Sabancı Üniversitesi

MICROMANIPULATION USING VISION and FORCE FEEDBACK

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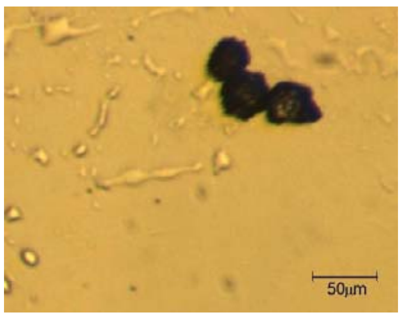
Dedicated to Bill Wolovich

Micromanipulation

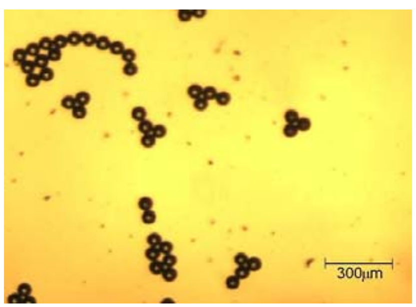
- Manipulation of objects at
  - microscale
  - mesoscale

  with micron/submicron tolerances

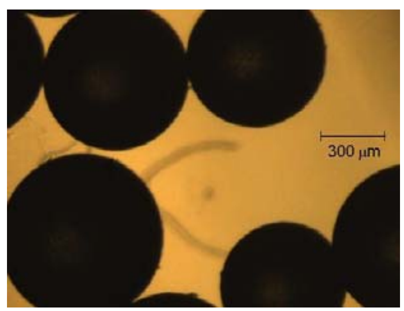


Pollens (~ 40μm)

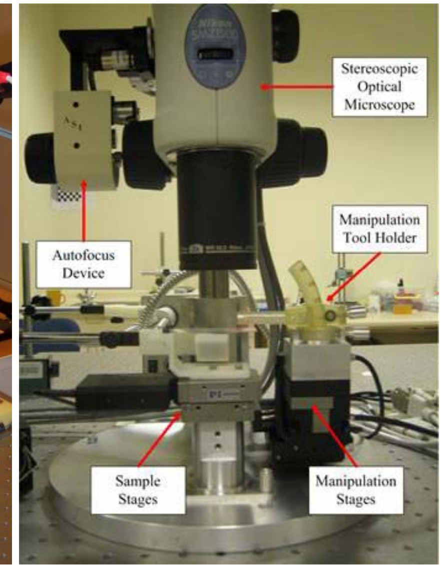
Glass Particle (~ 90μm)

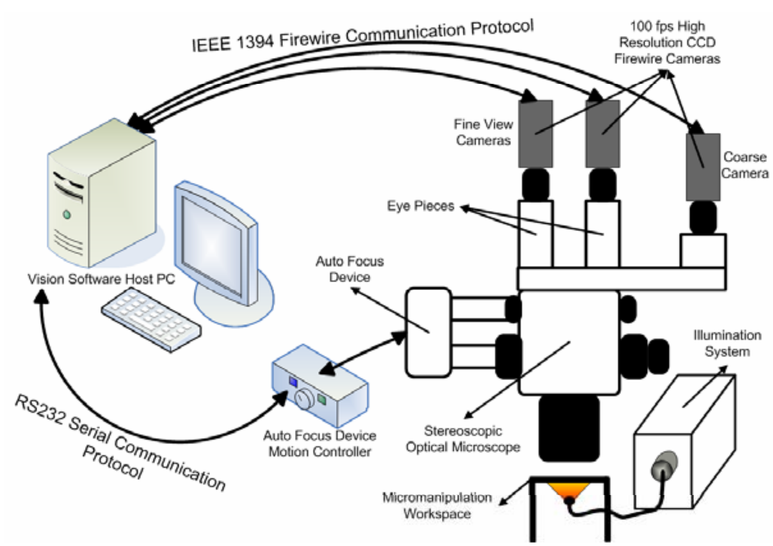


Polymer Balls (~ 65 μm)



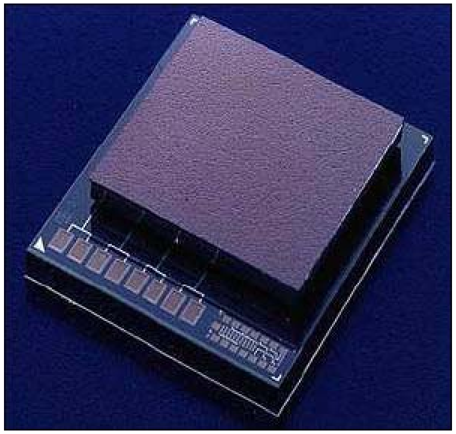
Polystyrene Balls (~ 450 μm)

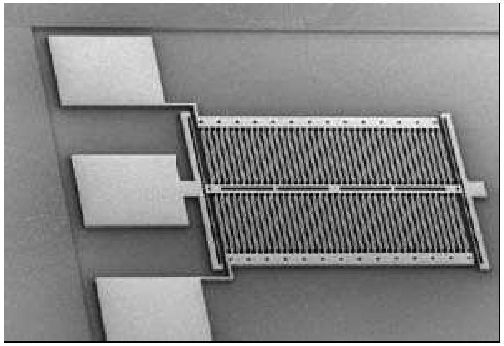




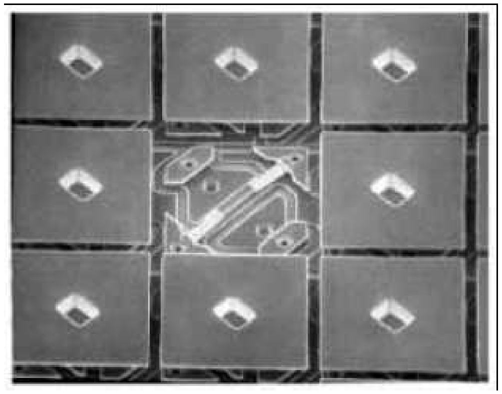
Relative accuracy of 1 - 5% → **0.5 – 2.5 μm**

Micro Devices

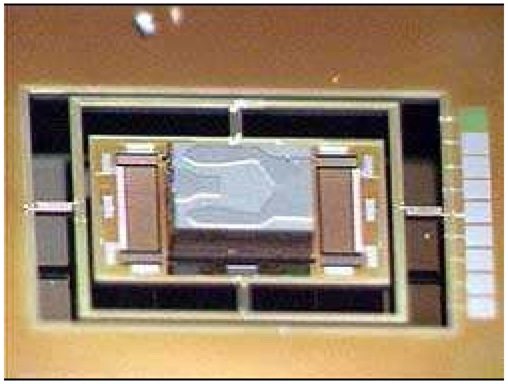




Low-g Accelerometer



Digital Micromirror Device

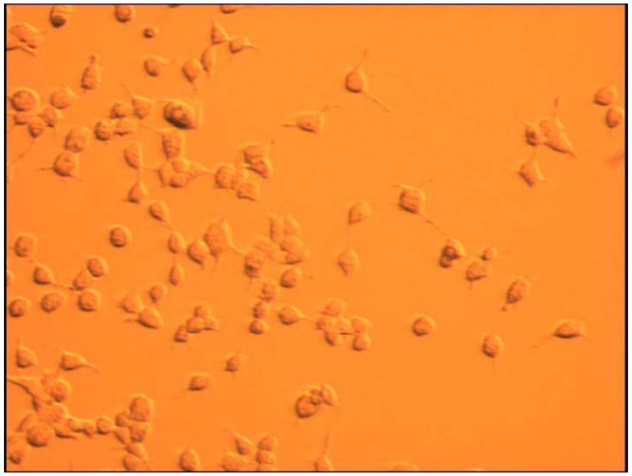


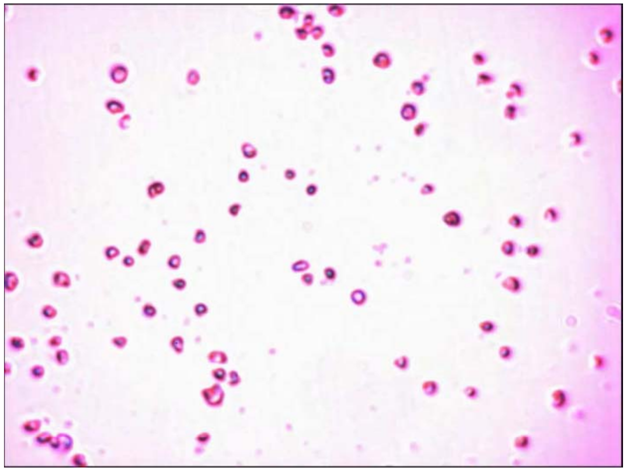
Hard Drive's Read/Write Head

Life Sciences and Medical Applications

Automated Tracking of Cell Populations

- measurements of a range of cell behaviors
    - *migration* (translocation),
    - *mitosis*(division),
    - *apoptosis*(death),
    - *lineage* (parent-daughter relations, e.g. Yeast model of ageing)
- valuable in medical research: genomics, proteomics, stem cell biology, and tissue engineering



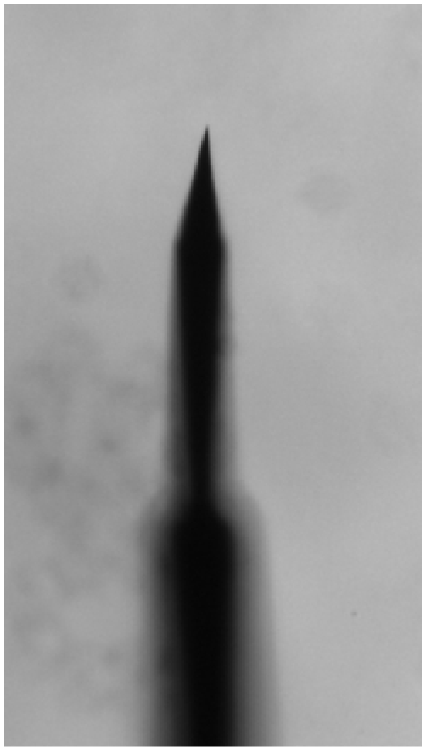


293T Human Kidney Cells and Jurkat Cancer Cells

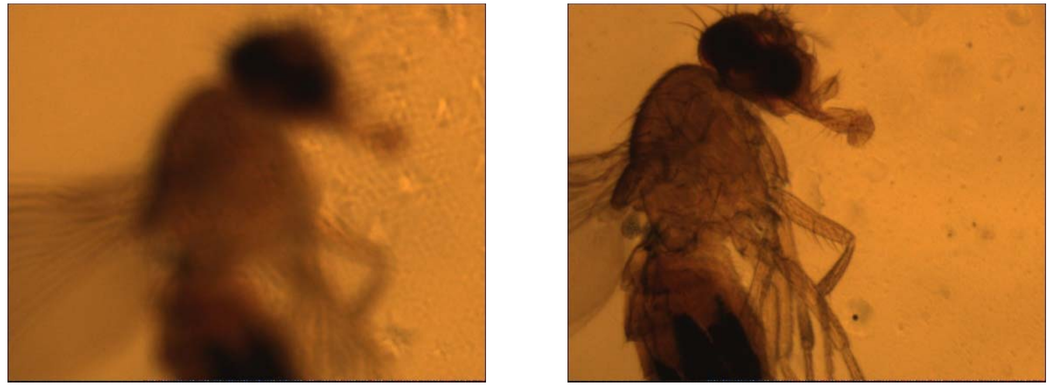
Challenges

- Autofocusing
- Calibration of the Optical System
- Robust Feature Extraction and Real-Time Tracking
- Robust Visual Servoing Algorithms
- 3D Reconstruction
- Force Estimation Using Image Data for Teleoperations

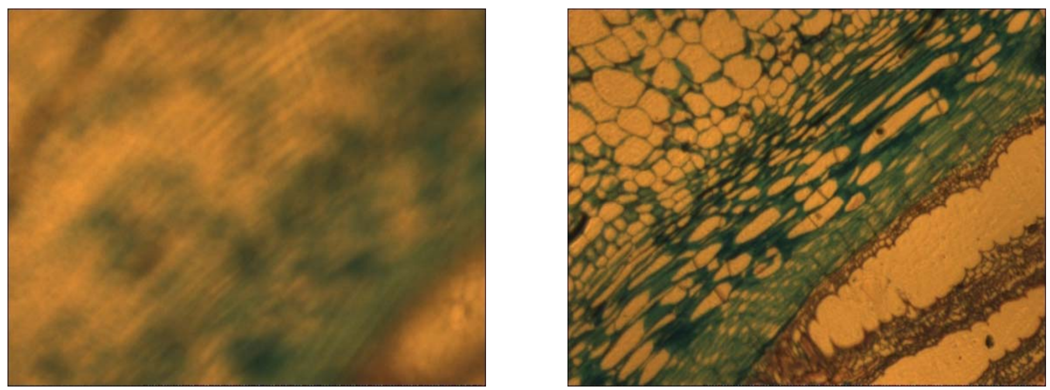
Autofocusing



Probe

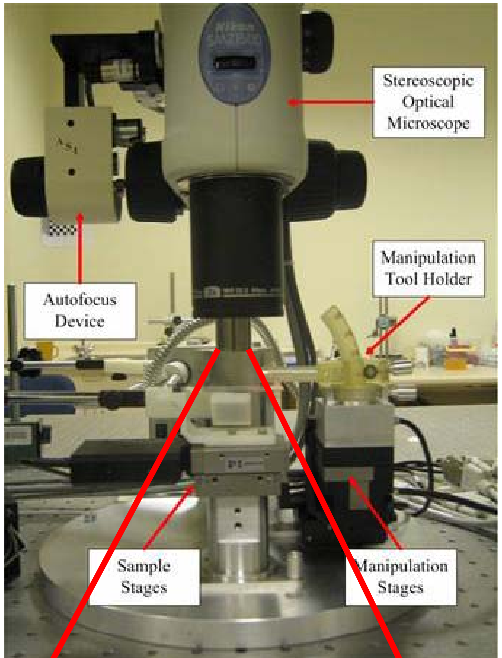


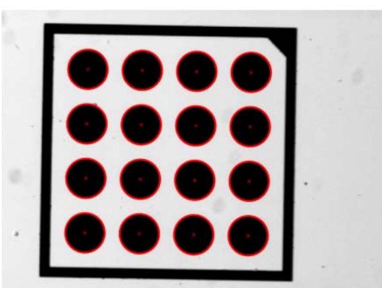
Defocused and Focused Images of Drosophila



Defocused and Focused Images of Pumpkin Cells

Optical System Calibration





Parameters

Objective focal length, Tube Length, Magnification etc.

Projection Model

$$u(1+k_1 r^2) = (T_{op} + f)\frac{r_{11}X_g + r_{12}Y_g + r_{13}Z_g + T_x}{r_{31}X_g + r_{32}Y_g + r_{33}Z_g + T_z}$$

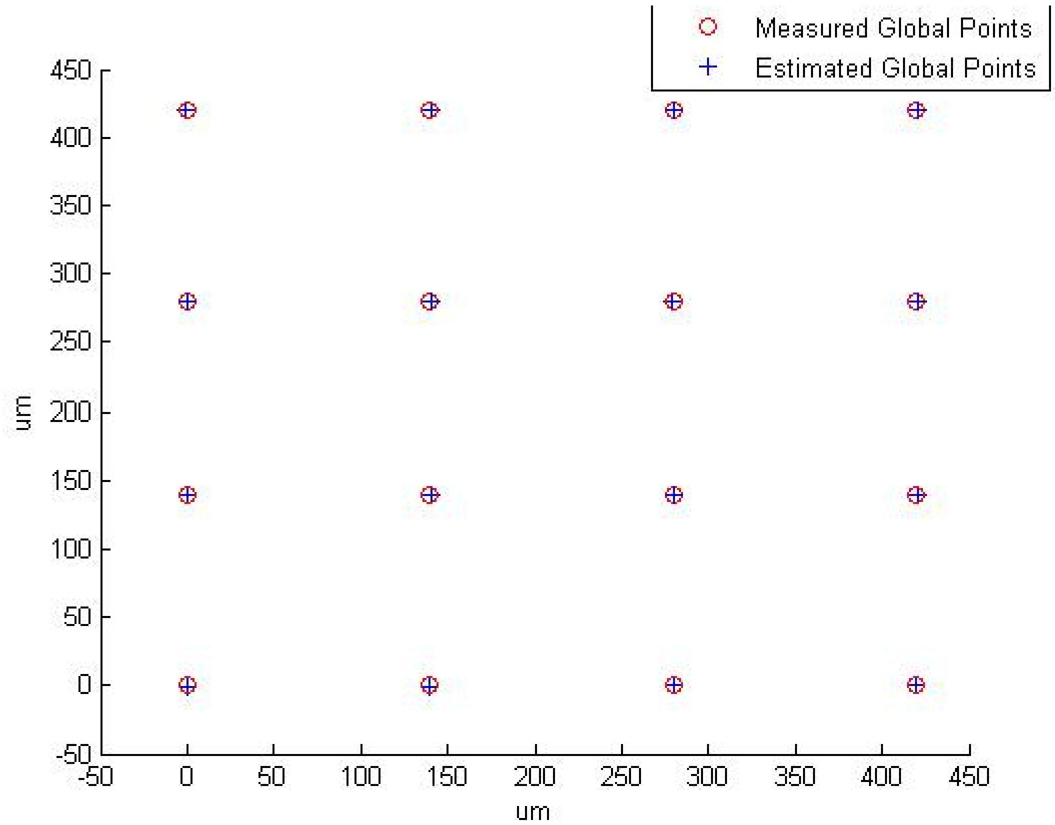
$$v(1+k_1 r^2) = (T_{op} + f)\frac{r_{21}X_g + r_{22}Y_g + r_{23}Z_g + T_y}{r_{31}X_g + r_{32}Y_g + r_{33}Z_g + T_z}$$

$$T_z \approx f + d$$

Nonlinear Optimization

ESTIMATED PARAMETERS

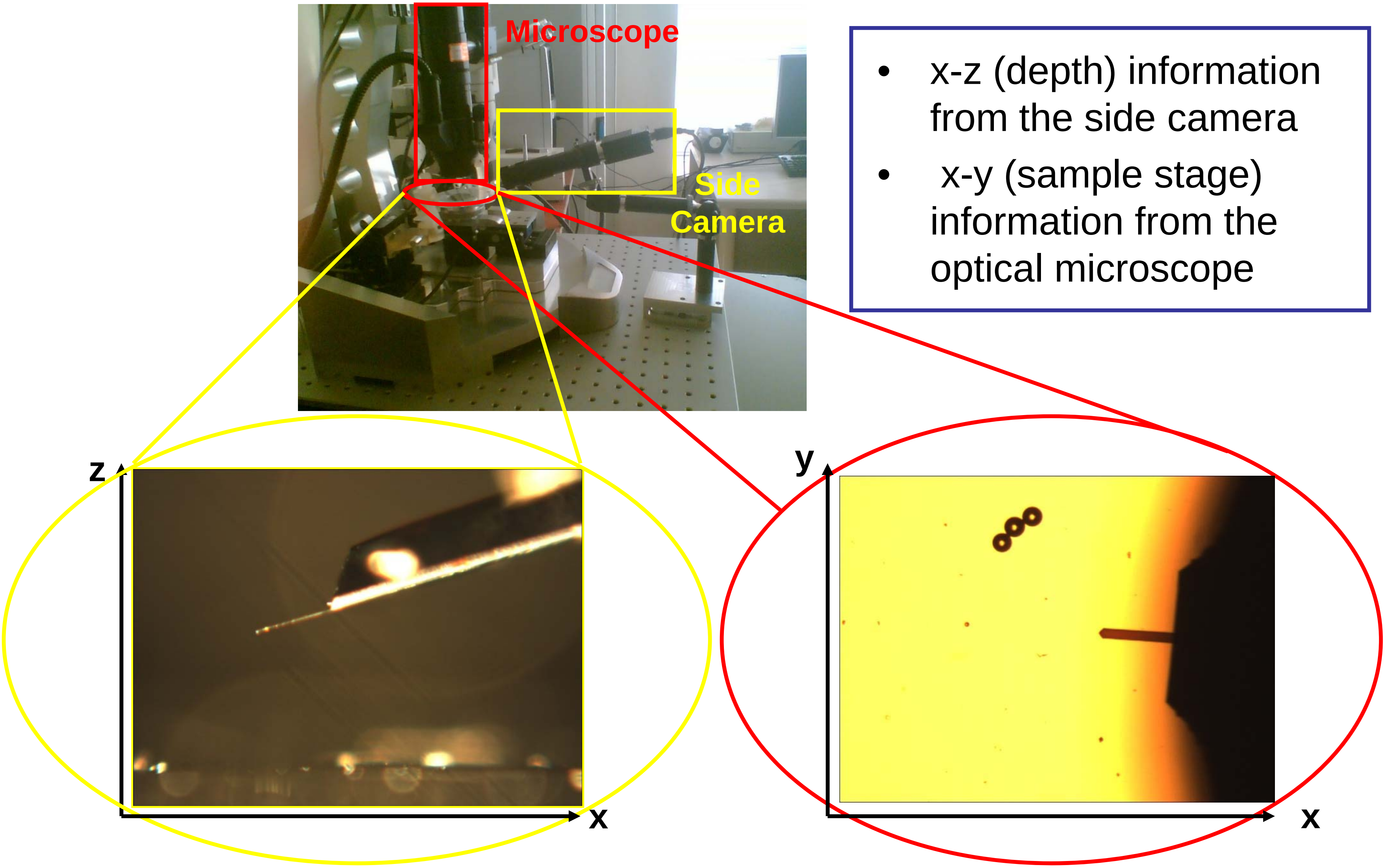
Reconstruction/Reprojection Errors



Reconstruction Errors

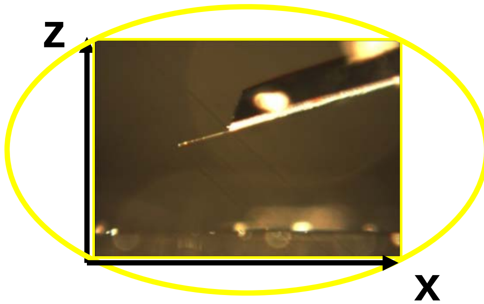
Magnification	1.6	6.4
Mean Error(µm)	0.220	0.063
Max Error (µm)	1.720	0.584

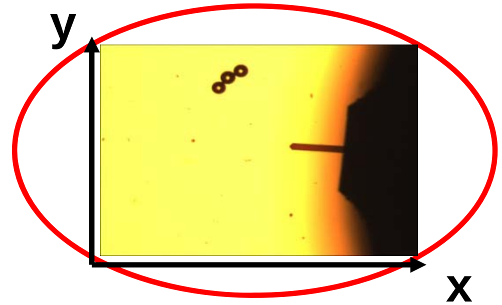
3D View by Side Camera

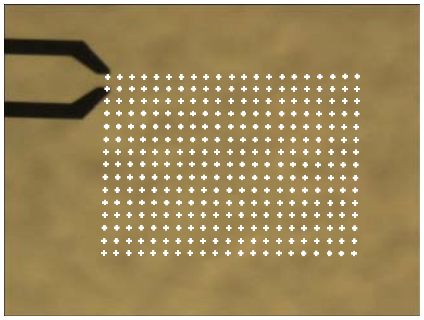


- x-z (depth) information from the side camera
- x-y (sample stage) information from the optical microscope

A Novel Online Calibration Technique







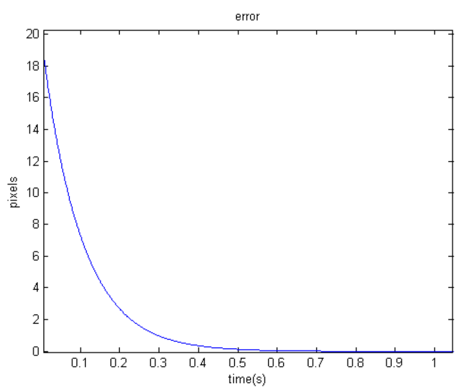
Virtual Pattern

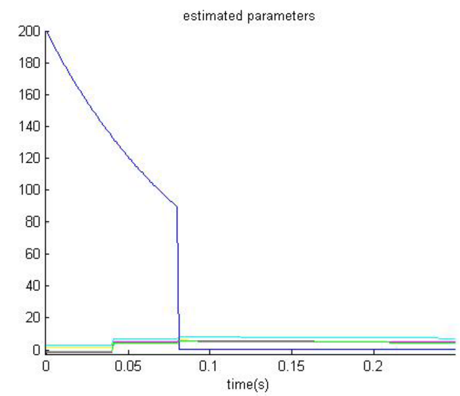
$$\begin{pmatrix} x_{im} \\ z_{im} \end{pmatrix} = \begin{pmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{pmatrix} \begin{pmatrix} x_w \\ z_w \end{pmatrix} + \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}$$

$$\begin{pmatrix} x_{im} \\ y_{im} \end{pmatrix} = \begin{pmatrix} k_{11} & k_{12} \\ k_{21} & k_{22} \end{pmatrix} \begin{pmatrix} x_w \\ y_w \end{pmatrix} + \begin{pmatrix} m_1 \\ m_2 \end{pmatrix}$$

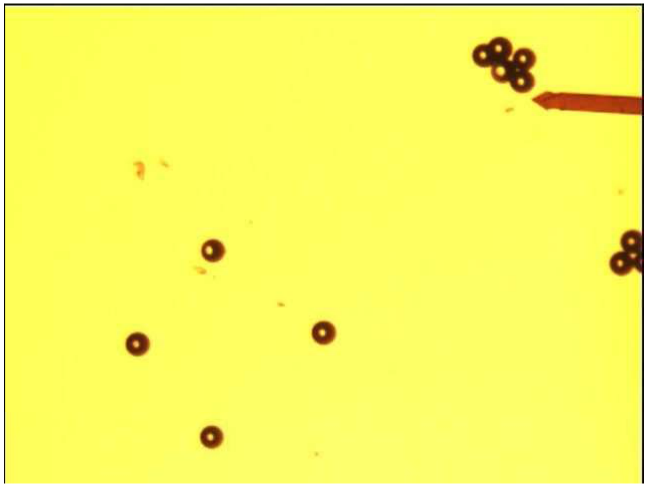
$$\begin{pmatrix} x_{im} \\ y_{im} \\ z_{im} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix} \begin{pmatrix} x_w \\ y_w \\ z_w \end{pmatrix} + \begin{pmatrix} t_x \\ t_y \\ t_z \end{pmatrix}$$

- adapted to different magnifications
- robust to noise
- high accuracy
- high convergence rate





Robust Feature Extraction



Top View of the Sample Stage

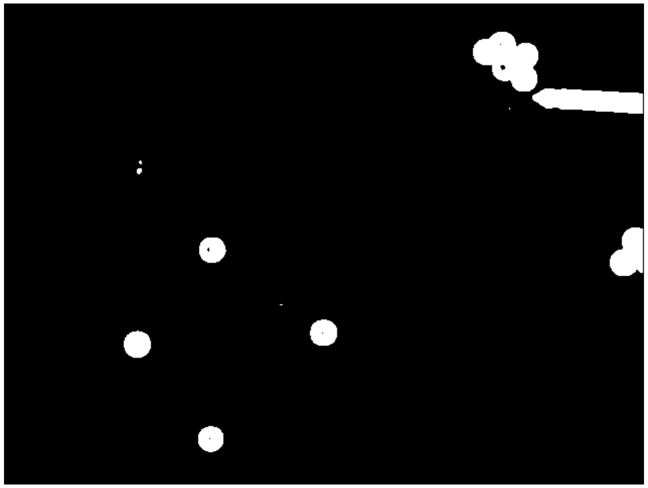
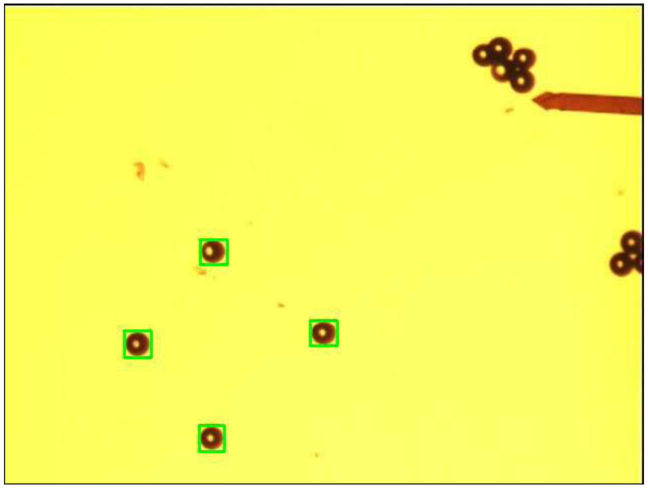
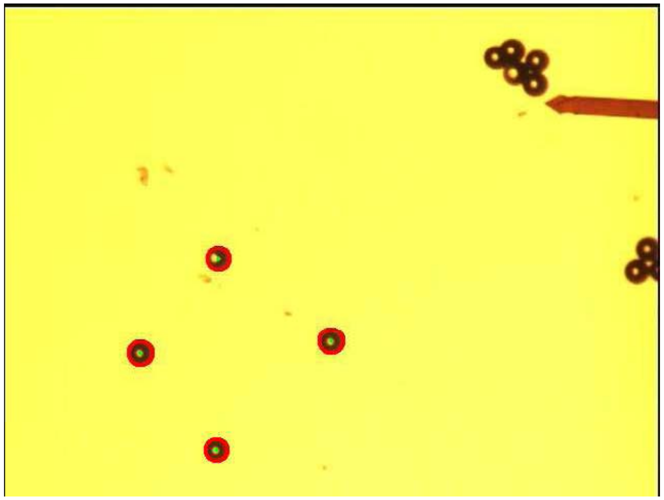


Image After Thresholding



Segmentation



Extracted Circles

Robust Feature Extraction

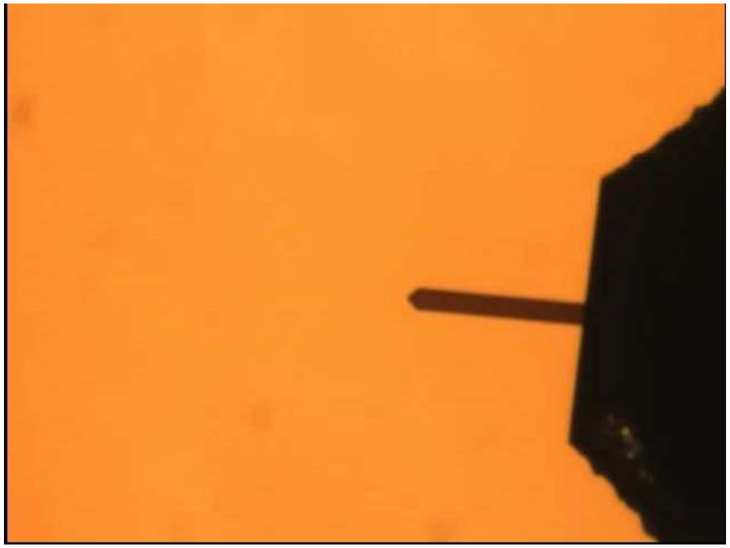
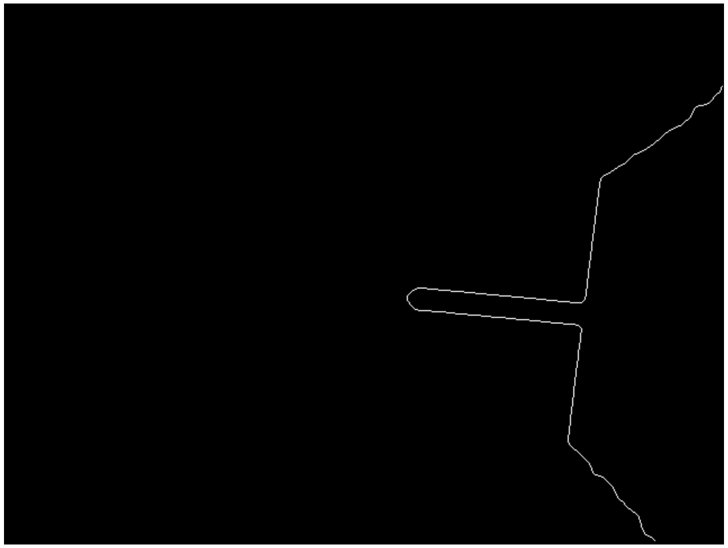


Image of the Probe



Edge Pixels of the Probe

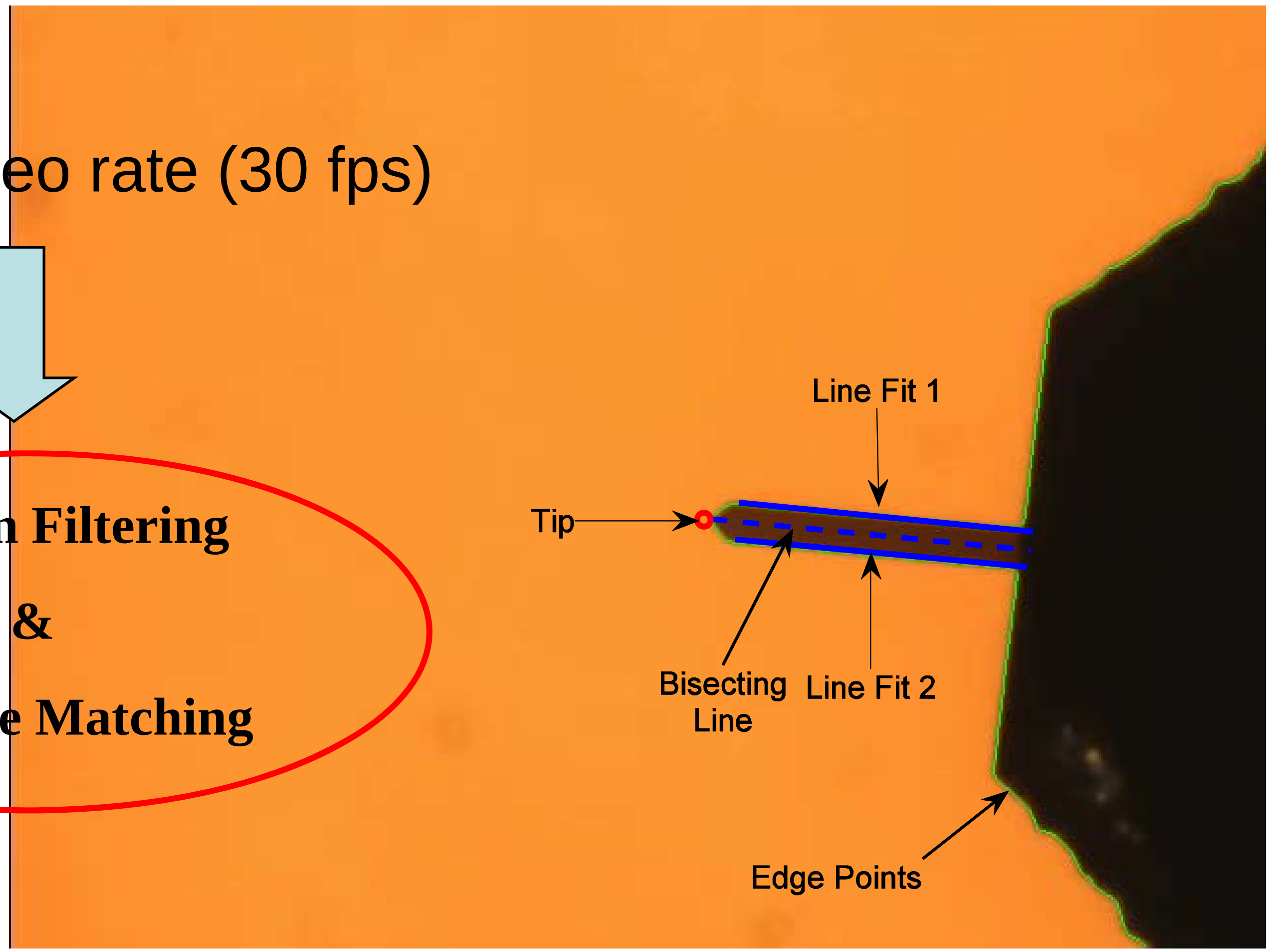
Probe Tip Detection
&
Real-Time Tracking

Tracking at video rate (30 fps)

Kalman Filtering

&

Template Matching



Design of Visual Controllers

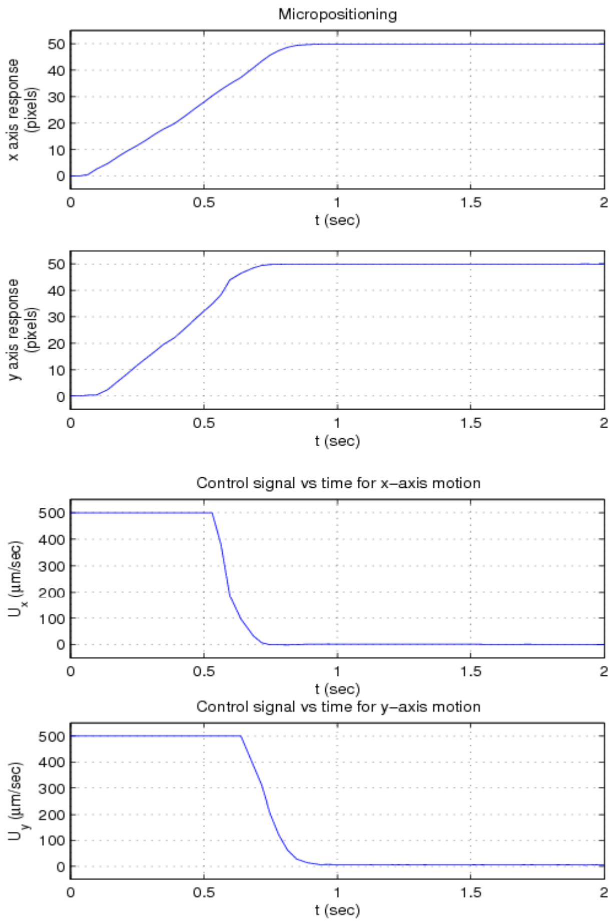
Having optical system parameters from calibration and real time image feature measurements from tracking, how do we implement vision based control algorithms to move the gripper?

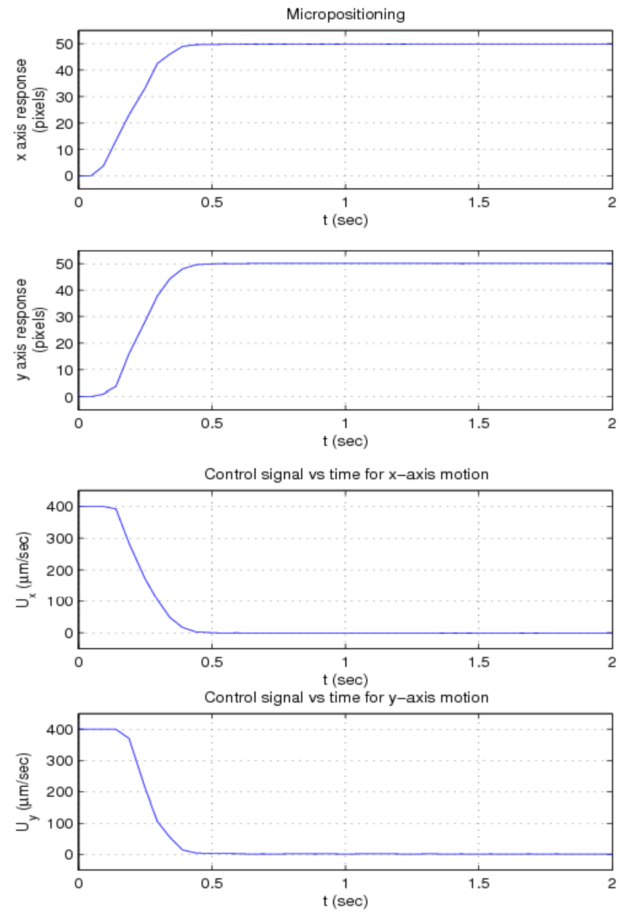
Optimal Control

$$E(k+1) = (f(k+1) - f^*(k+1))^T Q(f(k+1) - f^*(k+1)) + u^T(k)Lu(k)$$

$$u(k) = -(TJ^T(k)QTJ(k) + L)^{-1} TJ^T(k)Q(f(k) - f^*(k+1))$$

Micropositioning Results

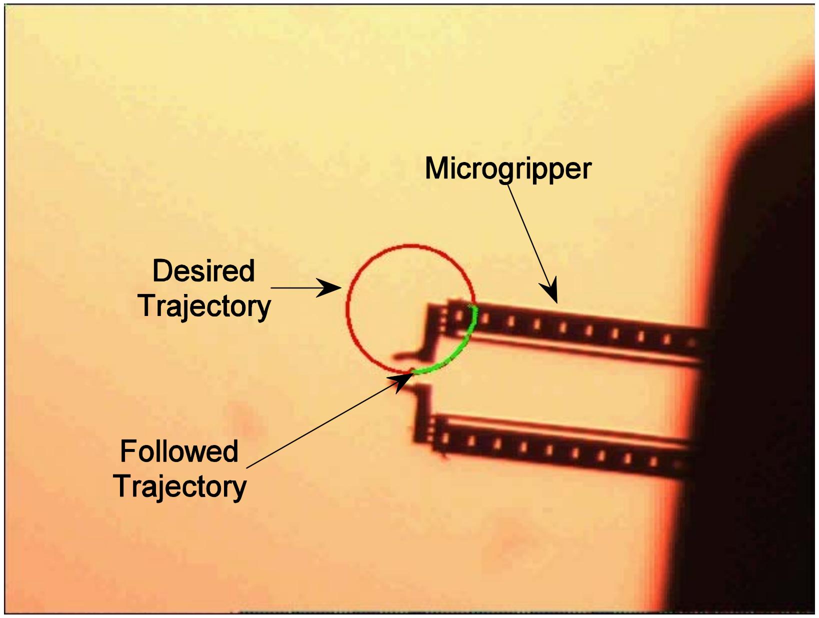


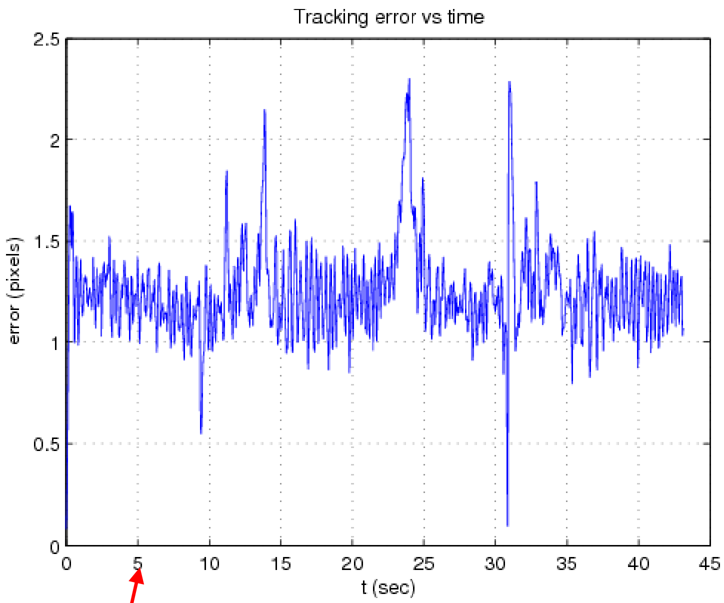


	Step (pixels)	ts (sec)	Acc. (µm)	Prec. (µm)
1x	50	0.8	9.86	2.71

	Step (pixels)	ts (sec)	Acc. (µm)	Prec. (µm)
4x	50	0.45	1.35	0.57

Trajectory Tracking Results

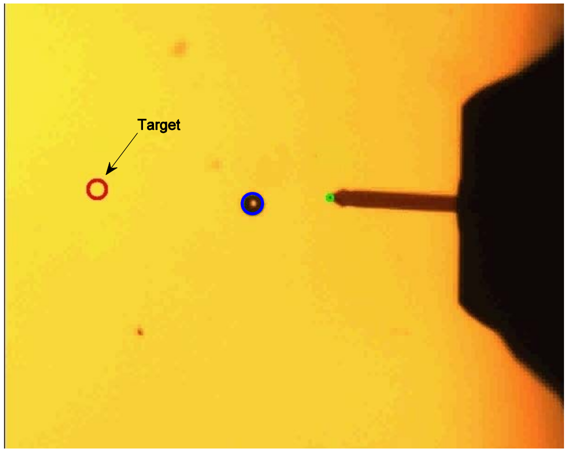




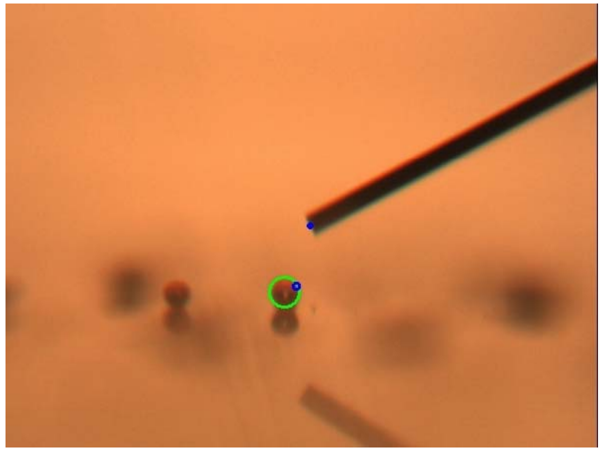
RESULTS OF TRAJECTORY TRACKING FOR CALIBRATED VISUAL SERVOING

	Square		Circular		Sinusoidal	
	Acc. (μm)	Prec. (μm)	Acc. (μm)	Prec. (μm)	Acc. (μm)	Prec. (μm)
1x	5.93	2.28	7.72	1.40	4.79	2.37
4x	1.47	1.19	1.57	0.95	1.12	1.31

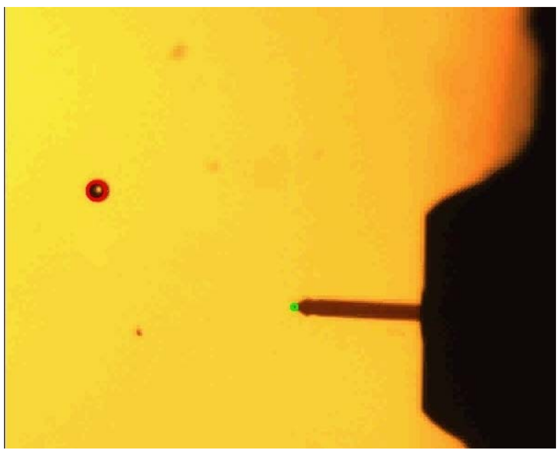
Automatic Manipulation by Pushing



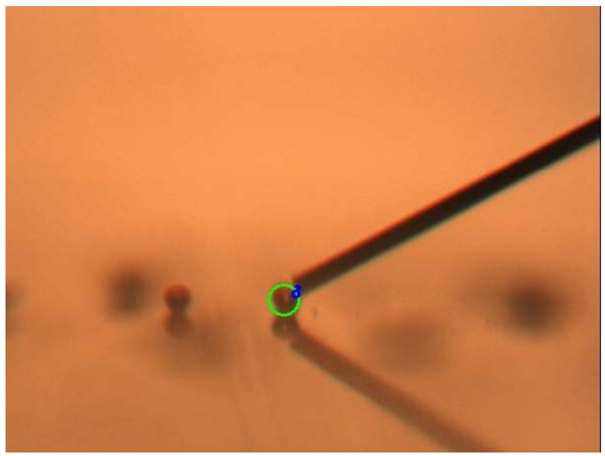
TOP VIEW



SIDE VIEW



TOP VIEW



SIDE VIEW

Mode 0. Explore

- Target Pose
- Probe Tip Detection
- Object (Ball) Detection
- Which Ball to Manipulate
- Tracking using Kalman Filters

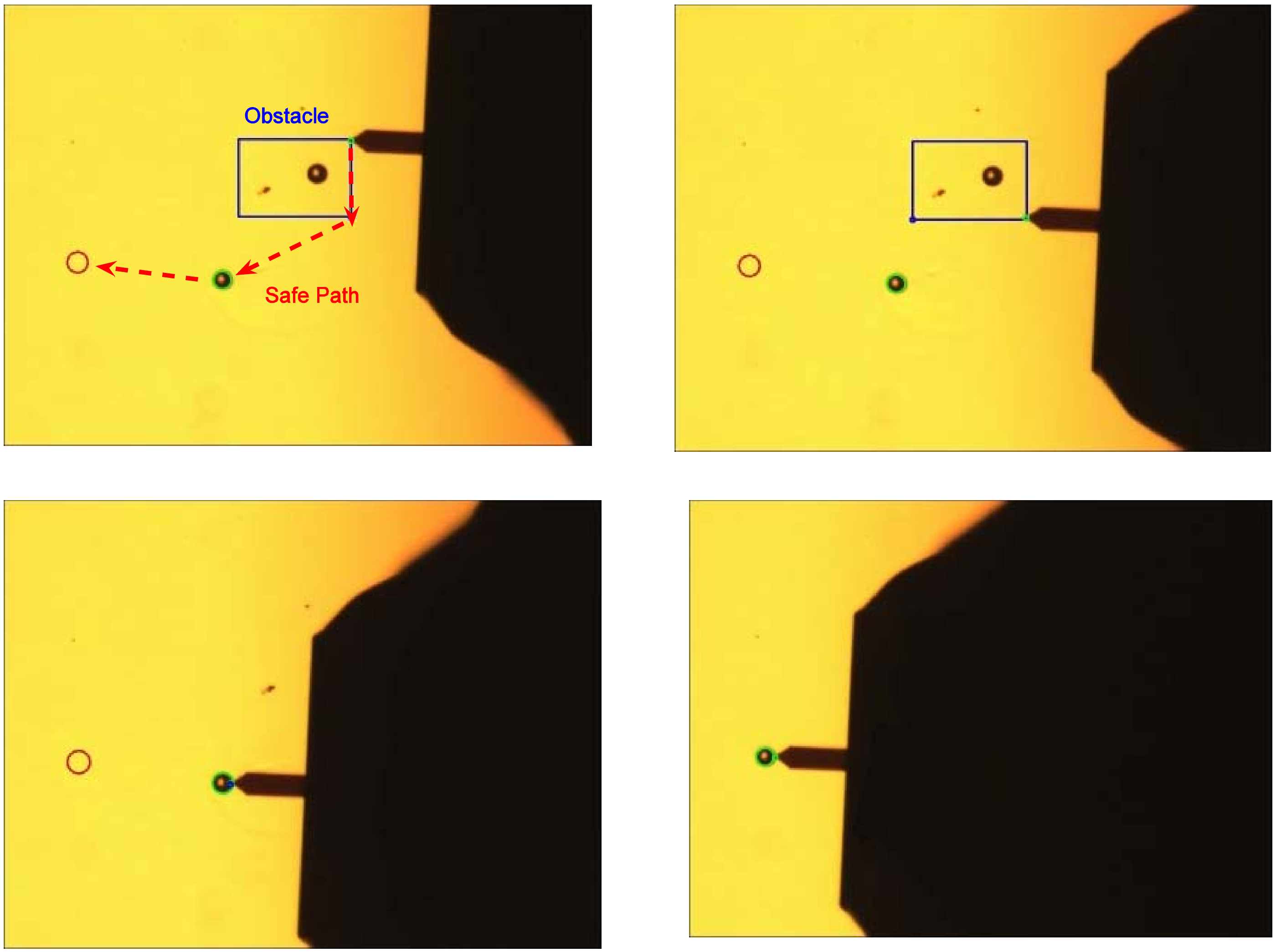
Mode 1. Obstacle Avoidance

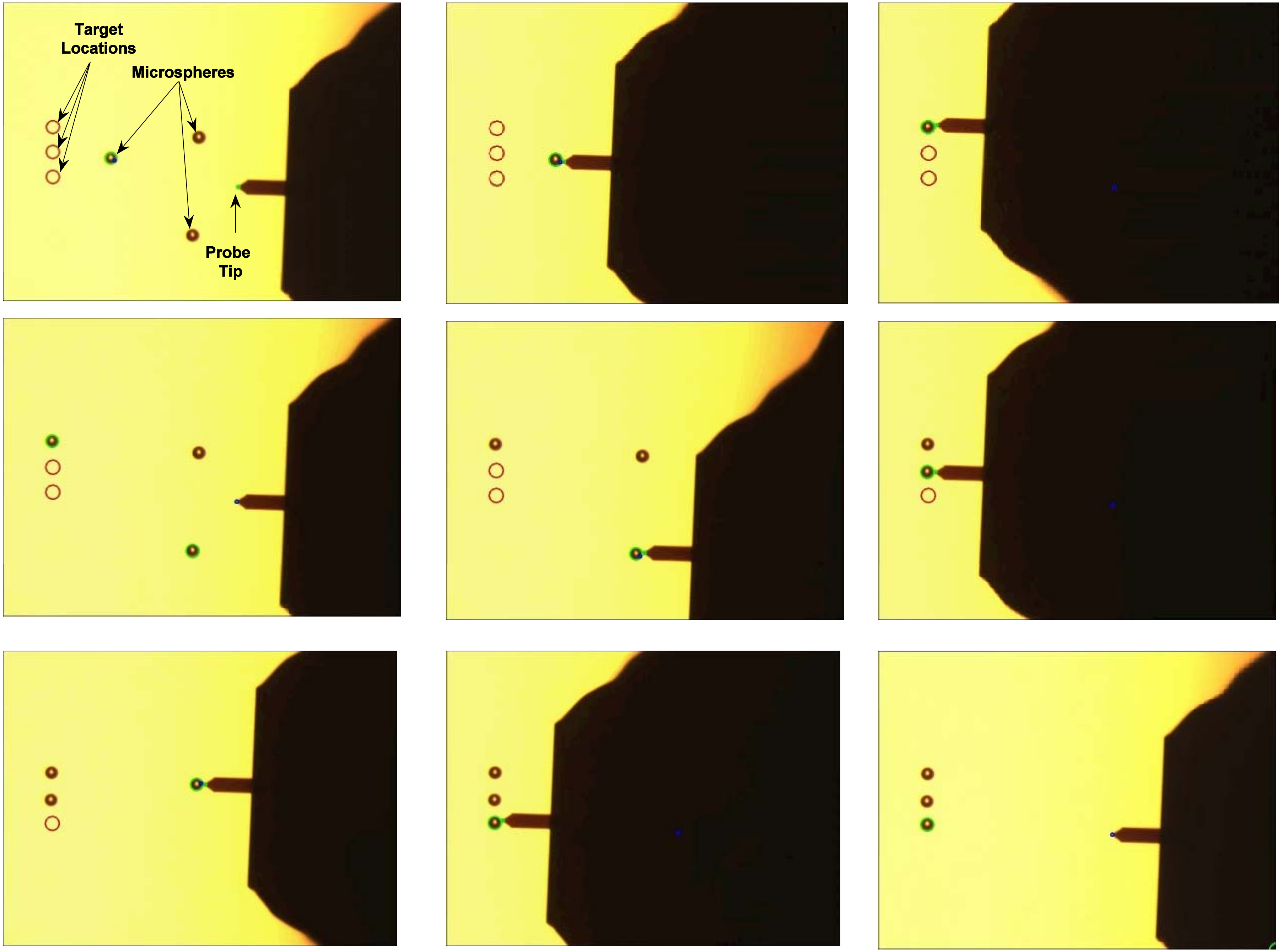
Mode 2. Automated Pushing

- Visual Servoing

Mode 3. Home

Obstacle Avoidance

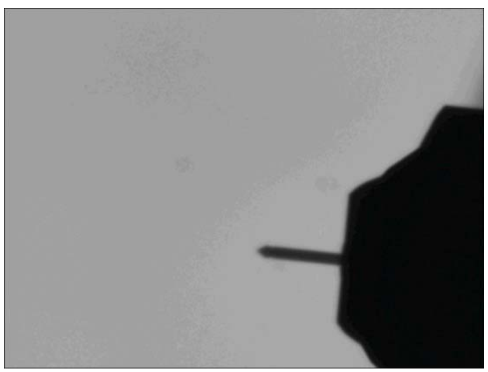


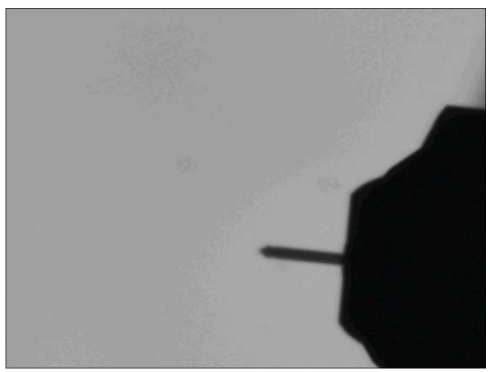

Target
Locations
Microspheres
Probe
Tip

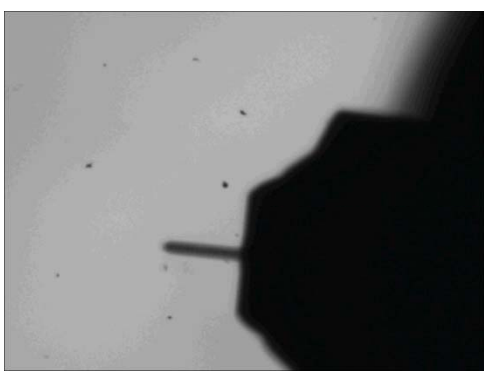
Active 3D Reconstruction

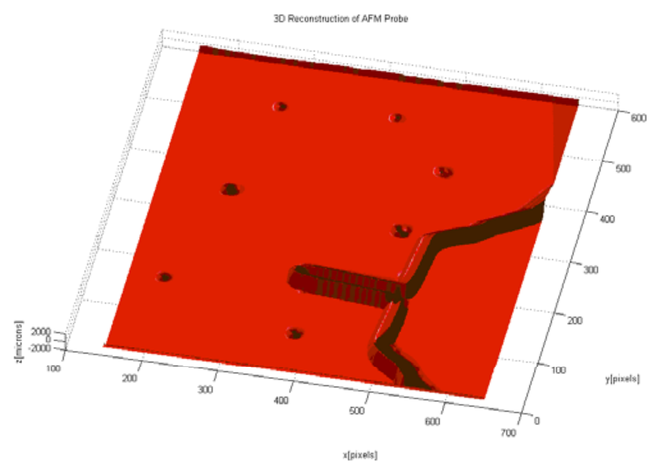
- **Shape from Focus**

2D Images → 3D Model







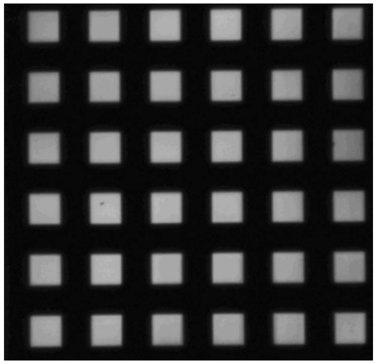


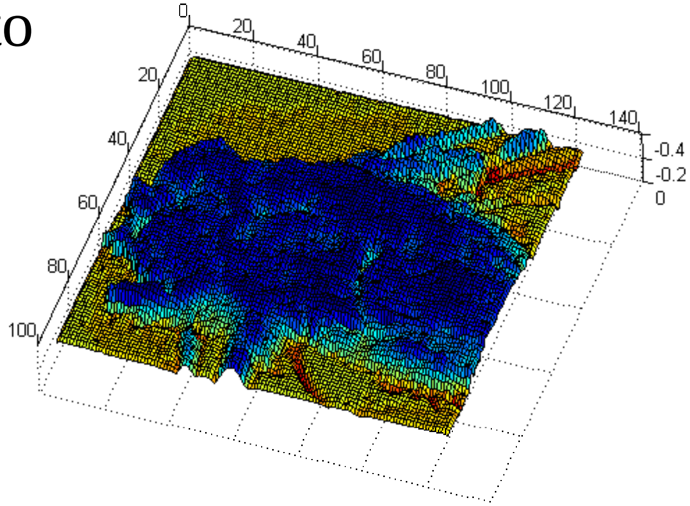
- 2D Images at different focus levels captured to create 3D model of AFM Probe

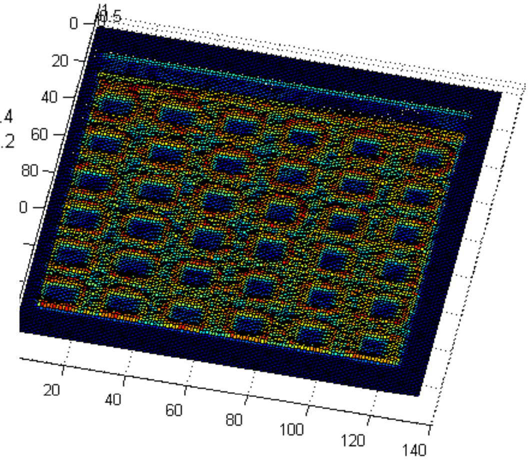
Passive 3D Reconstruction

Shape From Defocus

- estimating the 3D surface of a scene from a set of two or more images of the scene
- exploiting defocus to recover the depth



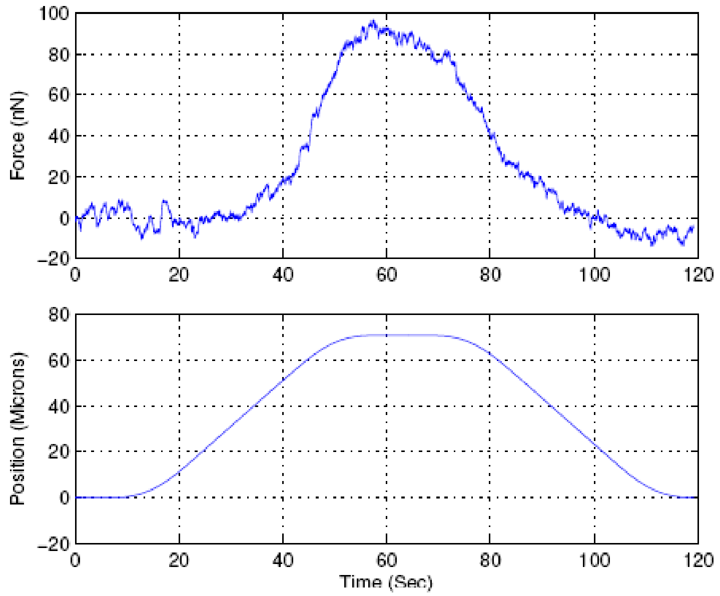




Force Sensing

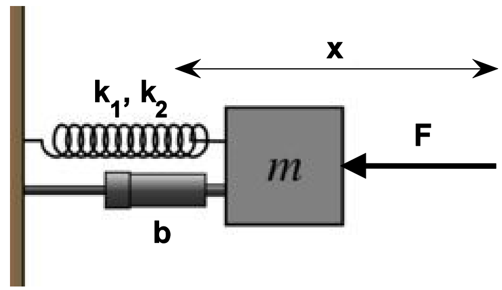
- In order to achieve high dexterity in manipulation, control of the interaction forces is required.

- In micro-manipulation, control of interaction forces necessitates force sensing in mili-Newton range with nano-Newton resolution



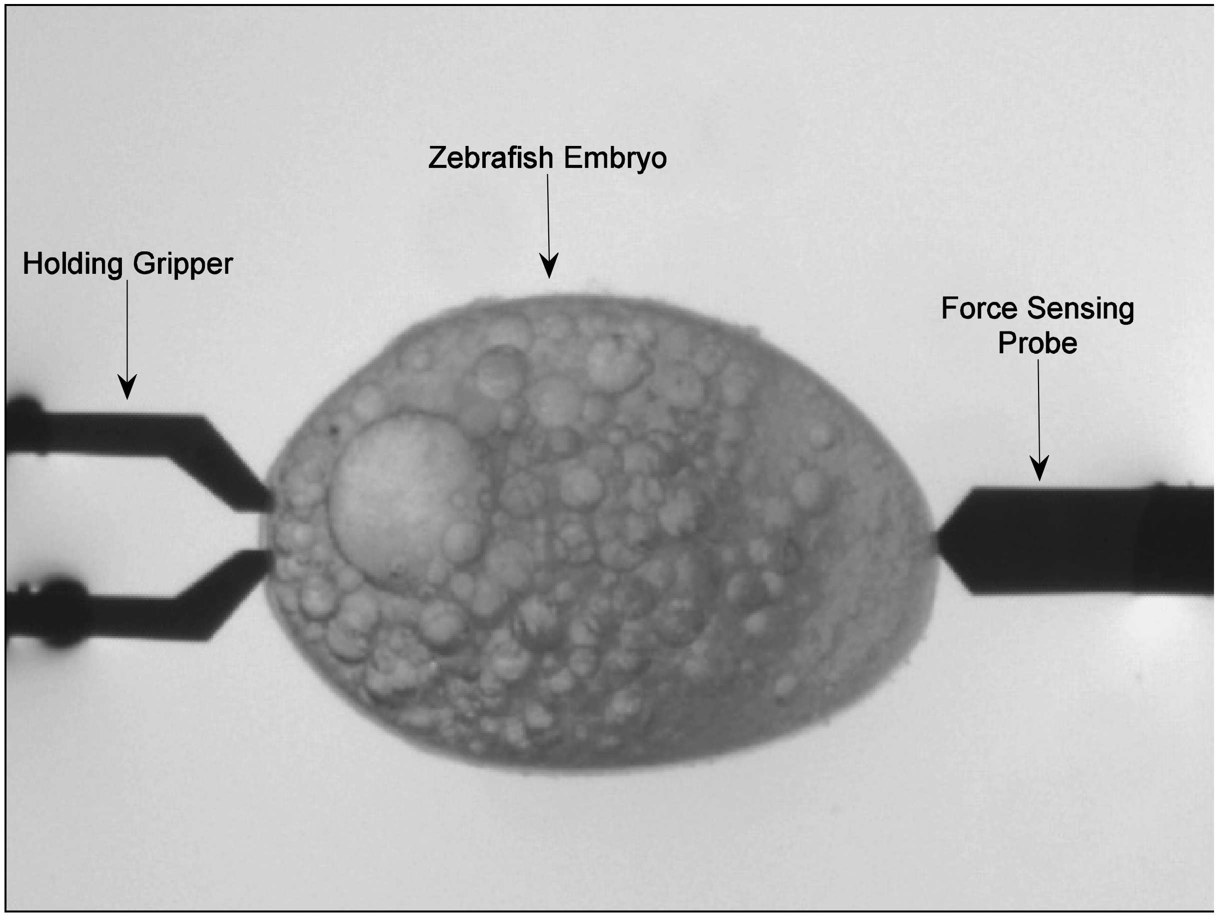
Pulling in-out for smooth step position references

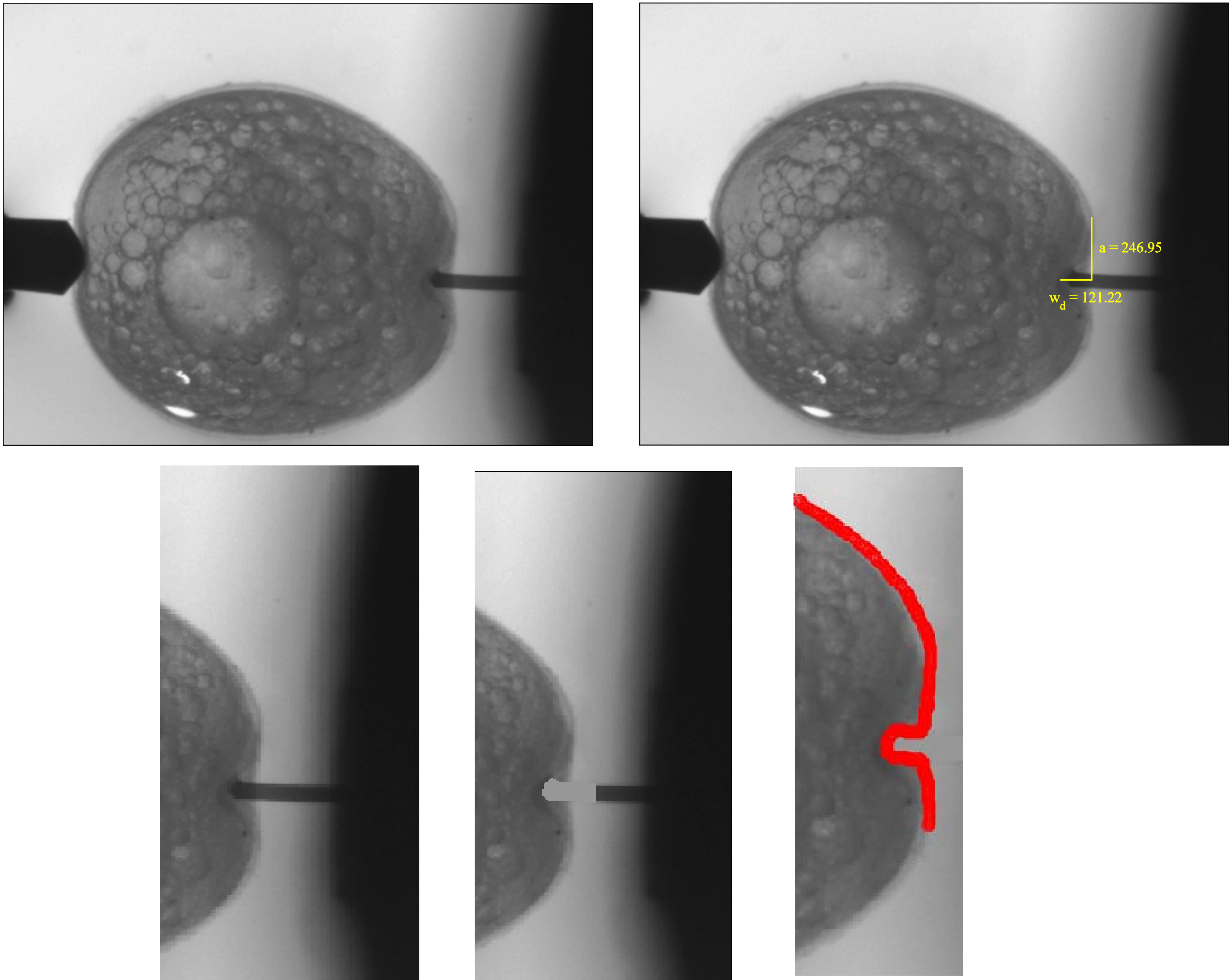
Force Estimation and Mechanical Characterization



$$F = m\ddot{x} + b\dot{x} + k_1 x + k_2 x^3 \Rightarrow F_i = \underbrace{(\ddot{x}_i \quad \dot{x}_i \quad x_i \quad x_i^{\,3})}_{\varphi_i^T} \underbrace{\begin{pmatrix} m \\ b \\ k_1 \\ k_2 \end{pmatrix}}_{\theta}$$

$$\boxed{\hat{\theta} = \arg\min \left(\left\| F - \Phi\theta \right\|^2 + \delta \left\| \theta \right\|^2 \right) = (\Phi^T \Phi + \delta I)^{-1} \Phi^T F}$$

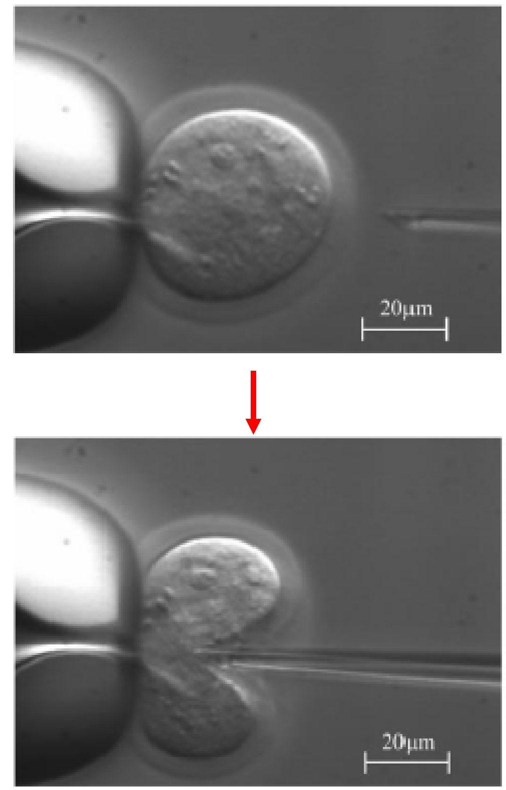

Zebrafish Embryo
Holding Gripper
Force Sensing
Probe

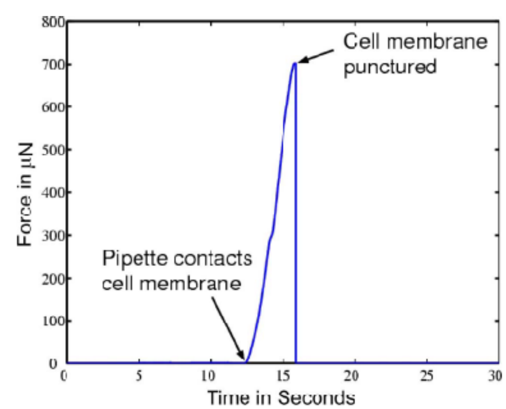


(a) (b) (c)

Applications

- Automated injection
  - intracytoplasmic sperm injection (ICSI), DNA injection, gene therapy
  - manual injection
    - low success rate and poor reproducibility
  - efficiency of injection can be improved by using visual feedback





Summary

- Robust and repeatable algorithms for optical system calibration
- Robust feature extraction and real-time tracking
- Path Planning, Visual servoing, Automatic Manipulation by Pulling
- 3D Reconstruction from Focus and Defocus
- Force Estimation and Mechanical Characterization

THANK YOU

&

BEST WISHES, BILL!