On Control System of the Two-Robot Coordination

Jin He

Faculty of Physics & Electronic Engineering, Yunnan Nationalities University, Kunming 650031, P. R. China

Abstract

Based on the features of two-robot coordination control system, a coordination system in layered modularization was set up from the human motor control system. A module of object hybrid impedance controller (HIC) was designed, so it can compensate the whole dynamics and its stability was analyzed. After make the inner force controller combine reasonably with the motor controller, the integrated controller of two-robot can be realized. The experiment results show that the control effect is satisfactory.

Keywords: Two-robot, Coordination, Impedance control, Layered modularization, Hybrid impedance.

1. Introduction

The design of coordination control system is the key problem of the two-robot coordination researching, while in the coordination control, in which the coordination mechanism is the core, which was defined as a method of any independent controlling of two-robots moving along a coordinated track by Cannon [1]. It is an important guarantee of two-robots complete the task together in a coordinated relation. A coordinated control system is quite different to a traditional robot control system. It needs not only high self control ability, but also the coordination with other robots to integrate in a mechanic and control ability of the system application. Thus, in term of integration ability and easy design, the existing single robot control technology should be utilized to the best of its ability to decompose and modularize the system functions for its better expansibility, and easily create the whole system from simple to complicated, on the condition of ensuring a high intelligence. This paper was focused on the researching of the impedance control in the layered modularized two-robot coordination controller.

2. Coordinated control plan based on HMCS structure

In the view of the human physiological enginery, the human movements itself materializes a sort of movement control in layered steps, with its controller in a distributed and modularize structure[2]. Such a control system in a layered modularization structure is the human motor control system, HMCS in short.

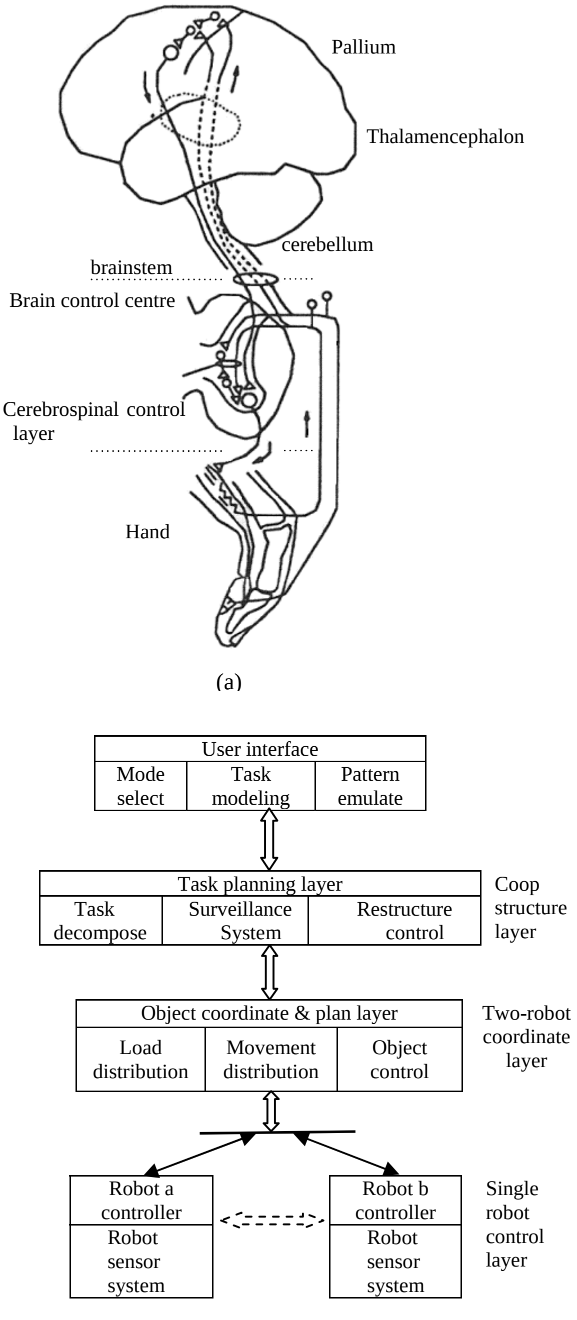
HMCS is composed of ganglia which are divided into several grades, from the example of human hand control structure(shown in fig.1 (a)); the HMCS can be divided from low level to high level into 3 layers: surrounding nervous system, low level central nervous system and high level central nervous system. The high level central nervous system (brain) is in charge of behavior choosing and to monitoring the running states of all organs in the body which includes all high level instructions such as thinking in progress, origin of consciousness and so on. Low level central nervous system (spinal cord) is controlled by the brain under normal condition; which is linked with all sorts of sense receptors, muscle effectors and high level ganglia, meanwhile, itself can be a centre to accomplish reflecting control. Surrounding nervous system (sensory nerve and motor nerve) utilizes all impulses that can be transmitted in the nerve fiber to make the central nervous system and organs of human body into a whole.

Thus, we adopt layered modularized control framework to construct two-robot coordination control system as shown in fig.1 (b).

The first layer is called cooperation structural layer, in charge of overall target modeling, selection of coordination mode, target decomposition, man-machine interface management, and the supervision of the task implementation, etc. of the whole system, and sending command to the lower levels in a task code.

The second layer is called two-robot coordination layer, in charge of receiving and explaining the task command from the upper level and coordinating the plan according to the specific movement task, mainly including the planning of the object movement and the force.

The third layer is called single robot control layer, in charge of converting all the previous plan commands into specific movement ones and sending them to the implementation level to drive the robot to realize the expected movement and feeding back the movement status to the upper level.



(a)

(b)

Fig.1: Schematic frame of two-robot system's control structure, (a) Human hand control structure, (b) Robot system's control structure.

3. Layered modularized coordination controller

Based on the general control concept mentioned above, the design of the two robot's layered modularized controller divides the whole system into several inter relating subsystems to judge whether the sub systems have completed their targets, while meeting the control target of the general system by setting coordinator in each sub system. Its structure block diagram is shown in Fig. 2.

In principle, the layered controller of the two-robot system can be divided into object control layer and robot control layer. In such a structure, each level's target has its own independency and individual features. At the same time, to ensure the system to have a good expansibility, each layer's function should be decomposed and modularized to the best of its ability. Thus, in reality, the controller also consists of modules of object movement planner, movement decomposer, load distributor, force synthesizer, movement synthesizer, and sensor system, etc.

(1) Object movement planner: according to the description of the task, the track and force movement rule in the object's target space should be planned. The output of this module is expected position and posture vector r_O^d , expected speed $\dot{r}_O^d$, expected acceleration $\ddot{r}_O^d$, expected driving force F_O^d and the expected force to the object by the environment F_d .

(2) Movement decomposer: according to the kinematics restriction relation between the robot end and the object and using the kinematics information of the object, calculate and output robot end's expected position and posture vector r_i^d , expected speed $\dot{r}_i^d$, expected acceleration $\ddot{r}_i^d$.

(3) Load distributor: according to the kinematics restriction relation between the robot end and the object and using the object's expected driving force F_O^d and expected internal force F_r^d , calculate and output robot end's optimum grasping force F_{Ci}^d .

(4) Force synthesizer: according to the measured robot end's optimum grasping force F_{Ci} , the counter operation of the load distributor calculates and outputs the object's actual driving force F_O and the environment force F_e .

(5) Movement synthesizer: according to the robot end's actual position and posture vector r_i and actual speed $\dot{r}_i$, the counter operation of the load distributor calculates and outputs the object's actual position and posture vector r_O and actual speed $\dot{r}_O$.

(6) Sensor system: through the encoders on each joint of the robot, the robot end's sensor of brawn, and feeling sensor on the tools, the joint position, end's grasping force, and tool touching force information can be checked out respectively.

(7) Object controller: according to the expected and actual values of the variables of object driving force, the environment force to the object, object position

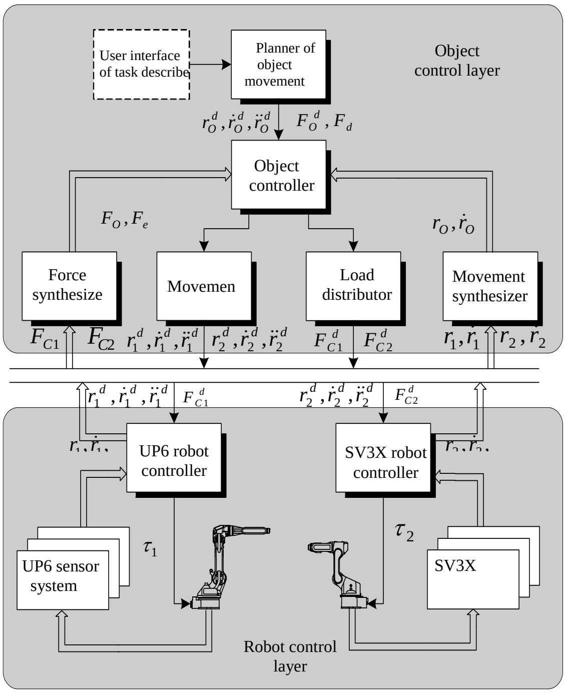


Fig. 2: layered modularization diagram of the two robotic controller.

And posture, speed, and acceleration and using active complaisance arithmetic, let the object run after the required movement track.

(H) Robot controller

According to the robot end's expected touching force, expected position and posture, speed and acceleration and using the sensor information, calculate the driving torque τ_i at each joint of the robot.

4. Object control layer designing

When the robot moves in the restriction space, not only its position track, but also the robot force to the environment are desired to control. At present, most of the control in restriction environment can be divided into two kinds of position/force hybrid control and impedance control [3] [4].

The traditional impedance control is a sort of control strategy applied on a robot end, considering the relation of robot and environment as a spring damping system, while in the two-robot coordination, the control of object movement is obviously more intuitive than the control of the robot movement, and during the controller design, the whole system is always desired to be compensated kinetically. Thus, the traditional impedance relation is needed to spread into object impedance control, i.e., an object impedance control [5]-[7] (OIC in short).

The impedance control only considers the impedance effect at the place contacting the environment and ignores the difference between the position and the sub space of the force control, and achieves proper force response through adjusting given position and the target impedance [8]. In order to control the force running after the expected track, the hybrid control was combined with the impedance control, called hybrid impedance control, (HIC in short). Thus, the position control and force control can be realized with different directions and using different targets.

(1) Lection of the object hybrid target impedance: when position controlling, the capacitive target impedance is:

$$M^d(\ddot{r}_O^d - \ddot{r}_O) + B^d(\dot{r}_O^d - \dot{r}_O) + K^d(r_O^d - r_O) = F_e \qquad (1)$$

When force controlling, the inertial target impedance is:

$$M^d \ddot{r}_O + B^d \dot{r}_O = F_d - F_e \qquad (2)$$

Where M^d, B^d, K^d — $M^d, B^d, K^d \in R^{n\times n}$ are the oblique symmetry matrixes of the target inertia, oblique symmetry matrix of the target damp, and oblique symmetry matrix of the target rigidity respectively;

$r_O^d, \dot{r}_O^d, \ddot{r}_O^d$ — $r_O^d, \dot{r}_O^d, \ddot{r}_O^d \in R^n$ are the object's reference position and posture, speed, and acceleration respectively;

$r_O, \dot{r}_O, \ddot{r}_O$ — $r_O, \dot{r}_O, \ddot{r}_O \in R^n$ are the object's actual position and posture, speed, and acceleration;

F_d — $F_d \in R^n$ is the environment command force to the object, a zero in a free space;

F_e — $F_e \in R^n$ is the environment force to the object.

(2) Object controller: according to the duality of the impedance select, the overall target impedance of the hybrid impedance controller can be achieved as:

$$\begin{aligned} &M^d(S\ddot{r}_O^d - \ddot{r}_O) + B^d(S\dot{r}_O^d - \dot{r}_O) + K^d S(r_O^d - r_O) \\ &= F_e - (I - S)F_d \end{aligned} \qquad (3)$$

Where $S = diag(s_i) \in R^{n\times n}$ is the selected matrix, *i* indicates the freeness in the operational space,

$$s_i = \begin{cases} 1 & positioncontrolsubspace \\ 0 & forcecontrolsubspace \end{cases}$$

Then, equation (3) can be impressed further as:

$$\begin{aligned} \ddot{r}_o^s = s\ddot{r}_o^d + \left(M^d\right)^{-1}\big[&(I - S)F_d - F_e + \\ &B^d(S\dot{r}_O^d - \dot{r}_O) + K^d S(r_O^d - r_O)\big] \end{aligned} \qquad (4)$$

Where $\ddot{r}_O^s$ — the expected acceleration.

It is necessary to explain that the expected acceleration and reference acceleration are two different concepts. The latter is an expected beforehand value, which is calculated through plan on the condition that the object movement is clear, whereas the former is real time generated. From the equation it can be know that it is related with the system status variable, command force, reference track, and target impedance parameters, representing the track that the object should run after in the hybrid impedance control.

In addition, in order to achieve the real time expected track, the environment force to the object F_e should be estimated. Before that, the object acceleration $\ddot{r}_O$ should be measured. However, it is very difficult to measure the acceleration signal, and even if it can be measured, its value may include very big noise, making it can not be used directly. Thus, this paper adopted limited differential coefficient to express approximately:

$$\hat{\ddot{r}}^s_{O(t)} = \frac{\dot{r}_{O(t)} - \dot{r}_{O(t-\Delta t)}}{\Delta t} \tag{5}$$

Or,

$$\hat{\ddot{r}}^s_{O(t)} = \frac{r_{O(t)} - 2r_{O(t-\Delta t)} + r_{O(t-2\Delta t)}}{(\Delta t)^2} \tag{6}$$

Then, the estimated environment force to the object is:

$$\hat{F}_e = M_O \hat{\ddot{r}}^s_O + C_O - WF_C \tag{7}$$

Where $C_O = \left[-mg^T \quad \{\omega \times (\omega I_O)\}^T\right]^T$, m, I_O and ω are object mass, inertia matrix around the mass center, and angle speed vector respectively. W is the converted matrix from the robot end’s force on the object at the contact to the force on the object at the mass center.

After the expected acceleration of the object is achieved, its expected speed $\dot{r}^s_O$ and expected position and posture r^s_O can be achieved through simple integral. At the same time, the expected driving force F^d_O necessary for obtaining object movement can be achieved, there is:

$$F^d_O = WF^d_C = M_O \ddot{r}^s_O + C_O - \hat{F}_e \tag{8}$$

The structure block diagram of the object hybrid impedance controller is shown in Fig. 3.

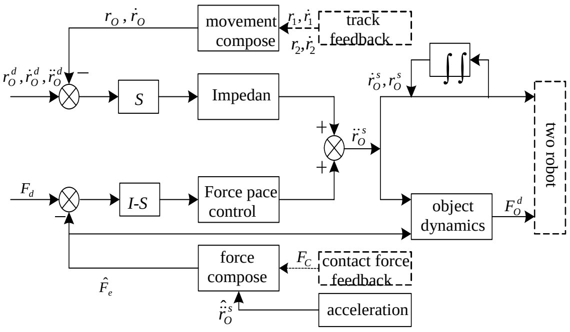


Fig. 3: Structure of object hybrid impedance controller.

(3) Selection of the target impedance parameters: in this paper, the environment is considered as a linear spring, let k_e be the environment rigidity, then, the environment module equation is $F_e = k_e r_O$, then, equation (2) can be expressed as:

$$M^d \ddot{r}_O + B^d \dot{r}_O + k_e r_O = F_d \tag{9}$$

It can be found that in the HIC, the position control direction and force control direction have the same expected movement equation form: $M\ddot{r} + B\dot{r} + Kr = F$, thus, a united standard can be used to select the target impedance parameters. The only difference is that the target rigidity in the position direction is a control variable that can be adjusted, whereas that in the force control direction is a relatively fixed environment parameter.

Laplace transforms the united equation, there is:

$$s^2R(s) + 2\xi_d\omega_n sR(s) + \omega_n^2 R(s) = \frac{1}{\mathrm{M}}F(s) \tag{10}$$

Where ω_n — $\omega_\mathrm{n} = \sqrt{\frac{\mathrm{K}}{\mathrm{M}}}$ is a natural frequency;

ξ_d — $\xi_d = \frac{\mathrm{B}}{2\sqrt{\mathrm{KM}}}$ is damping ratio.

Considering the system problem of real time, in the system feedback, a delay amount $e^{-2Ts} = \frac{1-Ts}{1+Ts}$ is introduced; then, equation (10) evolves into:

$$s^2R(s) + 2\xi_d\omega_n s e^{-2Ts} R(s) + \omega_n^2 e^{-2Ts} R(s) = \frac{1}{\mathrm{M}}F(s) \tag{11}$$

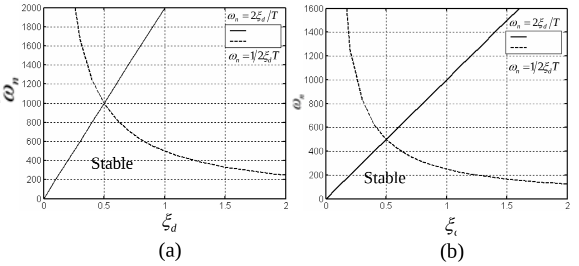
Where T is the sampling control cycle. Its feature equation is:

$$Ts^3 + (1 - 2\xi_d\omega_n T)s^2 + (2\xi_d\omega_n - \omega_n^2 T)s + \omega_n^2 = 0 \tag{12}$$

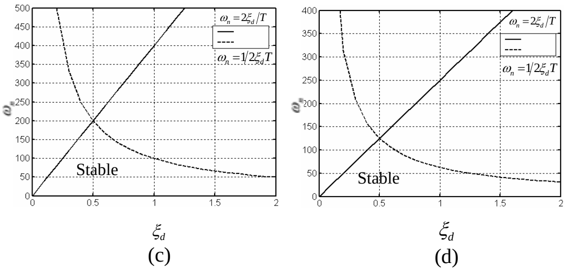
In order to stabilize the system, the pole point of the loop transmission function shall be strictly at the left half S plane, i.e., all the roots of the feature equation shall have negative true part. According to Routh stabilization criterion, there is:

$$\begin{cases} \omega_n < \dfrac{2\xi_d}{T} \\ \omega_n < \dfrac{1}{2\xi_d T} \end{cases} \tag{13}$$

Fig. 4 shows the stable areas when the system adopts different cycles. Emulation indicates that shortening the sampling control cycle is helpful to the system stability. After selecting proper ω_n and ξ_d in the figure, target impedance parameter stabilizing the system can be selected by combining equation (10).



(a) (b)



(c) (d)

Fig. 4: Stability region of the system, (a) *T*=1ms, (b) *T*=2ms, (c) *T*=5ms, (d) *T*=8ms.

5. Integrated controller of two-robot

The ultimate target of robot layered controller designing is to make the object achieve tracing the expected track by inner and external force. After make the inner force controller combined reasonable with the movement controller we mentioned above, the integrated controller of two-robot can be realized, as shown in fig5. It is noteworthy that because of the robot's terminal track deviation, it reflects the object's inner force deviation, external force deviation and movement deviation, so the non-linear dynamic compensating should be modulated as follows:

$$F'_{mi} = \ddot{r}_i^s + k_{vi}(\dot{r}_i^s - \dot{r}_i) + k_{pi}(r_i^s - r_i) \qquad (14)$$

Now, the general force need by robot to trace the expected track in operating space is:

$$F_i = \hat{M}_i(\ddot{r}_i)F'_{mi} + \hat{C}_i(r_i, \dot{r}_i) + F_{Ei}^d + F_{Ii}^d \qquad (15)$$

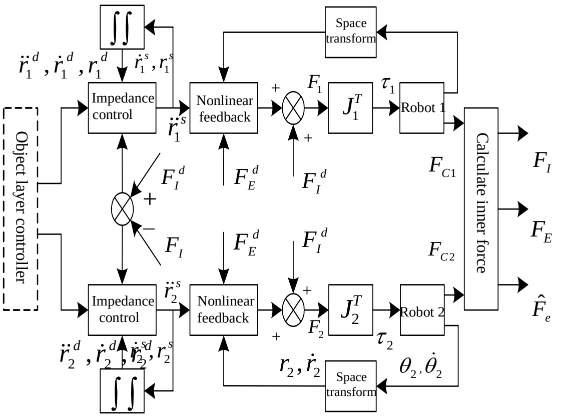
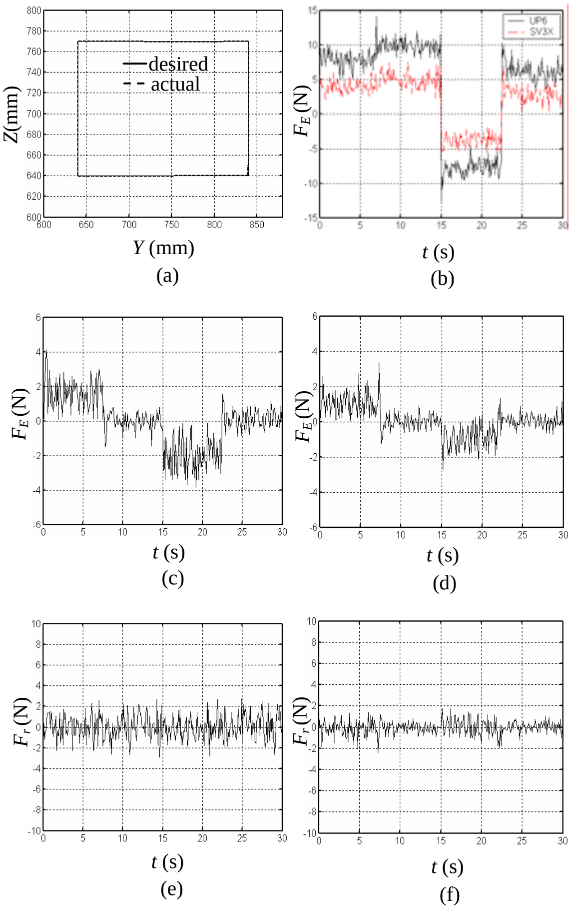


Fig. 5: Structure of two-robot complete controller

It is also found that the choosing of inner force impedance parameters and HIC impedance parameters is interactive, so we must decide the priority of inner force control and HIC control according to the system state and task quality. After that a control method can be decided based on the analyzing above.

6. Experiment Results

Now, we will give a experimental example in order to show the effective of the proposed method. In free space, let two-robot's claw-end grasp a cube box, which the size is 130×130×130mm^3 and weight is 1.30kg (aluminum). The box handed by claws is moved along a rectangular edge in *YOZ* plane. No master-slave distinguishing between the tow-robot in our experiment, their moving are limited on the designed track. The coordination control of the Inner and external force is achieved by wrist sensors.



(a) (b) (c) (d) (e) (f)

Fig. 6: Coordination of two-robots coordinated system, (a) Object tracking, (b) the inner force of robot along Z axis, (c) UP6 inner force along y axis, (d) SV3X inner force along *y* axis (e) Object external force along Z axis, (f) SV3X inner force along *y* axis.

The control inaccuracy on *y* and *z* direction is less than 1mm while tracking the position, as shown in fig6. Due to the influences from noise and impact force, the overshoot and jitter are obvious during the inner and external force tracking procedure. But, the error of overshoot and jitter average value are within ±2N and the control effect is satisfactory.

7. Conclusions

This paper researched the coordination control system of the two-robot. According to the control features of the two-robot, the control system was divided into object layer and robot layer to modularize respectively. In the object layer, the grasped object is considered controllable. An object controller was designed with object HIC control method, letting it compensate the whole dynamics and analyzing its stability.

Acknowledgement

This work is partially supported by Heilongjian Nature Science Foundation of China (Grant No. 60175029).

References

[1] S. Schneider and R.H. Cannon, Object Impedance Control for Cooperative Manipulator, Theory and Experimental Results. *IEEE Transaction on Robotics and Automation*, 8:383-394, 2002.

[2] Richard M. Murray, Li Zhexiang, Mathematic Introduction of Robot Operation, translated by Xu Weiliang and Qian Reimin. *Mechanical Industry Press*, 1998.

[3] Yin Yuehong, Zhu Jianying, and Wei Zhongxin, A Summary of Research of Manual Control of Robot, *Nanjing Aviation and Spaceflight University Transaction,* 29:220-226, 2004.

[4] Yin Yuehong, Wei Zhongxin, Zhu Jianying, research of Robust Complaisant Control, Robot, 20:232-240, 1998.

[5] Li Jie, Wei Qing, and Chang Wenshen, Object Controlled Multi Robot Harmonization Module, Arithmetic, and Experiment. *Automation Ttransaction*, 28: 349-355, 2002.

[6] Jung S, Yim S B, Experiment Studies of Impedance Force Control for robot Manipulator. *IEEE Transaction on Robotics and Automation*, 7:323-334, 2001.

[7] Hai Pengxie, Bryson. I.J, Shadpey, and Patel. R.V, A, Robust Control Scheme for Dual ArmRedundant Manipulators, Experimental Results. *IEEE International Conference on Robotics and Automation*, 8:2507-2512, 1999.

[8] G.J. Liu and A.A. Goldenberg, Robust Hybrid Impedance Control of Robot Manipulators. *IEEE International Conference on Robotics and Auto,* 4:287-292, 2001.