High-Speed Automated Micromanipulation System with Multi-Scalability

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Meeting

Introduction

"What I want to talk about is the problem of manipulating and controlling things on a small scale"

by Richard Feynman, "There is Plenty of Room at the Bottom"

at annual meeting of American Physical Society, in 1959.

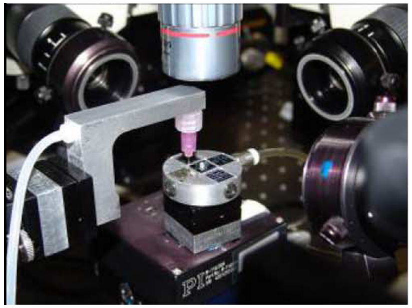
After five decades, micromanipulation still stays as a challenging issue

Micromanipulation

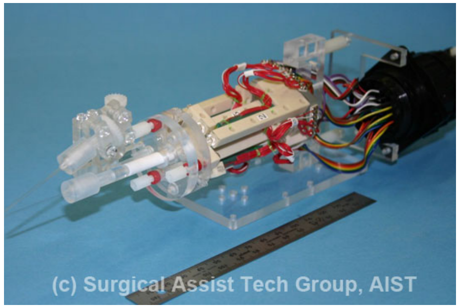
Micromanipulation

- to physically interact with a sample under a microscope
- level of precision of movement is necessary

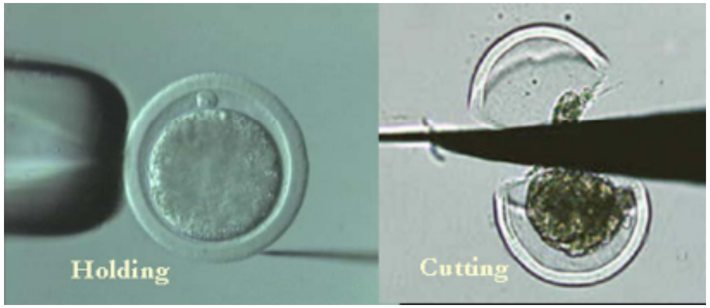
Application Areas



assembling micromachines



microsurgical operation



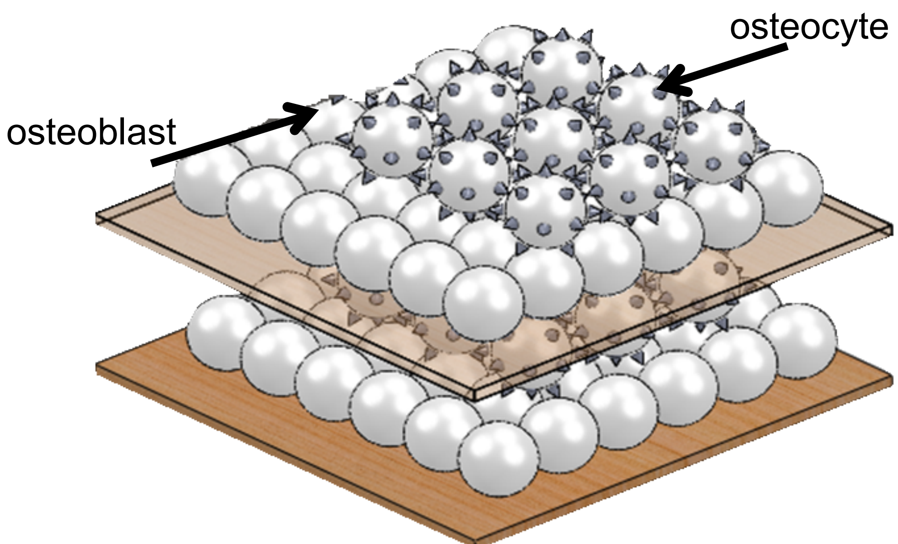
bio-micromanipulation

Important for biomechanics, microbiology, genetics, etc.

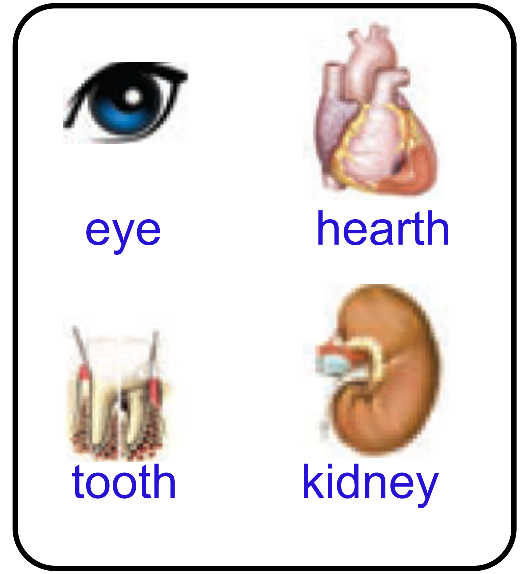
Cell characterization, cell sorting, cell fusion, sperm injection, etc.

Micromanipulation

Target Application: Tissue Regeneration



Multi-layered Cell Assembly



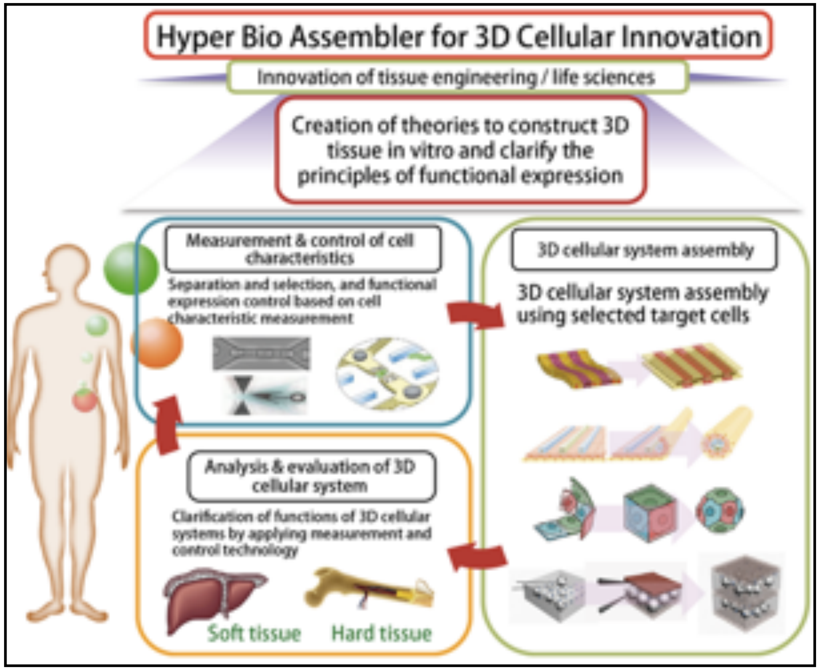
Regenerative Medicine

- regenerating damaged tissues of human in vitro,
- solve the problems of the shortage of organs available for donation,
- solve the problem of organ transplant rejection as regeneration is from own tissue.

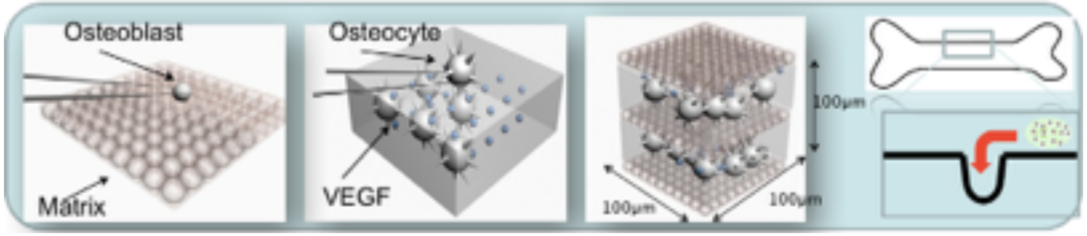
Target Application

REGENERATIVE MEDICINE

Purpose of the research is creating living, functional tissues.



my task

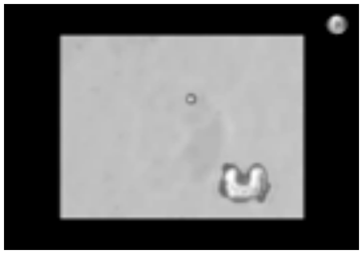


Necessary features: <u>Fast</u> and <u>precise</u> manipulation

Micromanipulation

Motorized stage, PZT, etc...

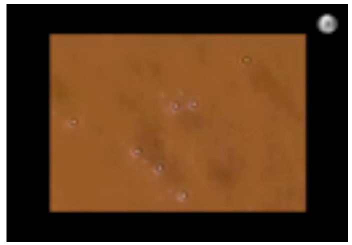
Magnetically Driven



Magnetic Microtransporters
(Univ. of Pennsylvania)

Enucleation by Microrobot
(Nagoya U., 2012)

Optical Tweezers

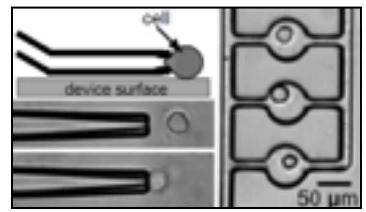


Optical Tweezers
(C. U. of Hong Kong)

Automatic Cell Sorting with
Combined (C. U. of Hong Kong)

Micropipette

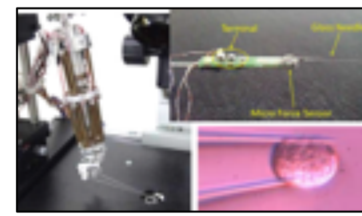
Position Control of Cells
(U. of Toronto, 2012)



Micropipette for Single Cell
Deposition (U. of Toronto)

Microfinger

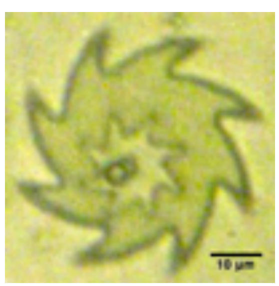
Automated Nanomanipulation
(U. of Toronto, 2012)



Cell Hardness Measurement by
Micro Force Sensor (Osaka U.)

Bacteria Driven

Bacteria Driven
Micro Crank
Nagoya U., 2012)

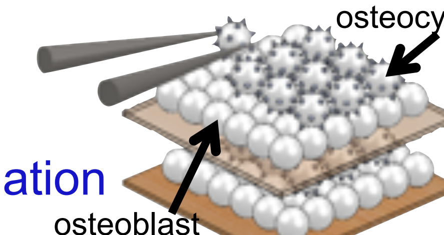


1-Dexterous handling,

2-3D manipulation ability,

3-Multi-sized objects manipulation

4- Bio-compatible

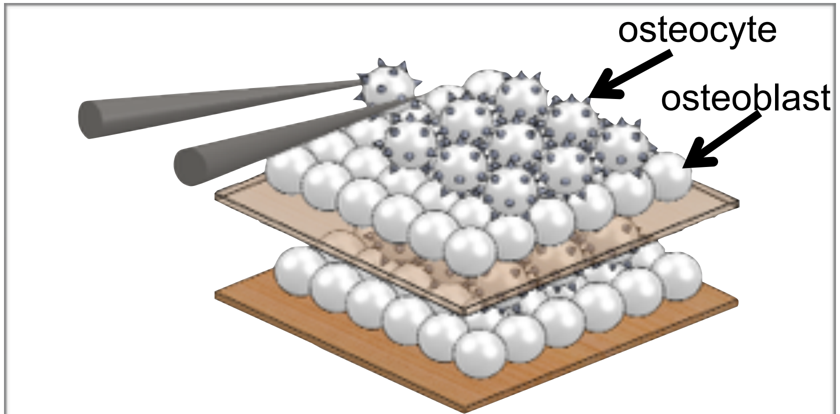


Multi-layered Cell Assembly

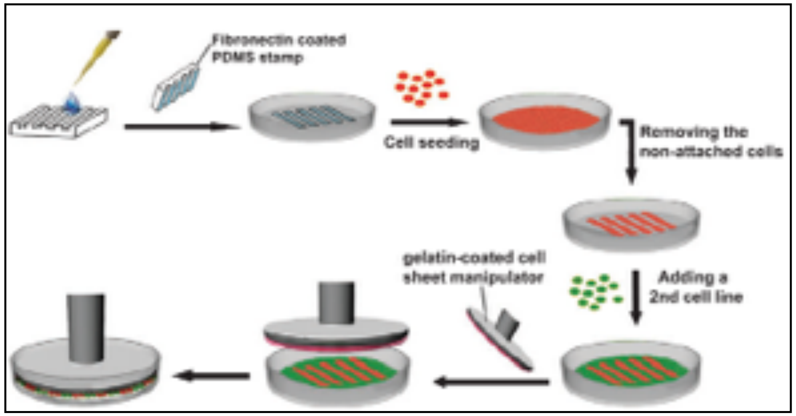
Tissue Regeneration

To grow tissues in the laboratory and safely implant them when the body cannot heal itself.

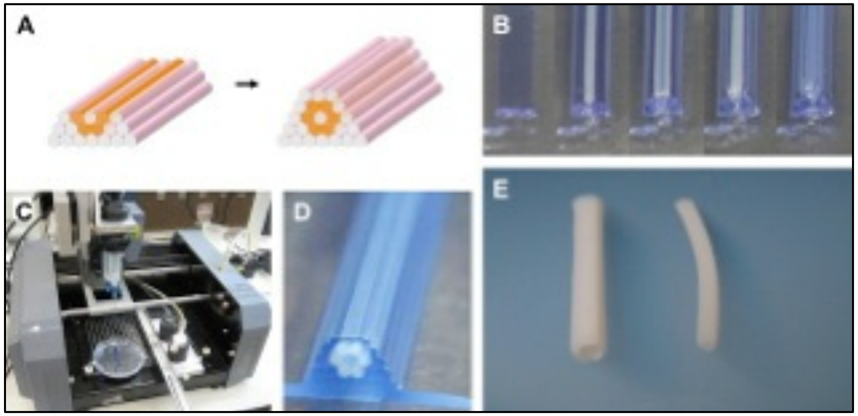
- Two common methods:
  1. Cell sheet engineering
  2. Bio-printing



Multi-layered Cell Assembly (Regeneration of Tissue)



Cell Sheet Engineering
(Tokyo Women Medical University)



Bio-printing
(University of Missouri)

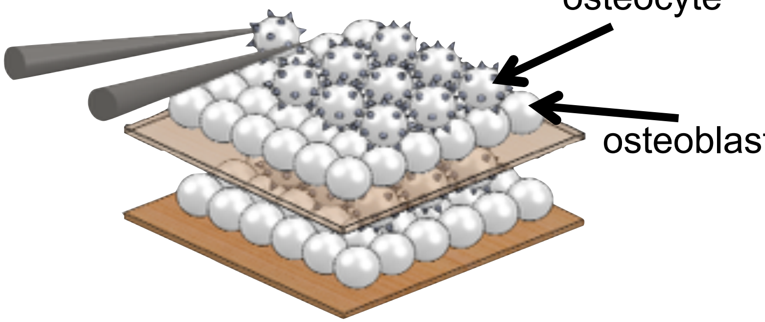
Required Features

1. A general purpose microhand that has multi-scalability

- Multi-sized objects handling
- Large workspace with precise positioning for transportation

2. High speed manipulation ability

- Presence of a vast number of cells
- Cells' restricted life span

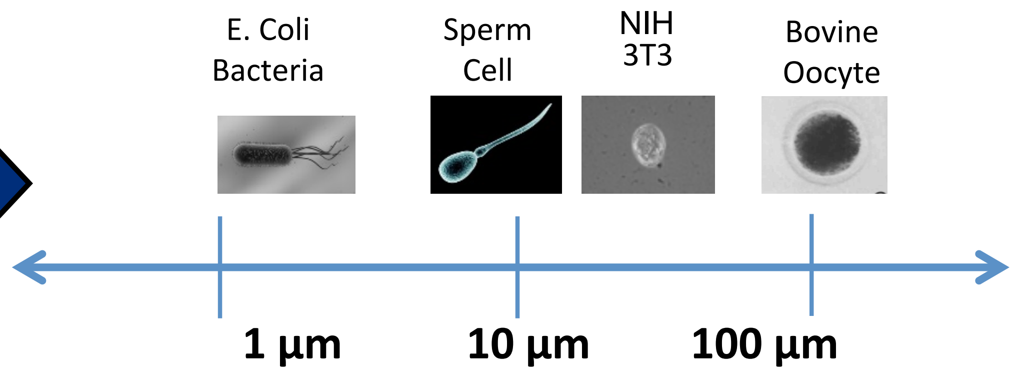


Regeneration of Tissue

A General Purpose Microhand

In literature, most micromanipulators have been designed as task-specific systems to manipulate particular microobjects

In micro environment, all kind of biological cells have different size.



Instead of task-specific systems, a general-purpose microhand is required.

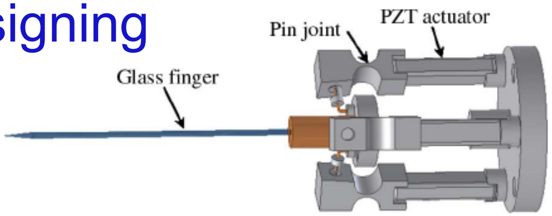
To achieve a general purpose microhand (concept of multi-scalability)

- A large workspace with a high resolution for grasping <u>different-sized microobjects</u>.
- A large workspace with a precise positioning for the <u>transportation</u> of microobjects.

Concept of Multi-Scalability

Challenges

- Mostly, end-effectors have limited workspace. Designing criteria of the microhand is crucial.

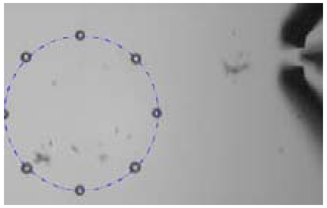


- Inverted microscope stage has limited space. Achieving large workspace with fine motion for the transportation is arduous task.

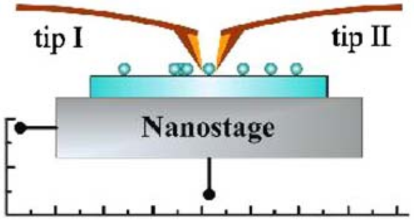
Proposed Solutions

- Workspace optimization for multi-sized objects handling.
- Coarse-to-fine motion strategy for transportation

High-Speed Micromanipulation



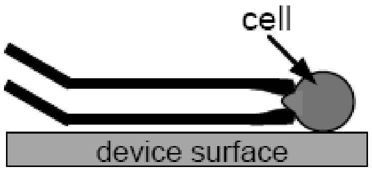
Robotic Pick-and-Place using Microgripper, Zhang et al., 2010



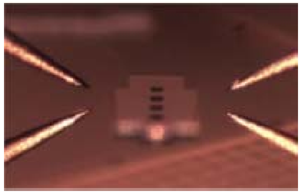
3D Micromanipulation using Nanogripper, Xie et al., 2009

A micromanipulation system that can realize pick-and-place task in 1 second

?



Single Cell Deposition using Pipette, Lu et al., 2010



3D Microstructures Assembly, Wason et al., 2010

0 sec.

10 sec.

Duration

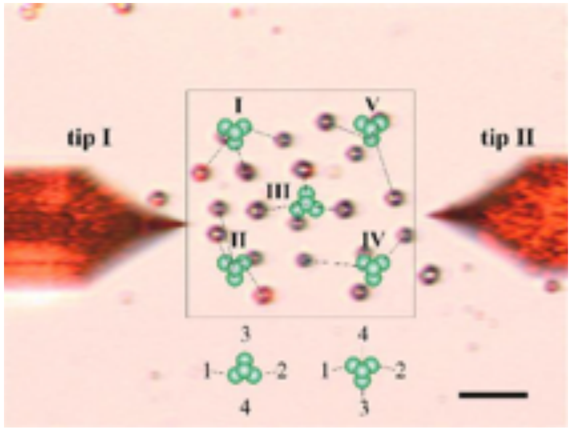
Duration for the simple pick-and-place task by various contact micromanipulator

Related Works (Fast Micromanipulation)

"Three-dimensional Automated Micromanipulation using a Nanotip Gripper with Multi-feedback" by Xie et al.

2009 - Journal of Micromechanics and Microengineering

grasping(20s) + transport(10s) + releasing(18s) = 48 sec.



"Autonomous Robotic Pick-and-Place of Microobjects"

by Zhang et al.

2010 – IEEE Transaction on Robotics

grasping + transport + releasing = 6 sec.

The highest speed reported in the literature thus far.

High-Speed Micromanipulation

Challenges

- **3D info** is necessary where as under standard microscopy 2D is feasible
- Control the **vibration** of the end effector caused by high speed motion

Proposed Solutions

- Implementation of fast detection algorithm to obtain 3D position
- Residual vibration suppression to success high-speed grasping

Contributions

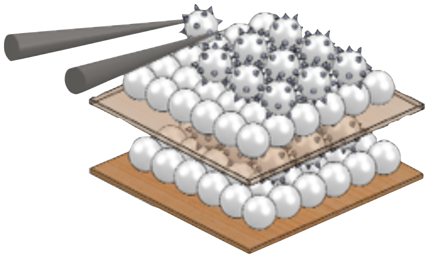
Summary of the solutions

- To realize a general-purpose microhand:
  - Workspace optimization for multi-sized objects handling.
  - Coarse-to-fine motion strategy for transportation
- To achieve high speed automated micromanipulation
  - Implementation of fast detection algorithm to obtain 3D position
  - Residual vibration suppression to success high-speed grasping

Academic Contributions

- **Multi-Scalability Concept**
- **First high-speed system**

Promote micro robotics/life science



Tissue Regeneration

Contents

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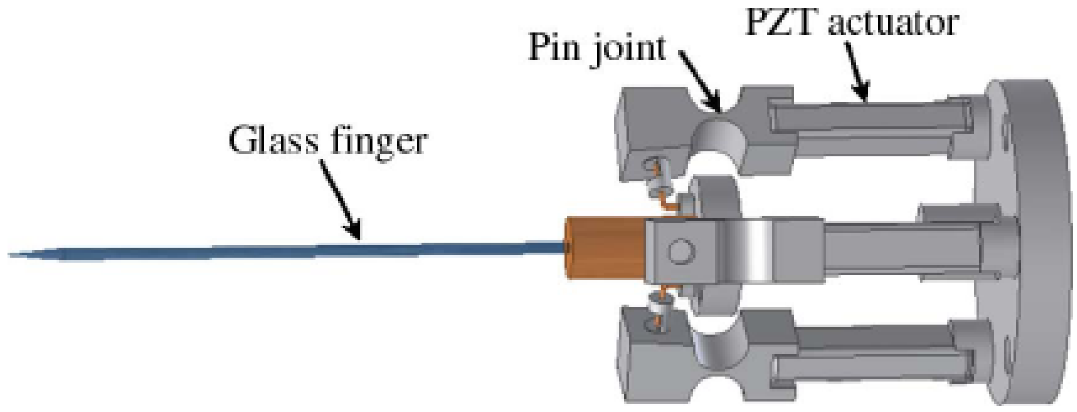
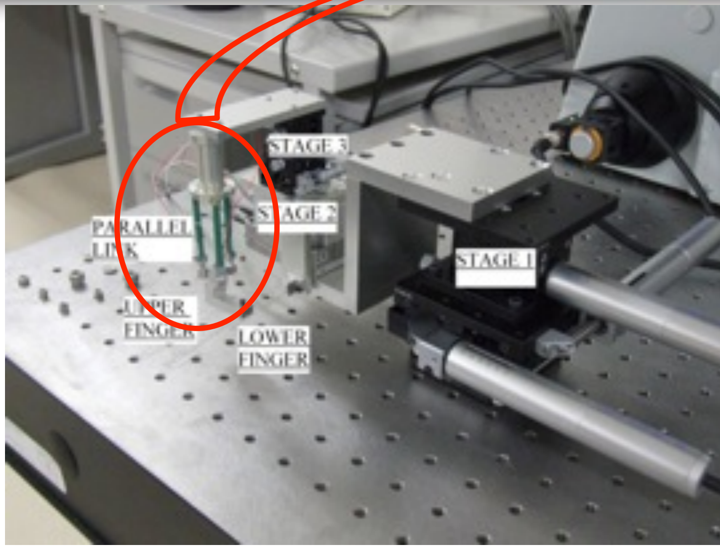
Manipulation of Multi-Sized Objects

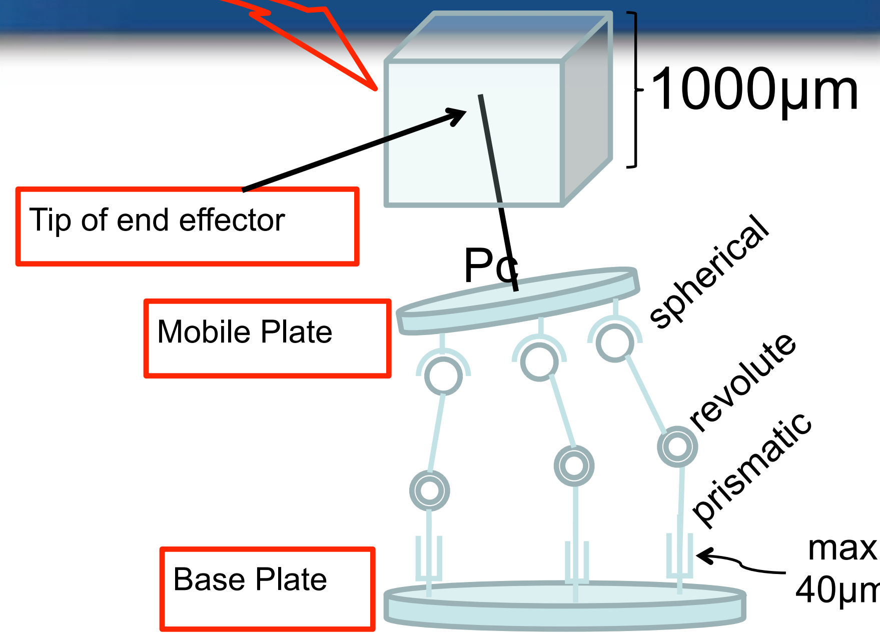
To manipulate different size microobjects, end effector of the microhand should have:

- Large workspace,
- High resolution.



Inverse Kinematics





Geometrical representation of parallel link mechanism

From tip of the end effector to center of mobile plate: Newton – Raphson Method

$$\begin{bmatrix} Pcx \\ Pcy \\ Pcz \end{bmatrix}^{k+1} = \begin{bmatrix} Pcx \\ Pcy \\ Pcz \end{bmatrix}^{k} - J^{-1}\left(Pcx, Pcy, Pcz\right)^{k} \bullet f\left(Pcx, Pcy, Pcz\right)^{k}$$

From mobile plate to fixed base plate:

- Transformation matrix=

$$Pc = \begin{bmatrix} Pcx \\ Pcy \\ Pcz \end{bmatrix}$$

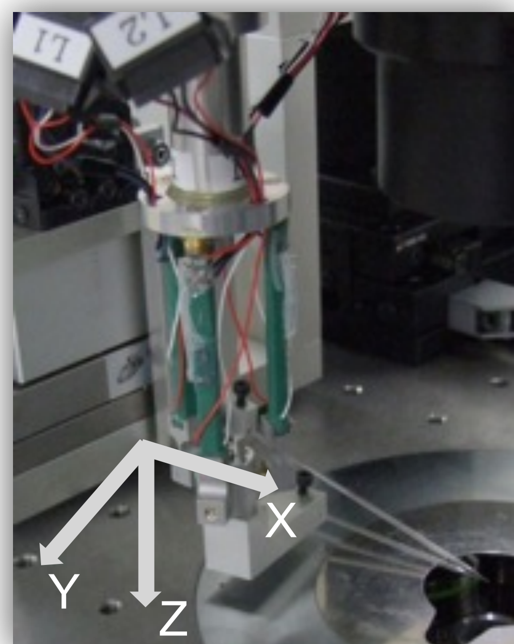
Position vector

$$ROT = \begin{bmatrix} Ux & Vx & Wx \\ Uy & Vy & Wy \\ Uz & Vz & Wz \end{bmatrix}$$

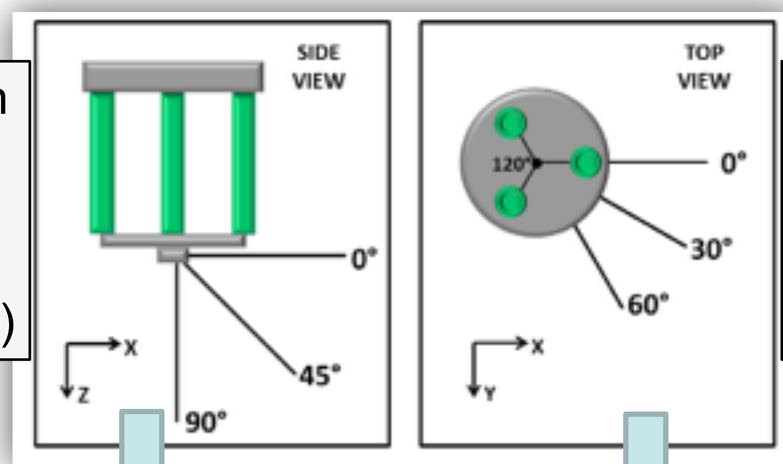
Rotation Matrix

Optimization of Workspace

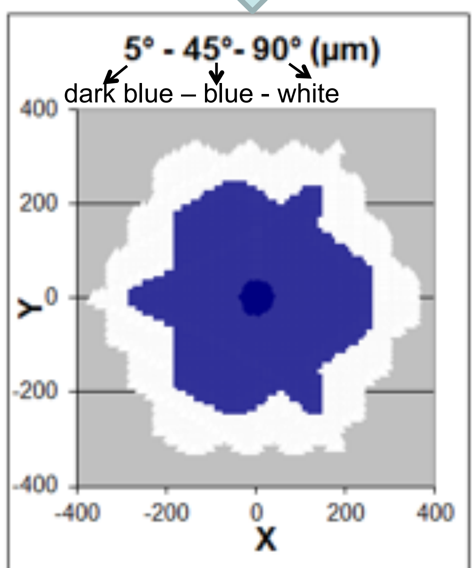
Workspace optimization in the X-Z plane and in the X-Y plane

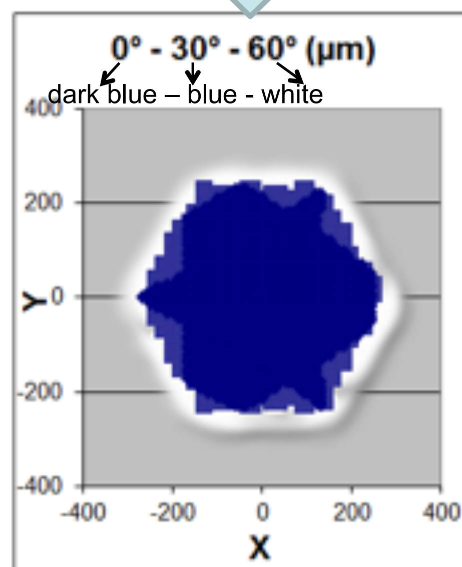


Orientation change in <u>vertical</u> direction (**X-Z plane**)



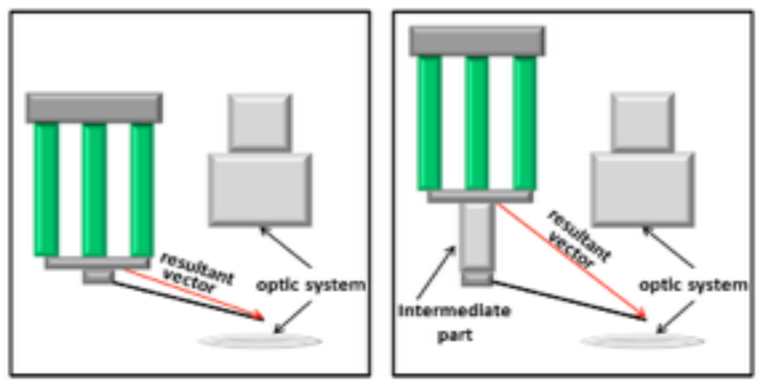
Orientation change in <u>horizontal</u> direction (**X-Y plane**)





X-Z plane	5°: 60 x 52 μm 45°: 530 x 480 μm 90°: 720 x 640 μm
X-Y plane	0°: 530x 480 μm 30°: 510 x 480 μm 60°: 540 x 480 μm

Optimization of Workspace



Workspace comparison between former and latter orientations

	X (μm)	Y (μm)
Former (27.5°)	45	22
Latter (39°)	132	40

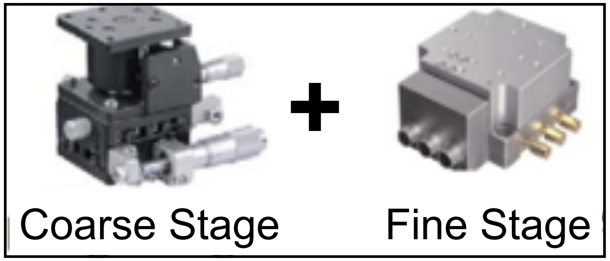
representation of cell fusion task
egg cell: bovine oocyte (100 μm)
donor cell: fibroblast (15 μm)

	Xmin (μm)	Xmax (μm)
related work 1	3	17
related work 2	20	100
proposed solution	1	132

Contents

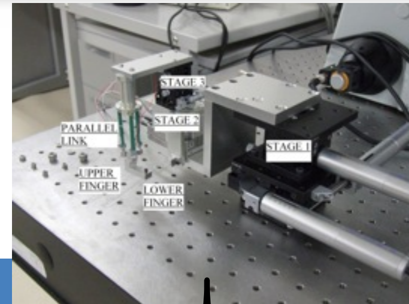
Coarse-to-Fine Motion Strategy

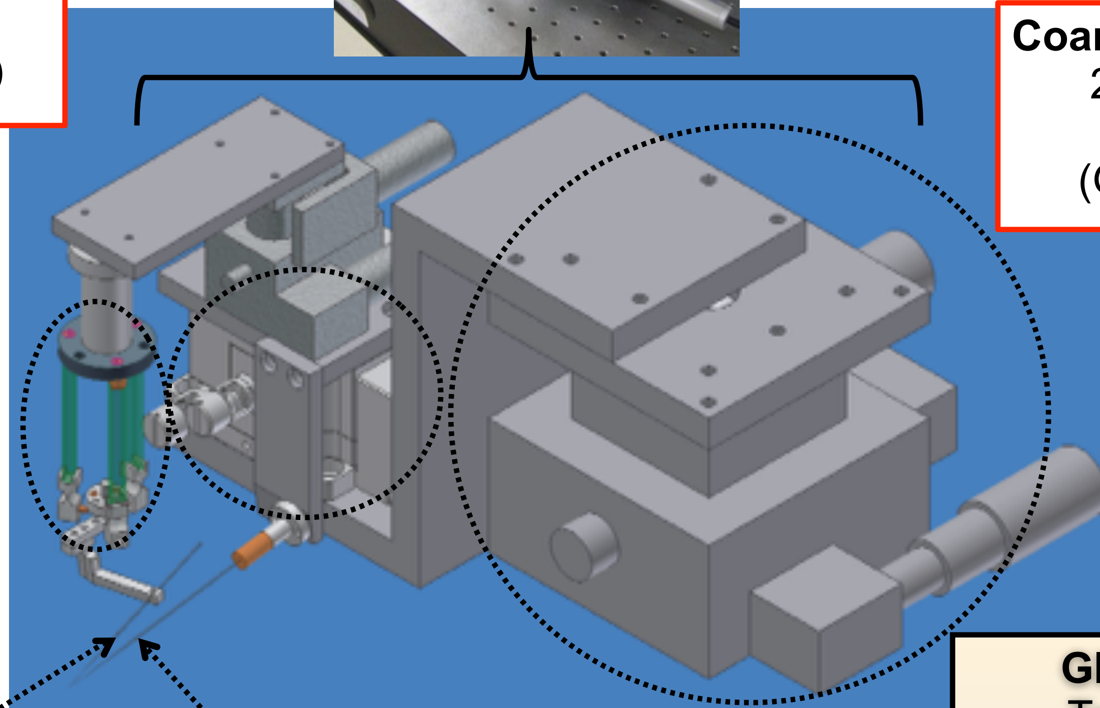
For the long distance transportation of microobjects with the precise positioning:



- Combination of <u>coarse motion</u> and <u>fine motion</u> functions.
- In our study, this combination was realized through visual feedback.

Details of Microhand





Fine Motion Stage
0.1x0.1x0.1 mm
2.3 mm/sec
(Global Motion)

Coarse Motion Stage
25x25x10 mm
1.1 mm/sec
(Global Motion)

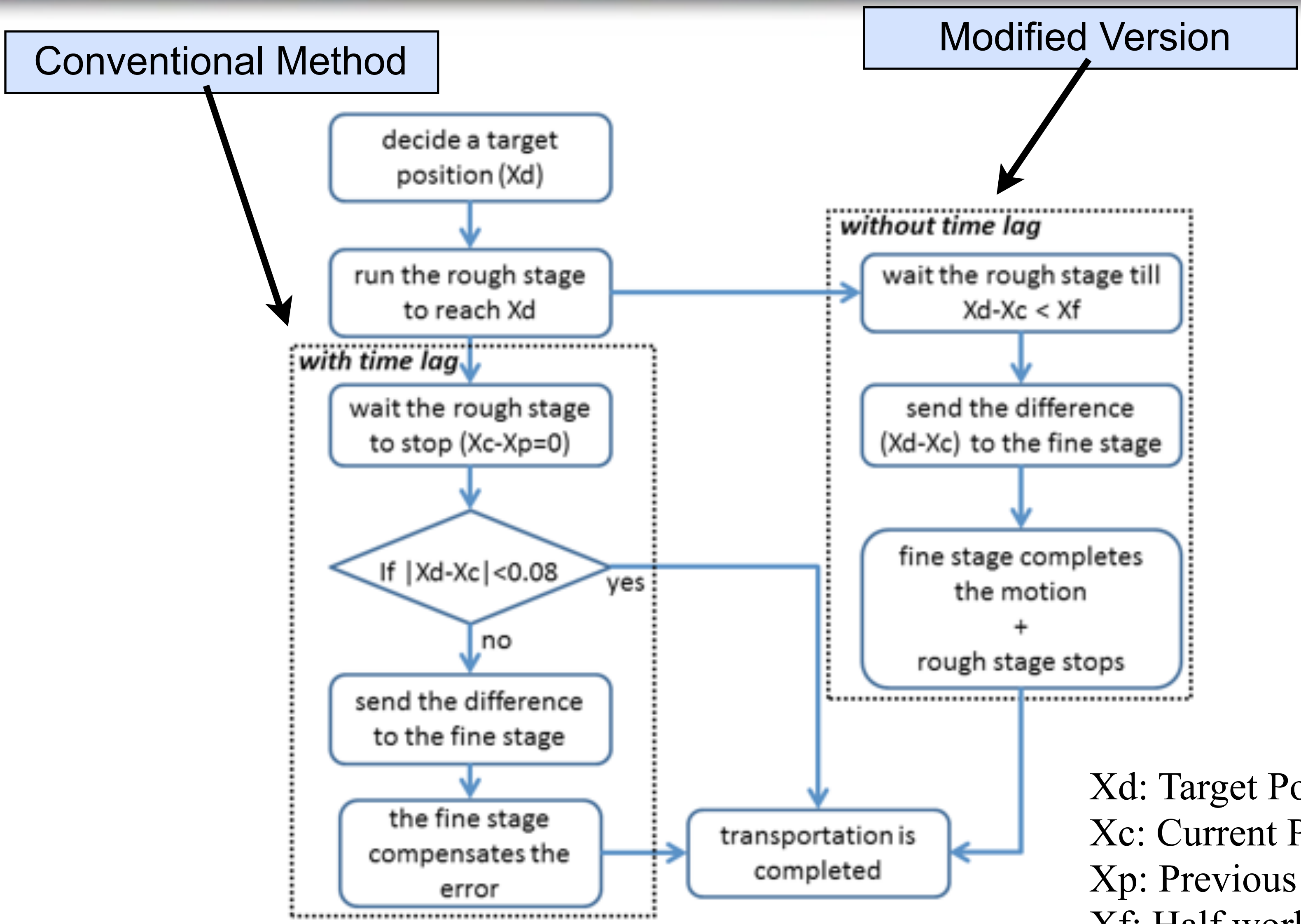
Parallel Mechanism
0.13x0.04x0.02 mm
10 cm/sec
(Local Motion)

Right end effector (needle 1)

Left end effector (needle 2)

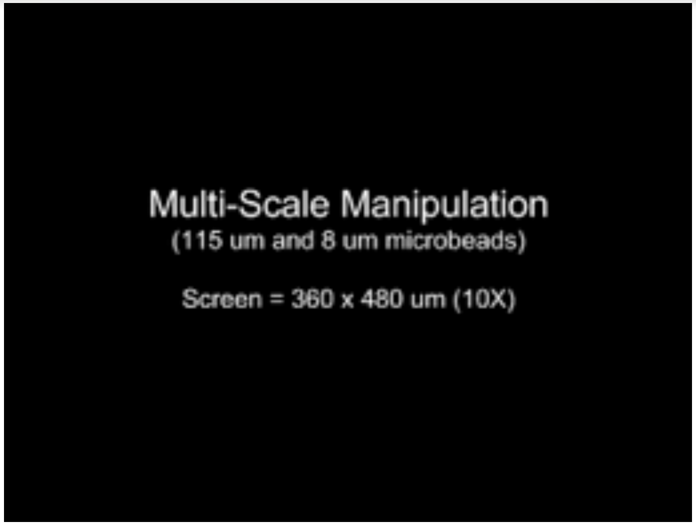
Global Motion:
Transportation, Positioning
Local Motion:
Grasping, Releasing

Flow Chart



Xd: Target Position
Xc: Current Position
Xp: Previous Position
Xf: Half workspace of Fine

Coarse-to-Fine Motion Strategy

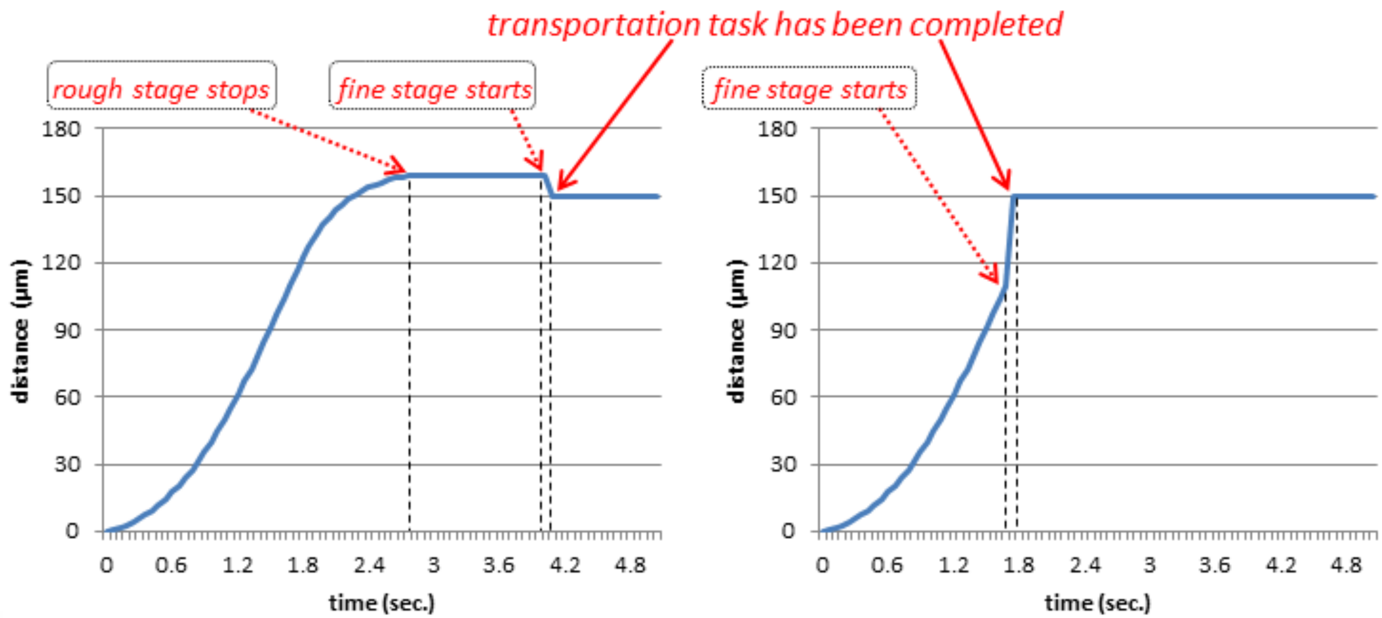


Coarse-to-fine motion:

- From 17 μm error to 0.1 μm

Without time lag

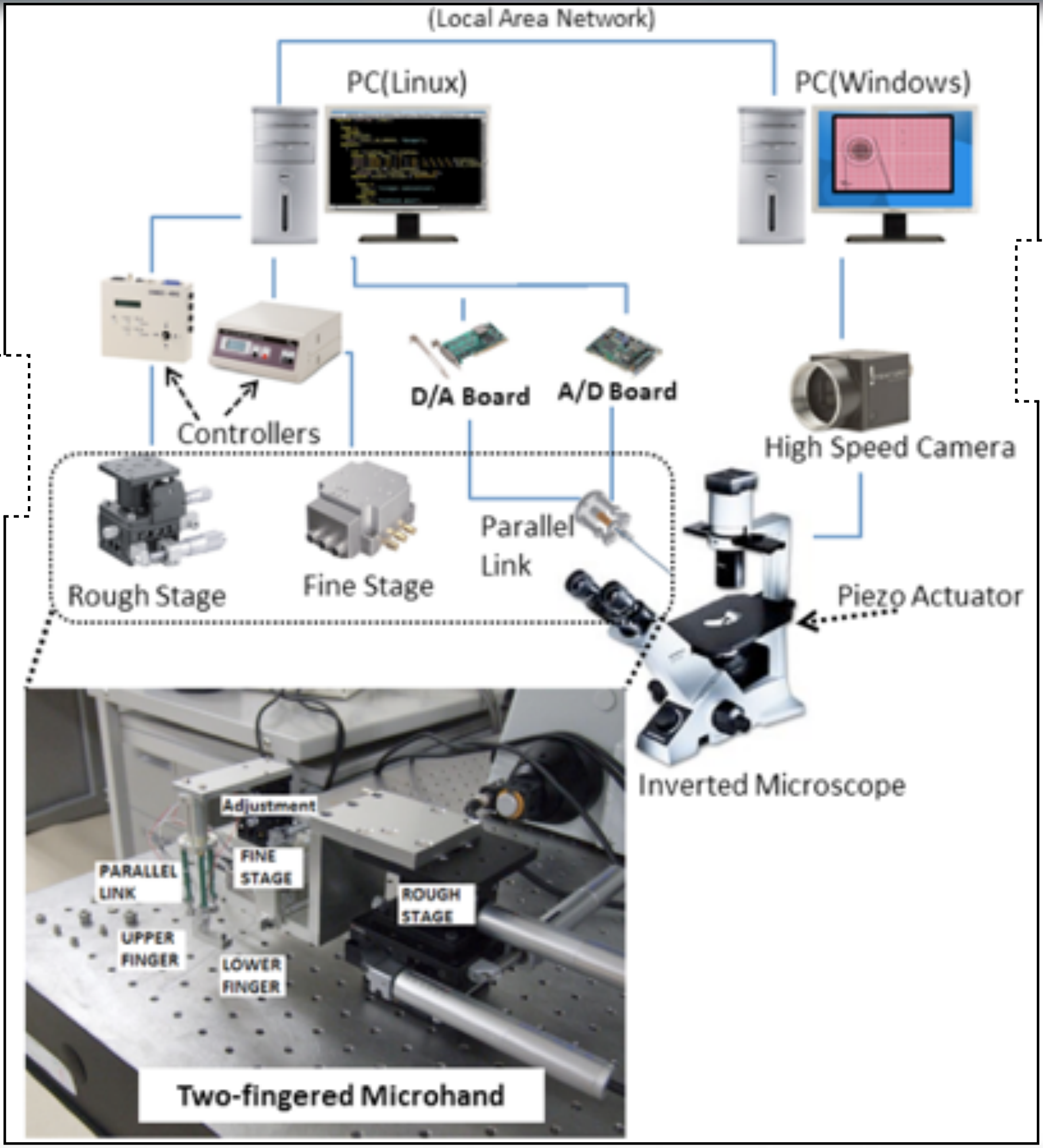
- Duration 4.1 sec to 2 sec.



Contents

System Configuration

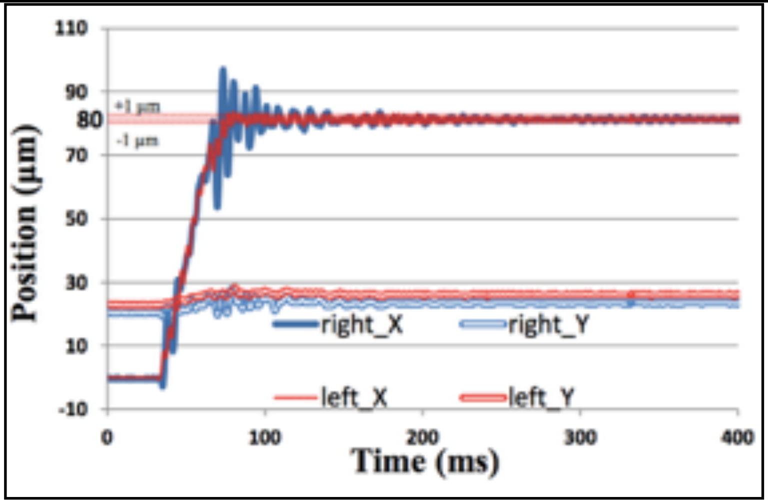
High-speed Actuation



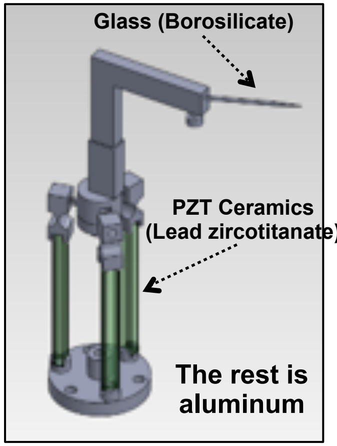
High-speed Sensing

Vibration Compensation

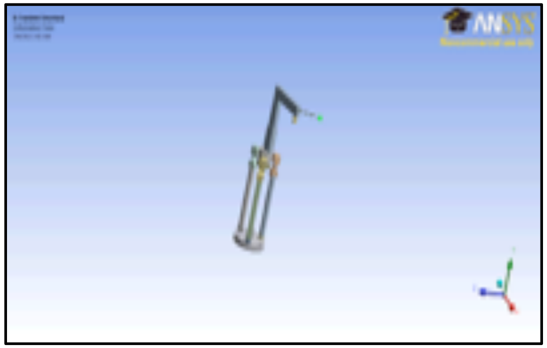
Vibration results of the end effectors for 2.3 mm/s



ANSYS result

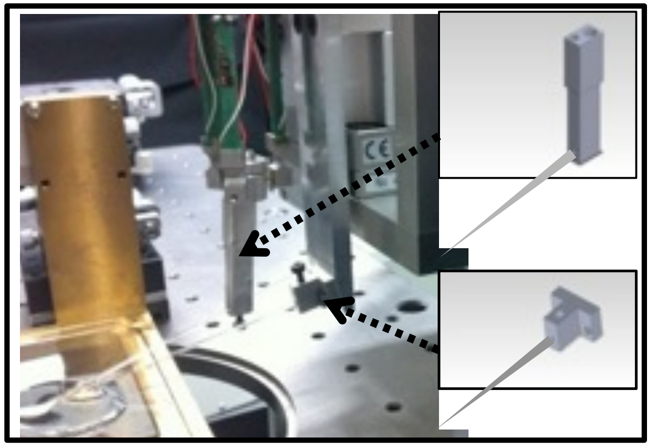


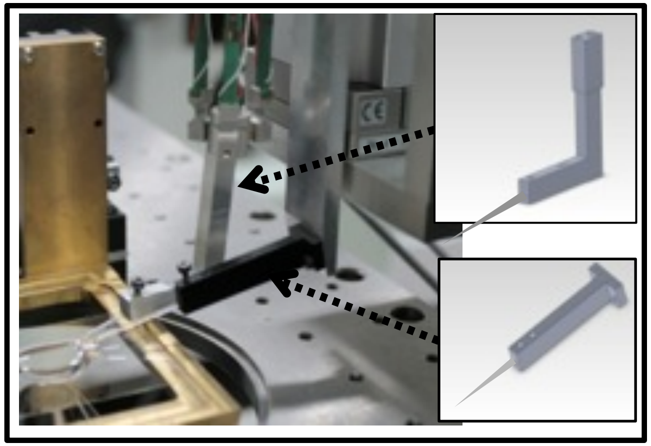
Parallel Link Mechanism



Residual vibration of the end effector is still great which is problem for grasping microobjects.

Structure Modification





Increasing Stiffness ($\delta_{max} \propto \frac{wL^4}{EI}$):

thickness: 3x, weight: 2x

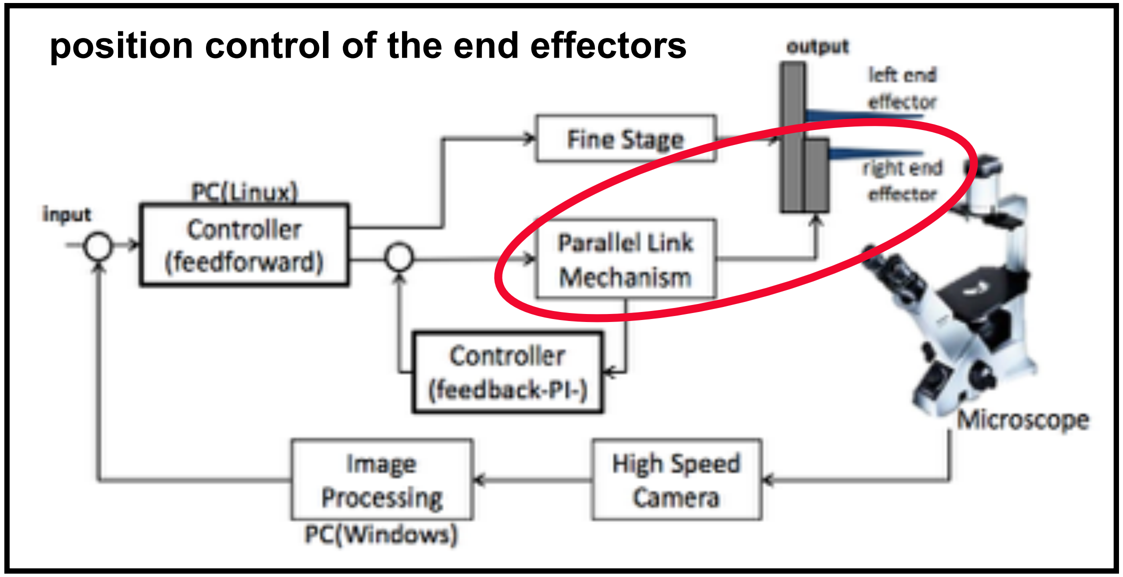
Residual Vibration Suppression

Possible Control Methods for Residual Vibration

- trajectory smoothing
- feedback control
- input shaping
- feedforward control

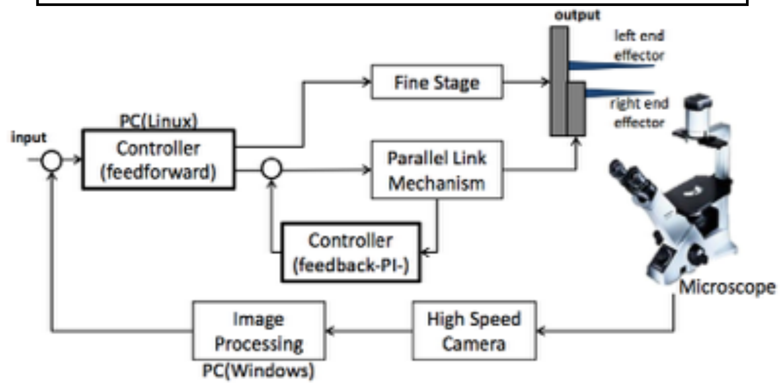
prediction of the behavior of the vibration is feasible:

- frequency,
- amplitude,
- settling time,
- etc.

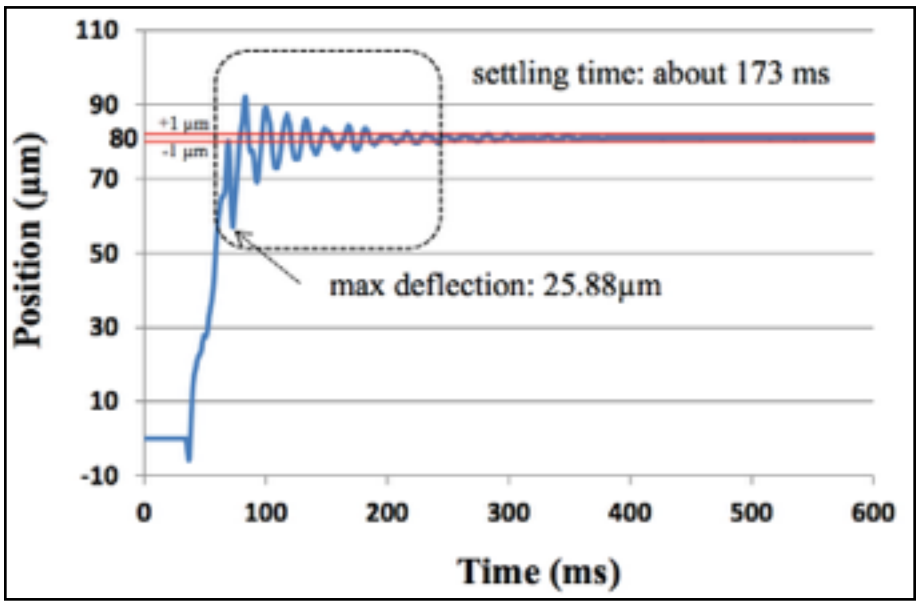


Feedforward Control

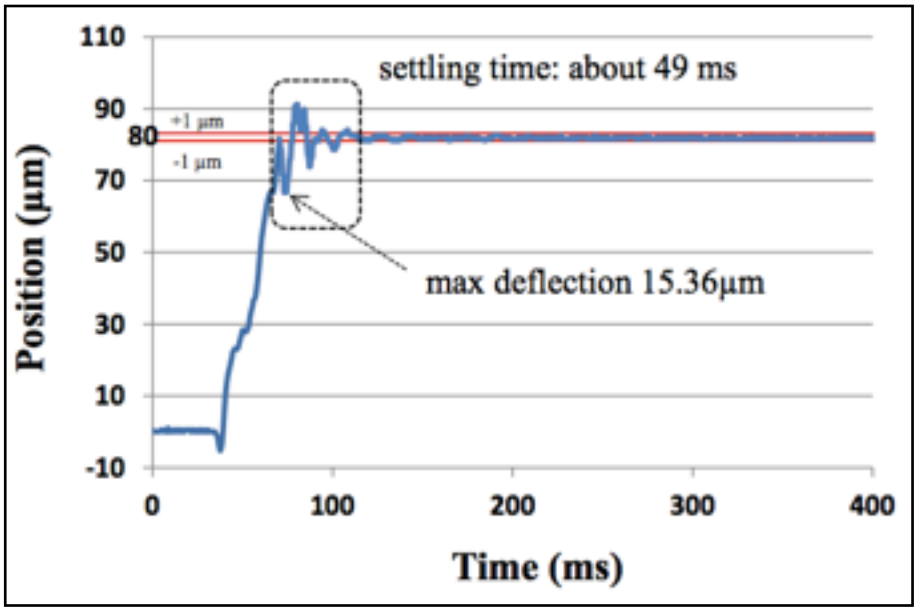
position control of the end effectors



open loop



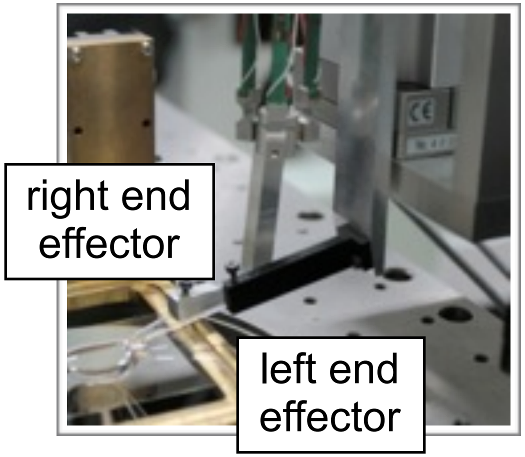
feedforward



Vibration Control Results

VIBRATION AND SETTLING TIME AFTER VIBRATION SUPPRESSION

	Left End Effector		Right End Effector	
	Deflection (μm)	Settling (ms)	Deflection (μm)	Settling (ms)
Original Values	5.76	226	29.1	192
Structural Design	1	20	25.88	173
Average Improvement (%)	83	91	12	10
Feedforward Control	-	-	15.36	49
Average Improvement (%)	-	-	47	74



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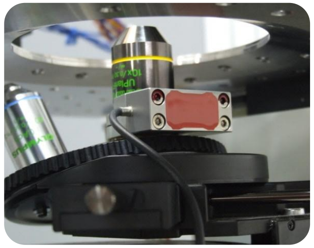
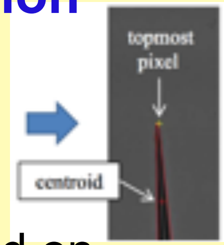
3D Object Detection at High-Speed

3D info is necessary where as under standard microscopy 2D is feasible.



End Effector Detection



- Top-down scanning
- Contour detection based on elongated orientation
- Determination of the tip (x, y)
- Definition of ROI automatically
- Template-matching for z-axis info

Target Object Detection

Depth from Border Intensity Variation (by Nghiem et al.)

- Top-down scanning
- Object's contour detection
- Stripe region defining
- Searching for the best focused image

Not Robust

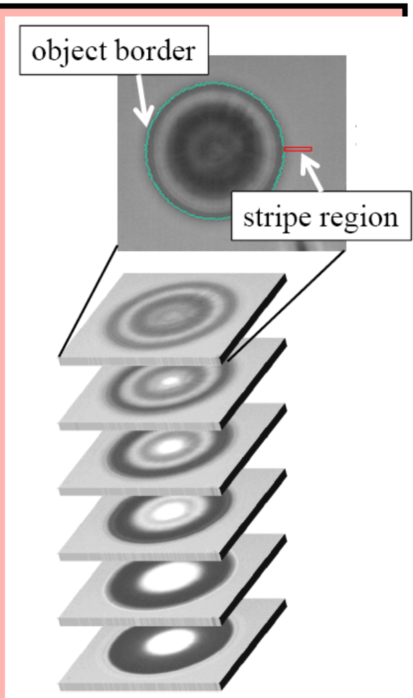


Image stack captured at different focal distances

High-Speed Detection of Object

Problem: Sometimes can not obtain depth information accurately, even for the same objects

Modification of the Detection Algorithm

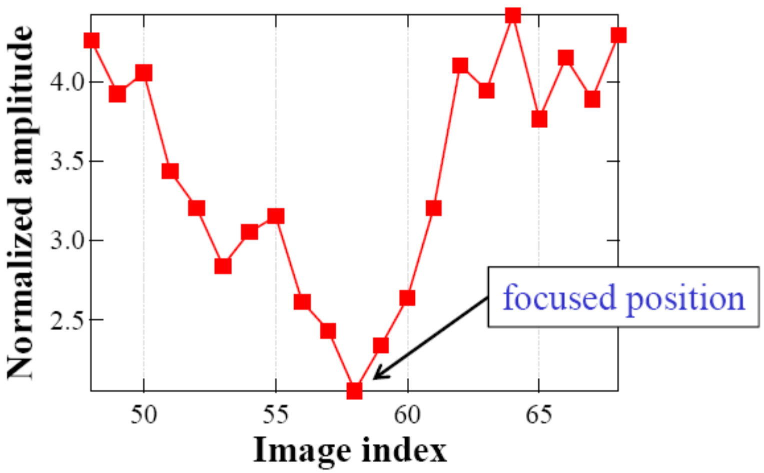
1. Instead of global thresholding --> adaptive thresholding
   - Uneven lighting condition in dynamic environment
2. All minimum point in the graph should be checked
   - There could be more than one local minimum

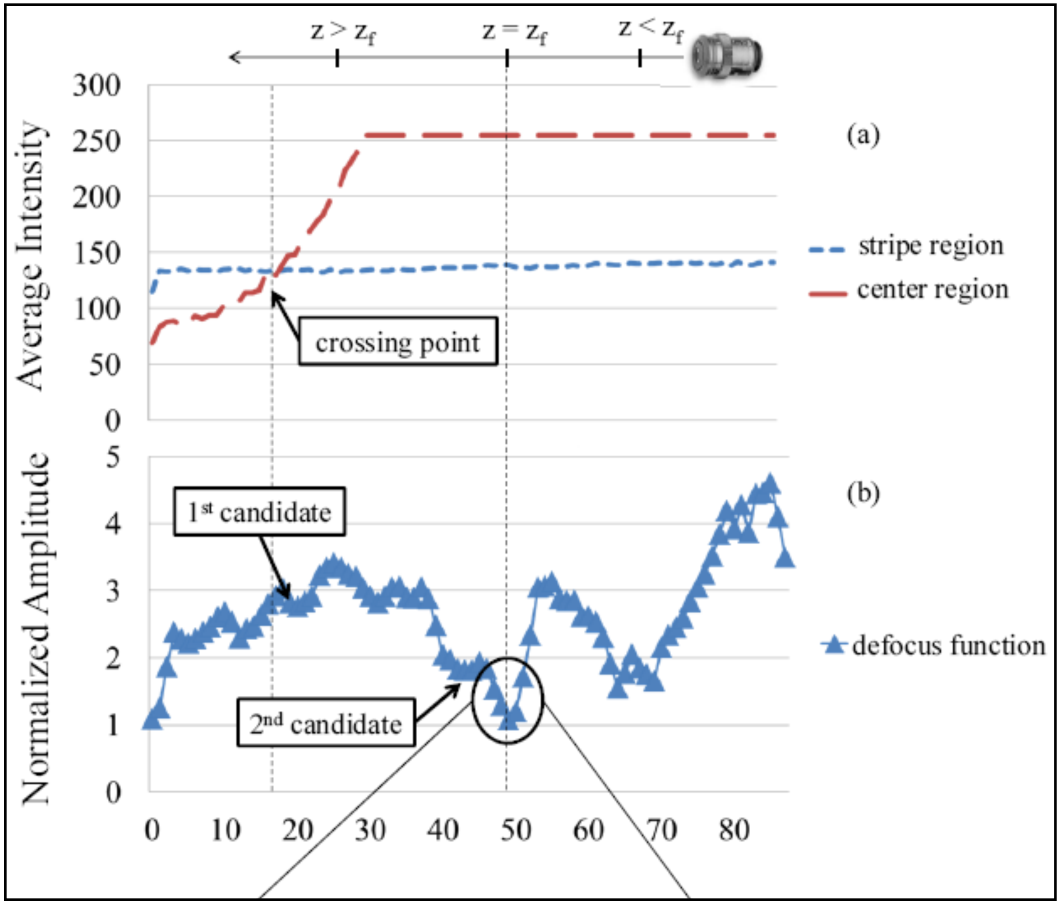
Result: Success rate 70% --> 96%

Comparison of Detection Algorithm

in reality

previous idea

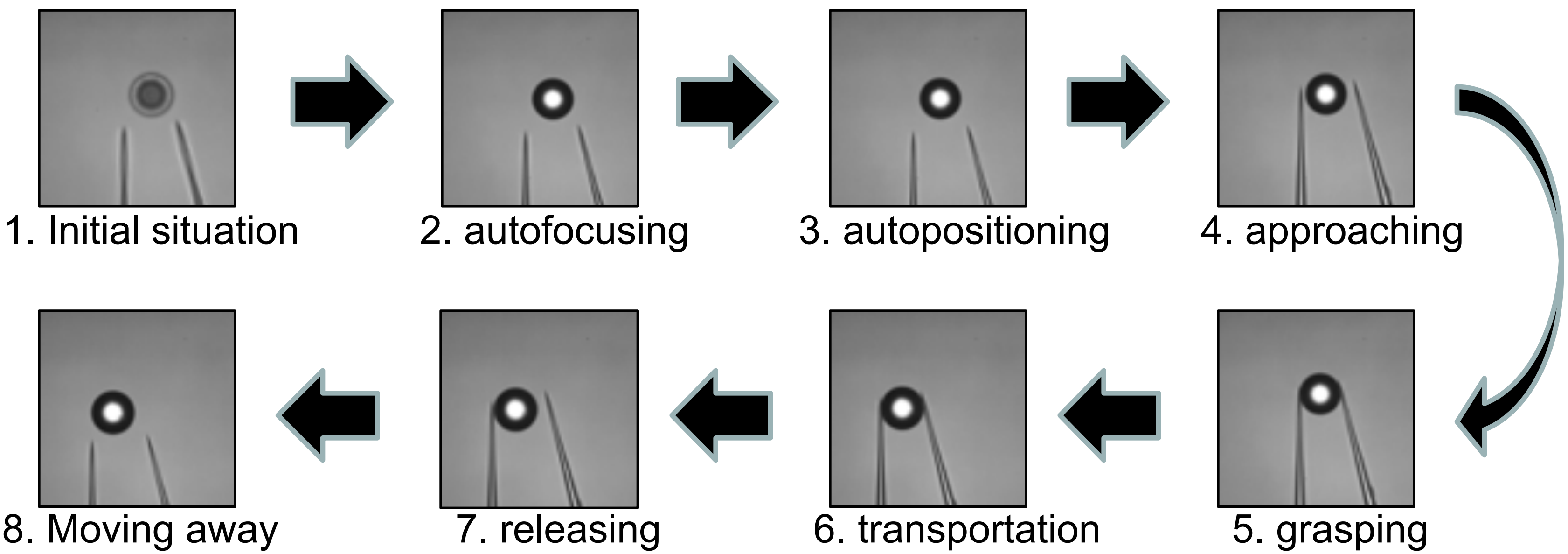




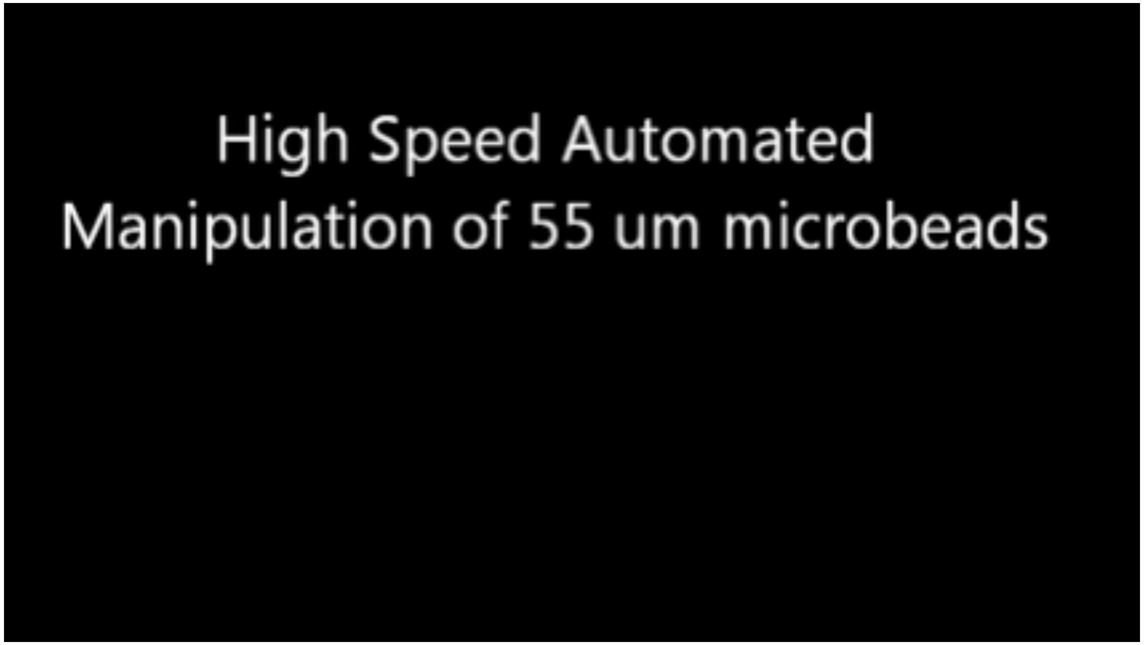
Pick-and-Place Task

Autopositioning
- Autofocusing
- z-alignment of end effectors and target object

Manipulation
- Approaching target object with vibration compensation
- Pick-and-place of target object

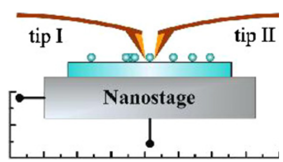


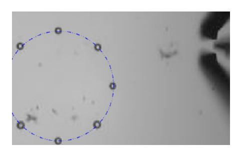
Pick-and-Place Task

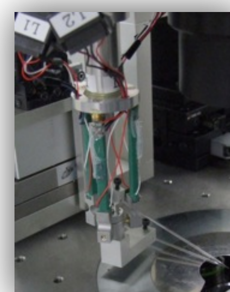


Video Speed: 0.1X

	Success rate	***Duration***
Autopositioning:	96%	340 ms
Grasping:	100%	290 ms
Transportation:	90%	
Releasing:	70%	340 ms



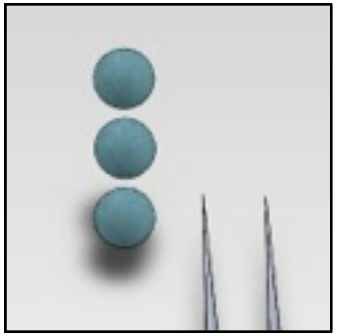




	Related Work1	Related Work2	Proposed System
Duration of Manipulation	48 s.	6 s.	0.97 s.

1D Array Realization

- **Target object :** 55 μm microbeads
- **Target structure:** 1D microsphere array (maybe aligned three microobjects), as workspace is very limited
- Pick and place automatically at high speed but repositioning is manual.



Cell Array in 1D

Experimental Result for 1D Microbeads Array

Contents

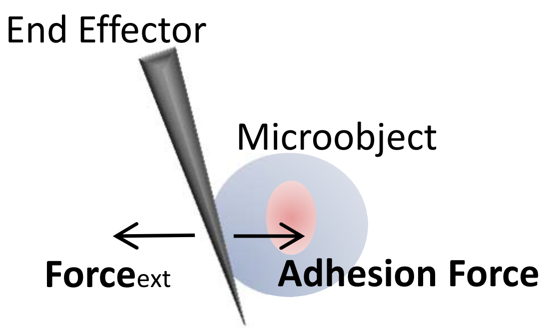
Conclusions

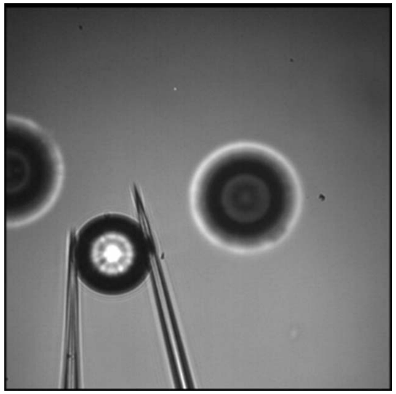
- Multi-Scalability Concept for a general purpose microhand
  - compatible with wide range of applications
- First high speed contact micromanipulation system

To promote micro-robotics / life science

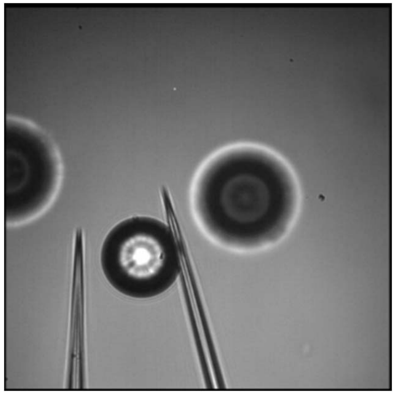
Contents

Active Releasing by Controllable Vibration

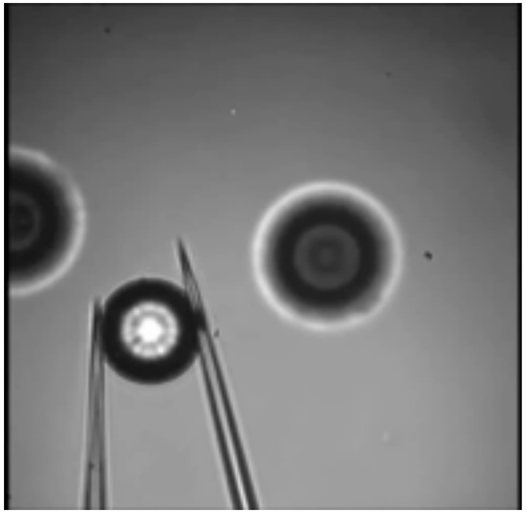


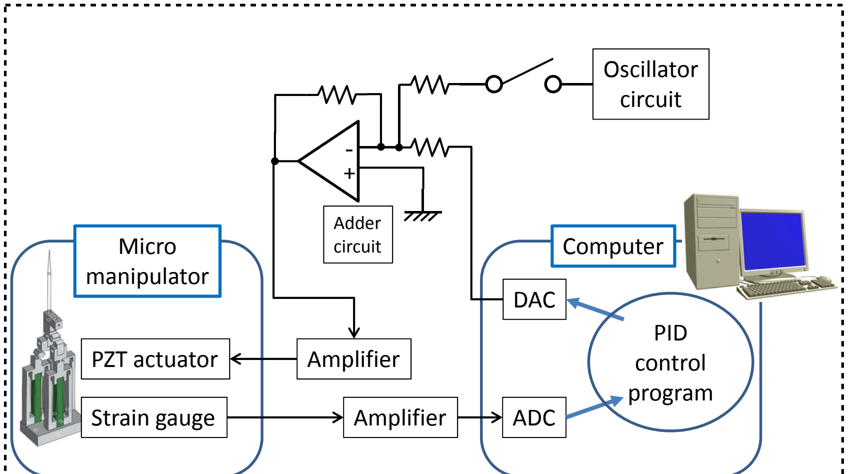


a)



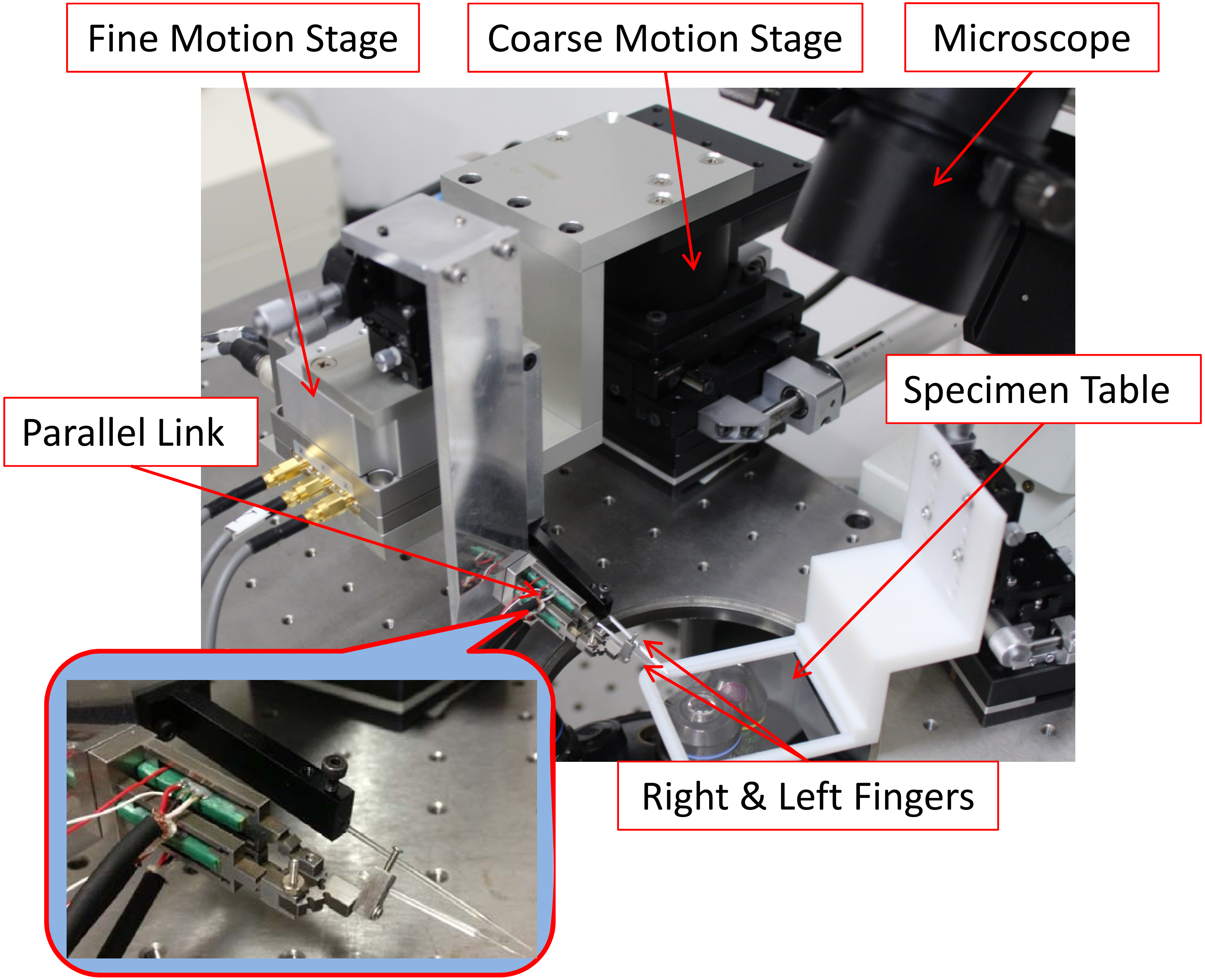
b)



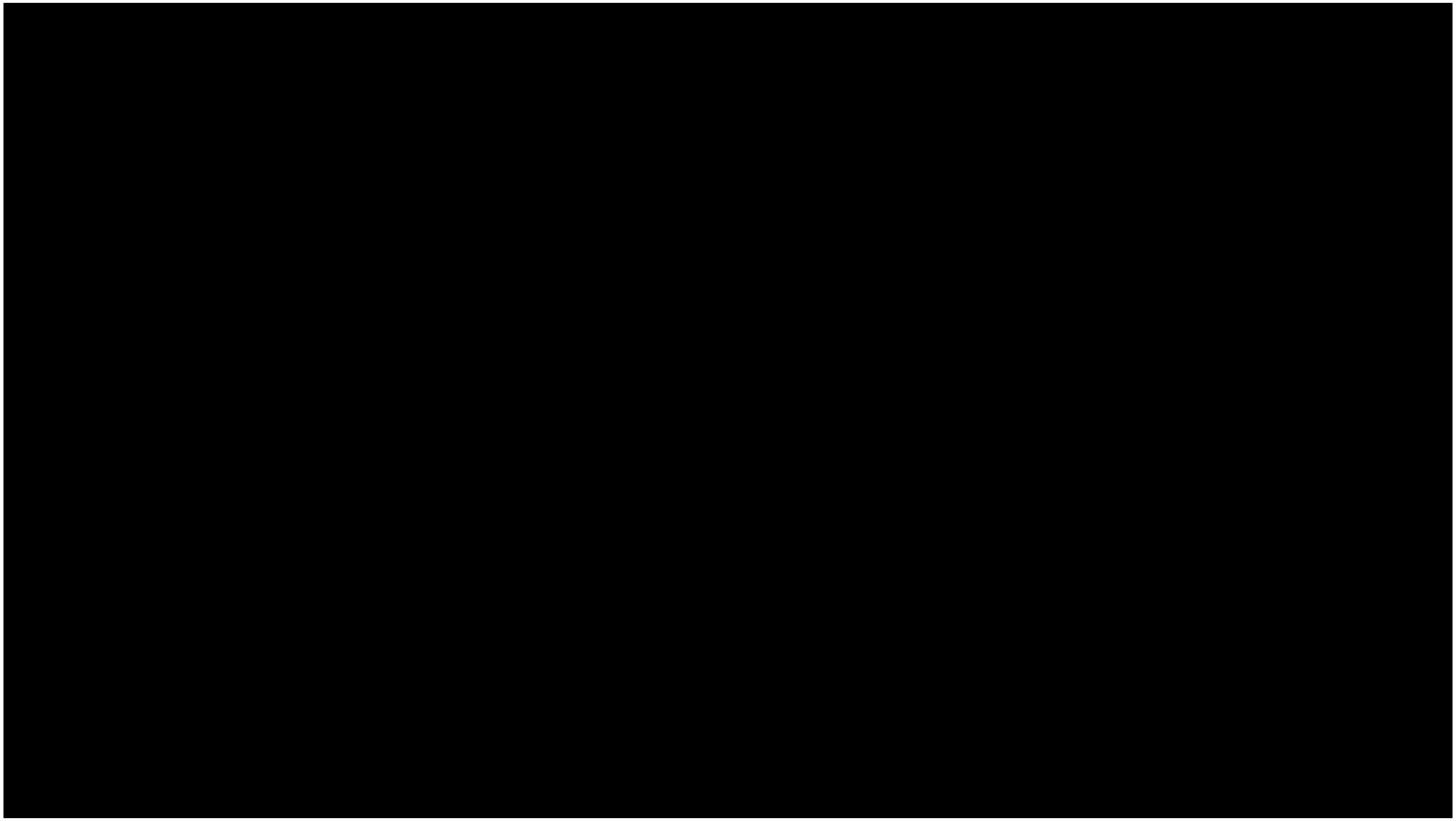


vibration control loop for the right end effectors

System Configuration



Active Releasing by Controllable Vibration



success rate: 84 %

Publications

Journals

1. Ebubekir Avci, Hiroyuki Yabugaki, Kazuto Kamiyama, Masaru Kojima, Yasushi Mae, Tatsuo Arai: “Precise Releasing of Biological Cells at High Speed Using Controllable Vibration”.(**In Preparation**).

2. Ebubekir Avci, Kenichi Ohara, Yasushi Mae, Tatsuo Arai, “Micromanipulation in a Second Using Two-fingered Microhand”, **IEEE Transaction on Industrial Electronics**(**Accepted**).

3. Ebubekir Avci, Chang-Nghiem Nguyen, Kenichi Ohara, Yasushi Mae, Tatsuo Arai, “Analysis and Suppression of Residual Vibration in Microhand for High-Speed Single-Cell Manipulation”, **International Journal of Mechatronics and Automation**, vol. 3, no. 2, pp. 110-117, 2013.

4. Ebubekir Avci, Kenichi Ohara, Tomohito Takubo, Yasushi Mae, Tatsuo Arai, “Development of Multi-Scalable Microhand System with Precise Motion”, **Journal of Robotics and Mechatronics** vol. 25, no.1, pp. 183-191, 2013.

5. Chang-Nghiem Nguyen, Kenichi Ohara, Ebubekir Avci, Tomohito Takubo, Yasushi Mae, Tatsuo Arai, “Real-time precise 3D measurement of micro transparent objects using All-In-Focus imaging system”, **Journal of Micro – Nano Mechatronics**, vol. 7, pp. 21-31, 2012.

Publications

International Conferences (full paper - reviewed)

1. “Vibration Reduction of Microhand for Transporting Operation”, (**ISFA 2014**).
2. “Dynamic Releasing of Biological Cells at High Speed Using Parallel Mechanism to Control Adhesion Forces”, (**ICRA 2014**).
3. “Contact Manipulation of Microsize Objects at High Speed”, (**IROS 2013 Workshop-Invited Speaker**).
4. “Towards High Speed Automated Micromanipulation”, (**ICRA 2013**).
5. “Towards High Speed Microassembly Using Two-fingered Microhand”, (**ICRA 2013 Workshop**).
6. “Development of End Effector for Cell Manipulation with Two-fingered Micro-hand”, (**MHS 2012**).
7. "Vibration Analysis of Microhand for High Speed Single Cell Manipulation”, (**ICMA 2012**).
8. "High Speed Micromanipulation System with Multi-Scalability",(**ROBIO 2011**).**Finalist of T. J. Tarn Best Paper in Robotics**
9. "Automated Micromanipulation of a Microhand with All-In-Focus Imaging System", (**IROS 2011**).
10. "Workspace Optimization for Multi-Scale Micromanipulation System", (**MHS 2010**).
11. “A new Multi-Scale Micromanipulation System with Dexterous Motion”, (**MHS 2009**).

Domestic Conferences

1. “Vibration Analysis of A Microhand Which Has A New Parallel Mechanism” (**RSJ 2013**).
2. "High-Speed 3D Detection and Tracking of a Two-Fingered Microhand", (**SICE 2011**).
3. “Optimum Design for Multi-Scalable Microhand”, (**RSJ 2010**).
4. “A new Multi-Scale Micromanipulation System”, (**RSJ 2009**).

Thank you for your kind attention