The Integration of Computational Solid Models and Computer Vision for Sensing, Control, and Manipulation at the Microscale

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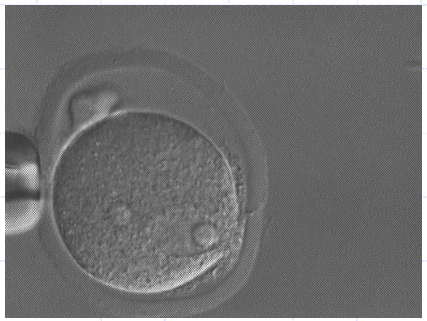
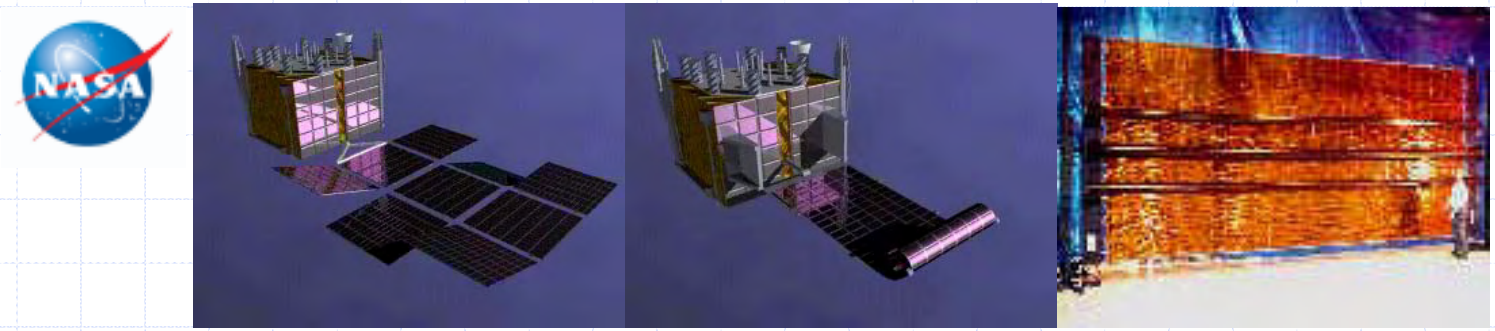
Robotics and Deformable Objects

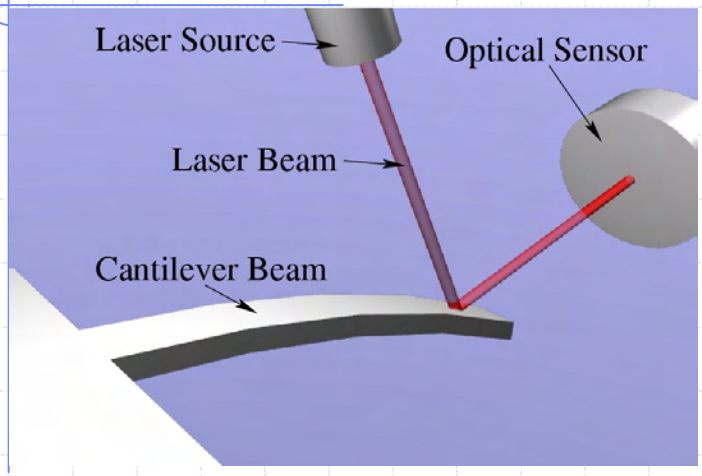
- Robotic surgery
- Biomanipulation



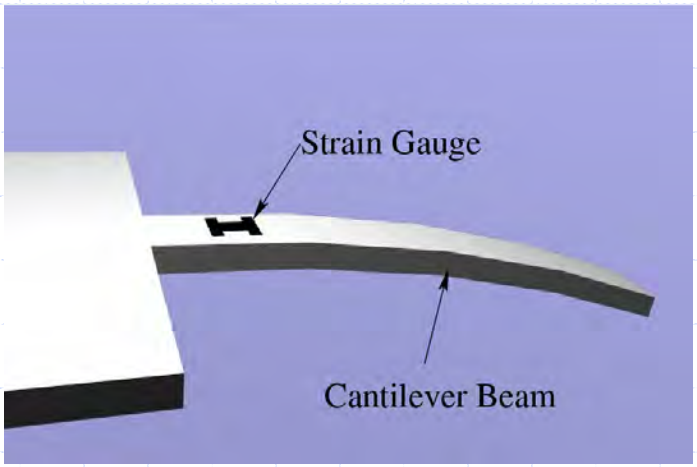
- Deformable Space structures



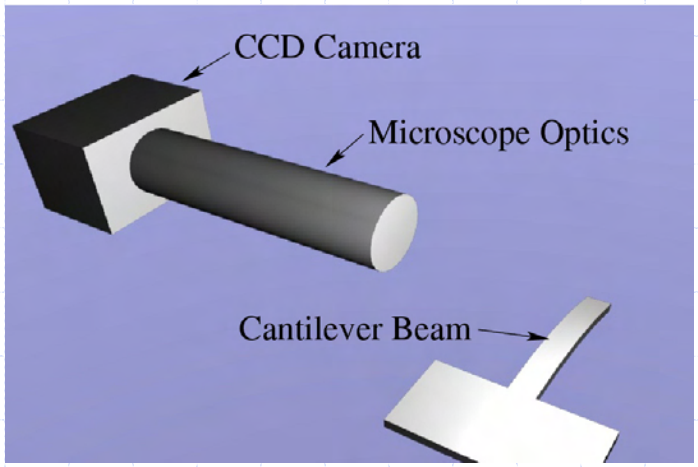
Feedback Mechanisms for the Manipulation Deformable Objects

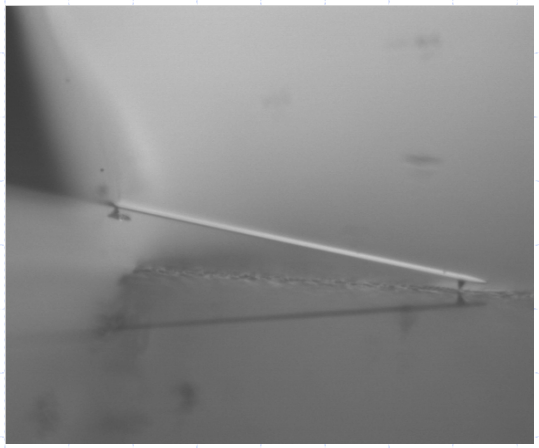


Laser feedback



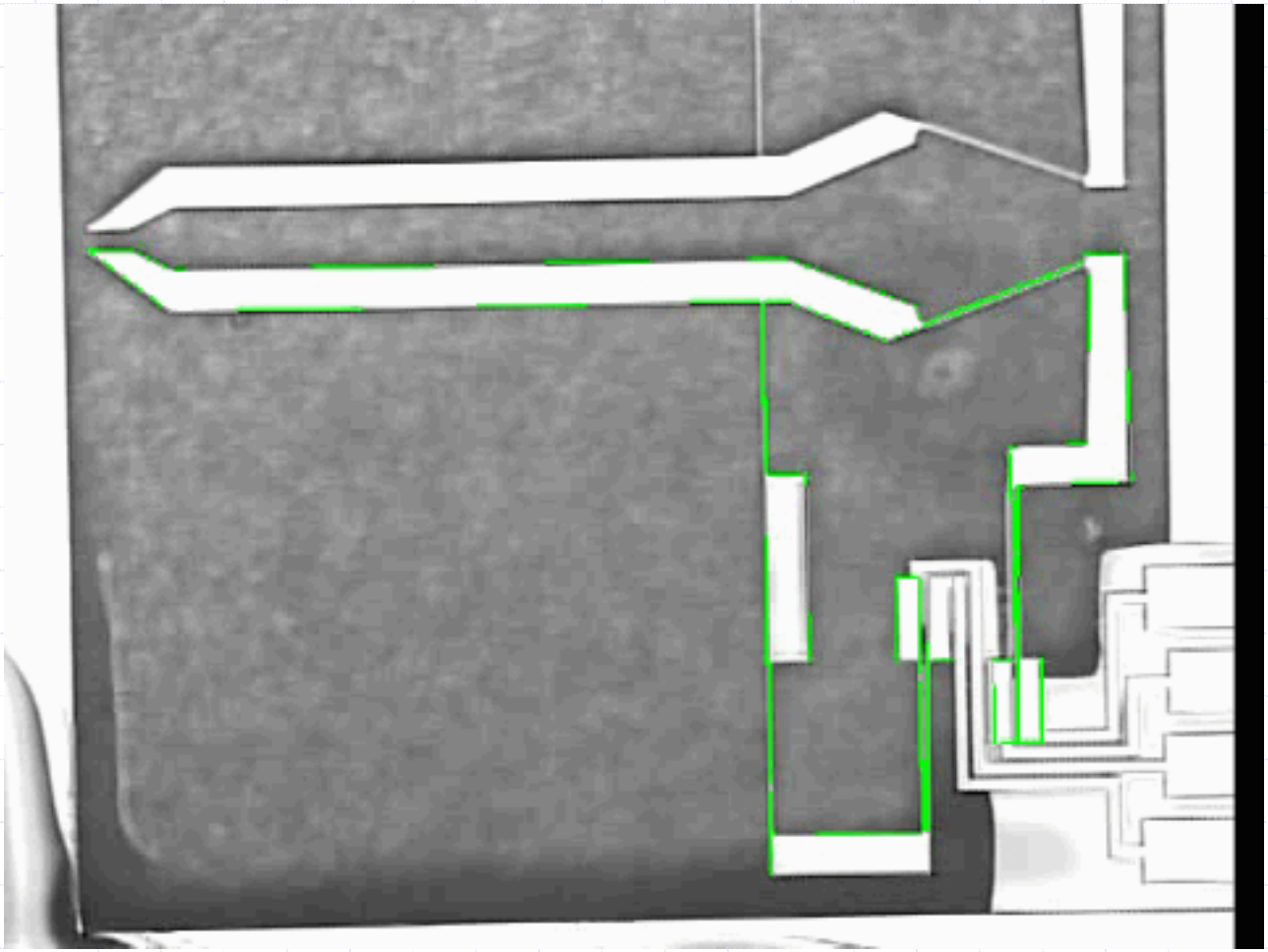
Strain gauge feedback





Vision feedback

The Deformable Object Tracking Problem

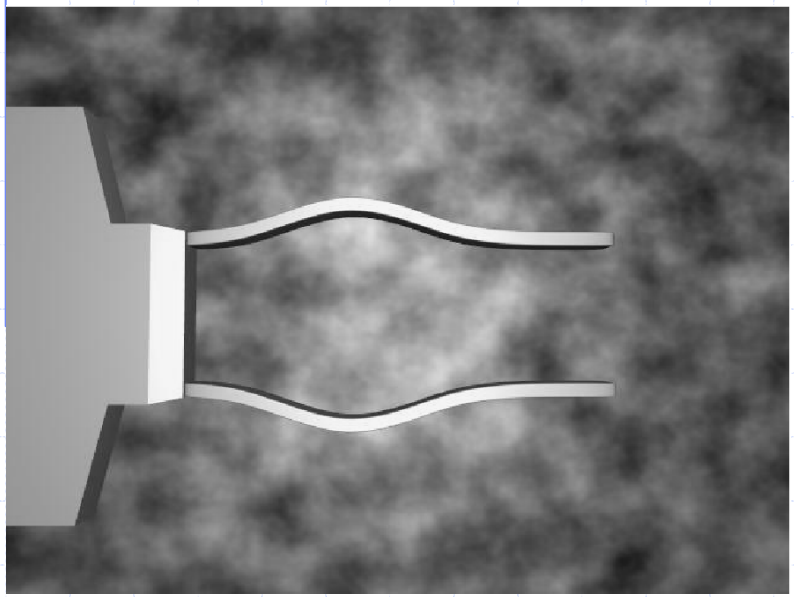


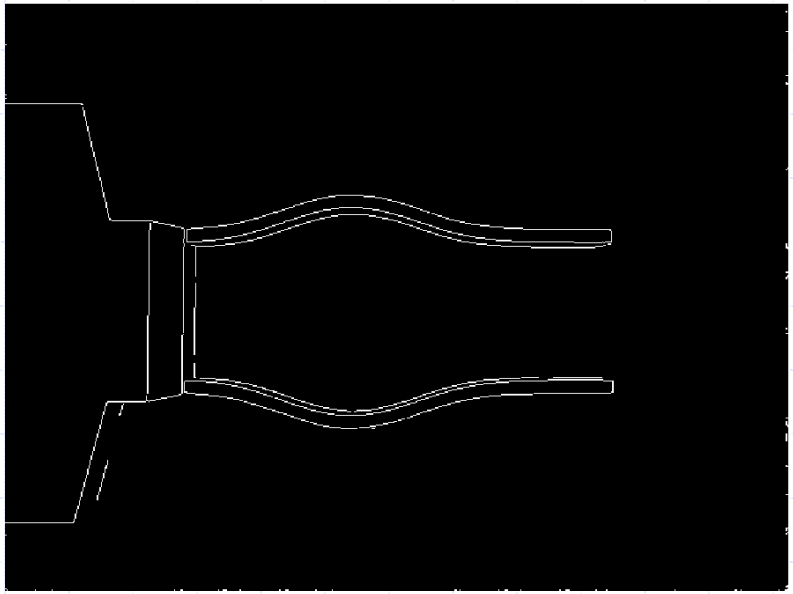
The Deformable Template Matching Approach Used

- Edge detection applied to source image using the Canny edge operator
- Template deformed according to a chosen model
- Error measured between images edges and template using least squares error measure
- Error function minimized using numerical optimization

Image Processing: Edge Detection

The canny edge detector





- Reduces amount of data to process while preserving boundary displacements

Image Processing: Template Matching

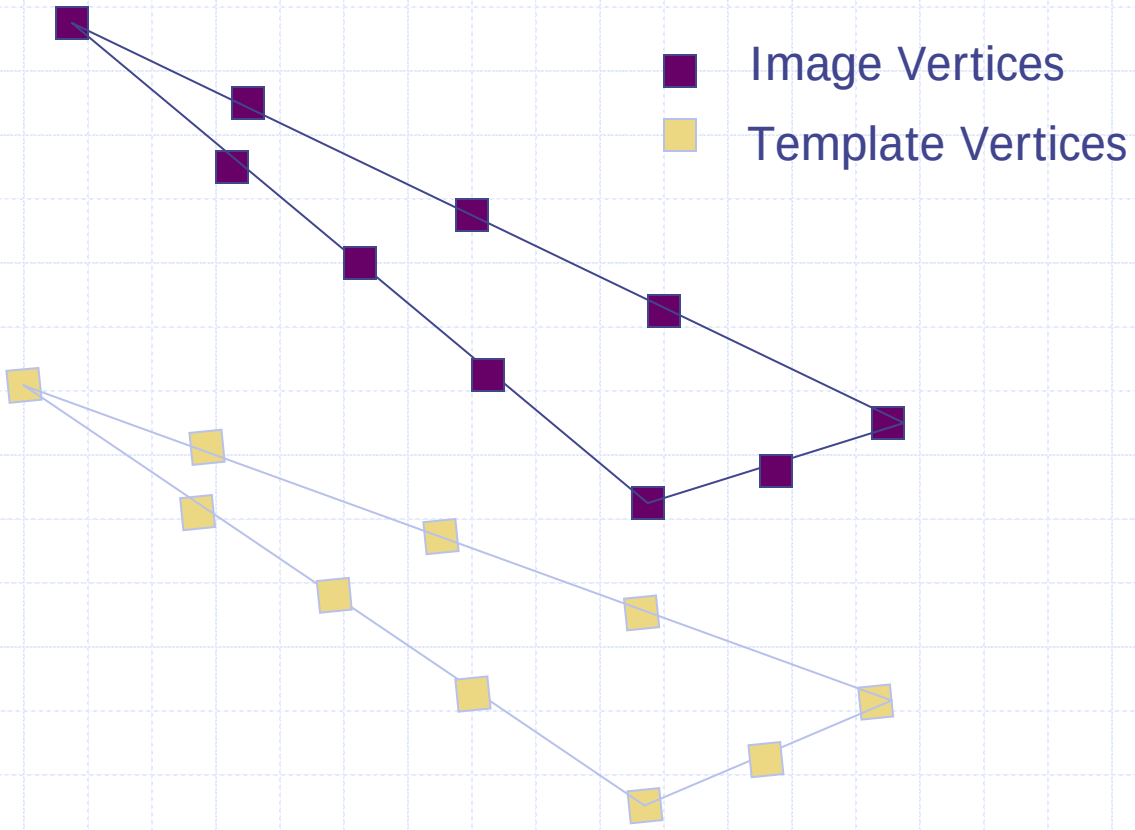
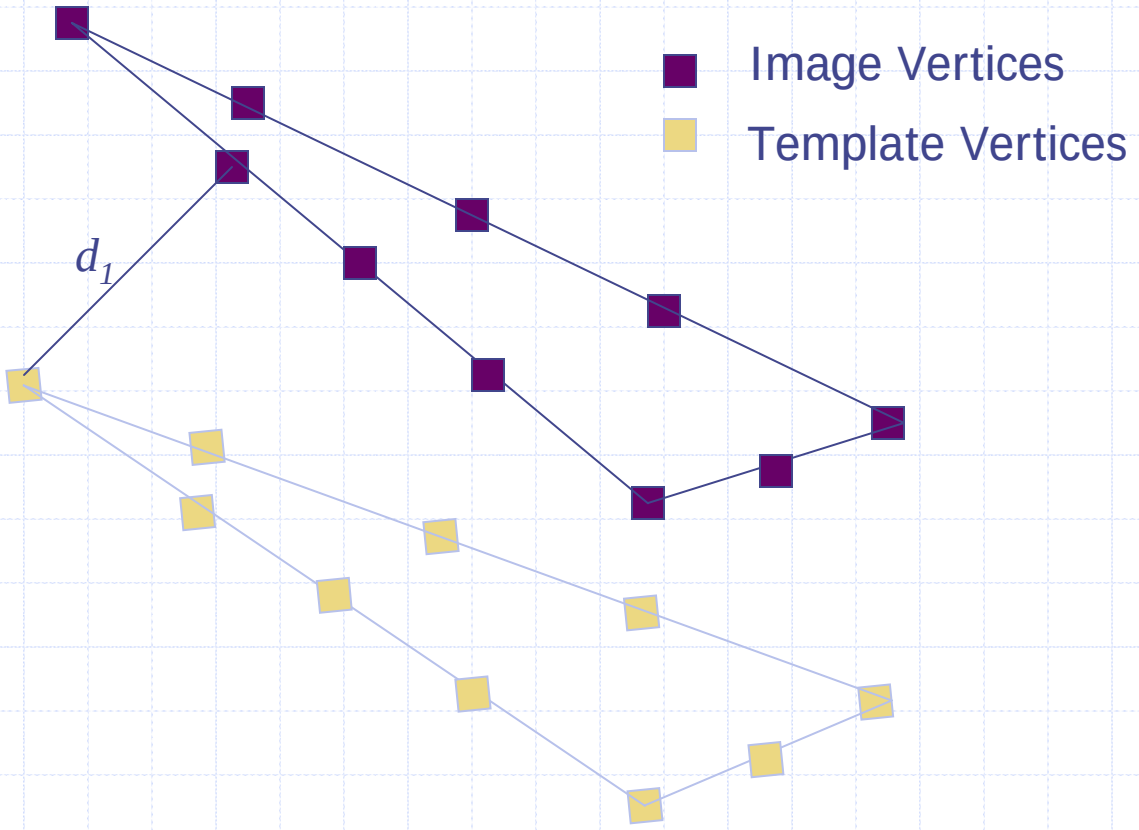
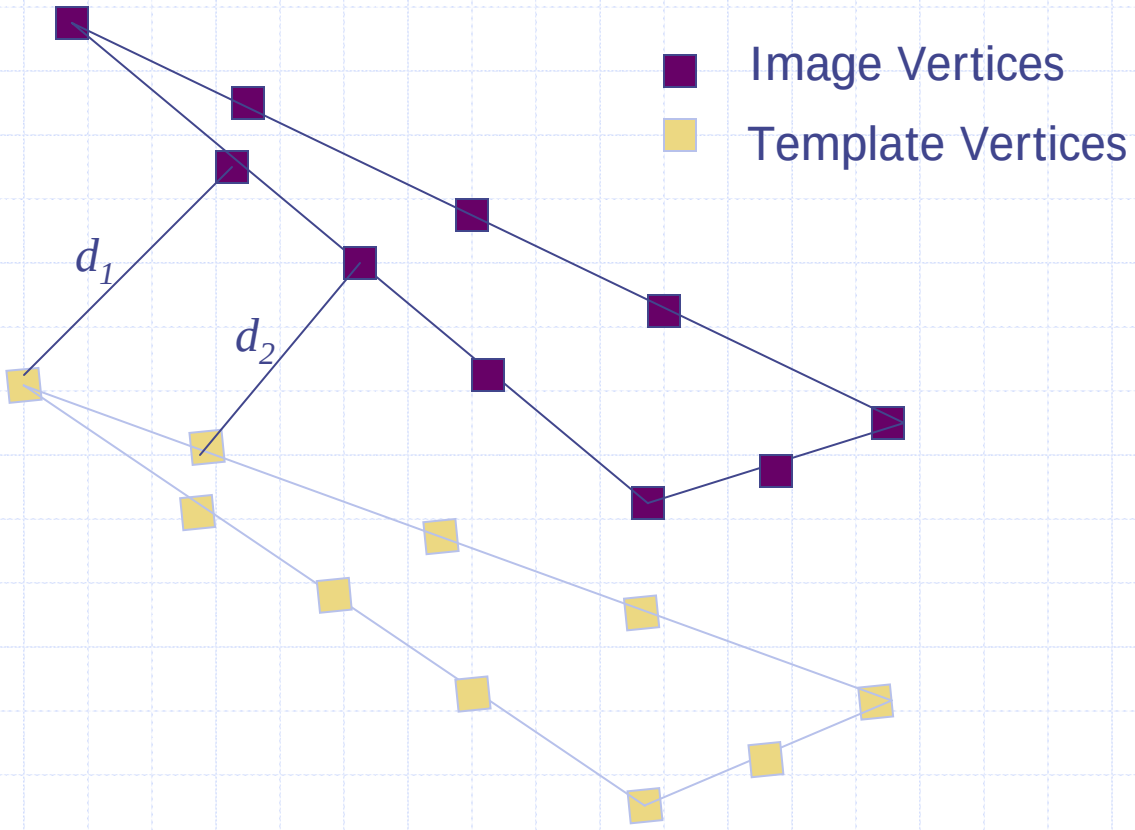


Image Processing: Template Matching



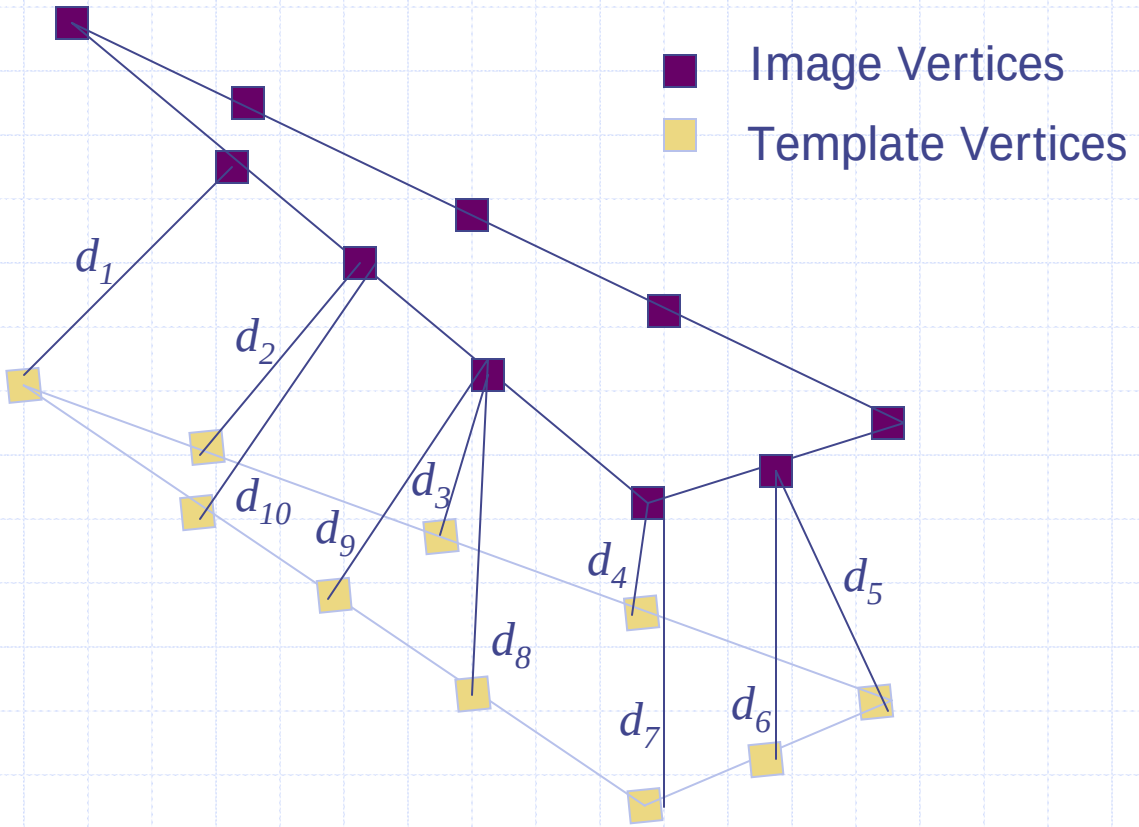
$$E = d_1^2 + \ldots$$

Image Processing: Template Matching



$$E = d_1^2 + d_2^2 + \ldots$$

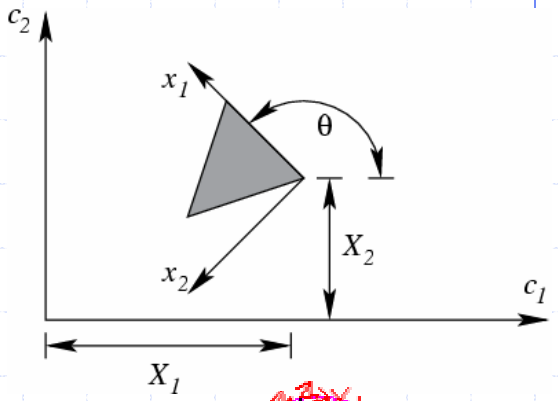
Image Processing: Template Matching

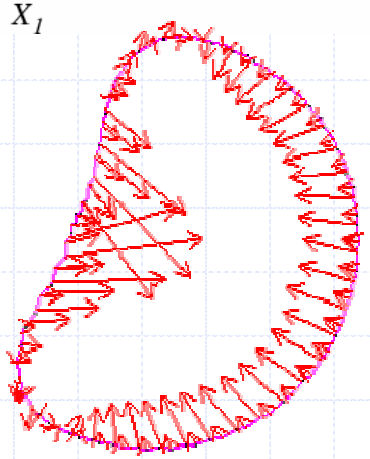


$$E = d_1^2 + d_2^2 + d_3^2 + d_4^2 + d_5^2 + d_6^2 + d_7^2 + d_8^2 + d_9^2 + d_{10}^2$$

Template Degrees of Freedom

- Rigid Body Motion Degrees of Freedom
  - Translation: X_1 and X_2
  - Rotation: θ
- Deformation Degrees of Freedom
  - Force distribution vector applied to template: $\{f\}$
  - Can be modeled using BEM, FEM, analytical solutions, or neural networks





$$E_{image}(X_1, X_2, \theta, \{f\}) = \sum_{i=1}^{M} \left\| \text{TemplatePixel}(X_1, X_2, \theta, \{f\}) - \text{NearestImagePixel} \right\|^2$$

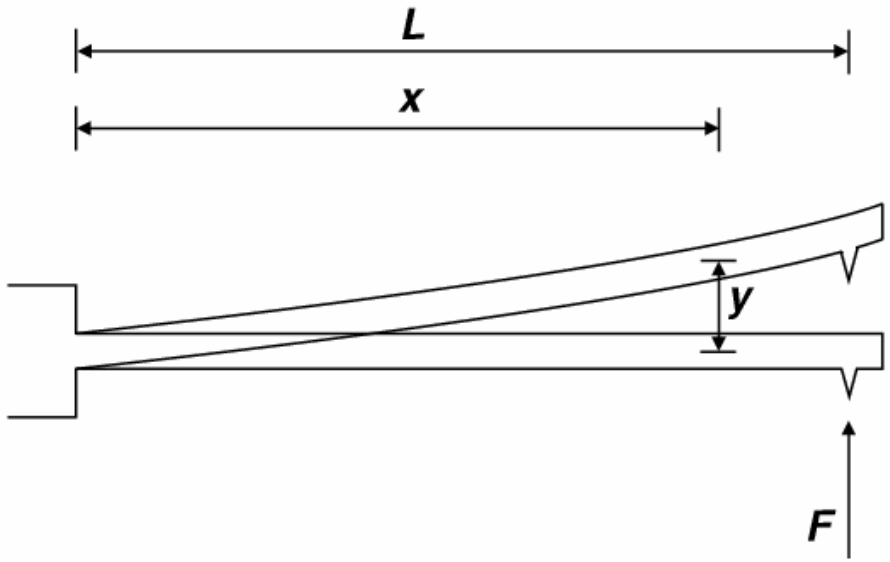
Deflections Models Used

- Material model is needed to deform the template
- Material models used:
  - Analytical material model: the beam equation
  - Numerical Material Model: FEM, BEM
  - Model learned from observing object: neural network elastic model

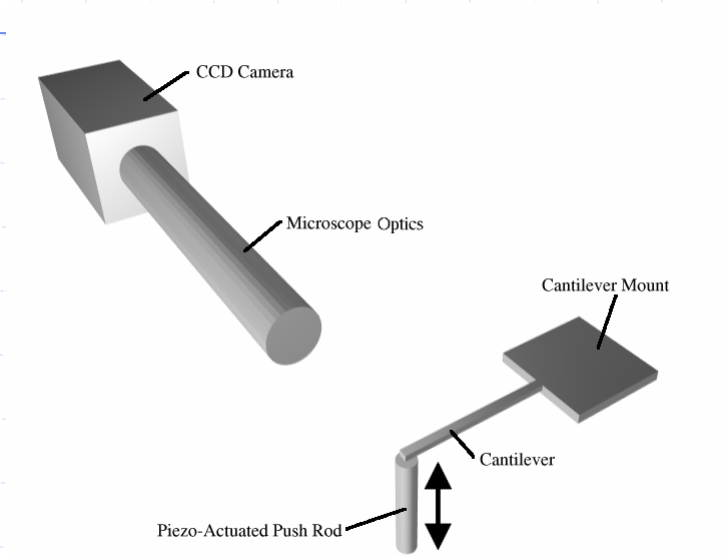
Deflection Models: Analytical Material Model

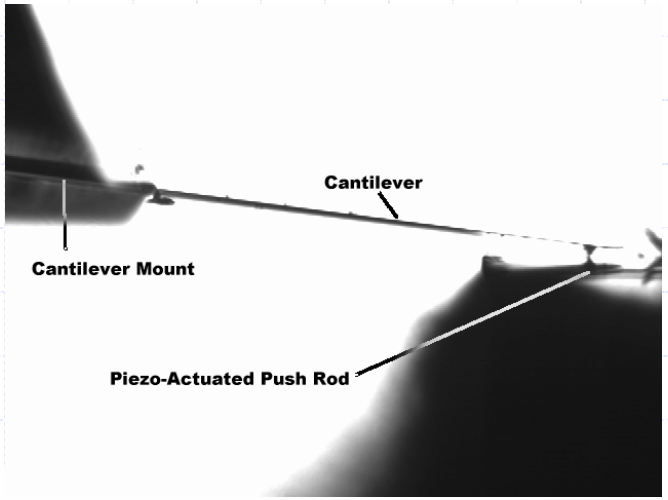
The beam equation:

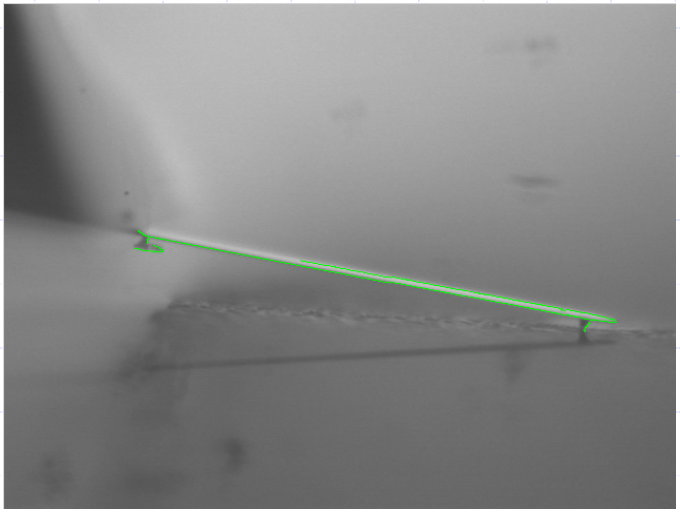
$$y = \frac{Fx^2}{6EI}(3L - x)$$

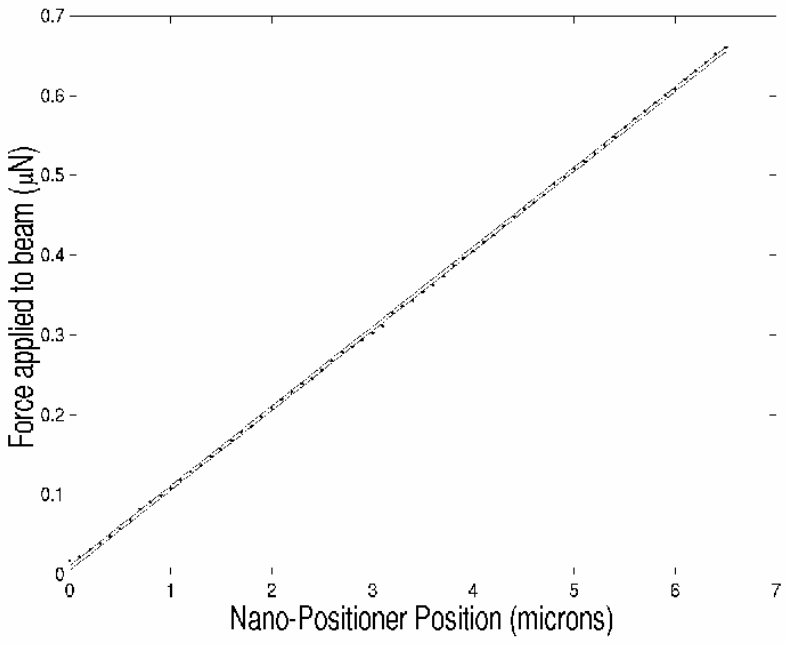


Vision-Based Force Measurement with a Cantilever Beam

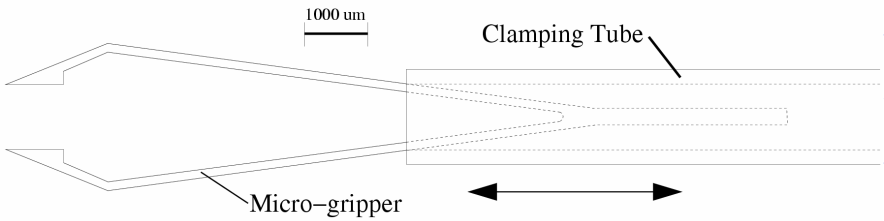


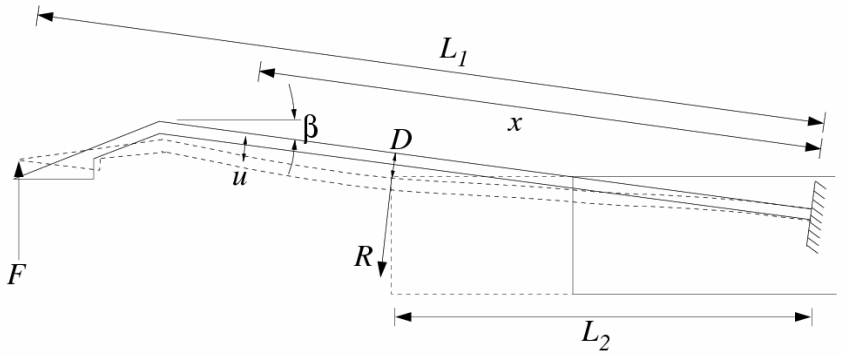


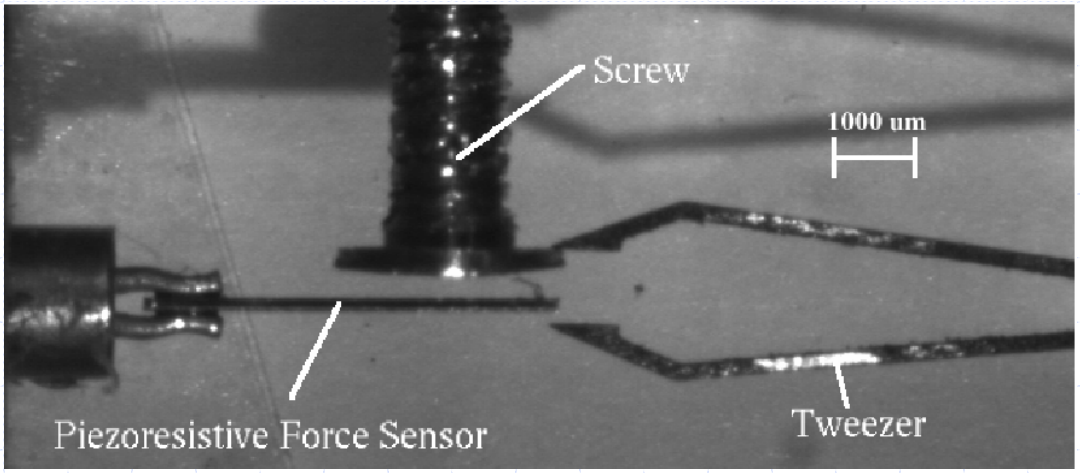


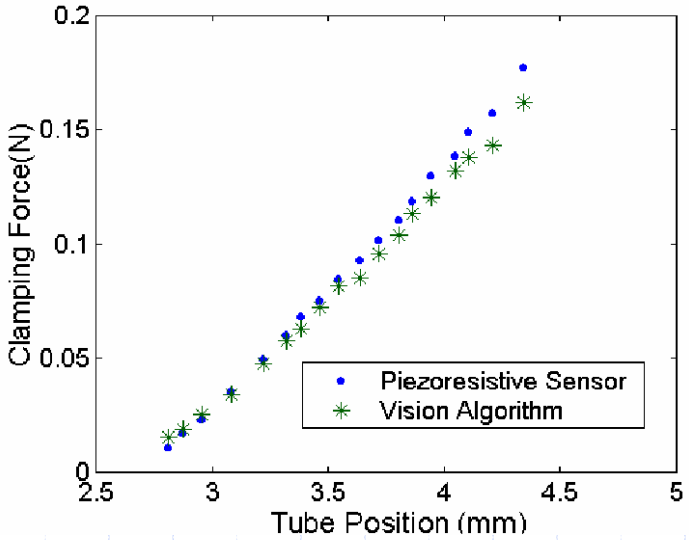


Vision-Based Force Measurement with a Microgripper



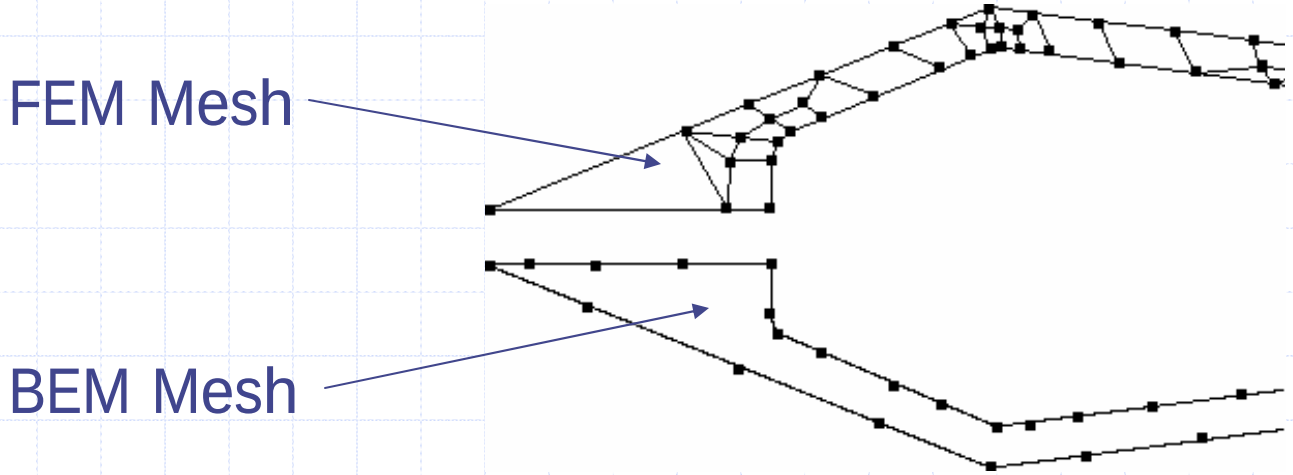






Deflection Models: Boundary Element Method

- Will use the Boundary Element Method (BEM) to model the deformation of the material
- BEM is a method to solve the equations of elasticity
- Similar to finite element method (FEM) FEM but only requires boundary of object to be partitioned

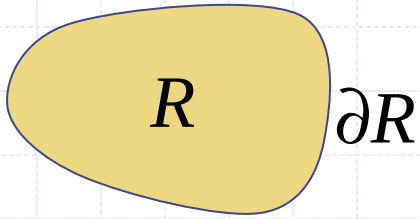


The Boundary Integral Equation for the Elasticity Problem

- Boundary integral equation

$$c_{ij}u_j(p) = \int_{\partial R} \left[U_{ij}(p,q)t_j(q) - T_{ij}(p,q)u_j(q) \right] \mathrm{d}\partial R(q)$$

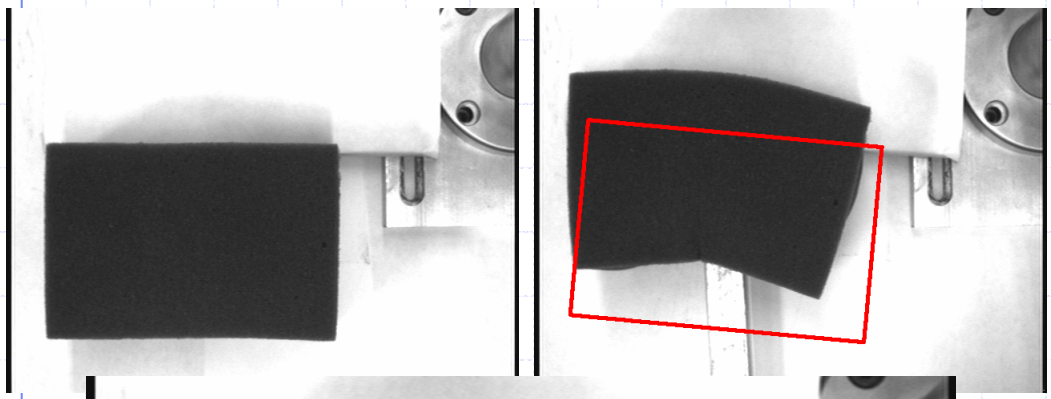
$$\forall p \in \partial R$$

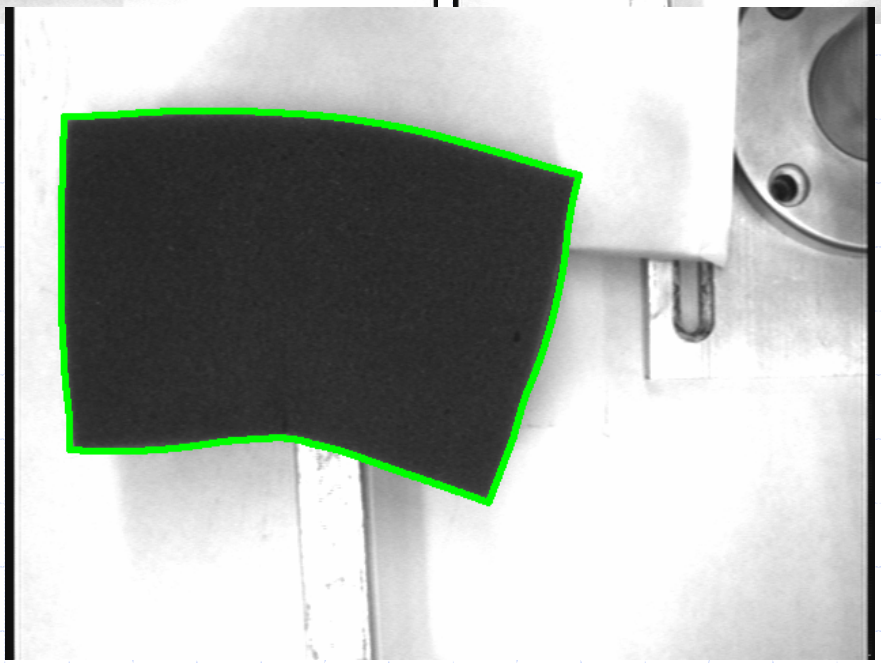


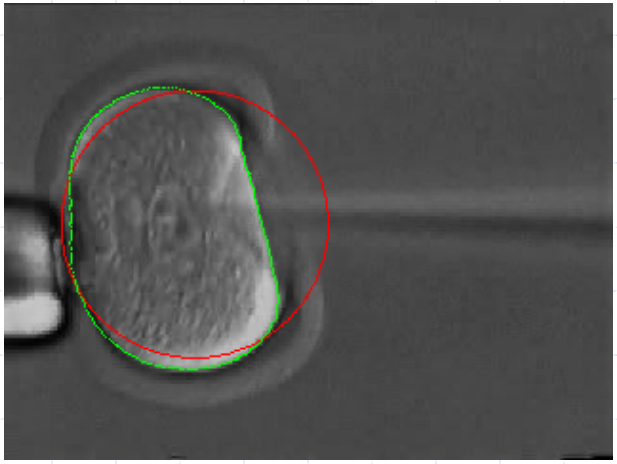
- Boundary integral equation in matrix form

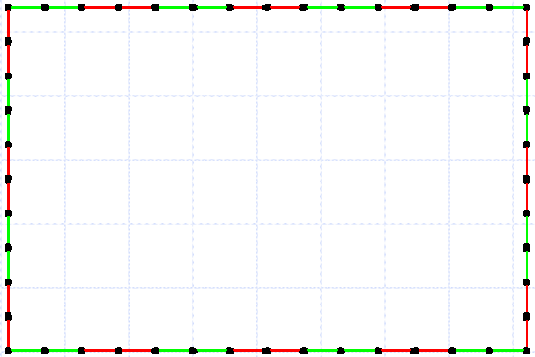
$$[F']\{u\} = [G]\{t\}$$

Examples of BEM Deformable Object Tracking

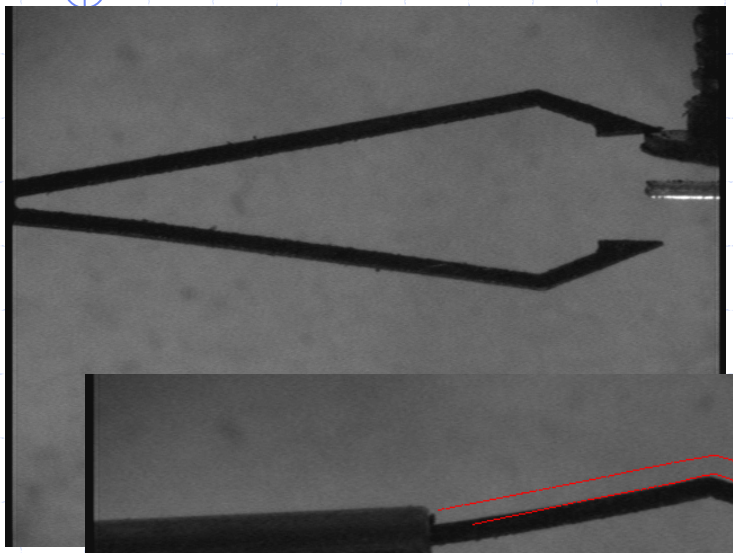


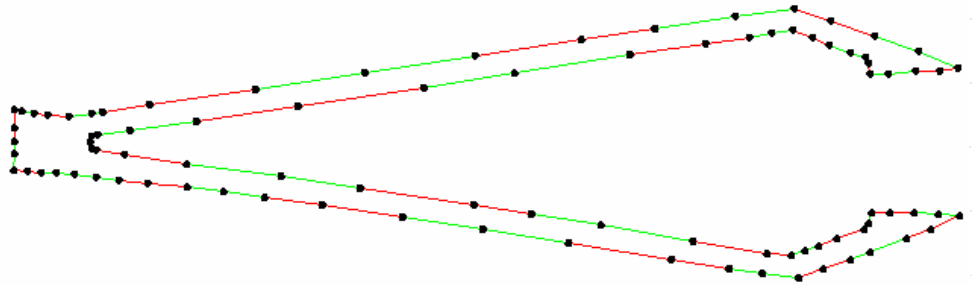


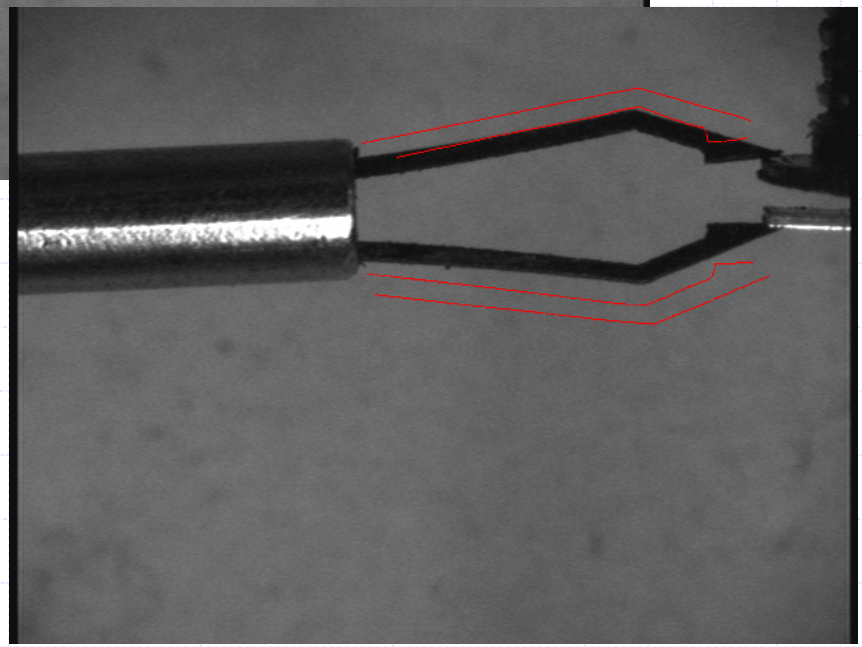


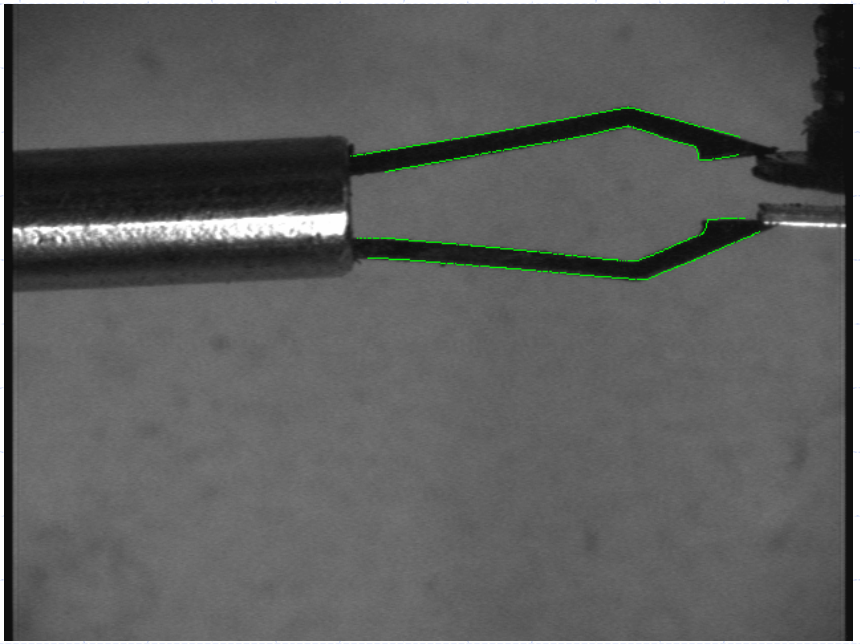


BEM Template Matching Results - Microgripper

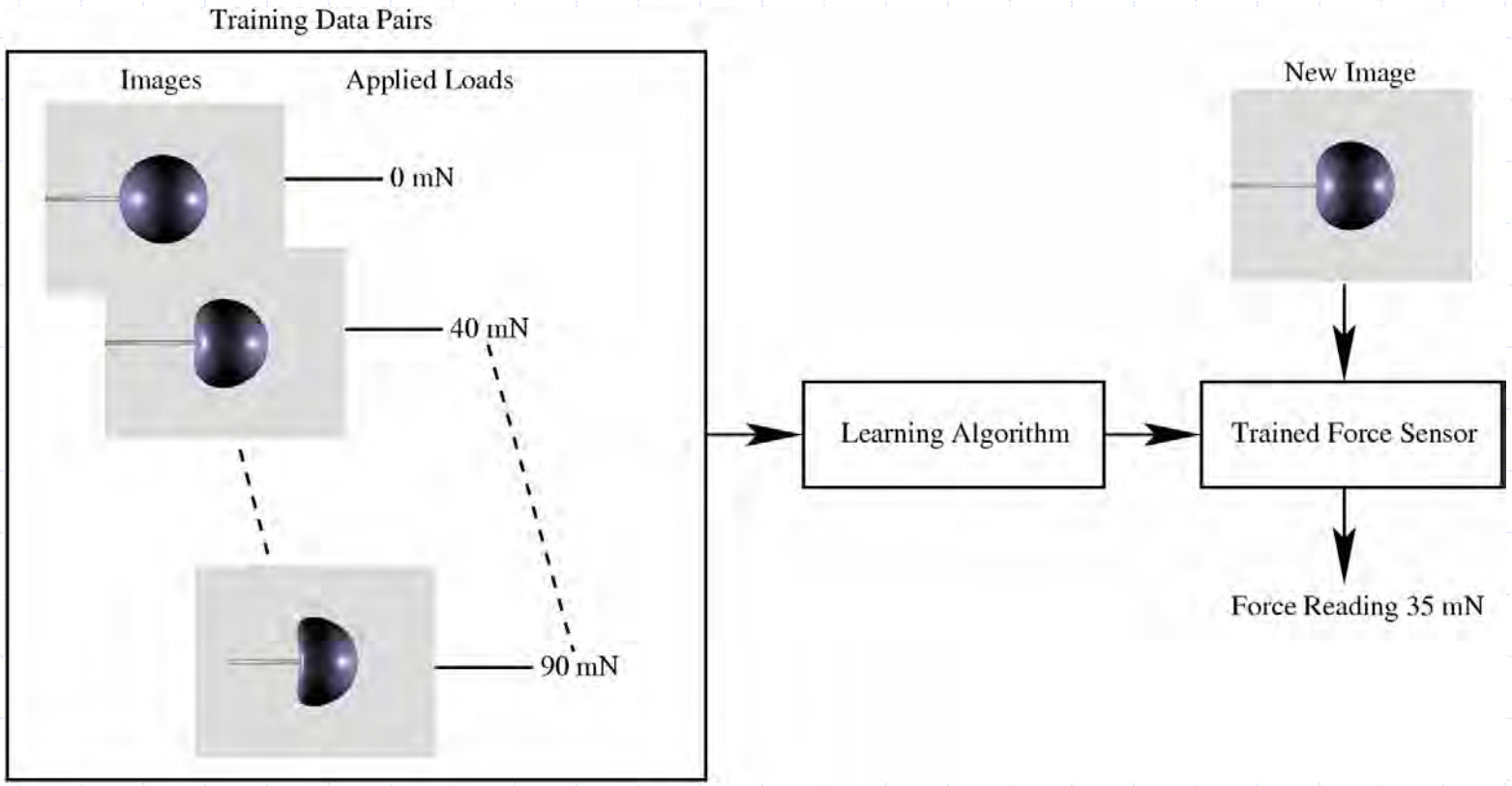




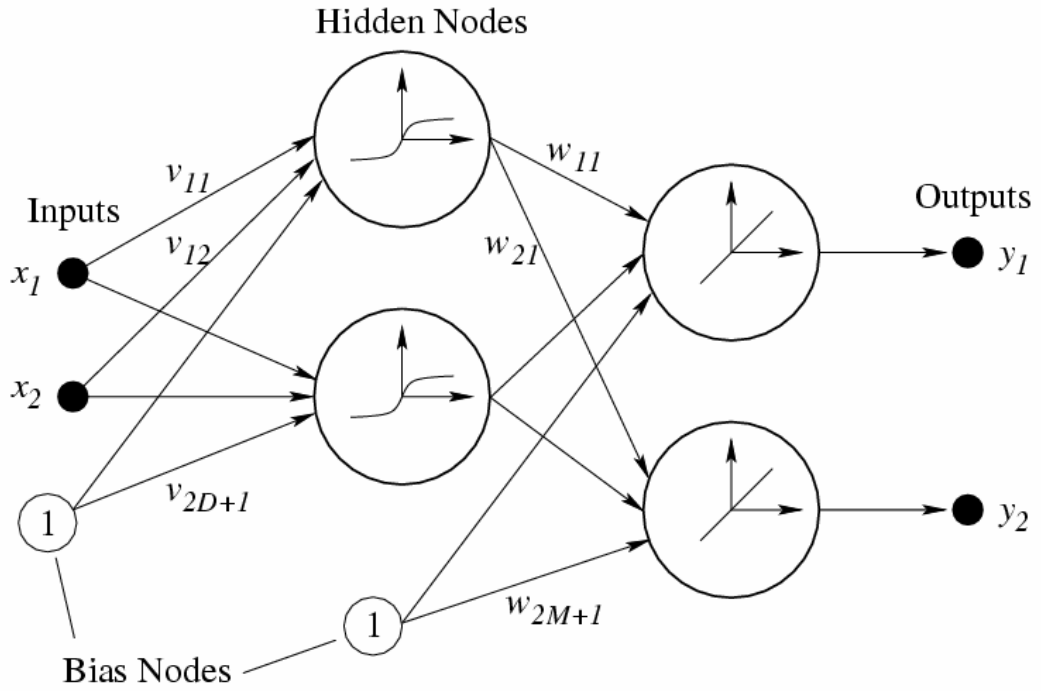




Deflection Models: Neural Network Deflection Model

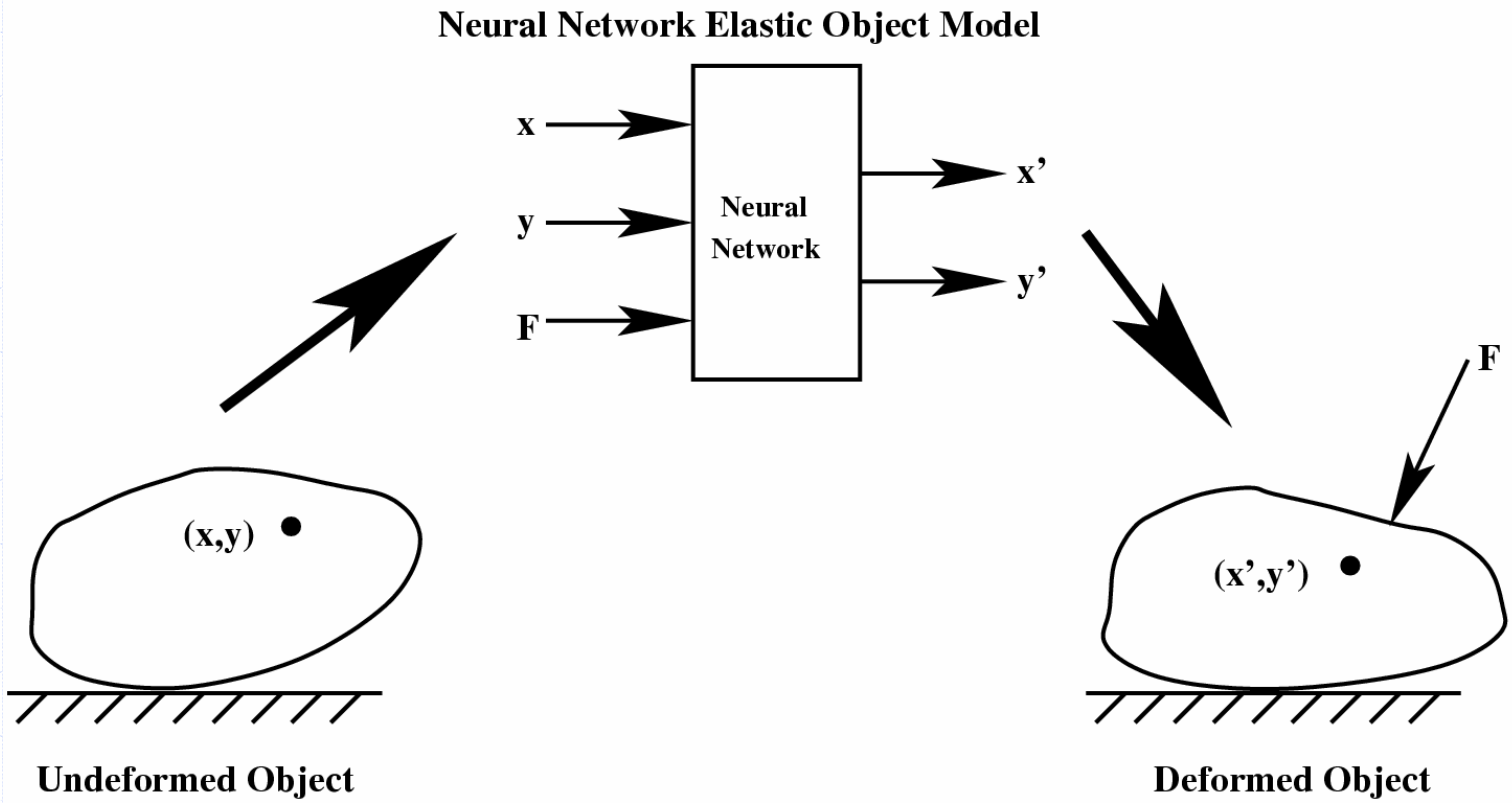


The Neural Network Structure

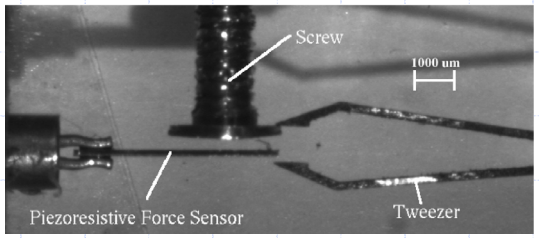


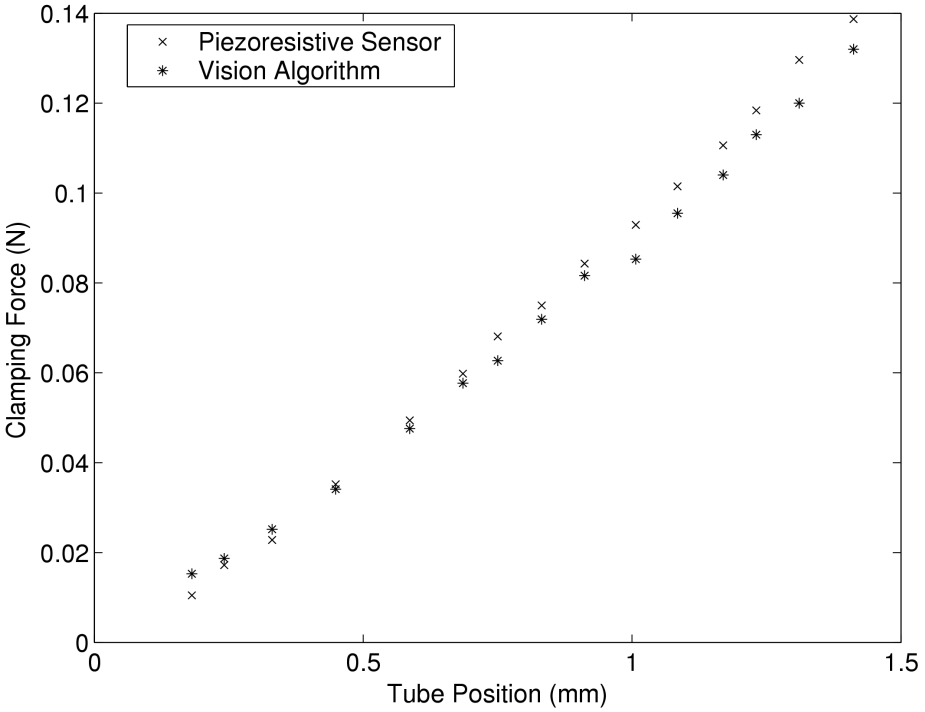
$$y_i = w_{iM+1} + \sum_{j=1}^{P} \left[g\left(v_{jD+1} + \sum_{k=1}^{D} [v_{jk} x_k] \right) w_{ij} \right]$$

The Neural Network Elastic Material Model

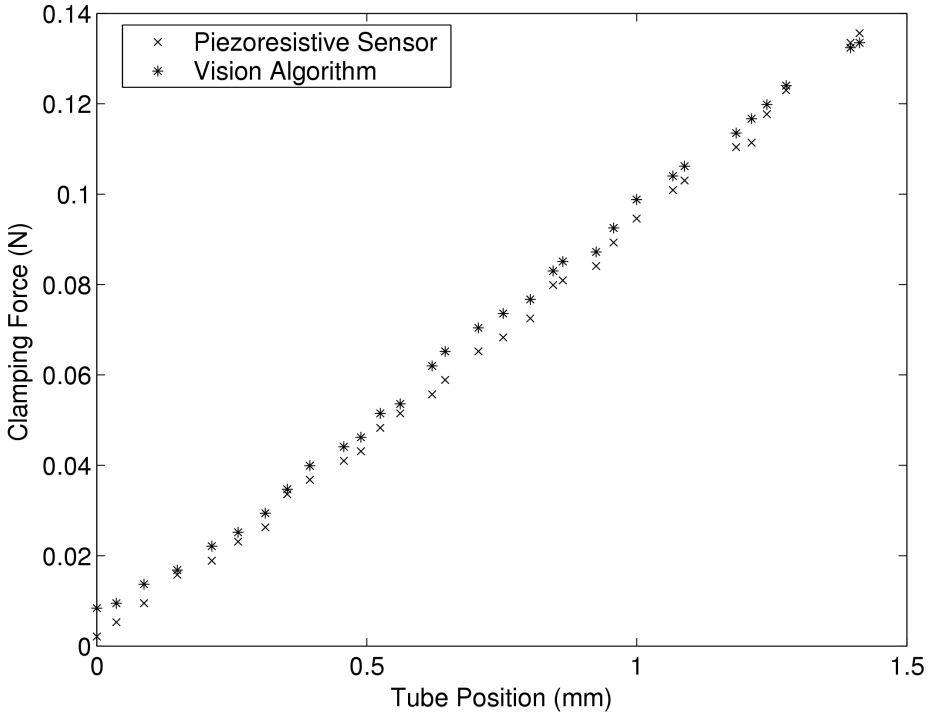


Microgripper Results Using Neural Net



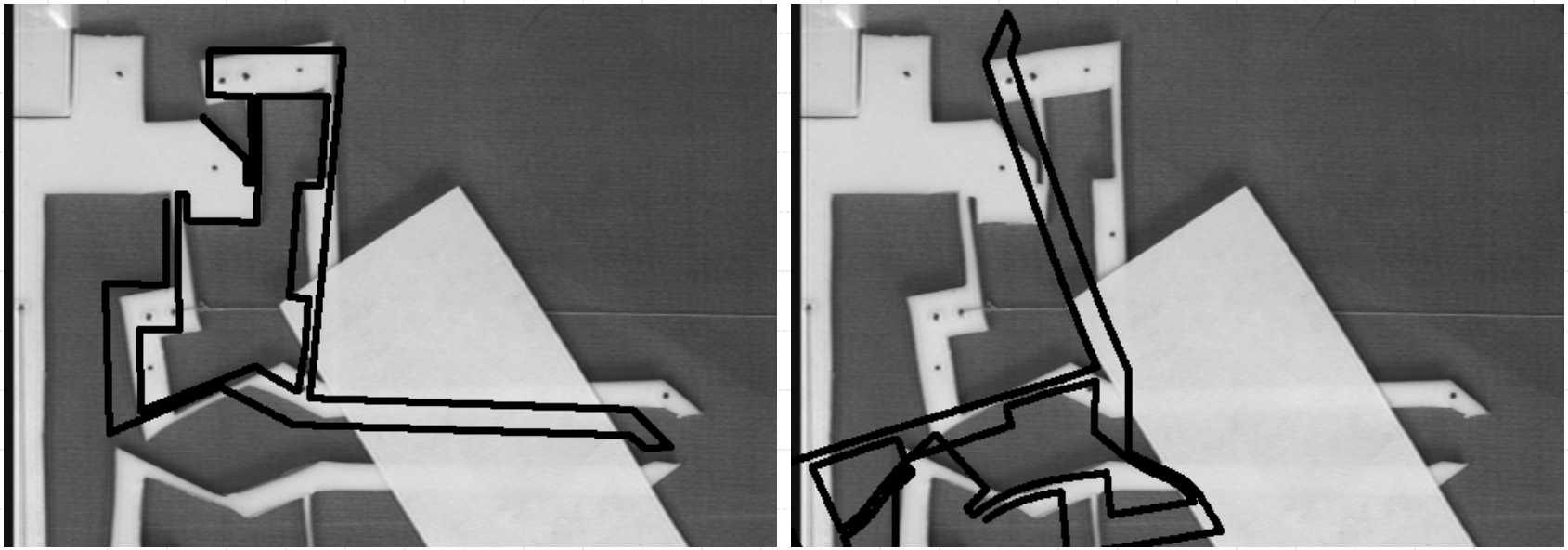


Cantilever beam model based VBFM results for microgripper showing an average error of 6.0 mN.



Neural network model based VBFM results for microgripper showing an average error of 3.4 mN.

The Problem of Occlusion



Solving the Occlusion Problem

- The object of interest is often occluded in the image
  - The tracking algorithm must use the parts of the object that are visible to complete the tracking task
  - Robust statistics will be used

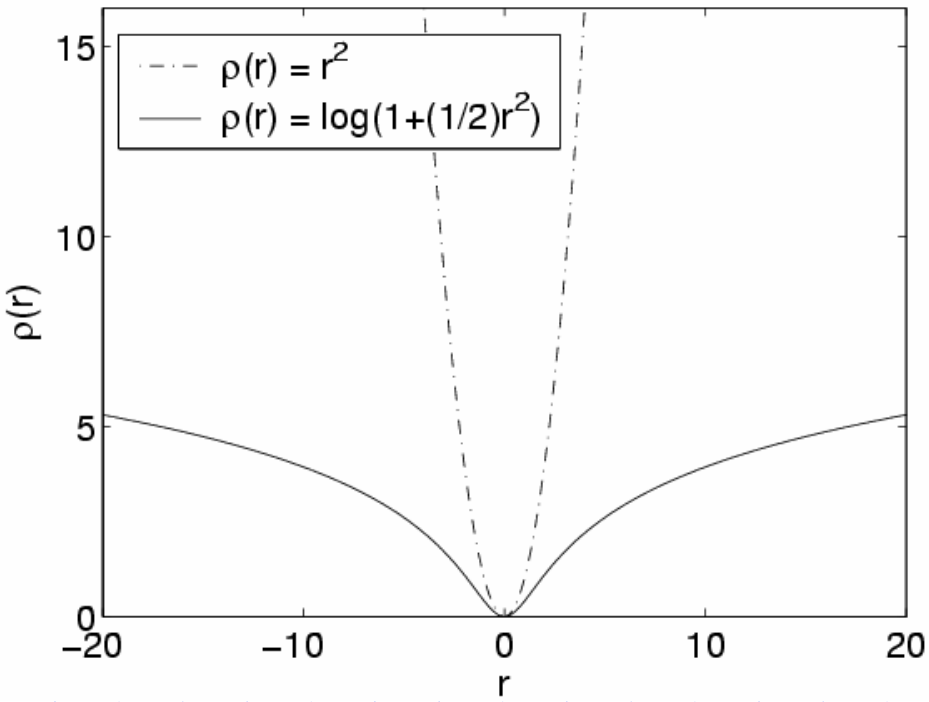
Robust Error Measures

Least squares error measure:

$$\rho(r) = r^2$$

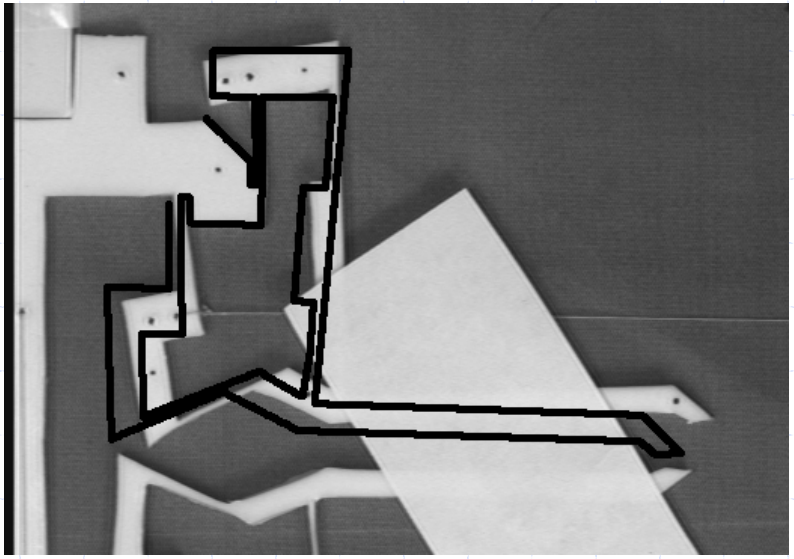
Cauchy error measure:

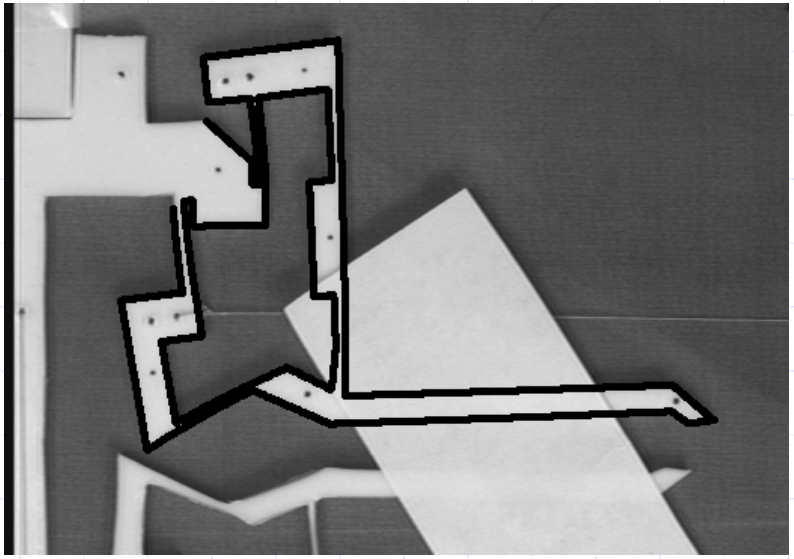
$$\rho(r) = \log\left(1 + \frac{1}{2}r^2\right)$$



Occlusion: Tracking Results

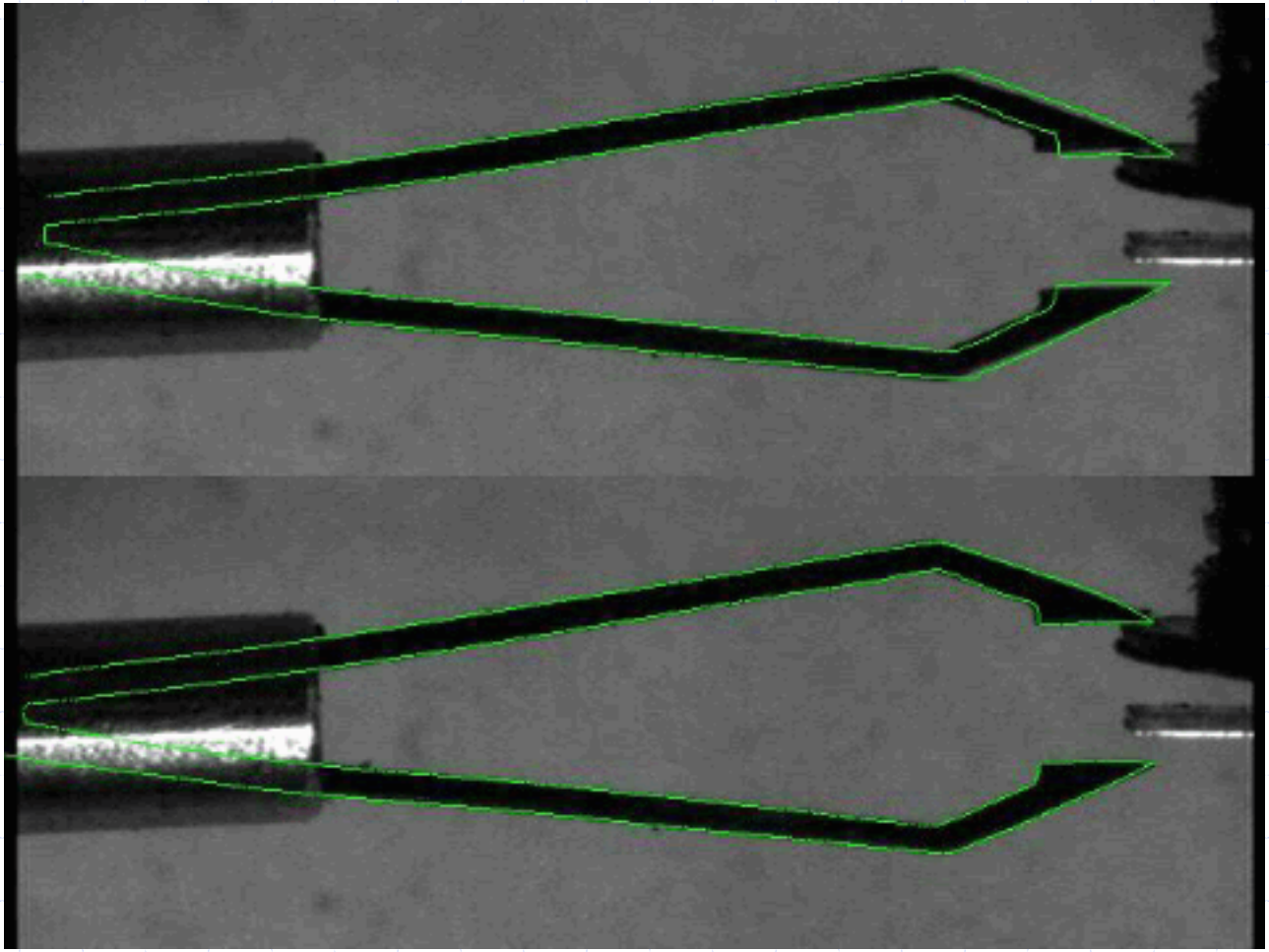
Tracking result using robust error measure





Occlusion: Tracking Video

Tracking a micro gripper with occlusion



Potential Applications: Cardiac Tracking

- MRI image slice of beating heart

Conclusions

- Computer vision can be used to provide high precision force and position feedback for microscale systems
- Vision-based deformable object tracking can provide displacement measurements where it would not otherwise be possible
- A variety of material models can be used including models learned from the object being deformed
- The tracking algorithm can be modified to be robust to occlusion

Thanks!

- Department of Energy
- Krell Institute

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