Cooperative Reaching Control for Dual-manipulators

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Leilei Yin
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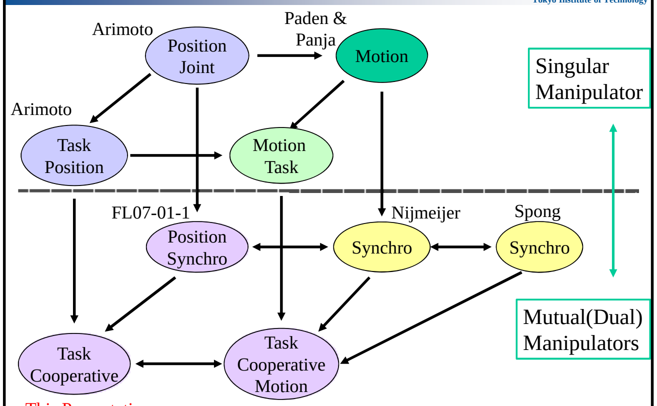
Outline

- Control of Robot Manipulators (Review)
- Introduction
- Problem Setting of Cooperative Reaching
- Simulation
- Conclusion & Future Work

Control of Robot Manipulators (Review)



Control of Robot Manipulators (Review)

Arimoto Position Control Based Synchronization

- Control Object $M_i\ddot{q}_i + C_i\dot{q}_i + g_i = \tau_i \ , i = L, R \quad \cdots\cdots\cdots \quad (1)$
- Controller $\tau_i = g_i - k_d\dot{q}_i - k_i\left(\left(q_i - q_d\right) + \lambda_{ij}\left(q_i - q_j\right)\right)$

$$= g_i - k_d\dot{q}_i - k_i\left(e_i + \lambda_{ij}e_{ij}\right) \ , i, j = L, R \quad \cdots (2)$$

- Closed-loop $M_i\ddot{q}_i + C_i\dot{q}_i + k_d\dot{q}_i + k_p e_i + k_p e_{ij} \ , i, j = L, R \ \cdots (3)$

Theorem

Consider the closed loop system formed by the controller (2), and the robot dynamics(1). Then errors e_i, e_{ij} $i, j = L, R$ are asymptotically stable if the control gains k_p, k_d are positive definite

Proof

Storage Function $V_i = \dot{q}_i^T M_i \dot{q}_i + e_i^T k_p e_i + \frac{1}{2} e_{ij}^T k_p e_{ij}, \ i, j = R, L \quad \cdots\cdots \quad (4)$

$$V = V_L + V_R$$

$$\frac{d}{dt}V = \frac{d}{dt}V_L + \frac{d}{dt}V_R = -2\left(\dot{q}_L^T k_d \dot{q}_L + \dot{q}_R^T k_d \dot{q}_R\right) \le 0 \cdots (5)$$

Then, LaSalle's Theorem can be used to proof system's asymptotically stability

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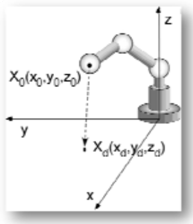
Introduction

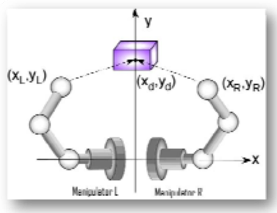
Reaching Control

move the manipulator from a start point to the desired point in the task coordinates



Cooperative Reaching control of Dual Robot Manipulators

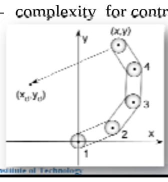
Control two manipulators from their start points move to the desired point in the task space



Introduction

Control for Redundant Manipulators

- A manipulator possesses more degrees of freedom than are required to achieve the desired end-effector motion
- Advantage of using the redundant manipulators
  - Humanlike natural motion
  - Obstacle and singularity avoidance
- Disadvantage
  - Self-motion
  - complexity for control



Humanlike Natural Motions for Redundant Manipulators

- S. Arimoto et al. (2005) "Natural Motions for Redundant Multi-joint Systems"
  - Definite an equilibrium-point manifold to stabilize the system

Motivation
Cooperative control of humanlike natural motions for dual redundant manipulators

S.Arimoto, et al. Journal of Robotic Systems , Vol.22, 2005.

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Problem Setting

- Control Objects (Right and Left two manipulators)

$$\begin{cases} M_L\ddot{q}_L + C_L\dot{q}_L + g_L = \tau_L \\ M_R\ddot{q}_R + C_R\dot{q}_R + g_R = \tau_R \end{cases} \quad \cdots\cdots\cdots\cdots \quad (6)$$

- Reaching Controller for singular manipulator (Arimoto)

$$\tau = -k_d\dot{q} - J_x^T k_p(x - x_d) \quad \cdots\cdots\cdots\cdots \quad (7)$$

Goal: Extend above equation to dual manipulators use the synchronization control scheme achieve the cooperative reaching

$$x_L = x_R = x_d \ , q_L = q_R, \ \dot{q}_L = \dot{q}_R$$

Problem

1. Which information we should use to synchronize?
2. How do we achieve cooperative reaching?

S.Arimoto, et al. Journal of Robotic Systems , Vol.22, 2005.

Cooperative Reaching Control -- Prepare

- Synchronization Control for Robot Manipulators
  - Nijmeijer: $q_i \to q_j = q_d, \dot{q}_i \to \dot{q}_j = \dot{q}_d, \ddot{q}_i \to \ddot{q}_j = \ddot{q}_d$
  - Spong : $y_i \to y_j$
  - Last Presentation : $q_L \to q_R = q_d$
- How about the reaching problem in the task space?
  $x_L \to x_R = x_d$? $q_L \to q_R$? $\dot{q}_L \to \dot{q}_R$?
- We choose $q_L \to q_R$ to achieve the cooperation

Then we define the coupling errors and position errors as

$$\Delta q_{LR} = q_L - q_R, \Delta q_{RL} = q_R - q_L$$
$$\Delta x_L = x_L - x_d, \Delta x_R = x_R - x_d$$

Cooperative Reaching Control-- Prepare

- We know the Arimoto Reaching Controller as (eq.7)

$$\tau = -k_d\dot{q} - J_x^T k_p \Delta x, \Delta x = x - x_d \quad \cdots\cdots\cdots \quad (7)$$

- Use the synchronization scheme to extend (eq.7) to dual manipulators, we can get the controller as

$$\tau_i = -k_{di}\dot{q}_i - J_{xi}^T k_p \Delta x_i + \overline{\tau}_i \ , i = L, R \quad \cdots\cdots\cdots \quad (8)$$

† Where, $\overline{\tau}_i$ denotes the new input required for coordination control

- Design the new cooperative input as

$$\overline{\tau}_i = -k_{pi}\lambda_{ij}\Delta q_{ij} \ , i = L, R \quad \cdots\cdots\cdots\cdots \quad (9)$$

Combine the controller(eq.8) to the dynamics (eq.6), we get

$$M_i\ddot{q}_i + C_i\dot{q}_i + k_{di}\dot{q}_i + J_{xi}^T k_{pi}\Delta x_i = \overline{\tau}_i \ , i = L, R \quad \cdots\cdots \ (10)$$

If we take $V_i = \frac{1}{2}\dot{q}_i^T M_i \dot{q}_i + \frac{1}{2}\Delta x_i^T k_{pi}\Delta x_i, i = L, R$, then

$$V_i\left(x(t)\right) - V_i\left(x(0)\right) = \int_0^t \overline{\tau}_i^T \dot{q}_i dt - \underbrace{\int_0^t \dot{q}_i^T k_{dL}\dot{q}_i dt}_{\geq 0}, i = L, R$$

Therefore the system is passive with $\left(\overline{\tau}_i, \dot{q}_i\right)$ as the input-output pair

Cooperative Reaching Control-- Prepare

- Definition [Cooperative Reaching]
  - Control two manipulators reach one common target point, as the same time they should move symmetically

N. Chopra and M. Spong (2006)

Passivity from $u_i \to \dot{q}_i$ guarantees passivity from $-u_i \to -\dot{q}_i$.

- Then, if we chose one set of the manipulator states and input output as it's inverse, we can get the stability as the same as the synchronization control

So, We choose the states of left manipulator as

$$q_L \to -q_L, \dot{q}_L \to -\dot{q}_L, \tau_L \to -\tau_L$$

Then, the controller can be written as

$$\begin{cases} \tau_L = -\left(-k_{dL}\left(-\dot{q}_L\right) - J_{xL}^T(-q_L)k_{pL}\Delta x_L(-q_L) + \overline{\tau}_L(-q_L, q_R)\right) \\ \quad = -k_{dL}\dot{q}_L - J_{xL}^T k_{pL}\Delta x_L - \overline{\tau}_L(-q_L, q_R) \\ \tau_R = -k_{dR}\dot{q}_R - J_{xR}^T k_{pR}\Delta x_R + \overline{\tau}_R(-q_L, q_R) \end{cases} \quad \cdots \ (11)$$

M. Spong et al. in Advances in Robot Control: From Everyday Physics to Human-Like Movements, Springer-Verlag, Berlin, 2006.

Cooperative Reaching Control

- Then Combine the controller(eq.11) into the dynamics (eq.6) , we get the closed-loop as

$$\begin{cases} M_L\ddot{q}_L + C_L\dot{q}_L + k_{dL}\dot{q}_L + J_x^T k_{pL}\Delta x_L = \overline{\tau}_L \\ M_R\ddot{q}_R + C_R\dot{q}_R + k_{dR}\dot{q}_R + J_x^T k_{pR}\Delta x_R = -\overline{\tau}_R \end{cases} \quad \cdots\cdots\cdots\cdots\cdots \quad (12)$$

Where, $\overline{\tau}_L = -k_{pL}\lambda_{LR}\left(q_L + q_R\right), \overline{\tau}_R = k_{pR}\lambda_{RL}\left(q_R + q_L\right)$

Theorem

Consider the closed loop system (12) formed by the controller (11), and the robot dynamics(6). Then the system errors $\Delta x_i, \Delta q_{ij}, \Delta\dot{q}_{ij},\ i, j = L, R$ are asymptotically stable , if $K_{di}, K_{pi} > 0, K_{ij} \geq 0,\ i, j = L, R$ and $k_{pR}\lambda_{RL} = k_{pL}\lambda_{LR}$

Storage Function

$$V_L = \frac{1}{2}\dot{q}_L^T M_L \dot{q}_L + \frac{1}{2}\Delta x_L^T k_{pL}\Delta x_L \ ,\ V_R = \frac{1}{2}\dot{q}_R^T M_R \dot{q}_R + \frac{1}{2}\Delta x_R^T k_{pR}\Delta x_R$$

$$V_{LR} = \frac{1}{4}\Delta q_{LR}^T\left(k_{pL}\lambda_{LR}\right)\Delta q_{LR} \ ,\ V_{RL} = \frac{1}{4}\Delta q_{RL}^T\left(k_{pR}\lambda_{RL}\right)\Delta q_{RL} \quad \cdots \ (13)$$

Proof for the theorem

Just consider the left-manipulator. Derivate the storage function

$$\dot{V}_L = \dot{q}_L^T M_L \ddot{q}_L + \frac{1}{2}\dot{q}_L^T \dot{M}_L \dot{q}_L + \Delta x_L^T k_{pL}\Delta\dot{x}_L = -\dot{q}_L^T k_{dL}\dot{q}_L - \dot{q}_L\left(k_{pL}\lambda_{LR}\right)\Delta q_{LR}$$

$$\dot{V}_R = -\dot{q}_R^T k_{dL}\dot{q}_R - \dot{q}_R\left(k_{pR}\lambda_{RL}\right)\Delta q_{RL}$$

$$\dot{V}_{LR} = \frac{1}{2}\Delta q_{LR}^T\left(k_{pL}\lambda_{LR}\right)\Delta\dot{q}_{LR} = \frac{1}{2}\Delta q_{LR}^T\left(k_{pR}\lambda_{RL}\right)\left(\dot{q}_L^T - \dot{q}_R^T\right)$$

$$\dot{V}_{RL} = \frac{1}{2}\Delta q_{RL}^T\left(k_{pR}\lambda_{RL}\right)\left(\dot{q}_R^T - \dot{q}_L^T\right)$$

The storage function of all system can be taken as

$$V = \underbrace{V_L + V_R}_{\text{Manipulators}} + \underbrace{V_{LR} + V_{RL}}_{\text{Coupling}}$$

If , $k_{pR}\lambda_{RL} = k_{pL}\lambda_{LR}$, $\because \Delta q_{LR} = -\Delta q_{RL}$

Then, $\dot{V} = \dot{V}_L + \dot{V}_R + \dot{V}_{LR} + \dot{V}_{LR} = -\dot{q}_L^T k_{dL}\dot{q}_L - \dot{q}_R^T k_{dL}\dot{q}_R \leq 0$

LaSalle's Principle Theorem can be used to prove system's asymptotical stability

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Simulation -- Prepare

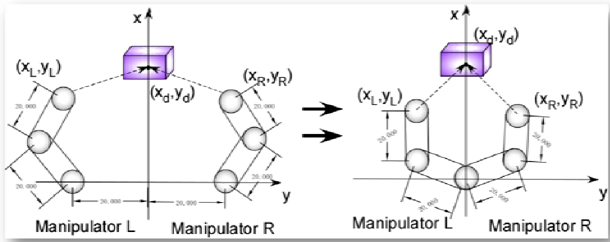


Fig.1 Simulation setting of dual manipulators cooperative reaching

Link No.	Length	Mass	Moment
Link 1	0.2[m]	12.27[kg]	0.1149
Link 2	0.2[m]	2.083[kg]	0.0144

Simulation -- Prepare

- Coordinates of the endpoint in task space

$$\begin{cases} x = L_1\cos q_1 + L_2\cos\left(q_1 + q_2\right) \\ y = L_1\sin q_1 + L_2\sin\left(q_1 + q_2\right) \end{cases} \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (14)$$

- Jacobian Matrix

$$J_x(q) = \begin{pmatrix} -L_1\sin q_1 - L_2\sin\left(q_1 + q_2\right) & -L_2\sin\left(q_1 + q_2\right) \\ L_1\cos q_1 + L_2\cos\left(q_1 + q_2\right) & L_2\cos\left(q_1 + q_2\right) \end{pmatrix} \quad \cdots\cdots \quad (15)$$

Inertial States Setting

➢Inertial Position (Left) : [x,y] = [0 ,-0.4] (-90° , 0°)
➢Inertial Position (Right): [x,y] = [0.07 ,0.39] (80° , 0°)

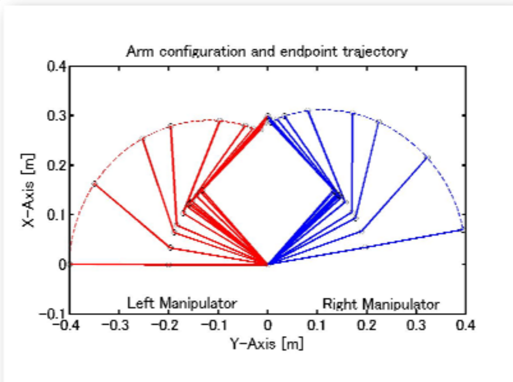
Target Point

$[x_d, y_d] = [0.3, 0]$

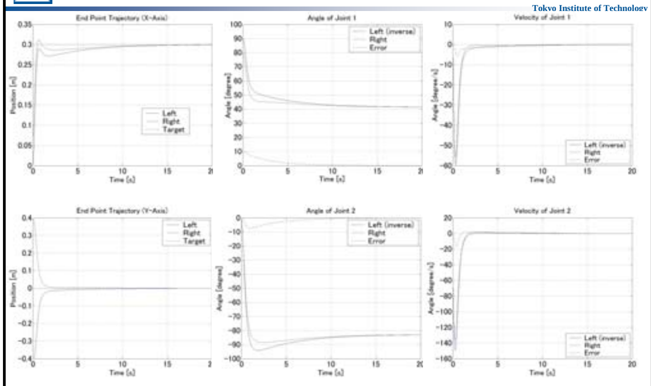
Gain Setting

➢Left $K_{pL} = diag[40,40], K_{dL} = diag[4,1],\ K_{LR} = diag[0.5,0.5]$
➢Right $K_{pR} = diag[40,40], K_{dR} = diag[4,1],\ K_{RL} = diag[0.5,0.5]$

Simulation



Simulation



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Conclusion & Future Work

- In this presentation
  - Introduction for Control of Robot Manipulators
  - Problem setting of Cooperative Reaching Control
  - Cooperative Reaching Control using the Synchronization Coupling scheme
  - Simulation of Cooperative Reaching Control
- Future Work
  - Discuss the coupling scheme of two manipulators
  - Extend to Redundant Manipulators
  - Consider the Humanlike Nature Motion
  - Absorb the visual feedback scheme into this method to observe the information in task space