Cooperative reaching control for bimanual robotic system

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Outline

Over view

Cooperative control

Control multiple agents to achieve one common project

- Examples of cooperative control
  - Formation, Sensor networks, Coverage Problem ect.
  - Bimanual robot arm motion, Cooperative operation, Man-machine Cooreration ect.

Human may have the finest cooperativebility

Cooperative on human being

- bimanual movement, walking ect.

Focus on the cooperative of human being!

Present works

Present works on robotics

- Arimoto et al. 2005 : Reaching for redundant manipulators
- Spong et al. 2006 : Output synchronization
- Nijmeijar et al. 2004 : Synchronization of robot manipulators
- Utiyama et al. 2000 : Space Telerobotics
- S. Amano et al. 2007 : Modeling of Dual-arm Robot

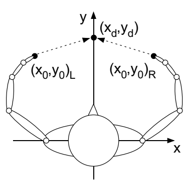
Present works on physiology

- Corbetta et al. 2002 : Two-hand reaching of infants
- White et al. 1964 : synchronization of two hand reaching movement
- D. Nozaki 2007 : Analysis of unimanual and bimanual movements

Motivation

definition (Cooperative Reaching)

Use the cooperative control scheme to cooperate two manipulators reach a desired target point



Motivation

Cooperate bimanual manipulators' reaching movement

Motivation

Where to use?

- Space robot : Dual arm operation robot
- Rehabilitation Robot

From"Kobe robot technology project", "http://www.kobe-rt.jp/index.shtml"

- Humanoid robot

Manipulator dynamics

The Euler-Lagrange equations

$$
\begin{aligned}
M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) &= \tau \\
y &= \dot{q}
\end{aligned} \tag{1}
$$

- $q, \dot{q}, \ddot{q} \in \mathbb{R}^n$: Manipulator joint angular, velocity, accelerate
- $M \in \mathbb{R}^{n\times n}$: Positive difinite inertia matrix
- $C \in \mathbb{R}^{n\times n}$: Centripetal and cCoriolis torques
- $g \in \mathbb{R}^n$: Gravitational torques
- $\tau \in \mathbb{R}^n$: generalized forces acting on the system

Redundant Manipulator

A manipulator has more articulate degrees of freedom than are required for a given object

Control of robot manipulators

- Motion control
  - Joint space coordinate based
  - Tracking the desired position and velocity $q \to q_d, \dot{q} \to \dot{q}_d$
  - Controller :

$$
\begin{aligned}
\tau = M(q)\ddot{q}_d + C(q,\dot{q})\dot{q}_d + g(q) - K_d\dot{e} - K_p e \\
e = q - q_d, \dot{e} = \dot{q} - \dot{q}_d
\end{aligned} \tag{2}
$$

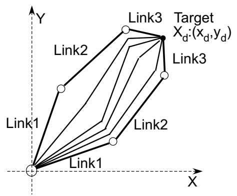
  $q_d, \dot{q}_d, \ddot{q}_d$ denote the desired joint angle, velocity, accelerate
  K_p, K_d : Positive defined control gain
- Reaching Control
  - Task space coordinate based
  - Reaching the target point in task space $x \to x_d$
  - Controller :

$$
\begin{aligned}
\tau = g(q) - K_d\dot{q} - K_p J_{\mathrm{x}}^T \Delta\mathrm{x} \\
\Delta\mathrm{x} = \mathrm{x} - \mathrm{x}_d
\end{aligned} \tag{3}
$$

  x, x_d : current end-point position and desired end-point position
  J_{x}^T : Jacobian Matrix

Control for redundant manipulators

- Self Motion → manipulator joint states uncertain



- On redundant manipulator control, dimension difference between the joint states and end-point

⇩

To control the redundant manipulator, have to solve previous problems

Reaching Control for redundant manipulators

- Arimoto reaching control for redundant manipulators
- Controller : The same as nonredundant manipulators

$$
\begin{aligned}
\tau = g(q) - K_d\dot{q} - K_p J_{\mathrm{x}}^T \Delta\mathrm{x} \\
\Delta\mathrm{x} = \mathrm{x} - \mathrm{x}_d
\end{aligned} \tag{4}
$$

- Stability :
  "Stability on an EP manifold", and "Transferability to an EP Manifold"
  Energy Function :

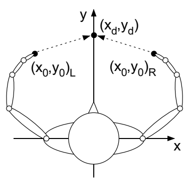
$$
W = \underline{\frac{1}{2}\dot{q}^T M(q)\dot{q} + \frac{1}{2}\Delta\mathrm{x}^T K_p \Delta\mathrm{x}} + \underline{\alpha\sqrt{K_p}\Delta\mathrm{x}^T (J^{\dagger})^T M\dot{q}} \tag{5}
$$

  α : A very small positive define constant to make sure stability
  K_p, K_d : Positive defined control gain

Bimanual robot manipulators

- Dual-manipulator located as the same as the two arms of human

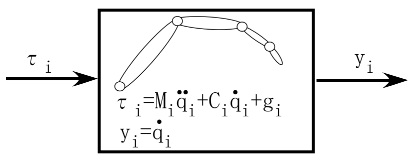
$$
M_i\ddot{q}_i + C_i\dot{q}_i + g_i = \tau_i, i = L, R \tag{6}
$$



Planar manipulator
→ Ignore the gravitational torques g_i

Bimanual robot manipulator

- For each manipulator $i = L, R$



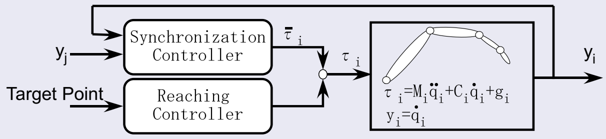
⇒ τ_i: Input, $\dot{q}_i$: Output

Passivity

- Kinetic energy as storage : $V_i = \frac{1}{2}\dot{q}_i M_i \dot{q}_i$
- Passive from input τ_i to output $\dot{q}_i$ as $\dot{V}_i = \tau_i^T \dot{q}_i - g_i$
  - Lossless for $g_i = 0$
  - Strictly passive for $g_i \neq 0 : \dot{V}_i < \tau_i^T \dot{q}_i$

Cooperative reaching control

System Block Diagram



Cooperative reaching controller contains two parts

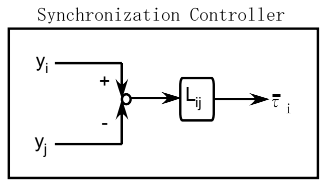
- Reaching Controller to reach target point

$$u_i = -K_{d,i}\dot{q}_i - J_{x_i}^T K_{p,i}\Delta \mathrm{x}_i, i = L, R \quad (7)$$

  - Target Reaching requires $u_i = 0$ for $\Delta x_i = 0 \Rightarrow x_i = x_d$
- Synchronization Controller requires information sharing to coorperate

Interconnection for two manipulators

- Synchronization controller



$\bar{\tau}_i, i = L, R$: New input for synchronization
y_i, y_j : Output of each manipulator

- Interconnection : Linear protocol
  $\bar{\tau}_i = L_{ij}(y_i - y_j) = \Delta\dot{q}_{ij}, i = L, R$
  $\Delta\dot{q}_{ij} = \dot{q}_i - \dot{q}_j = y_i - y_j$:
- Synchronization $\Rightarrow \bar{\tau}_i = 0$ for $y_L = y_R$

Cooperative Reaching Controller : $\tau_i = \bar{\tau}_i + u_i$

Closed loop system

Closed loop system

$$M_i\ddot{q}_i + C_i\dot{q}_i + K_{d,i}\dot{q}_i + J_{x_i}^T K_{p,i}\Delta \mathrm{x}_i = \bar{\tau}_i, i = L, R \quad (8)$$

assumption

- control gain $K_{p,L}, K_{p,R}, K_{d,L}, K_{d,R}$: positive definite
- coupling gain $\lambda_{LR}, \lambda_{RL}$: semi-positive define & $K_{d,L}\lambda_{LR} = K_{d,R}\lambda_{RL}$
- Jacobian Matrix J_x : non-singular

The Goal

Asymptotic to reaching the target point : $x_i = x_d, i = L, R$
Joint velocity symmetric synchronization : $\dot{q}_L = -\dot{q}_R$
(Want joint position symmetric synchronization : $q_L = -q_R$)

Stability for non-redundant manipulators

Theorem

For previous assumption, equilibrium states $(q_d, 0)$ corresponding to the target position x_d in closed-loop system (8) are asymptotically stable in a local sense

Proof.

- Storage Function :
  $V_i = \frac{1}{2}\dot{q}_i^T M_i \dot{q}_i + \frac{1}{2}\Delta \mathrm{x}_i^T K_{p,i}\Delta \mathrm{x}_i$
  $\dot{V}_i = -\dot{q}_i^T K_{p,i}\dot{q}_i - \dot{q}_i^T K_{d,i}\lambda_{ij}\Delta\dot{q}_{ij}, i = L, R$
- Overall system storage :
  $V = V_L + V_R$
  $\frac{d}{dt}V = -\dot{q}_L^T K_{p,L}\dot{q}_L - \dot{q}_R^T K_{p,R}\dot{q}_R - \Delta\dot{q}_{LR}^T K_{d,R}\lambda_{RL}\Delta\dot{q}_{LR} \le 0$
- $\dot{V} = 0 \iff \dot{q}_L = -\dot{q}_R = 0$

$\Rightarrow$ Asymptotically Stable □

Stability for redundant manipulators

Problem of the redundant manipulators case

Storage function V can't be positive definite for the self-motion

- First Step: Ignore self-motion to stabilize reaching control
  The same as non-redundant case
  $\Rightarrow V_i = \frac{1}{2}\dot{q}_i^T M_i\dot{q}_i + \frac{1}{2}\Delta \mathrm{x}_i^T K_{p,i}\Delta \mathrm{x}_i$
- Consider a additional energy function to stabilize self-motion for each manipulator $\alpha\sqrt{K_{p,i}}\Delta \mathrm{x}_i^T (J^\dagger)^T M_i\dot{q}_i$

$\Rightarrow$ overall system storage function as :

$$\begin{aligned} & W_i = V_i + \alpha\sqrt{K_{p,i}}\Delta \mathrm{x}_i^T (J^\dagger)^T M_i\dot{q}_i, i = L, R \\ \Rightarrow \quad & W = W_L + W_R \end{aligned} \quad (9)$$

Where α is a positive constant.

- Use next inequation

$$\alpha\sqrt{K_p}\Delta \mathrm{x}^T (J^\dagger)^T M\dot{q} \le \frac{\alpha}{2}K_p\Delta \mathrm{x}^T (J^\dagger)^T M J^\dagger \Delta \mathrm{x} + \frac{\alpha}{2}\dot{q}^T M\dot{q} \quad (10)$$

$$W_i \ge \frac{1-\alpha}{2}\dot{q}_i^T M_i\dot{q}_i + \frac{K_{p,i}}{2}(1-\alpha h_{0i}) \parallel \Delta \mathrm{x}_i \parallel^2 = W_{im}, i = L, R \quad (11)$$

where, $\lambda_M\{(J^\dagger)_i^T M_i J_i^\dagger\} \le h_{0i}$

- if the positive α is small enough,
  $W_i \ge W_{im} \ge 0 \Rightarrow W \ge W_{Lm} + W_{Lm} = W_m \ge 0$
- for a given $\alpha \ge 0$ there exists a $\gamma(\alpha)$ such that

$$\frac{dW}{dt} \le -\gamma(\alpha)W_M \le -\gamma(\alpha)W \quad (12)$$

- which means $W_m(t) \le W(t) \le e^{-\gamma(\alpha)t}W(0)$

$\Rightarrow$ Exponetially stability

Advantage and disadvantage of this method

Advantage

- Simple reaching controller
- Don't need calculate the pseudo-inverse Jacobian matrix

Disadvantage

- Cannot use to obstacle and singularity avoidance
- Synchronization on the velocity level $\Rightarrow$ Cannot satisfy the position synchronization

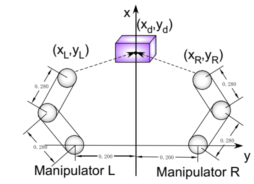
⇩

- Synchronize information $\dot{q} \rightarrow q$ and $\dot{q}$
- Take the output as $y_i = \dot{q}_i + \lambda_i q_i$

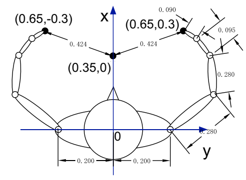
Stability analysis is same, but satisfied the position synchronize.

Simulation Setting

- Non-redundant



- Redundant

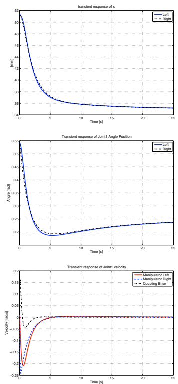


- Parameter (non-redundant)
  $L_1 = L_2 = 0.28$
  $M_1 = 1.407, M_2 = 1.108$
  $I_1 = 9.758 \times 10^{-3}$
  $I_2 = 7.73 \times 10^{-3}$

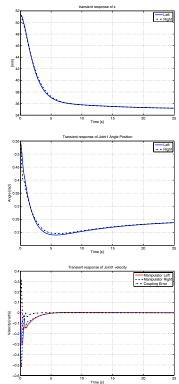
- Parameter (redundant)
  $L_1 = L_2 = 0.28$,
  $L_3 = 0.095, L_4 = 0.09$
  $M_1 = 1.407, M_2 = 1.078,$
  $M_3 = 0.242, M_4 = 0.0255$
  $I_1 = 9.758 \times 10^{-3}$
  $I_2 = 7.73 \times 10^{-3}$
  $I_3 = 2.004 \times 10^{-4}$
  $I_4 = 1.78 \times 10^{-5}$

Simulation Result for Non-redundant manipulators

No information sharing



With information sharing



Simulation with different manipulator parameters and same initial states : $M_L, I_L = 5M_L, 5I_L$, Gain well tuned

Simulation Result for Redundant manipulators

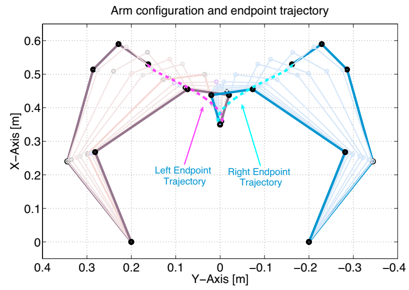
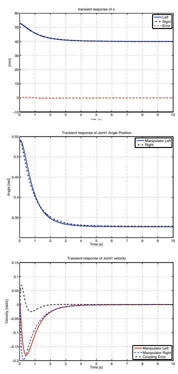


Figure: **Trajectory of the robot manipulator and end-point**

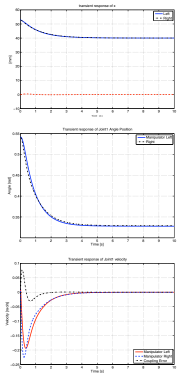
Simulation with the same parameter and initial states

Simulation Result for Redundant manipulators

No information sharing



With information sharing



Simulation with different manipulator parameters and same initial states : $M_L, I_L = 2M_L, 2I_L$, Gain well tuned

Conclusion of the simulation result

- Each situation of the simulations
  - End-point stable to reach the target point
  - Joint velocity stable to asymptoticly
- With the same parameter and initial states
  - Off cause have the same reaching motion
- Different parameter or initial states or both
  - When bad tuning
    $\Rightarrow$ Good advantage with cooperative but bad calculate performance
  - When well tuning
    $\Rightarrow$ small advantage with cooperative but good calculate performance

Conclusion and future works

In this seminar

- Proposal of the "Cooperative reaching control"
  - Two parts of the controller "Reaching Control" and "Cooperative control"
- Stability and the proof

Current and Future Works

- Conside the EXOS method
- Visual feedback to estimate the end-point position
- Experiment