On Control System of the Two-Robot Coordination

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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.
3. Layered modularized coordination controller

Based on the general control concept mentioned above, the design of the two robots’ 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 \( v_o^d \), expected acceleration \( a_o^d \), expected driving force \( F_o^d \) and the expected force to the object by the environment \( F_e \).

(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 \( v_i^d \),

(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 \( F_i^d \), calculate and output robot end’s optimum grasping force \( F_{ci} \).

(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 \( v_i \), the counter operation of the load distributor calculates and outputs the object’s actual position and posture vector \( r_o \) and actual speed \( v_o \).

(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
At each joint of the robot, impedance control [5]-[7] (OIC in short), always desired to be compensated kinetically. Thus, during the controller design, the whole system is more intuitive than the control of the robot movement, and the control of object movement is obviously more damping system, while in the two-robot coordination, the relation of robot and environment as a spring impedance control [3] [4].

The traditional 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:

\[ M^c (\ddot{r}_o^d - \ddot{r}_o^e) + B^c (\dot{r}_o^d - \dot{r}_o^e) + K^c (r_o^d - r_o^e) = F_e \]  

(2) When force controlling, the inertial target impedance is:

\[ M^f r_o^d = F_e - F_e \] 

Where \( M^f, B^f, K^f \rightarrow M^c, B^c, K^c \in \mathbb{R}^{n \times n} \) 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; \( r_o^d, \dot{r}_o^d, \ddot{r}_o^d, r_o^e, \dot{r}_o^e, \ddot{r}_o^e \in \mathbb{R}^n \) are the object’s reference position and posture, speed, and acceleration respectively; \( r_o^d, \dot{r}_o^d, \ddot{r}_o^d, r_o^e, \dot{r}_o^e, \ddot{r}_o^e \in \mathbb{R}^n \) are the object’s actual position and posture, speed, and acceleration; \( F_e - F_e \in \mathbb{R}^n \) is the environment command force to the object, a zero in a free space; \( F_e - F_e \in \mathbb{R}^n \) 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:

\[ M^F (S^d r_o^d - r_o^e) + B^F (S^d \dot{r}_o^d - \dot{r}_o^e) + K^F (r_o^d - r_o^e) = F_e \]  

(3)

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

\[ s_i = \begin{cases} 1 & \text{positioncontrolspspace} \\ 0 & \text{forcecontrolspspace} \end{cases} \]

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

\[ \ddot{r}_o^e = \ddot{r}_o^e + (M^F)^{-1} \left\{ (I - S) F_e - F_e + B^F (S^d \dot{r}_o^d - \dot{r}_o^e) + K^F S (r_o^d - r_o^e) \right\} \]  

(4)

Where \( \ddot{r}_o^e \) — 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:

$$\ddot{r}_{o(\Delta t)} = \frac{\dot{r}_{o(t)} - \dot{r}_{o(t-\Delta t)}}{\Delta t} \tag{5}$$

Or,

$$\ddot{r}_{o(\Delta t)} = \frac{r_{o(t)} - 2r_{o(t-\Delta t)} + r_{o(t-2\Delta t)}}{(\Delta t)^2} \tag{6}$$

Then, the estimated environment force to the object is:

$$\hat{F}_e = M_o \ddot{r}_o + C_o - W F_c \tag{7}$$

Where $C_o = \left[ -m g \right] + \{ \omega \times (\omega_o) \}^T$, $m$, $I_o$, and $\omega$ 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 $\dot{r}_o^e$ and expected position and posture $r_o^e$ can be achieved through simple integral. At the same time, the expected driving force $F_o^e$ necessary for obtaining object movement can be achieved, there is:

$$F_o^e = W F_c + M_o \dot{r}_o^e + C_o - \hat{F}_e \tag{8}$$

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

(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:

$$M \ddot{r}_o + B \dot{r}_o + k_e r_o = F_e \tag{9}$$

It can be found that in the HIC, the position control direction and force control direction have the same expected movement equation form: $M \ddot{r} + B \dot{r} + K r = F$, 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:

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

Where $\omega_n = \frac{1}{\sqrt{K M}}$ is a natural frequency;

$$\xi = \frac{B}{2 \sqrt{K M}}$$

is damping ratio.

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

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

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

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

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:

$$\begin{align*}
\omega_n &< \frac{2 \xi}{T} \\
\omega_n &< \frac{1}{2 \xi T}
\end{align*} \tag{13}$$

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 $\omega_n$ and $\xi$ in the figure, target impedance parameter stabilizing the system can be selected by combining equation (10).
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:

\[ F'_{\text{in}} = \ddot{r}'_i + k_i (\dot{r}'_i - \dot{r}_i) + k_p (r'_i - r_i) \]  \hspace{1cm} (14)

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

\[ F_i = M_i (\ddot{r}_i) F'_{\text{in}} + C_i (\dot{r}_i, \dot{r}_i) + F_{Ei}^{d} + F_{Fi}^{d} \]  \hspace{1cm} (15)

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 130×130×130mm³ 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.

The control inaccuracy on y and z direction is less than 1mm while tracking the position, as shown in fig6.
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.

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References