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

\[ M \frac{(x_{n+1} - x_n) - (x_n - x_{n-1})}{(\Delta t)^2} + D \frac{x_n - x_{n-1}}{\Delta t} + K(x_n - \hat{x}_n) = f_n \]

- \(x_n\): position of robot
- \(f_n\): sensed force
- \(\hat{x}_n\): desired position of robot
- \(\Delta t\): sampling time
- \(M, C, K\): virtual impedance parameters
Desired Robot Position in Virtual Compliance Control

\[ M \frac{(x_{n+1} - x_n) - (x_n - x_{n-1})}{(\Delta t)^2} + D \frac{x_n - x_{n-1}}{\Delta t} + K(x_n - \hat{x}_n) = f_n \]

\( x_n \) : position of robot
\( \hat{x}_n \) : desired position of robot

\[ K = O \quad \text{(Direct Teaching Mode)} \]

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

More Active Control

Passive Compliant Motion

... Passive Compliant Motion (Direct Teaching Mode)
3. Estimation of Human Motion

Minimum Jerk Model [Flash and Hogan 85]

\[ J = \int_0^{t_f} \| \dddot{x} \|^2 dt \rightarrow \text{min} \]

Point-to-Point Movement

\[ x = f(t; t_f, x_f) \]
\[ = -\left\{ 15 \left( \frac{t}{t_f} \right)^4 - 6 \left( \frac{t}{t_f} \right)^5 - 10 \left( \frac{t}{t_f} \right)^3 \right\} x_f \]

- \( x_f \): goal position
- \( t_f \): duration of movement
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

\[ x_f : \text{goal position} \]
\[ t_f : \text{duration of movement} \]

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

Residual:
\[ \sum_{i=0}^{n} \left( \frac{\| x_i - f(i\Delta t; t_f, x_f) \|}{\alpha^{n-i}} \right)^2 \rightarrow \min \]

\[ \hat{x}_n = f(n\Delta t) \]

\( \alpha \): forgetting factor
Control of Virtual Stiffness

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

\[ K = aK_0 \]

“active” control with estimation

“passive” control without estimation

(start time) (estimated) goal time
4. Experiments of Cooperative Manipulation

Cooperative Manipulation

Horizontal One-Dimensional Transportation

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

**Experimental Setup Diagram**

- **Robot Controller** (Js-2) connected to a **PC (Linux)** via **VME bus** and **RS-232C**
- **Force Sensors** attached to the object
- **Video Tracker** linked to a **PC (Linux)**
- **Cameras** for monitoring

**For robot control**

**Only for evaluation of results**

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**Specifications**

- **Sampling Time of Force Sensor** = 2 [ms]
- **Control Interval of Manipulator** = 16 [ms]
Virtual Impedance Parameters

\[
M = \begin{bmatrix}
1.79 & 0 & 0 \\
0 & 1.79 & 0 \\
0 & 0 & 1.79
\end{bmatrix} \text{ [kg]}
\]

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

\[
K = \begin{bmatrix}
0 \sim 800 & 0 & 0 \\
0 & 0 \sim 800 & 0 \\
0 & 0 & 0 \sim 800
\end{bmatrix} \text{ [Nm]}
\]
Movie: Cooperative Manipulation
Experimental Results (Velocity)

with Estimation
Both human and robot trajectories are similar to minimum-jerk one
“light” to manipulate

without Estimation
Human trajectory is not similar to minimum-jerk one
“heavy” to manipulate
5. Quantitative Evaluation of Experimental Results

Necessary/Unnecessary Energy Transfer

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

⇒ Performance Index of “good” cooperation
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

This research was partly supported by HMS (Holonic Manufacturing Systems) project of IMS and The Hara Research Foundation.