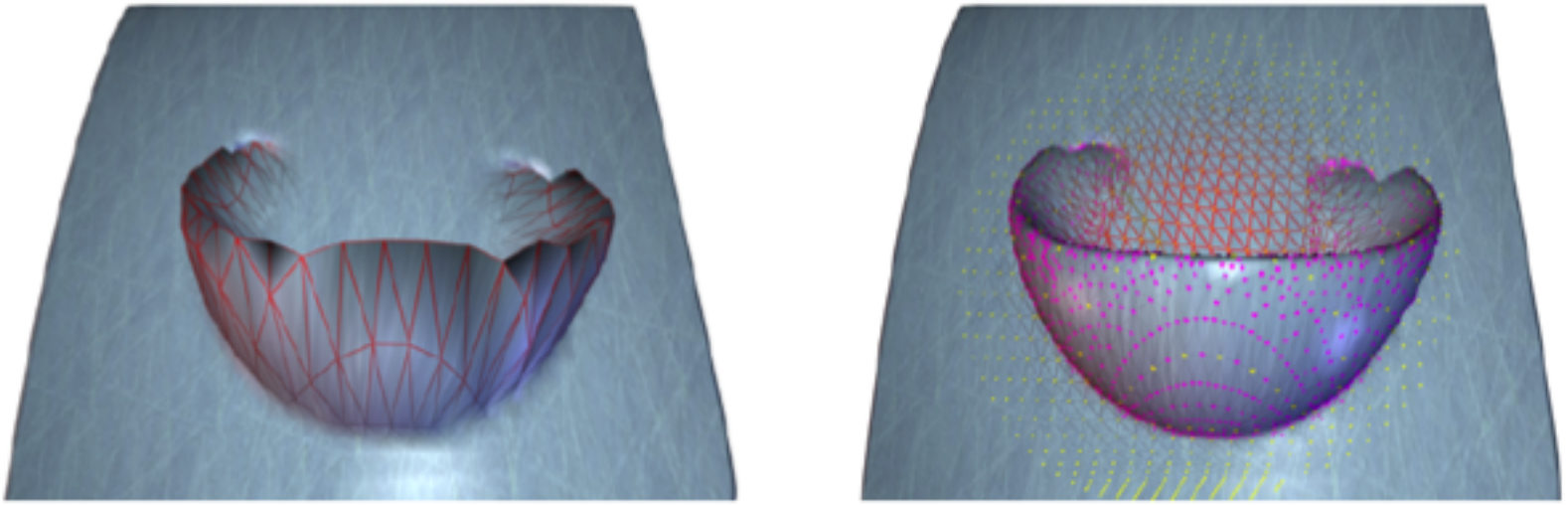


# Adaptive subdivision

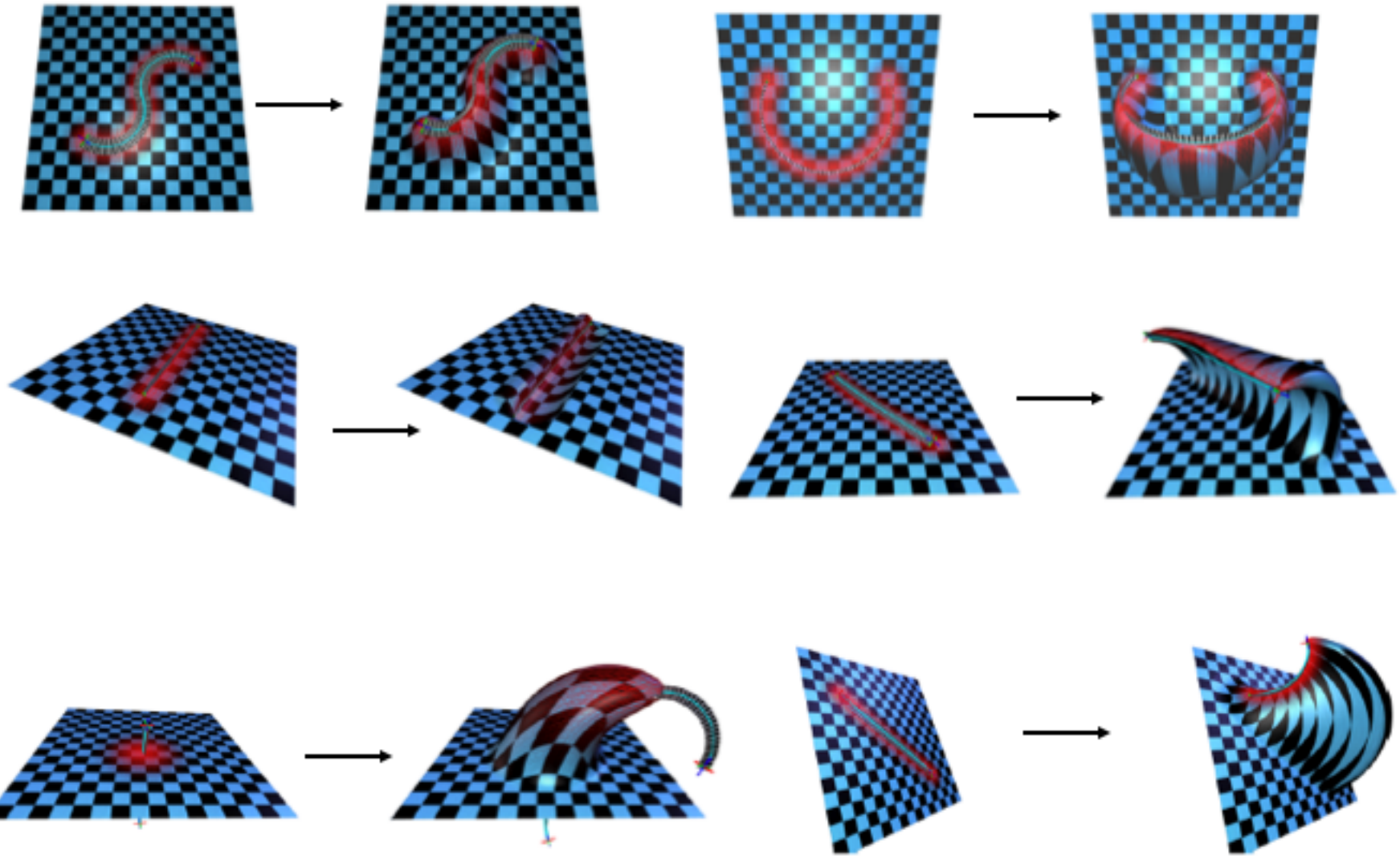
- **The triangulation is automatically refined where needed**



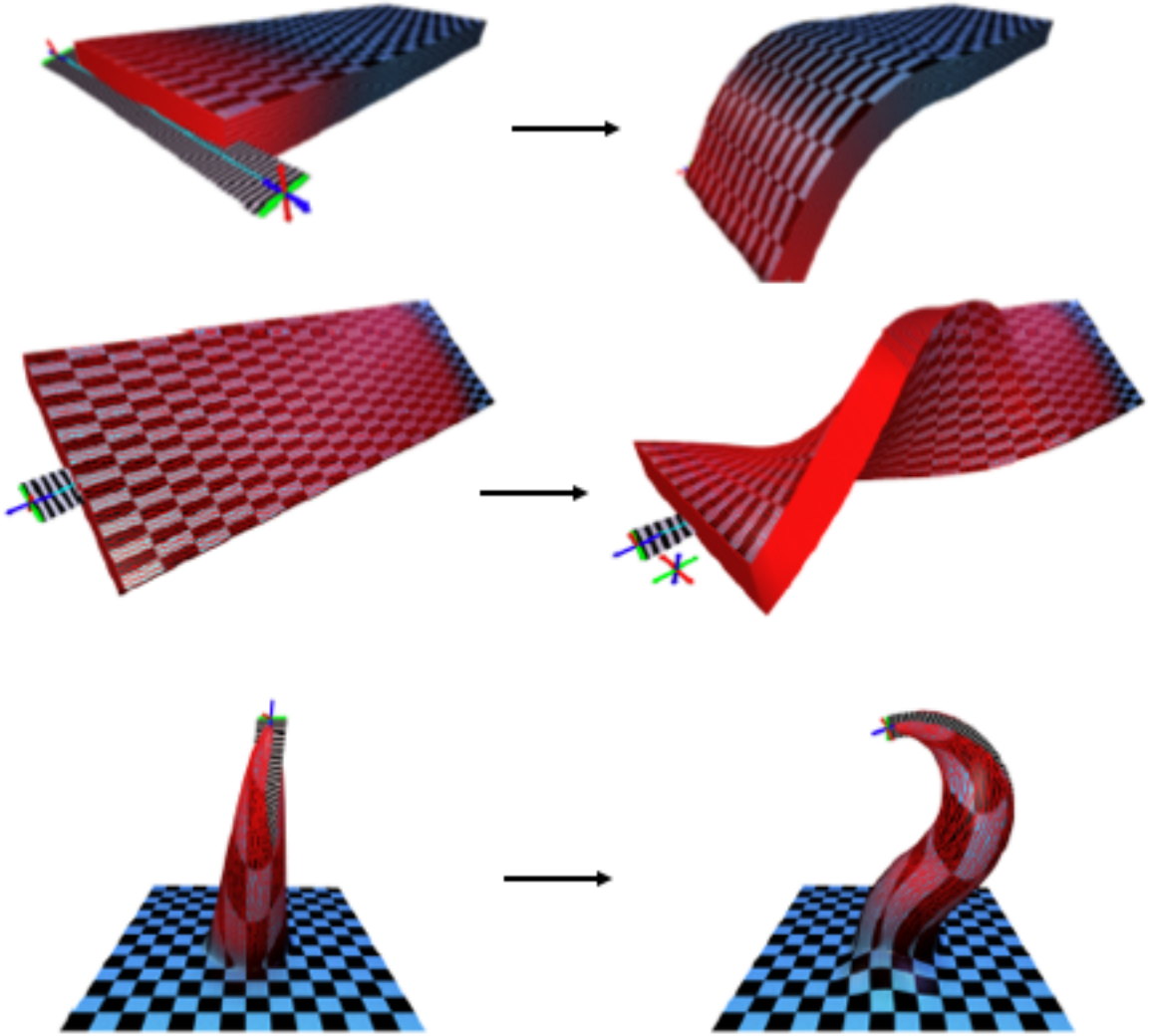
No subdivision

With subdivision

# Creating features with BENDER

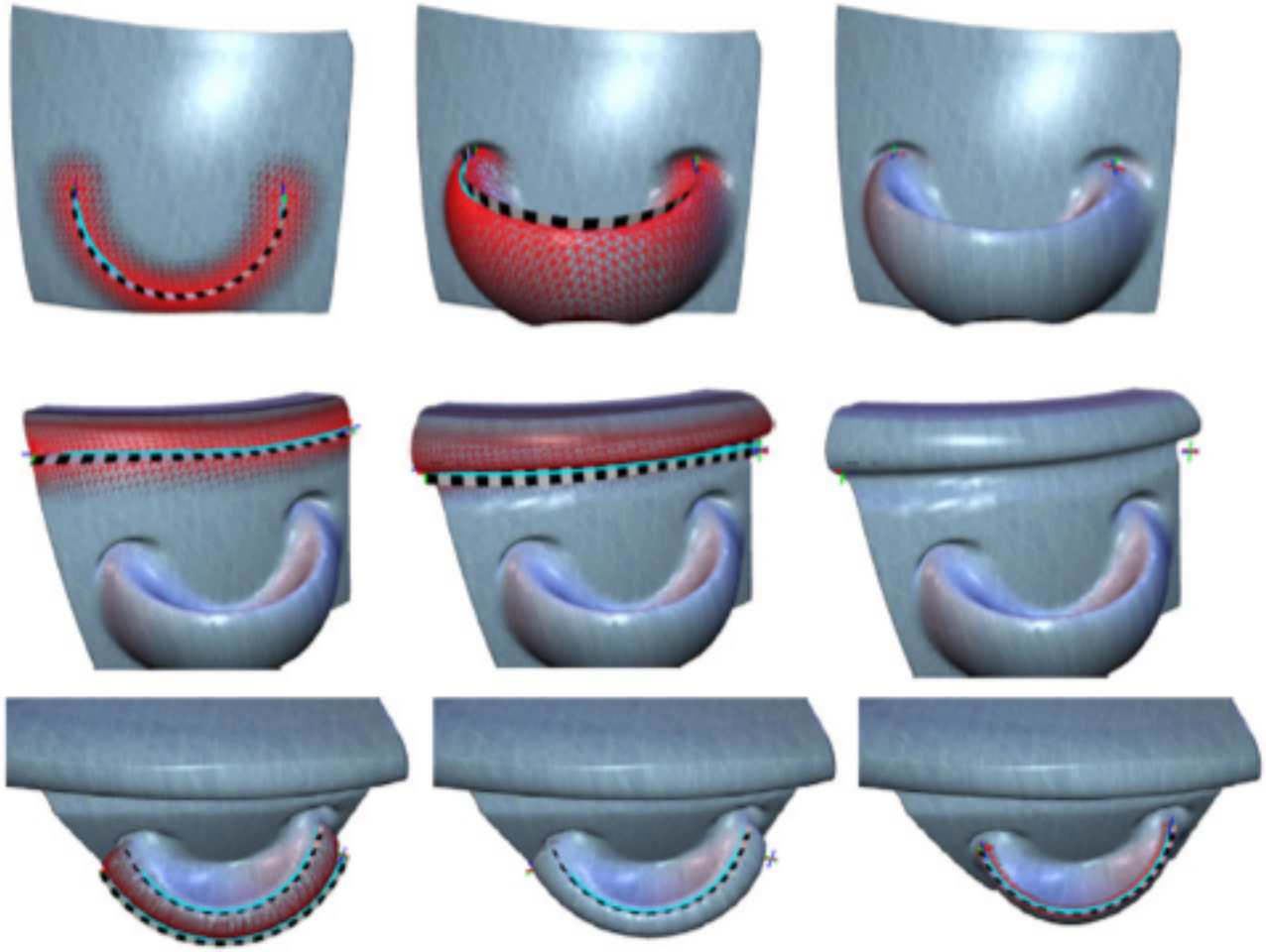


# Deforming existing features with BENDER



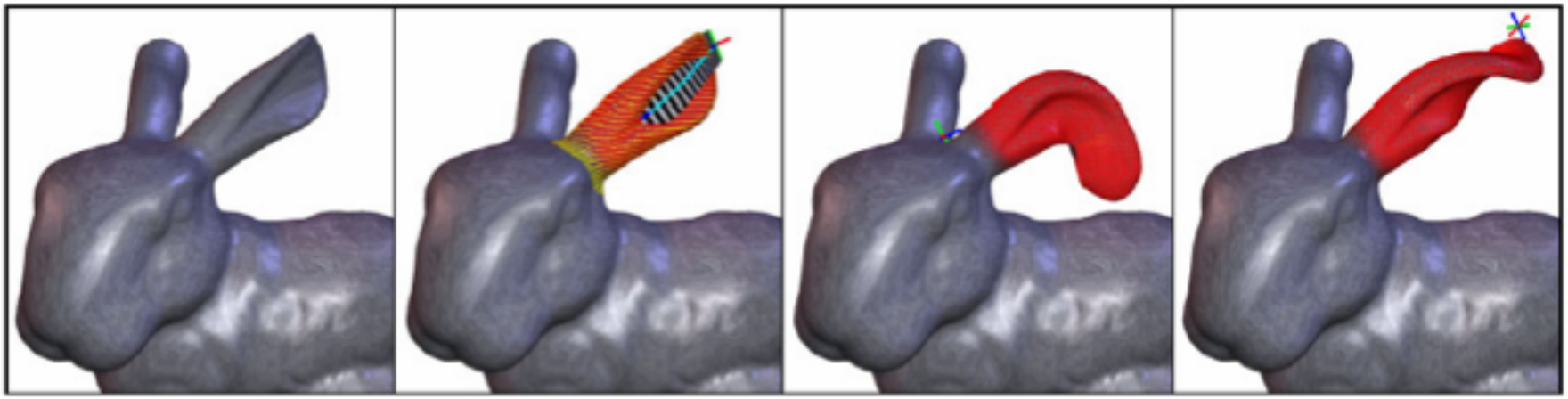
# Sculpting walls

- **Make and edit complex features with only a few gestures**



# Twisting ears

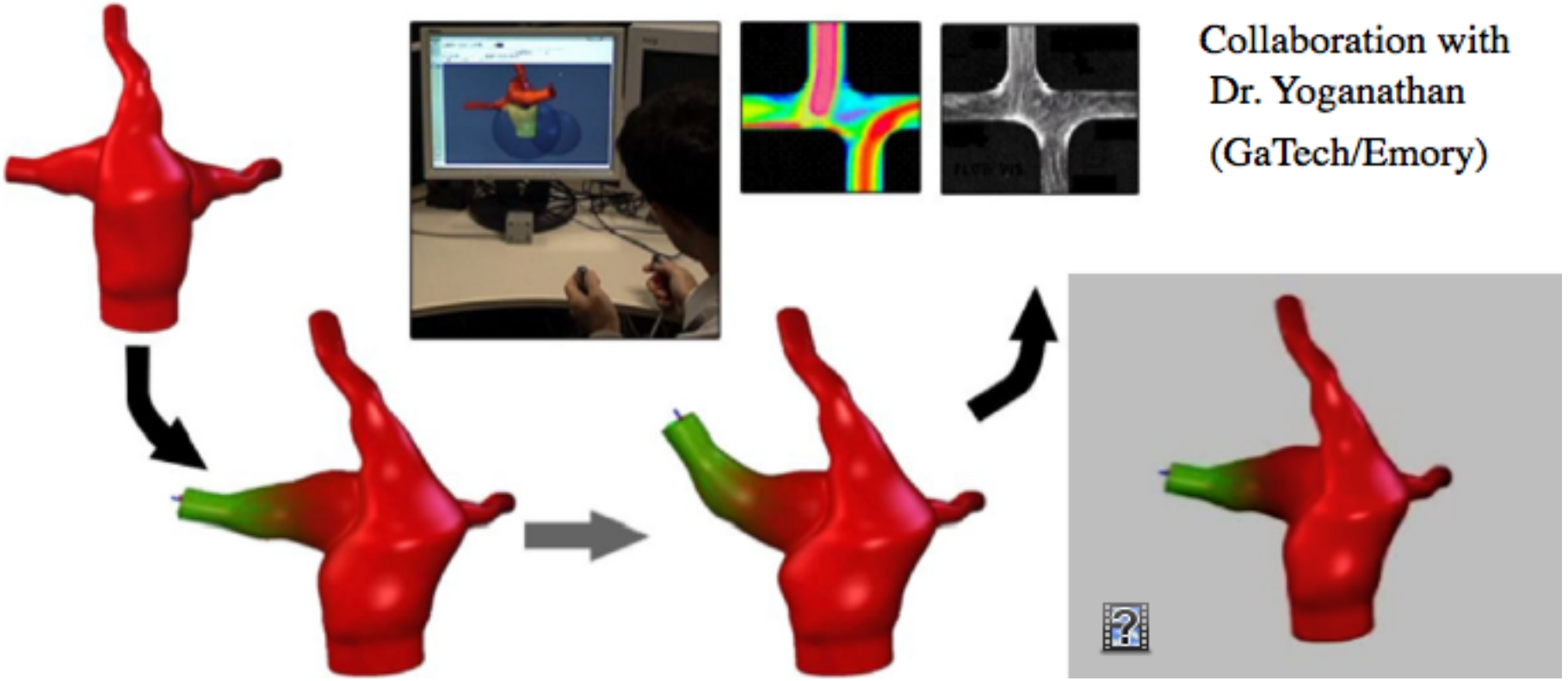
- **Position ribbon along the ear axis**
- **Grab and bend or twist**
- **Release**



# Genetic manipulation (?) with BENDER

# Supporting surgery planning

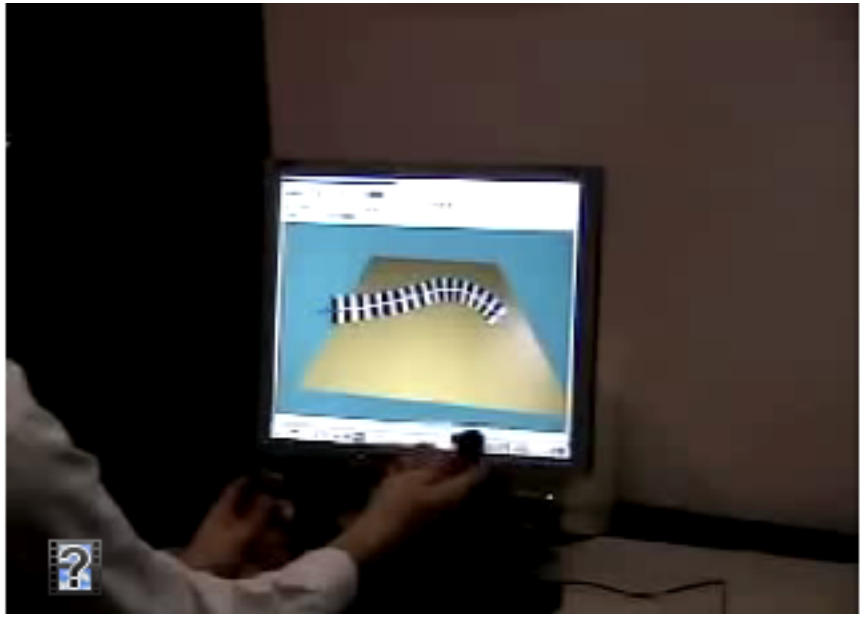
- 0.2% of babies in the US are born with a single ventricle.
- Surgeons want a tool to design the shape of the **Fontan repair** (cavopulmonary connection placing the pulmonary and systemic circuits in series with the univentricular heart).

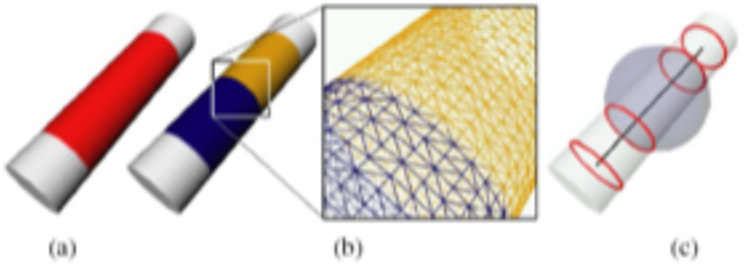


Collaboration with
Dr. Yoganathan
(GaTech/Emory)

# 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)