Macro-micro manipulators

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Quiz (10 pts)

- (4 pts) Explain why it is important to have continuous and globally consistent behavior for redundant manipulators?
- (3 pts) Define a cost function that optimizes for repetitive motion
- (3 pts) What is the different between pointwise, pathwise and globally consistent IK resolution?

Consistent and predictable robot behavior

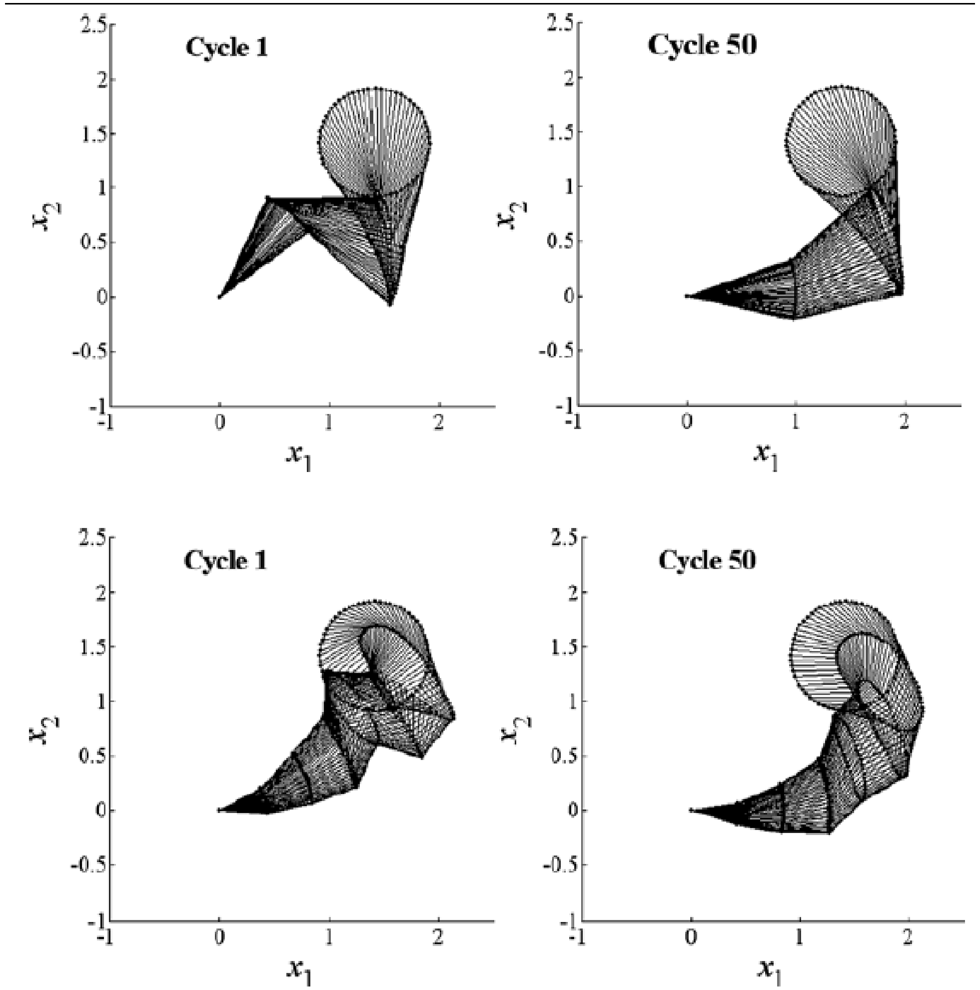
- To be consistent and predictable, robot motion needs to be repetitive in both task and configuration space
  - Close path in task space → close path in configuration space
- Unpredictable robot behavior
  - Joint angle drift
  - Readjusting the manipulators‘ configuration with self-motion at every cycle → inefficient

Closed-loop pseudo-inverse

- Compute the joint position through time integration pseudo-inverse

$$\Delta q = \mathbf{J}^{\dagger} \Delta x$$

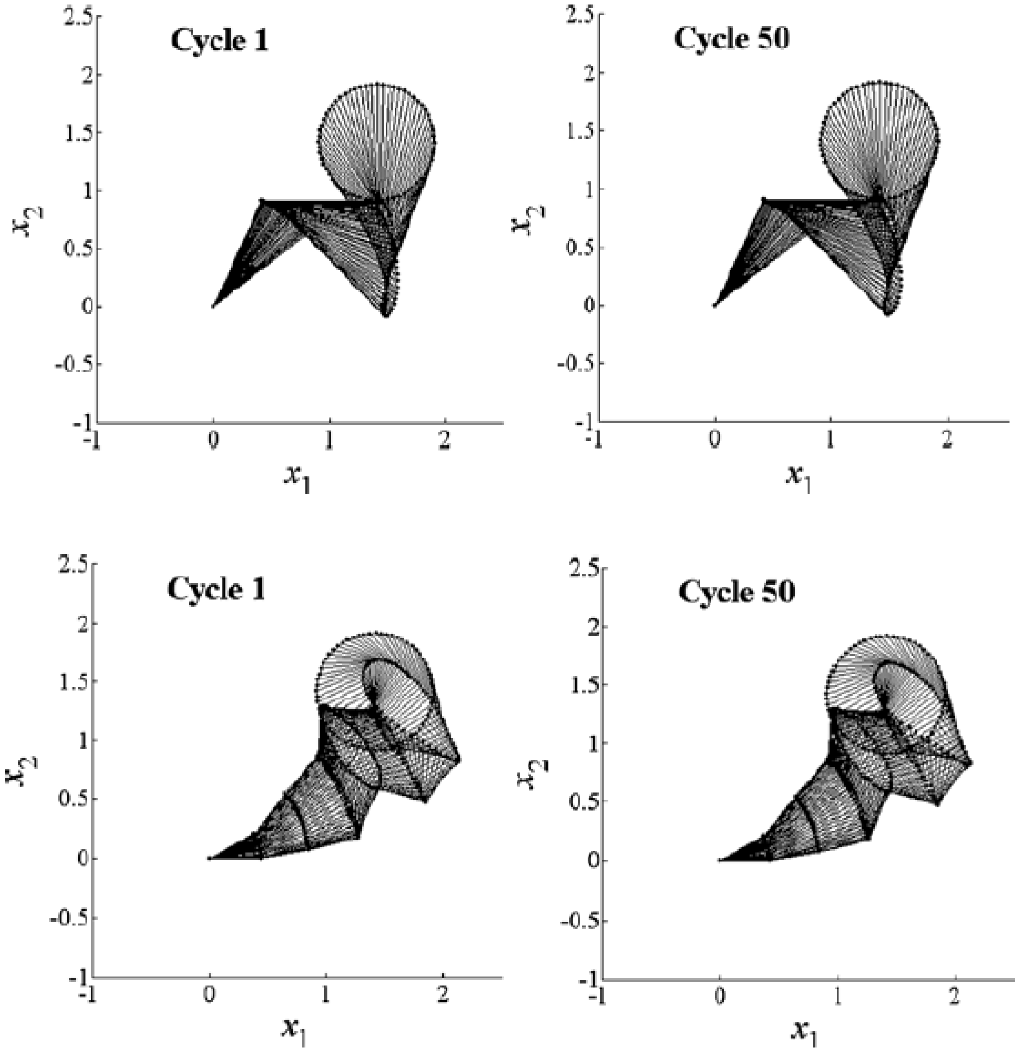
Unpredictable, not repeatable arm configurations



Simulation Result

CLGA	$r = 0.7$	$r = 1.0$	$r = 2.0$
$3R$	9.96E−04	8.84E−04	1.08E−03
$4R$	7.12E−04	7.38E−04	5.70E−04
$5R$	6.73E−04	5.42E−04	6.15E−04
$6R$	5.98E−04	4.81E−04	8.57E−04
$7R$	1.26E−03	5.44E−04	5.39E−04

CLP	$r = 0.7$	$r = 1.0$	$r = 2.0$
$3R$	1.35E+01	6.41E+00	5.80E−01
$4R$	8.2E+00	4.4E+00	5.8E−01
$5R$	7.2E+00	2.2E+00	4.4E−01
$6R$	5.4E+00	4.9E+00	3.0E−01
$7R$	4.2E+00	2.4E+00	2.0E−01



Cost function for GA

$$f_1 = A\dot{\mathbf{q}}^{\mathrm{T}}\dot{\mathbf{q}} + B\left(\frac{\mathbf{q}-\mathbf{q}_0}{\Delta t}\right)^{\mathrm{T}}\left(\frac{\mathbf{q}-\mathbf{q}_0}{\Delta t}\right)$$

Weighted least squares

Minimize the displacement between initial and current joint configurations over a time step

Multi-objective optimization

- Formulation of Optimization Problem

$$\text{minimize} \quad \frac{(\dot{\theta}+\mathbf{p})^{\mathrm{T}}(\dot{\theta}+\mathbf{p})}{2}$$

→ **Repetitive motion**

$$\text{subject to} \quad J_{\mathrm{e}}(\theta)\dot{\theta} = \dot{\mathbf{r}}_{\mathrm{d}}$$

→ **Tracking EE trajectory**

$$J_{\mathrm{o}}\dot{\theta} \leqslant \mathbf{b}_{\mathrm{o}}$$

→ **Obstacle constraints**

$$\zeta^{-} \leqslant \dot{\theta} \leqslant \zeta^{+}$$

→ **Joint limit**

Formulation of Optimization Problem

$$\begin{aligned} \text{minimize} \quad & \frac{(\dot{\theta} + \mathbf{p})^{\mathrm{T}}(\dot{\theta} + \mathbf{p})}{2} \\ \text{subject to} \quad & J_{\mathrm{e}}(\theta)\dot{\theta} = \dot{\mathbf{r}}_{\mathrm{d}} \\ & J_{\mathrm{o}}\dot{\theta} \leqslant \mathbf{b}_{\mathrm{o}} \\ & \zeta^{-} \leqslant \dot{\theta} \leqslant \zeta^{+} \end{aligned}$$

Repetitive motion

$$\mathbf{p} = \eta(\theta(t) - \theta(0))$$

$$\frac{\|\dot{\theta}(t) + \eta(\theta(t) - \theta(0))\|_2^2}{2}$$

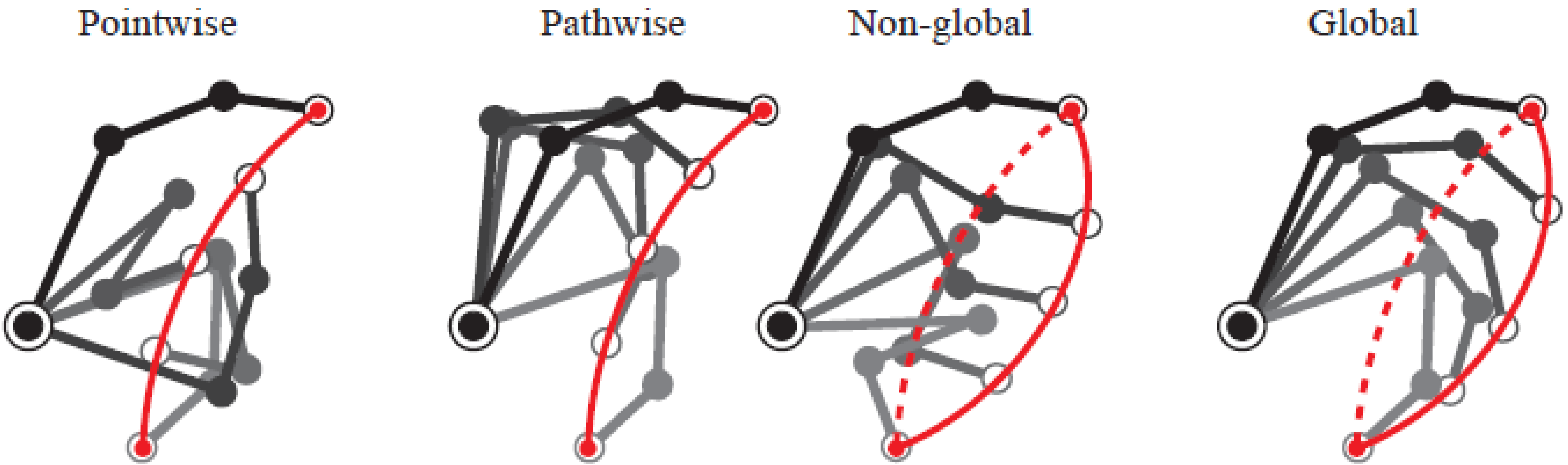
$$\mathbf{z}(t) = \theta(t) - \theta(0)$$

$$\eta > 0 \in R$$

$\Rightarrow$ $\dot{\mathbf{z}}(t) = -\eta\mathbf{z}(t)$ $\Rightarrow$ $\|\mathbf{z}(t)\|_2 = \exp(-\eta t)\|\mathbf{z}(0)\|_2 \to 0$

$$\theta(t) = \theta(0), \; t \to \infty$$

Continuous, globally consistent redundancy resolution



Optional Assignment:
Student talk on Trajectory Optimization

Optional assignment

- Student talk on "trajectory optimization"
  - If you need to make up for your low-score/late submission assignment
  - Allow maximally 3 students to team up, 10 min talk each
  - Submit your slides with notes on Canvas by April 2nd
- Reference:
  - http://www.matthewpeterkelly.com/tutorials/trajectoryOptimization

Macro-micro manipulators

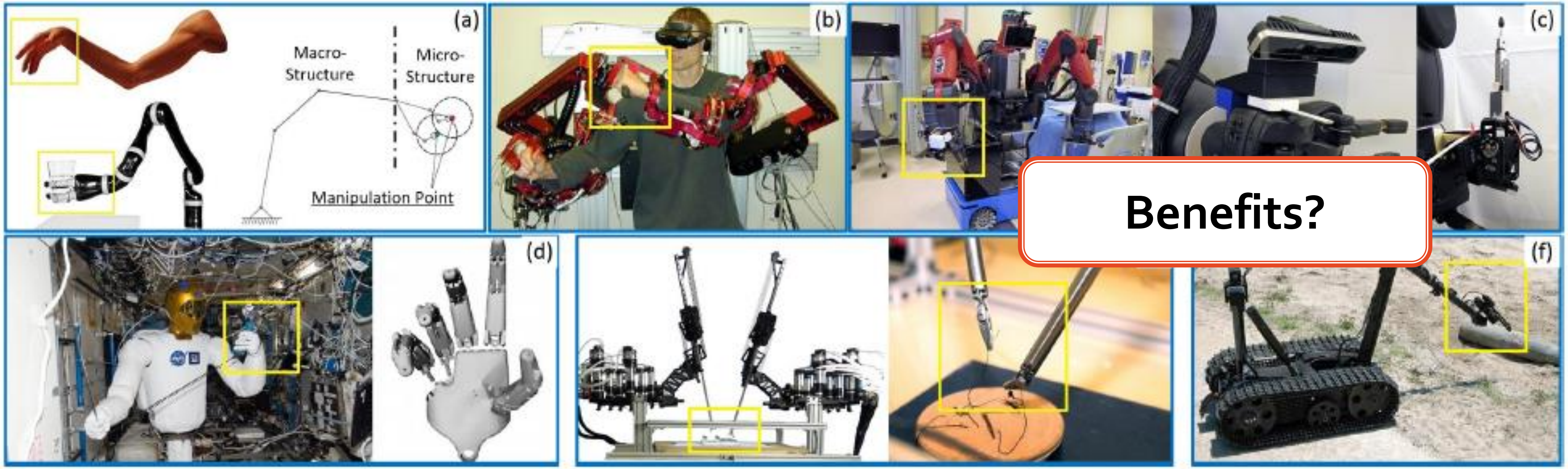
Research Questions

- How to resolve the kinematic redundancy?
- <u>How to coordinate macro- and micro-structures?</u>
  - Arm-hand structure
  - Body-arm structure
- How to handle bimanual coordination?

Overview

- How to coordinate macro- and micro-structures
  - Macro-micro manipulators
  - Mobile manipulator
  - Loco-manipulation

Macro-micro manipulator system



Benefits?

- Reduce endpoint inertia
- Inherent stable physical configuration for force control

Related work

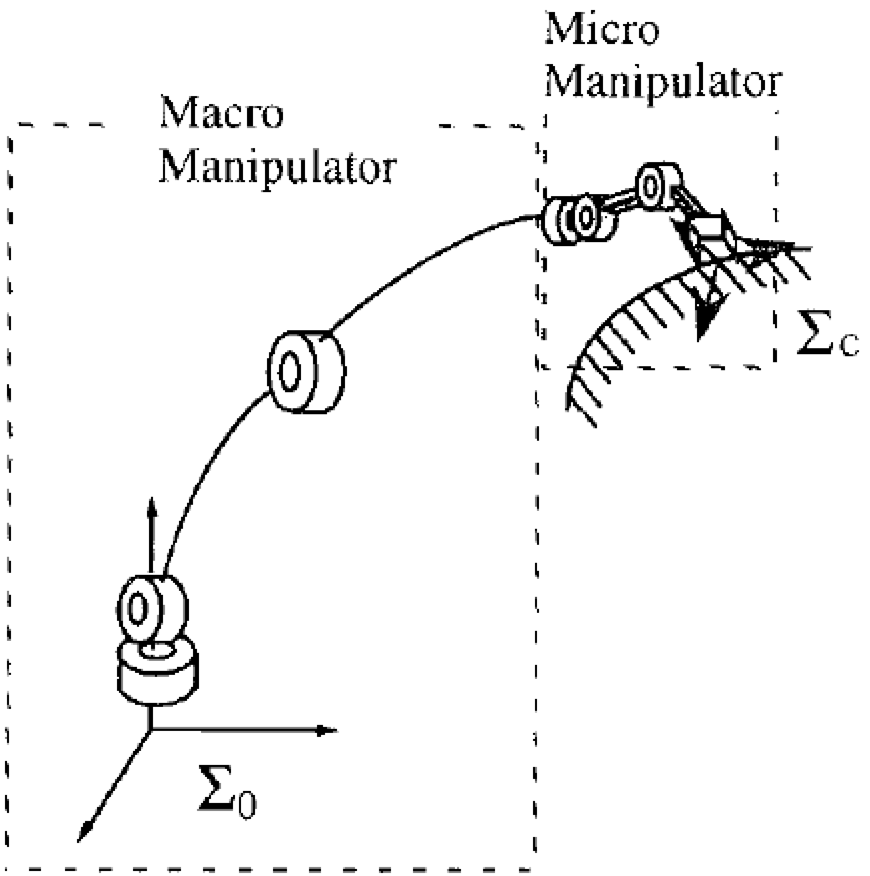
- Macro-micro structures
  - Flexible-macro/rigid-micro manipulators [1,3]
  - Compliant base manipulators [4]
  - Coarse/fine dual-stage manipulators [5, 6, 7]
- Control strategy
  - Additional task constraints [8]
  - Optimizing manipulability[9,10]

Early work

- Motivated by industry robots
  - Long arms for improved high-mobility
  - Light arm in comparison to their load
  - Elasticity – need compensation for arm deformation and vibration

Flexible-macro rigid-micro manipulators

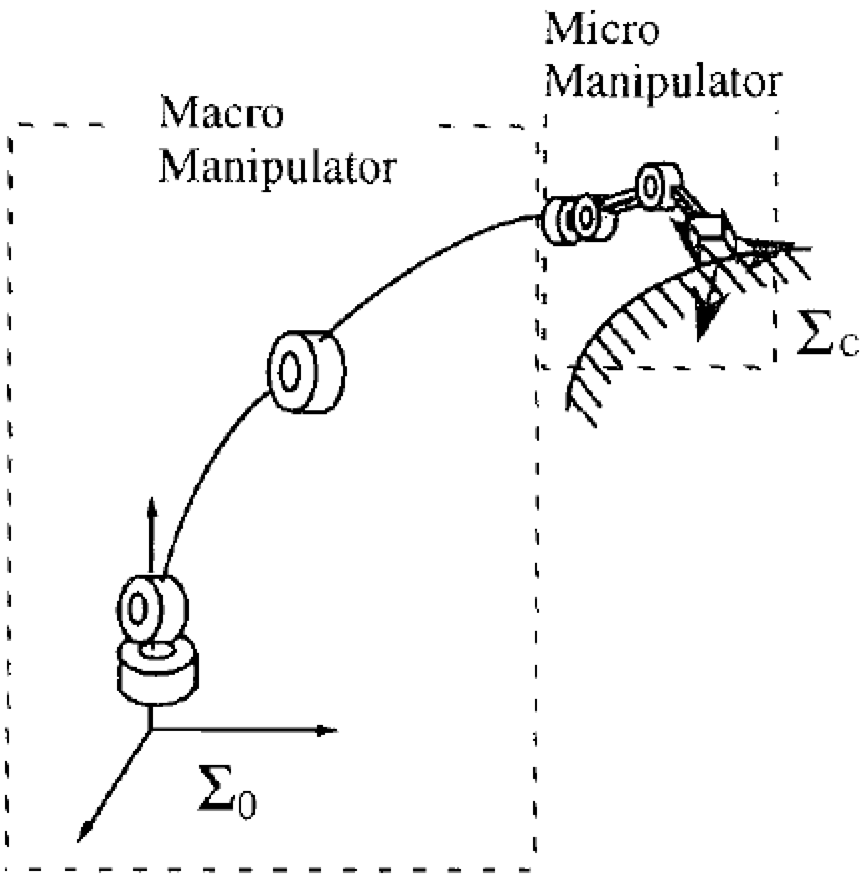
- Macro-structure
  - Flexible arm of wide motion range
  - Neither fast nor precise due to flexibility
- Micro-structure
  - Limited motion range
  - Fast and precise motion



Tesla Robots

Hybrid position/force control for flexible macro-micro manipulators [1]

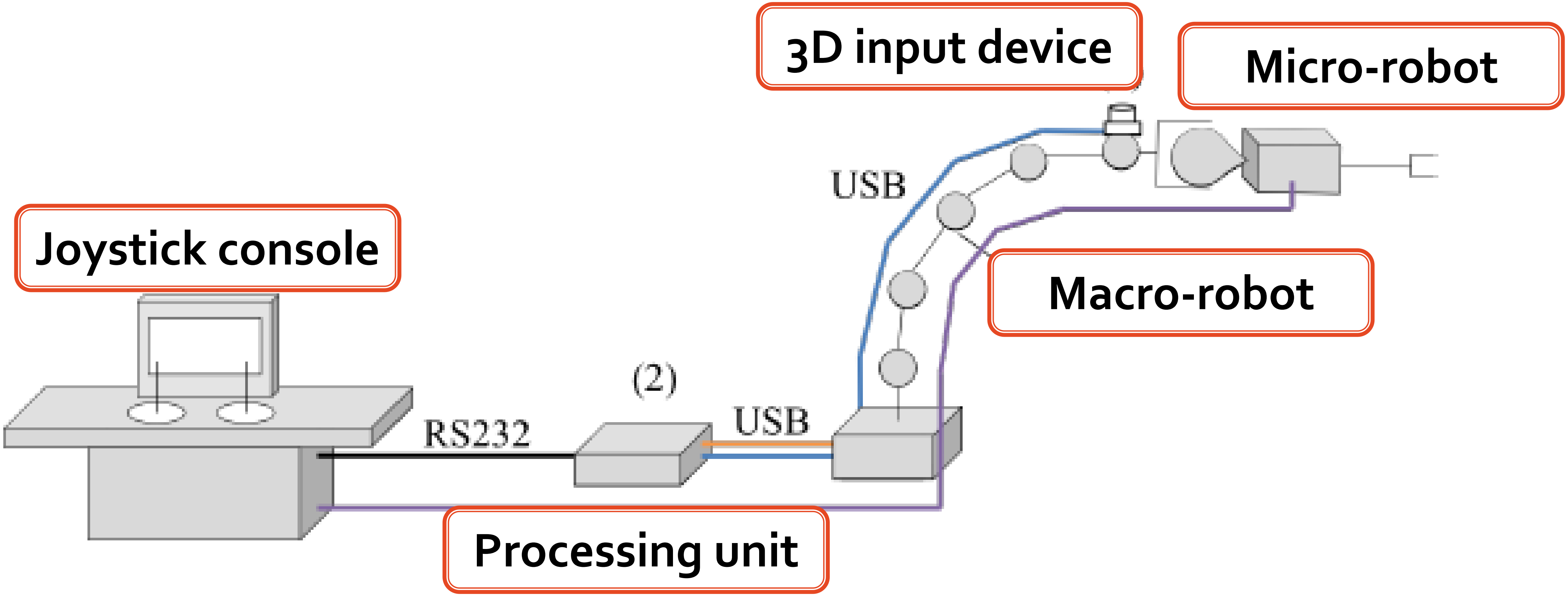
- Macro-structure
  - Roughly realize the desired trajectory, and suppress vibration
- Micro-structure
  - Compensate for the position and force errors due to the elasticity in the macro-structure



Recent Example

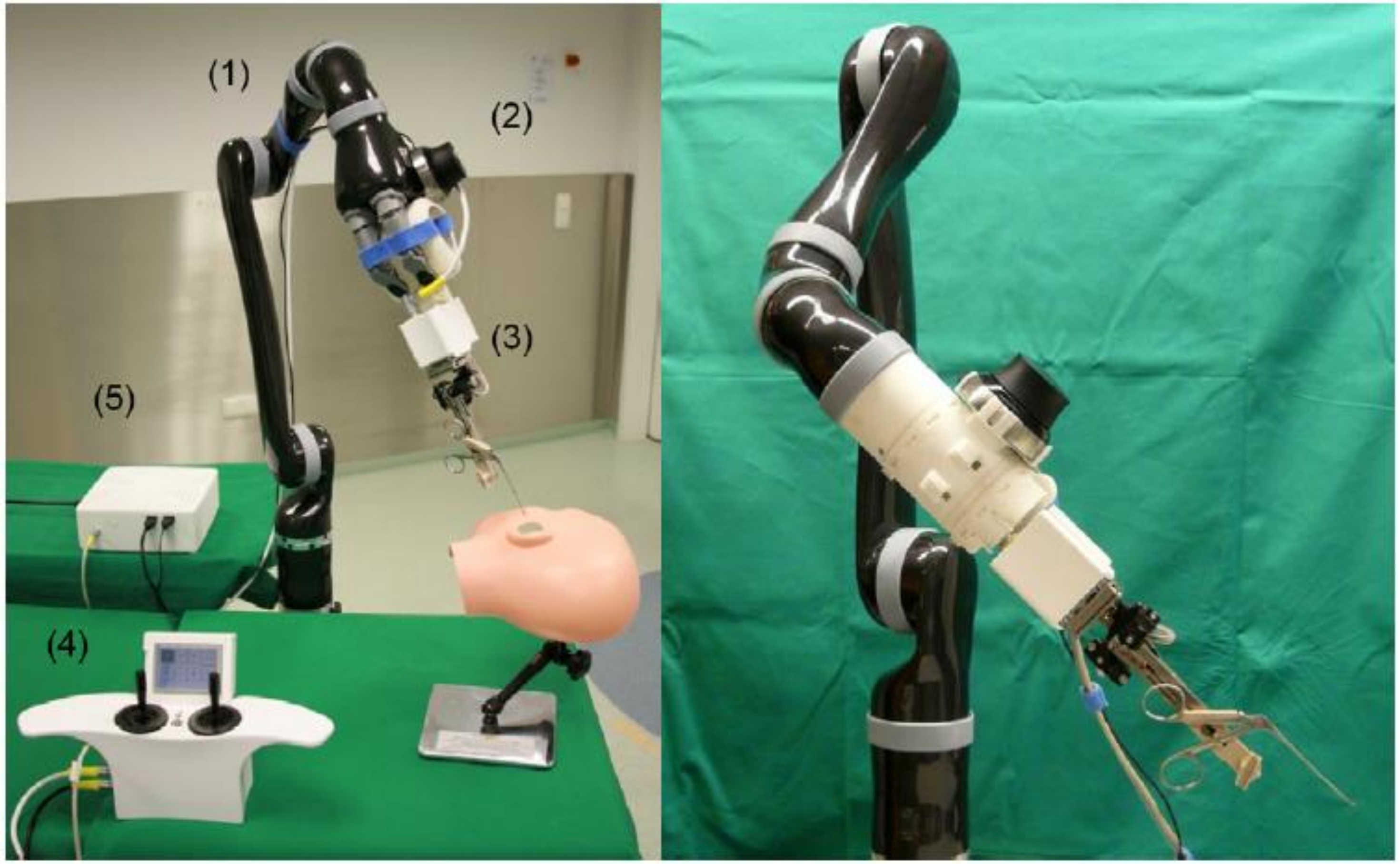
- A modular micro-macro robot system for ear surgery [2]
  - Handheld micro instruments
  - Sub-millimeters precision
  - Limited view due to narrow ear canal
  - Delicate intervention

Micro-Macro Telemanipulator System



Micro-Macro Telemanipulator System

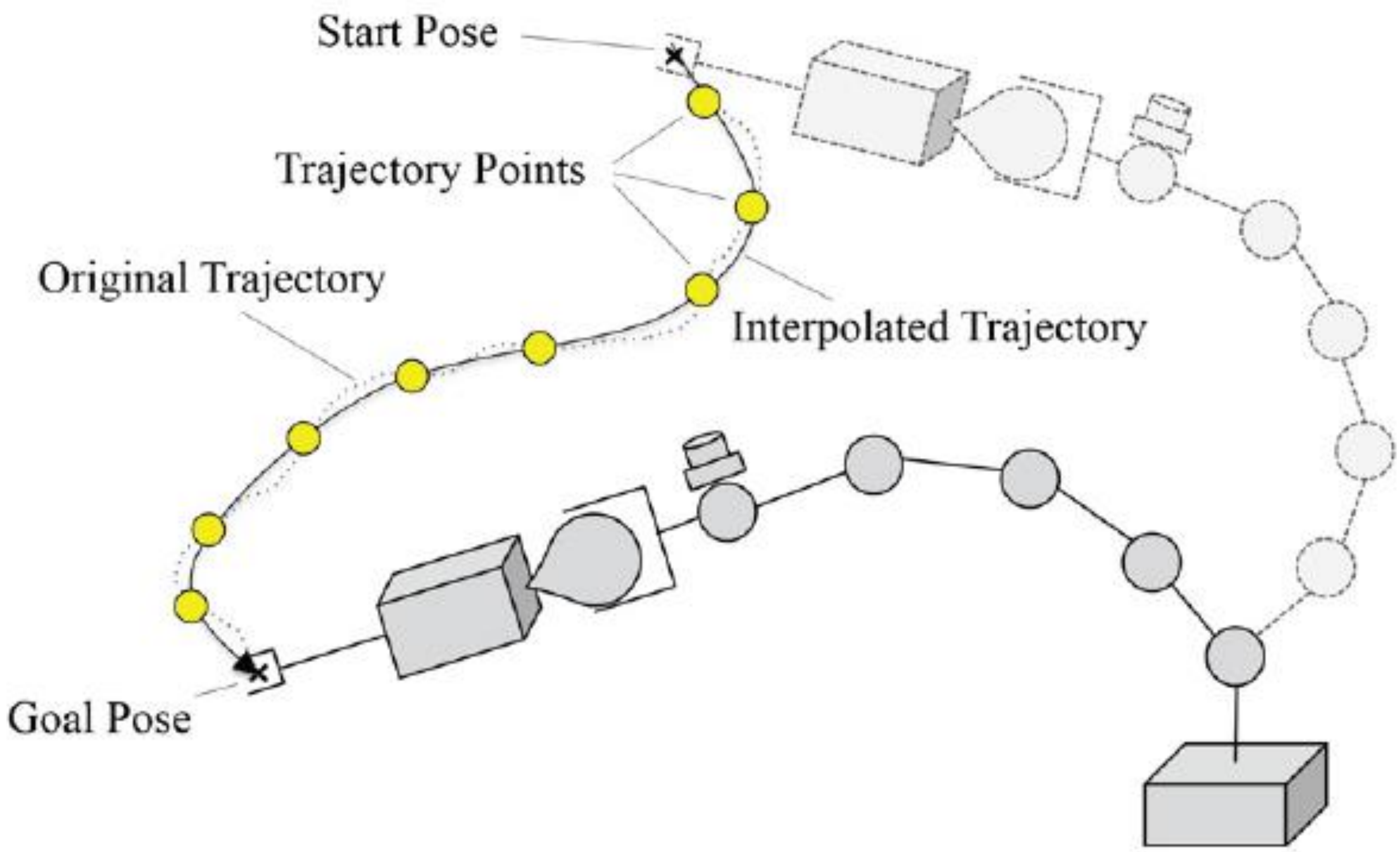
- Hand-on control
  - 3D mouse
- Teleoperation
  - Joysticks



Separate control for macro/micro-structure

No.	Control Mode	Involved Robots	Input Mode
1	Coarse Alignment with Path Recording	Macro	Hands-On
2	Coarse Alignment along Recorded Path	Macro	Hands-On
3	Rotation	Macro	Telemanipulated
4	Translation	Macro	Telemanipulated
5	Fine Manipulation 1:1	Micro	Telemanipulated
6	Fine Manipulation 1:3	Micro	Telemanipulated
7	Fine Manipulation 1:5	Micro	Telemanipulated
8	Workspace Expansion	Macro, Micro	Telemanipulated

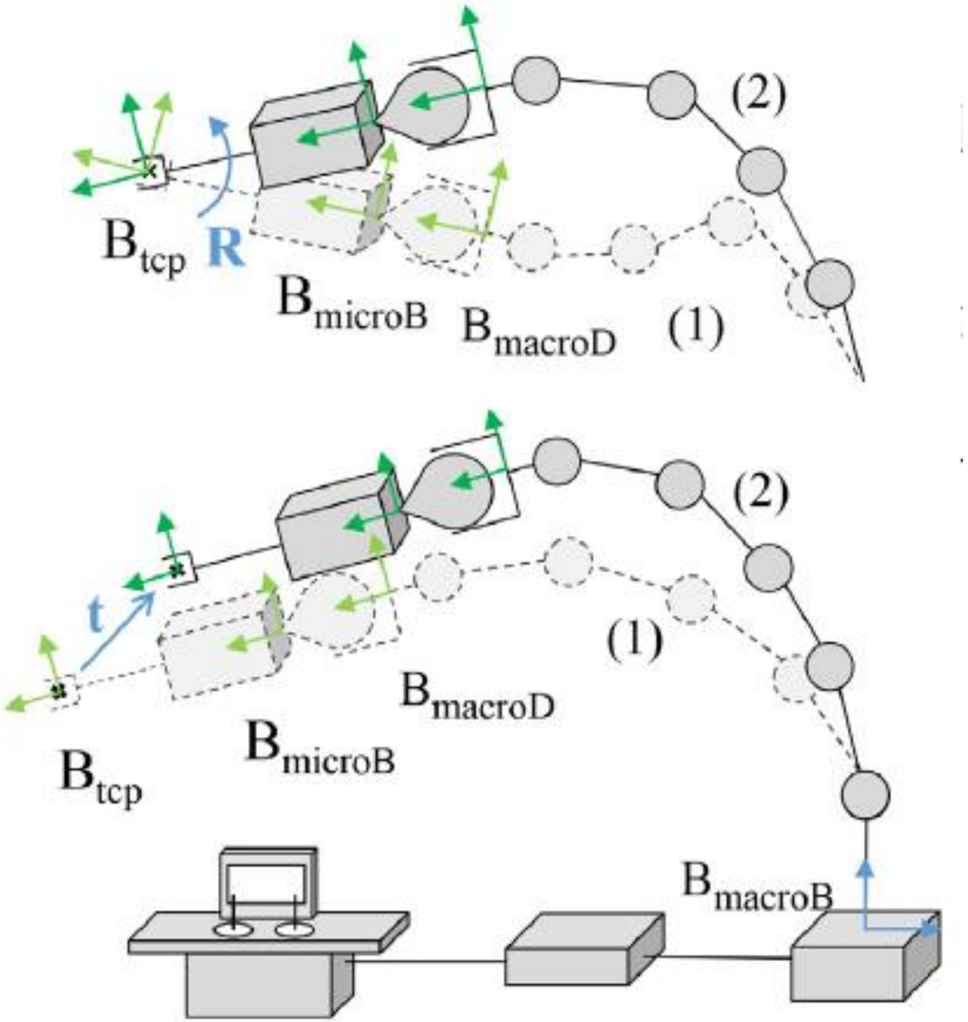
Coarse alignment



Macro- and micro-manipulator control

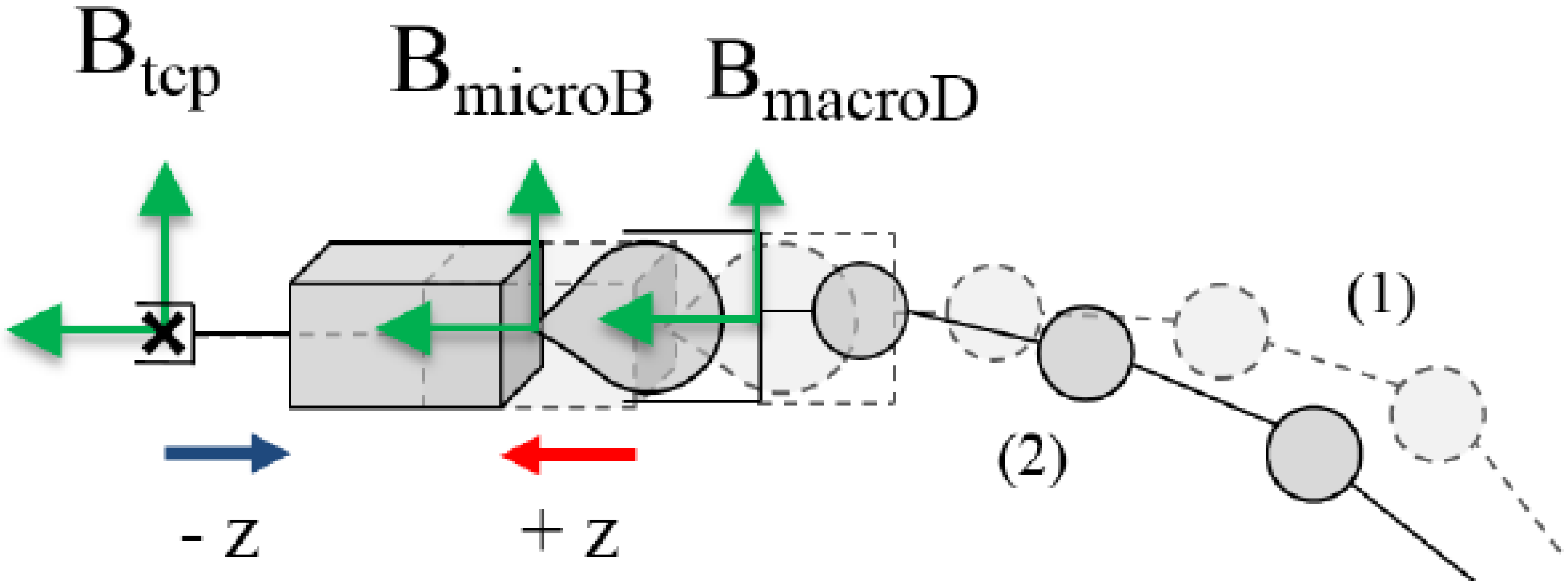
- Control Macro-manipulator
  - Rotation about instrument tip (TCP)
  - Translation along micro robot axis

- Fine manipulation
  - Macro-manipulator remains motionless
  - Three different scaling for control input

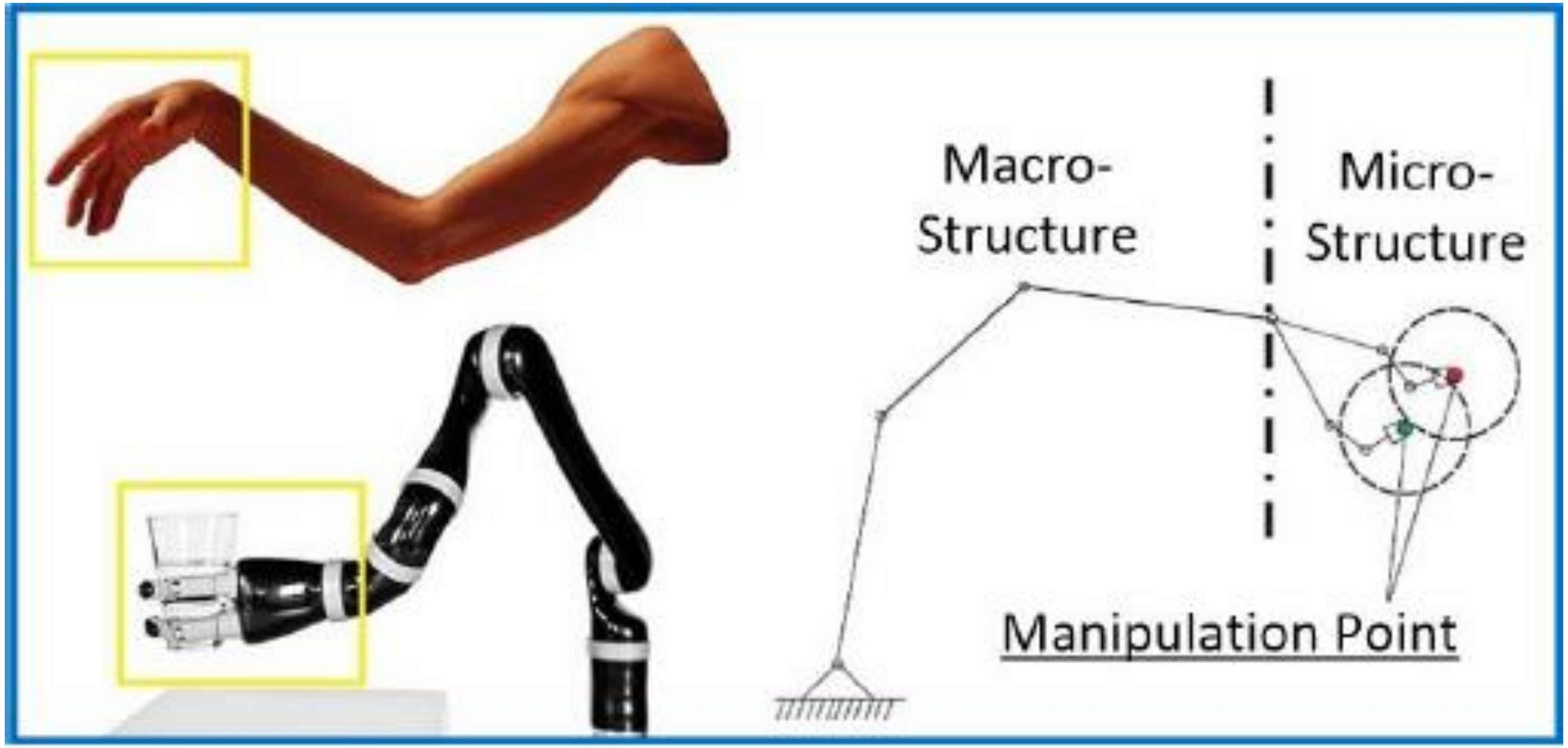


Workspace expansion

- Micro-structure has limited workspace
  - Ear canal = 25~35 mm, while the micro-robot = 20 mm



A control strategy inspired by hand-arm coordination



Optimize micro-structure manipulability [10]

- Whole manipulator

$$\dot{\boldsymbol{p}}_f = \boldsymbol{J} \cdot \dot{\boldsymbol{\theta}}$$

- Macro-structure

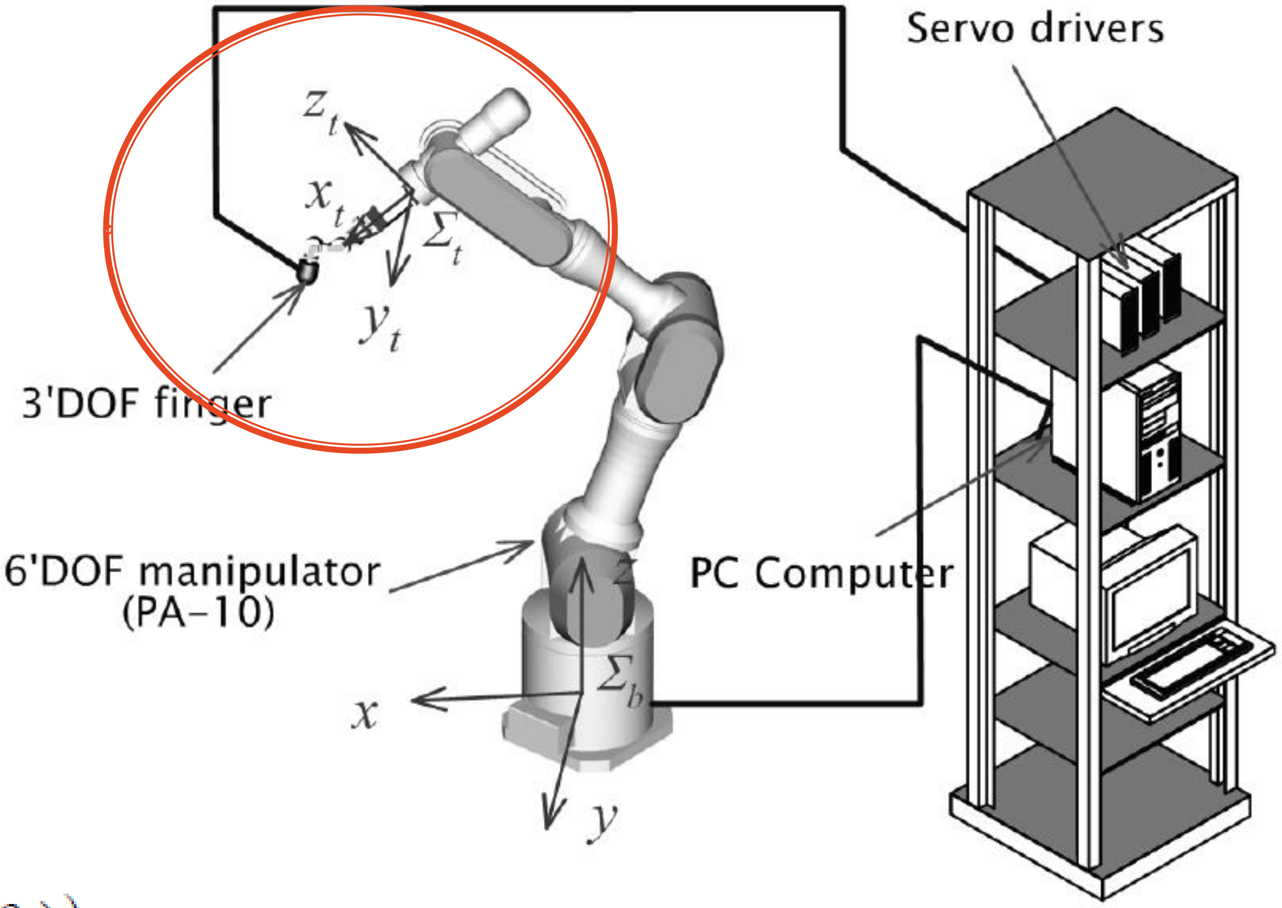
$$\dot{\boldsymbol{p}}_t = \boldsymbol{J}_a \cdot \dot{\boldsymbol{\theta}}_a$$

- Micro-structure

$${}^t\dot{\boldsymbol{p}}_f = \boldsymbol{J}_f \cdot \dot{\boldsymbol{\theta}}_f$$

- Finger manipulability

$$W_f = \sqrt{\det(\boldsymbol{J}_f(\boldsymbol{\theta}_f) \cdot \boldsymbol{J}_f^T(\boldsymbol{\theta}_f))}$$
$$= l_2 l_3 \sin\theta_3 (l_1 + l_2 \sin\theta_2 + l_3 \sin(\theta_2 + \theta_3))$$



Heuristic Method

- Choose a reference finger manipulability W_{fr}
  - If $W_f(k) \geq W_{fr}$, the finger will keep moving and tracing the desired trajectory, while the arm maintains its previous position
  - If $W_f(k) < W_{fr}$, moving the arm becomes necessary

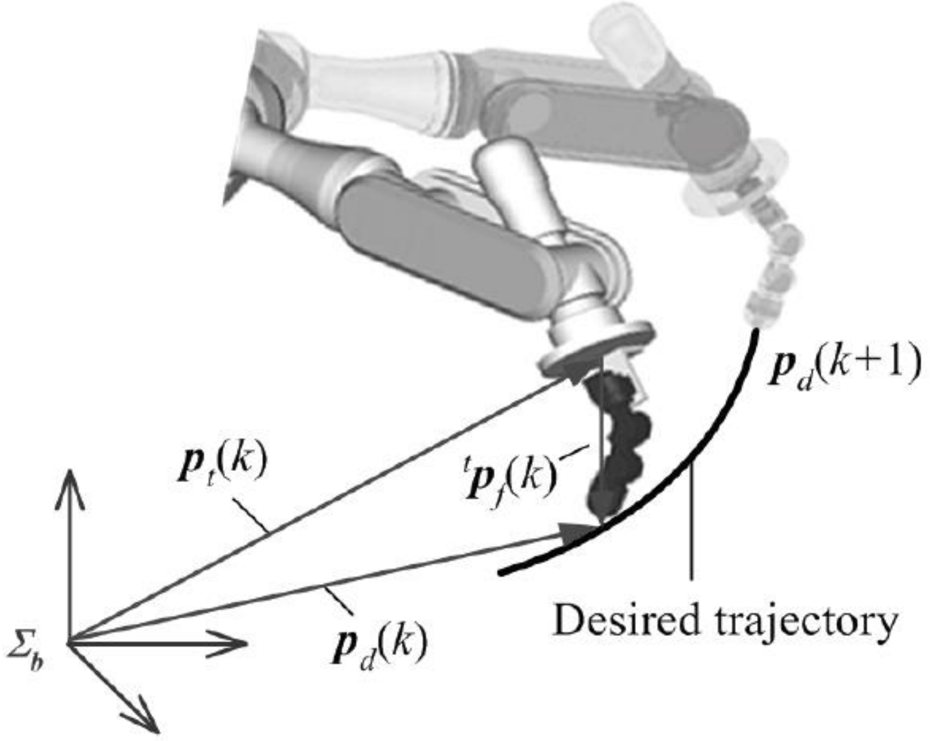
Heuristic Method

- At time $t=kT, (k=0, 1, 2, \cdots)$

$$\boldsymbol{p}_d(k) = \boldsymbol{s}_1 \boldsymbol{p}_t(k) + \boldsymbol{R}_t \cdot {}^t\boldsymbol{p}_f(k)$$

- Where

$$\boldsymbol{s}_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix}$$



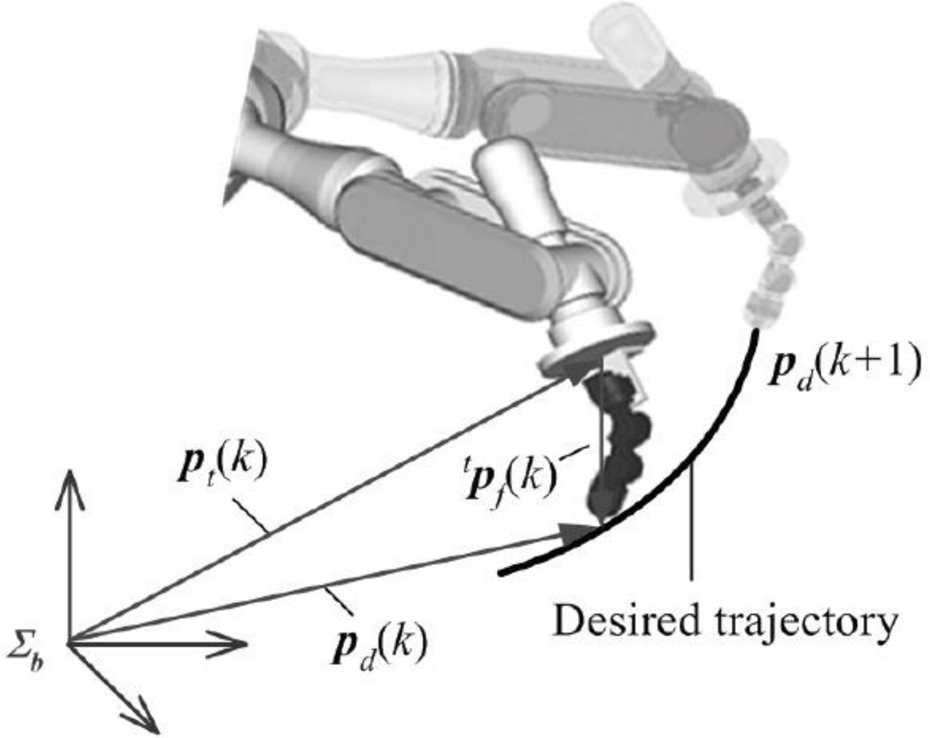
Heuristic Method

- Assuming the orientation of the arm remains unchanged

$$\Delta \boldsymbol{p}_d(k) = s_1 \Delta \boldsymbol{p}_t(k) + \boldsymbol{R}_t \cdot \Delta {}^t\boldsymbol{p}_f(k)$$

- Where

$$\Delta \boldsymbol{p}_d(k) = \boldsymbol{p}_d(k) - \boldsymbol{p}_d(k-1)$$
$$\Delta \boldsymbol{p}_t(k) = \boldsymbol{p}_t(k) - \boldsymbol{p}_t(k-1)$$
$$\Delta {}^t\boldsymbol{p}_f(k) = {}^t\boldsymbol{p}_f(k) - {}^t\boldsymbol{p}_f(k-1)$$



Heuristic Method

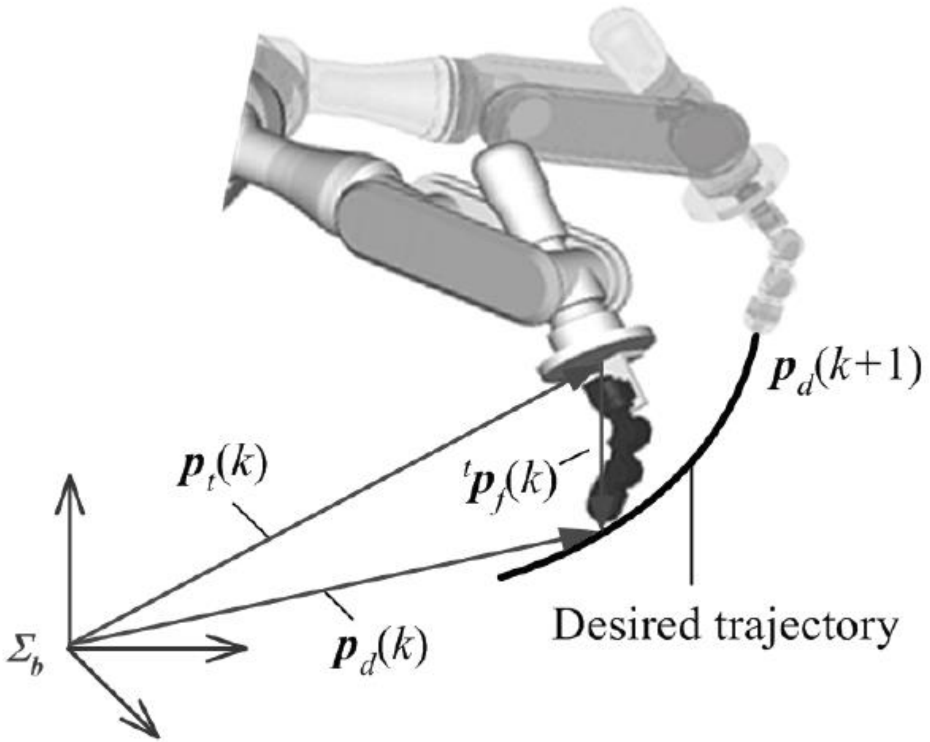
- Given that $^{t}\dot{\boldsymbol{p}}_f = \boldsymbol{J}_f \cdot \dot{\boldsymbol{\theta}}_f$

$$\Delta \boldsymbol{p}_d(k) = s_1 \Delta \boldsymbol{p}_t(k) + \boldsymbol{R}_t T \cdot {}^{t}\dot{\boldsymbol{p}}_f(k)$$
$$= s_1 \Delta \boldsymbol{p}_t(k) + T\boldsymbol{R}_t \boldsymbol{J}_f \dot{\boldsymbol{\theta}}_f(k)$$

- No need to move arm

$$\Delta \boldsymbol{p}_t(k) = 0$$

$$\Delta \boldsymbol{p}_d(k) = T\boldsymbol{R}_t \boldsymbol{J}_f \dot{\boldsymbol{\theta}}_f(k)$$



Heuristic Method

- When it is necessary to move the arm

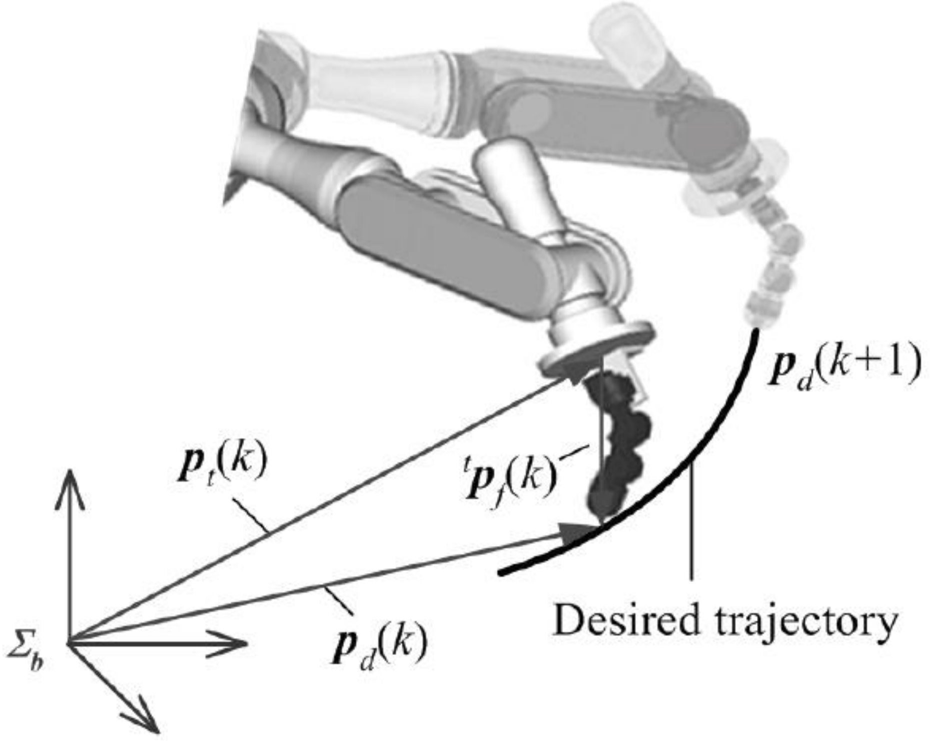
$$\Delta p_d(k) = s_1 \Delta p_t(k)$$

- Finger remains motion less

$$\dot{\theta}_f(k) = 0$$

- Finger manipulability unchanged

$$\Delta W_f = 0$$



- **Moving the arm instead of moving the finger can theoretically prevent any further decrease**
- **However, switching control between the arm results in a sudden change in velocity**

Heuristic Method

- To achieve smooth motion,

$$p_{td}(k) = p_t(k-1) + \Delta p_{td}(k)$$

- Where $\Delta p_{td}(k) = A(W_f) s_1^T \Delta \vec{p}_d(k)$
-

$$\Delta \vec{p}_d(k) = \Delta p_d(k) / |\Delta p_d(k)|$$

an unit motion vector in the direction of the desired trajectory

$$A(W_f) = \begin{cases} 0 & W_f(k) \geq W_{fr} \\ K_a(W_{fr} - W_f(k)) & W_f(k) < W_{fr} \end{cases}$$

How to increase the finger manipulability?

Steepest Ascent Method

- When the finger manipulability is under the defined threshold,
  - Computer the finger joint angles needed for increase manipulability

$$\boldsymbol{\theta}_{fd}(k) = \boldsymbol{\theta}_{fd}(k-1) + \lambda \frac{\partial W_f}{\partial \boldsymbol{\theta}_f}$$

  - Computer desired frame transform of finger w.r.t. to the EE of arm

$${}^{t}\boldsymbol{p}_f(k) = \Lambda_f(\boldsymbol{\theta})$$

  - Given the desired finger EE position, compute the desired the EE of arm

$$\boldsymbol{p}_{td}(k) = \mathbf{s}_1^T(\boldsymbol{p}_d(k) - \boldsymbol{R}_t \cdot {}^{t}\boldsymbol{p}_f(k))$$

Reference

- [1] Yoshikawa, T., Harada, K., & Matsumoto, A. (1996). Hybrid position/force control of flexible-macro/rigid-micro manipulator systems. IEEE Transactions on Robotics and Automation, 12(4), 633-640.

- [2] Entsfellner, K., Schuermann, J., Coy, J. A., Strauss, G., & Lueth, T. C. (2015, December). A modular micro-macro robot system for instrument guiding in middle ear surgery. In *2015 IEEE International Conference on Robotics and Biomimetics (ROBIO),* (pp. 374-379).

- [3] Lew, Jae Y., et al. "Micro manipulator motion control to suppress macro manipulator structural vibrations." *Robotics and Automation, 1995. Proceedings., 1995 IEEE International Conference on*. Vol. 3. IEEE, 1995.

- [4] Lew, Jae Young, and S-M. Moon. "A simple active damping control for compliant base manipulators." *IEEE/ASME Transactions on Mechatronics* 6.3 (2001): 305-310.

Reference

- [5] Kumar, Rajesh, et al. "An augmentation system for fine manipulation." *International Conference on Medical Image Computing and Computer-Assisted Intervention*. Springer, Berlin, Heidelberg, 2000.

- [6] Kwon, SangJoo, Wan Kyun Chung, and Youngil Youm. "On the coarse/fine dual-stage manipulators with robust perturbation compensator." *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*. Vol. 1. IEEE, 2001.

- [7] Dong, Wei, Lining Sun, and Zhijiang Du. "Stiffness research on a high-precision, large-workspace parallel mechanism with compliant joints." *Precision Engineering* 32.3 (2008): 222-231.

- [8] Quan, Bui Trong, et al. "Control of a macro-micro robot system using manipulability of the micro robot." *JSME International Journal Series C Mechanical Systems, Machine Elements and Manufacturing* 49.3 (2006): 897-904.

Reference

- [9] Huang, Jian, et al. "Emulating the Motion of a Human Upper Limb: Controlling a Finger-arm Robot by using the Manipulability of its Finger." *Robotics and Biomimetics, 2006. ROBIO'06. IEEE International Conference on*. IEEE, 2006.

- [10] Huang, Jian, Masayuki Hara, and Tetsuro Yabuta. "Controlling a finger-arm robot to emulate the motion of the human upper limb by regulating finger manipulability." *Motion Control*. InTech, 2010.