Human-Robot Cooperative Manipulation with Motion Estimation

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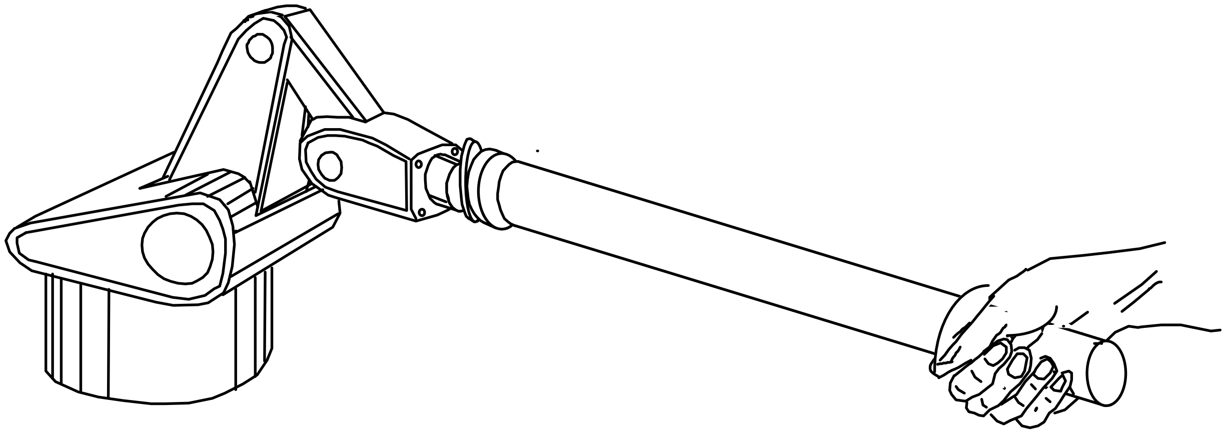
1. Introduction

Human-Robot Cooperative Manipulation

- Typical Human-Robot Cooperative Task
- Combination of Human Intelligence and Robot Power

[Al-Jarrah 97], [Luh 99], [H. Arai 00], [Kosuge 00], …



Human-Friendly Characteristics for Cooperative Manipulation

[Rahman 99]

- Variable impedance control of 1-DOF robot for human-robot cooperative manipulation
- Impedance parameters are controlled so that the human arm can move naturally (like Minimum-Jerk Trajectory [Flash and Hogan 85])

⇨ Valid only for a Specific Trajectory

Objective

Propose a Control Method to Implement Human-Friendly Characteristics on Robots for Cooperative Manipulation

- Effective for various trajectories

Our Approach

- Virtual Compliance Control [Hirabayashi 86]
- Real-Time Estimation of Human Motion based on the Minimum Jerk Model

2. Virtual Compliance Control

Virtual Compliance Control [Hirabayashi 86]

Implement Impedance Characteristics on Conventional Position-Controlled Manipulators by Force Sensors

$$\boldsymbol{M}\frac{(\boldsymbol{x}_{n+1}-\boldsymbol{x}_n)-(\boldsymbol{x}_n-\boldsymbol{x}_{n-1})}{(\Delta t)^2}+\boldsymbol{D}\frac{\boldsymbol{x}_n-\boldsymbol{x}_{n-1}}{\Delta t}+\boldsymbol{K}(\boldsymbol{x}_n-\hat{\boldsymbol{x}}_n)=\boldsymbol{f}_n$$

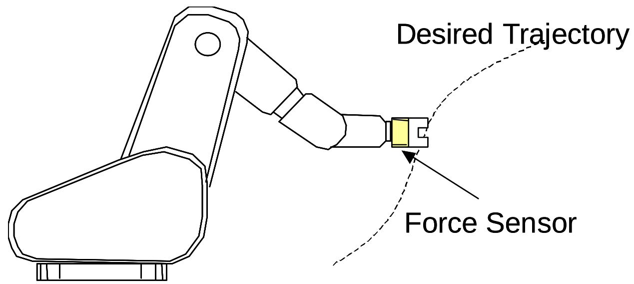
$\boldsymbol{x}_n$: position of robot

$\hat{\boldsymbol{x}}_n$: desired position of robot

$\boldsymbol{f}_n$: sensed force

Δt: sampling time

$\boldsymbol{M}, \boldsymbol{C}, \boldsymbol{K}$: virtual impedance parameters



Desired Robot Position in Virtual Compliance Control

$$\boldsymbol{M}\frac{(\boldsymbol{x}_{n+1}-\boldsymbol{x}_n)-(\boldsymbol{x}_n-\boldsymbol{x}_{n-1})}{(\Delta t)^2}+\boldsymbol{D}\frac{\boldsymbol{x}_n-\boldsymbol{x}_{n-1}}{\Delta t}+\boldsymbol{K}(\boldsymbol{x}_n-\hat{\boldsymbol{x}}_n)=\boldsymbol{f}_n$$

$\boldsymbol{x}_n$: position of robot
$\hat{\boldsymbol{x}}_n$: desired position of robot

~~$\boldsymbol{K}=\boldsymbol{O}$ (or $\hat{\boldsymbol{x}}_n=\boldsymbol{x}_n$) … Passive Compliant Motion (Direct Teaching Mode)~~

⇩ More Active Control

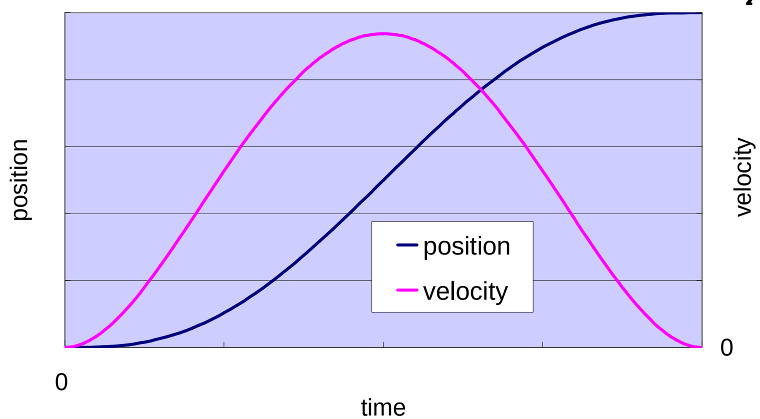
Real-time generation of desired trajectory $(\hat{\boldsymbol{x}}_n)$ based on motion estimation

3. Estimation of Human Motion

Minimum Jerk Model [Flash and Hogan 85]

$$J = \int_0^{t_f} \left\| \dddot{\boldsymbol{x}} \right\|^2 dt \rightarrow \min$$

Point-to-Point Movement



$$\boldsymbol{x} = \boldsymbol{f}(t; t_f, \boldsymbol{x}_f)$$

$$= -\left\{ 15\left(\frac{t}{t_f}\right)^4 - 6\left(\frac{t}{t_f}\right)^5 - 10\left(\frac{t}{t_f}\right)^3 \right\} \boldsymbol{x}_f$$

$\boldsymbol{x}_f$: goal position

t_f : duration of movement

Minimum Jerk Model for Cooperative Manipulation

Minimum jerk model is also appropriate to human-robot cooperative manipulation [Rahman 99]

⇨ Desired trajectory of virtual compliance control:
minimum jerk trajectory

However…

Trajectory that human intends is unknown to robot

⇩

Estimate the human motion in real-time

Parameter Identification for Motion Estimation

Identify two Parameters of the Minimum Jerk Model in Real-Time

$\boldsymbol{x}_f$: goal position

t_f : duration of movement

Non-Linear Least-Squares Method (Levenberg-Marquardt Method)

Residual: $$\sum_{i=0}^{n}\left(\frac{\left\|\boldsymbol{x}_i - \boldsymbol{f}(i\Delta t; t_f, \boldsymbol{x}_f)\right\|}{\alpha^{n-i}}\right)^2 \rightarrow \min$$

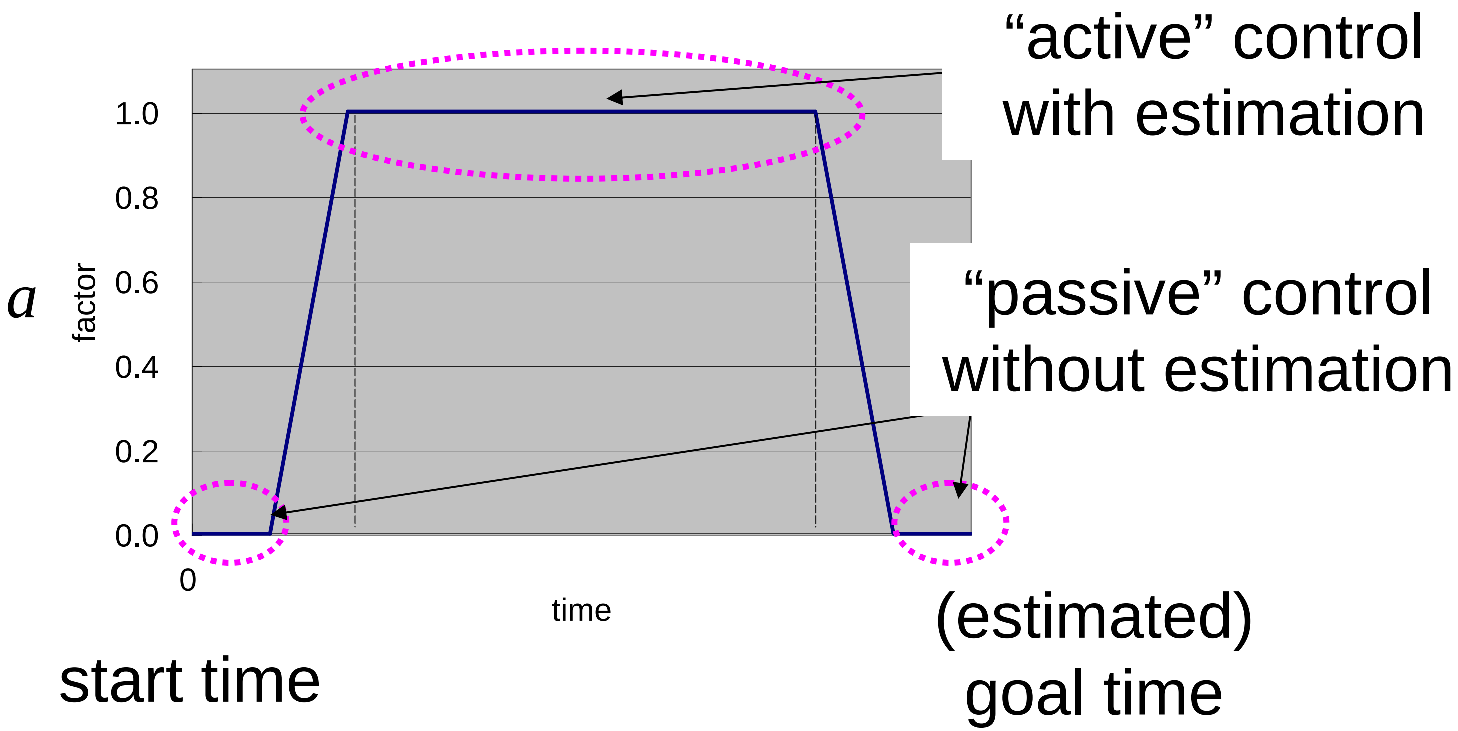
α: forgetting factor

$$\hat{\boldsymbol{x}}_n = \boldsymbol{f}(n\Delta t)$$

Control of Virtual Stiffness

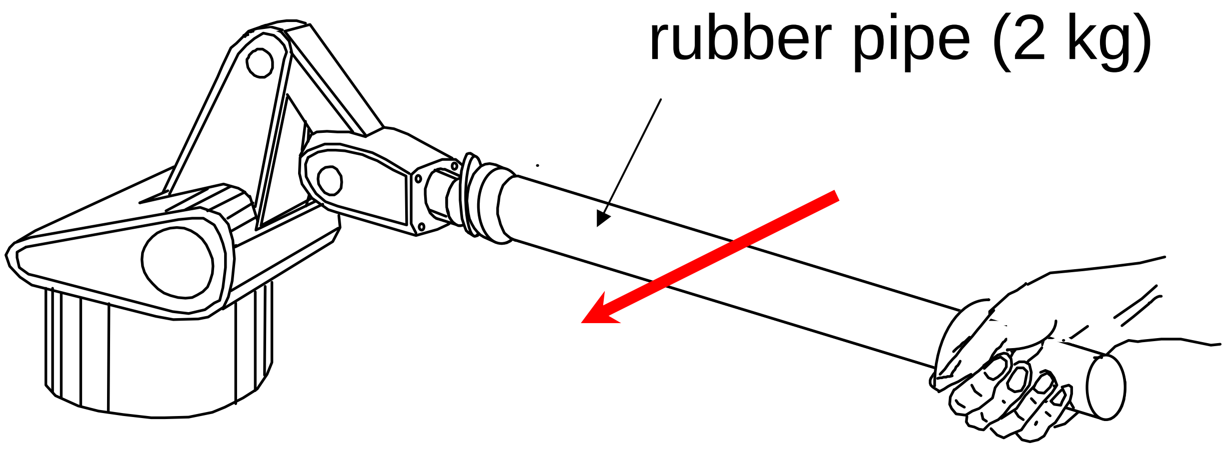
- First stage: Motion estimation may cause unstable motion
- Last stage: Motion estimation may prevent positioning

$$\boldsymbol{K} = a\boldsymbol{K}_0$$



4. Experiments of Cooperative Manipulation

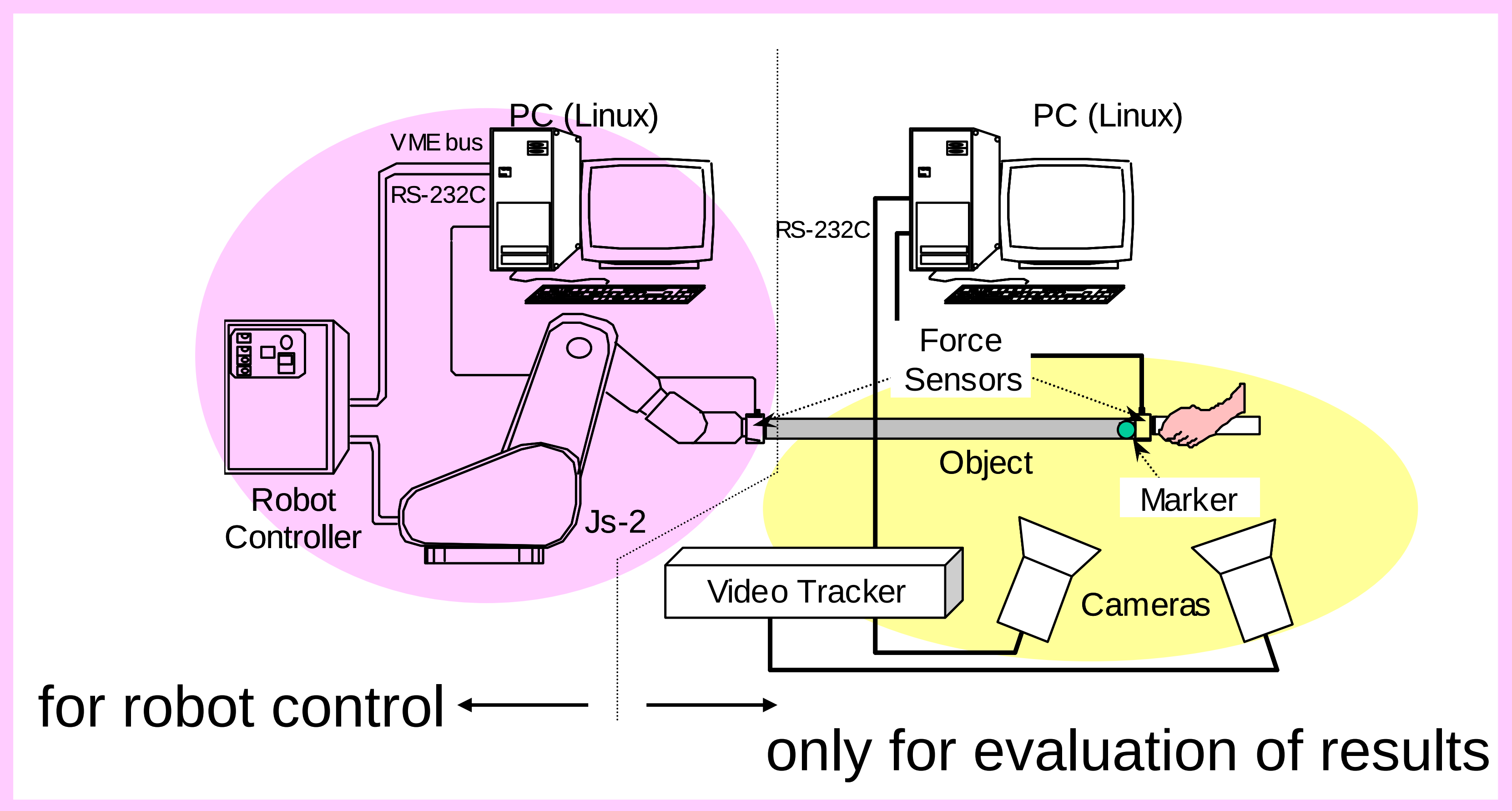
Cooperative Manipulation



Horizontal One-Dimensional Transportation

- To a goal position unknown to the robot
- At arbitrary speed

Experimental Setup



Sampling Time of Force Sensor = 2 [ms]

Control Interval of Manipulator = 16 [ms]

Virtual Impedance Parameters

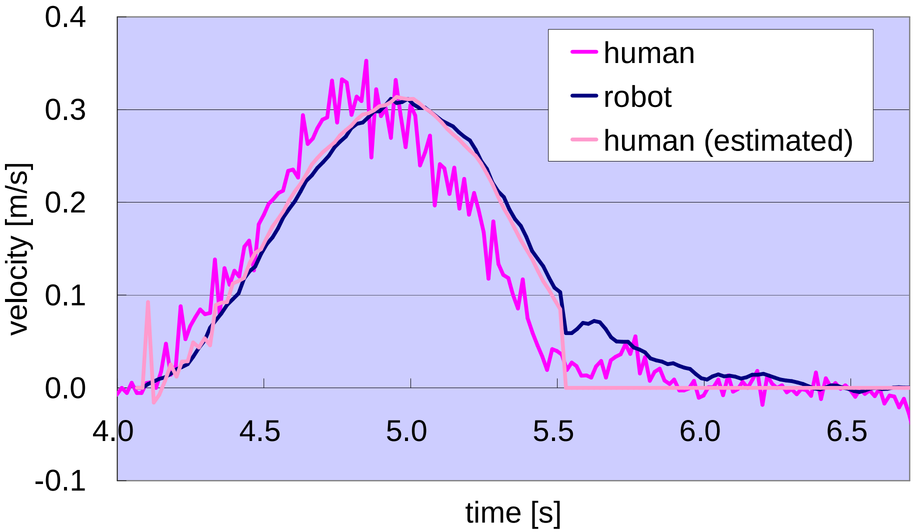
$$\boldsymbol{M} = \begin{bmatrix} 1.79 & 0 & 0 \\ 0 & 1.79 & 0 \\ 0 & 0 & 1.79 \end{bmatrix} [\mathrm{kg}]$$

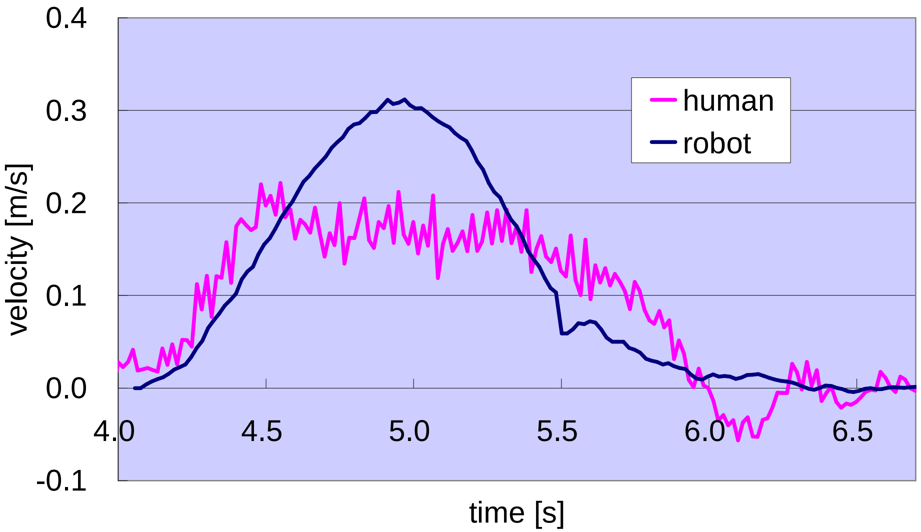
$$\boldsymbol{D} = \begin{bmatrix} 48.0 & 0 & 0 \\ 0 & 48.0 & 0 \\ 0 & 0 & 48.0 \end{bmatrix} [\mathrm{Ns/m}]$$

$$\boldsymbol{K} = \begin{bmatrix} 0 \sim 800 & 0 & 0 \\ 0 & 0 \sim 800 & 0 \\ 0 & 0 & 0 \sim 800 \end{bmatrix} [\mathrm{Nm}]$$

Movie: Cooperative Manipulation

Experimental Results (Velocity)





<u>with Estimation</u>

Both human and robot trajectories are similar to minimum-jerk one

⇩

"light" to manipulate

<u>without Estimation</u>

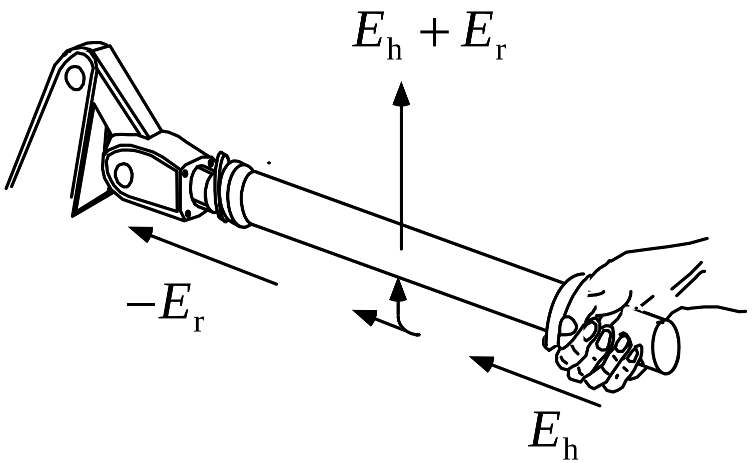
Human trajectory is not similar to minimum-jerk one

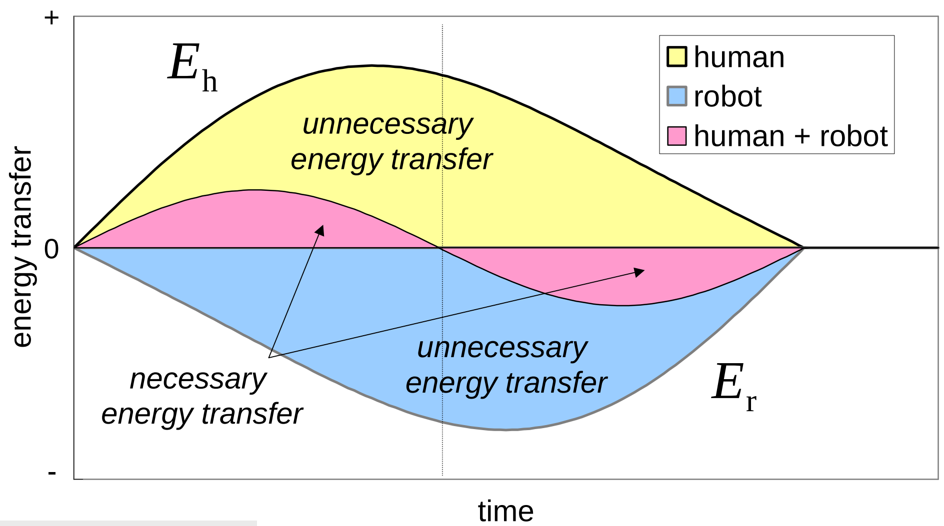
⇩

"heavy" to manipulate

5. Quantitative Evaluation of Experimental Results

Necessary/Unnecessary Energy Transfer

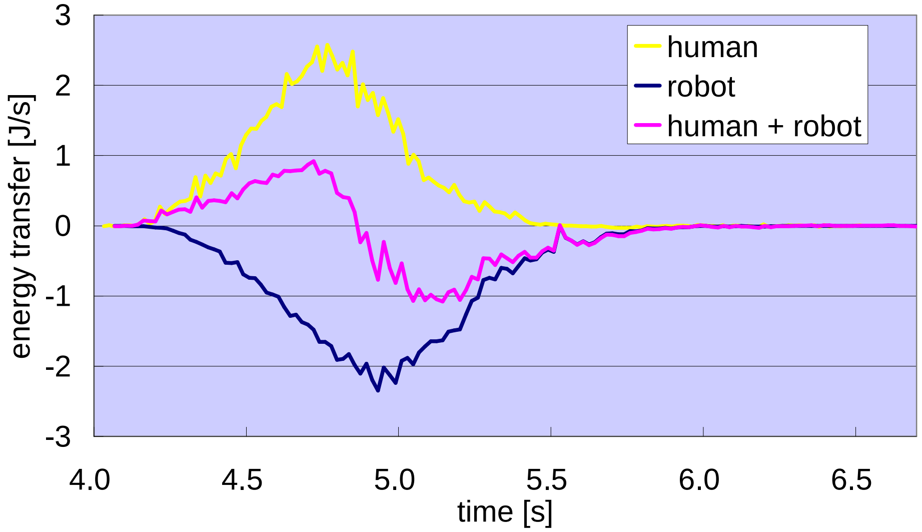




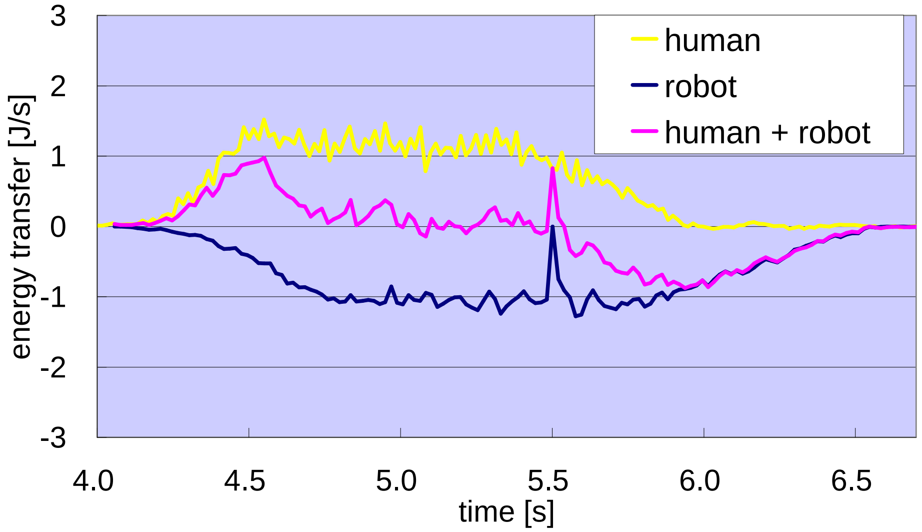
$$E_{unnecessary} = \frac{1}{2}\int (|E_h - E_r| - |E_h + E_r|)dt$$

⇨ <u>Performance Index of “good” cooperation</u>

Energy Transfer in Cooperative Manipulation

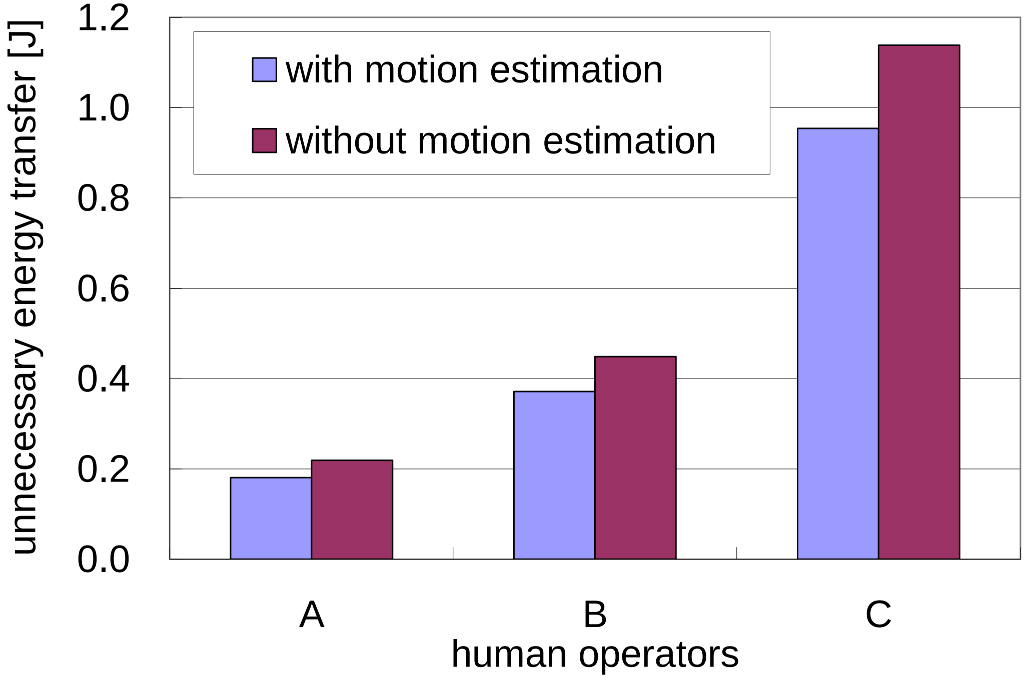


with Estimation



without Estimation

Unnecessary Energy Transfer with/without Motion Estimation



Motion estimation reduces unnecessary energy transfer

⇨ Improvement of Human Feeling

6. Conclusion

Summary

- A robot control method with human-friendly characteristics for cooperative manipulation was proposed
  - Real-Time Estimation of Human Motion based on the Minimum Jerk Model
  - Virtual Compliance Control using the Estimated Trajectory
- The proposed method was experimentally tested on a conventional 6-DOF manipulator with a force sensor
- Improvement of human-friendliness was quantitatively evaluated from the viewpoint of “unnecessary energy transfer”

Future Works

- More Complex Manipulation
- Stability against Impulsive Disturbances

Acknowledgments

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