Low-Force Kinesthetic Guidance for Accurate Positioning and Tracking

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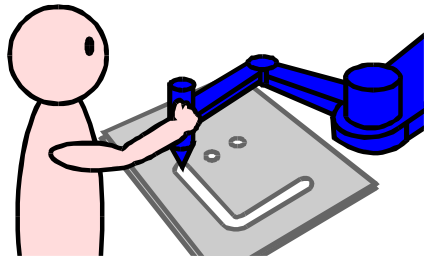
- Kinesthetic (haptic) guidance: Robotic guidance to help a human user to move his/her arm toward a predetermined position or along a predetermined trajectory.



- Applications:
  - upper-limb rehabilitation
  - skill transfer and motion teaching to human
  - human-machine coordination in manufacturing industry (full automation is often inefficient even if technically possible)
- For accuracy, the guidance should be as **stiff** as possible.
- For safety, the guiding force should be **weak**er than the user's force.

question: How **damped** should the guidance be?

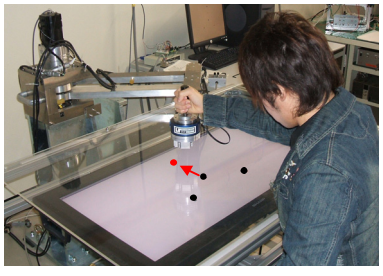
- Experiments:
  - Employed a modified version of sliding mode control ("proxy-based sliding mode control," see below), which is similar to a very stiff PD control with bounded torque.

$$\boldsymbol{\tau} \approx F\,\mathbf{sgn}\left(\boldsymbol{p}_d - \boldsymbol{p} + \boldsymbol{H}(\boldsymbol{v}_d - \boldsymbol{v})\right)$$
$$\approx \min\left(F, \max\left(-F, K(\boldsymbol{p}_d - \boldsymbol{p}) + K\boldsymbol{H}(\boldsymbol{v}_d - \boldsymbol{v})\right)\right)$$

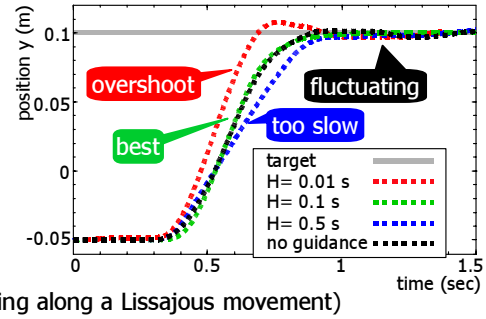
  - Actuator torque limit $\boldsymbol{F}$ = 7 Nm < Joint Friction 10 Nm

- $\boldsymbol{\tau}$: actuator torque
- $\boldsymbol{p}_d$ & $\boldsymbol{v}_d$: desired position & velocity
- $\boldsymbol{p}$ & $\boldsymbol{v}$: actual position & velocity
- $\boldsymbol{H}$: time constant (0.5 s, 0.1 s, 0.01 s)
- $\boldsymbol{F}$: actuator torque limit (7 Nm)
- $\boldsymbol{K}$: stiffness (proportional gain), very high

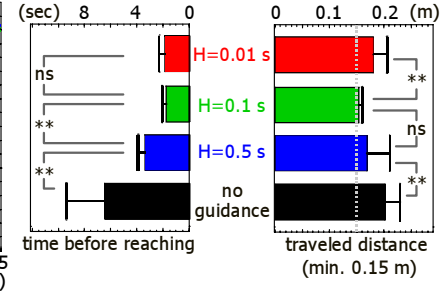
- **Experiment 1: Positioning** (reaching to a target of 0.15-m distance)
  - snapshot



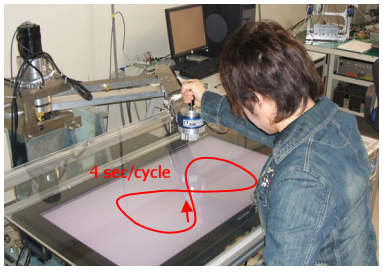
  - typical data



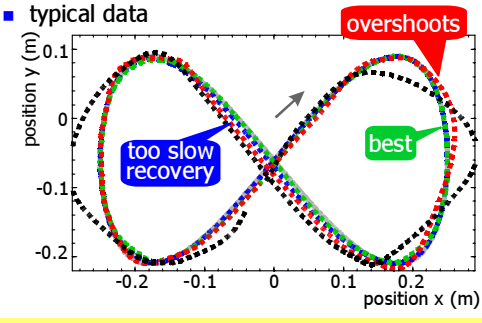
  - statistical analysis (8 participants)



- **Experiment 2: Tracking** (tracking along a Lissajous movement)
  - snapshot



  - typical data



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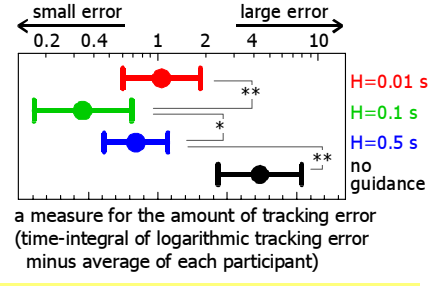

answer: Guidance should be of about **0.1-sec** time constant.

- Small time constant (e.g., 0.01 sec): too responsive, causing overshoots.
- Large time constant (e.g., 0.5 sec): too slow, too damped.
- May be related to frequency characteristics of human voluntary movement; it is usually lower than 2 Hz.
  ⇒ 1/(2 Hz × 2 π) = 0.079 sec ≈ 0.1 sec !!

Ordinary PD control is **not** suitable for kinesthetic guidance.

- In ordinary PD control, 0.1-sec time constant cannot coexist with a high P-gain because a high D-gain (P-gain × time constant) magnifies noise in velocity measurements.

Proxy-Based Sliding Mode Control will be needed for kinesthetic guidance.

- It is a modified version of sliding mode control and also is an extension of PD (and PID) control.
- It is capable of high damping without sacrificing high stiffness or magnifying velocity noise.
- details to be presented in ICRA2006, May, 2006.