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Robust Impedance Control of High-DOF Robot Based on ISMC and DOB

ABSTRACT

This paper proposes a robust impedance controller for high-DOF robots. The model-based control of a higher DOF robot uses a numerical dynamic model because the analytical dynamic model is difficult to be derived and this means that modeling error is inevitable. The impedance control in the task space is affected by joint motions and has more difficulties in the higher DOF robots. In addition, the disturbances must be decoupled in the control of high DOF robot. This paper proposes a robust impedance controller based on integral sliding mode control (ISMC) and disturbance observer (DOB) for high-DOF robot manipulator. The ISMC is used to improve the robustness of the impedance control and to preserve its nominal performance. DOB is also employed to cancel the effects of input disturbances and to reduce the maximum gain of the ISMC which eventually determines the input chattering size.

Key word : Impedance Control, Robust Control, Integral Sliding Mode, Disturbance Observer, High DOF robot
I. INTRODUCTION

Nowadays, robots work in various environments and their impedance must be properly chosen according to their respective environment.

The widely known impedance control that was proposed by Hogan [1] received numerous citations in the past three decades. Impedance control determines the dynamic relationship between the robot and its environment [2-7]. It is based on the robot dynamics, however, its control performance is deteriorated by the uncertainties and disturbances.

The analytical dynamic model of a high DOF robot is difficult to be derived but only numerical model is possible. With the numerical model, the modeling error is unavoidable and with the high DOF, the control in the task space is affected by the moving joints as disturbances.

The integral sliding mode control(ISMC) improves the robustness preserving the nominal control performance in its sliding mode dynamics and has no reaching phase by choosing the initial value of integral properly [8-14].

In this paper, the impedance control characteristic is preserved in the sliding mode of the ISMC. Disturbance observers (DOB) have been used to decouple the disturbances. Among them, the DOB which uses the inverse of plant dynamic is conceptually simple and easy to implement and has many applications [15-17]. Recently, it is utilized in the sensor-less impedance control for human-compliant application [17].

In this paper, the desired impedance is achieved by PD type controller and implemented on the sliding mode dynamic of ISMC. A DOB is supplemented to decouple the disturbance \(d_q\) in impedance control of robot manipulator. For the above joint space description, the task space dynamics is described as follows:

\[ A(x)\ddot{x} + \mu_x(x, \dot{x}) + p(x) + d_x = F \]  

where \(A(x) = J^T A(q) J^{-1}\), \(\mu_x = J^T b(q, \dot{q}) q A(x) J_q\), \(p(x) = J^T g(q)\), \(F = J^T \tau\) and \(x \in R^n\) is the end-effector configuration, \(d_x\) is the projected disturbance in the task space, and \(J\) is the Jacobian matrix.

After the compensation for Coriolis-centrifugal, and gravity forces in joint space, Eq. (2) is as

\[ A(x)\ddot{x} - A(x)Jq + d_x = F_x \]  

where \(F_x = \mu_x(x, \dot{x}) + p(x) + A(x)F_u\).

The term \(-A(x)Jq\) is considered as part of the disturbance, so Eq. (3) is written as

This paper is the extended version of [21] which includes only brief description of this paper.

This paper is organized as follows: Robot dynamic is given in chapter II, DOB and ISMC are designed in the chapter III. In the chapter IV, computer simulation shows the overall performance of the proposed controller.

II. PROBLEM STATEMENT

Dynamic model of a n-link robot manipulator can be expressed by

\[ A(q)\dot{q} + b(q, \dot{q})\dot{q} + g(q) + d_q = \tau \]  

where \(q \in R^n\) is the joint variable, \(A(q)\) is the n×n inertia matrix, \(b(q, \dot{q})\dot{q}\) is the centrifugal and Coriolis, \(g(q)\) is the gravity, and \(d_q\) is disturbance and \(\tau\) is the input torque.

The problem is to decouple the disturbance \(d_q\) in impedance control of robot manipulator. For the above joint space description, the task space dynamics is described as follows:

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The term \(-A(x)Jq\) is considered as part of the disturbance, so Eq. (3) is written as
\[ A(x)\ddot{x} + d_i = A(x)F_u \] (4)

where \( d_i = d_i - A(x)J_q \).

This is the starting point for the following sections.

The goal of position-tracking impedance control is to make the desired error dynamics as

\[ \ddot{e} + B_e\dot{e} + Ke = 0 \] (5)

where \( e \) is the position error and \( B_e \) and \( K \) are the desired damping and stiffness of the robot manipulator.

The force from the environment must be nullified for position tracking.

If control law is determined in the task space as

\[ F_u = A(x)(\ddot{x}_d - B_e\dot{e} - Ke) \] (6)

Then, equation (4) will be rewritten as

\[ \ddot{x} + A(x)d_p = A(x)(\ddot{x}_d - B_e\dot{e} - Ke) \] (7)

Under the assumption of \( d_i = A(x)d_p \),

\[ A(x)\ddot{x} + A(x)d_p = A(x)(\ddot{x}_d - B_e\dot{e} - Ke) \] (8)

Then, the error dynamic is

\[ \ddot{e} + B_e\dot{e} + Ke = d_p \] (9)

In the above equation, the impedance is affected by the disturbance \( d_p \). This shows that conventional impedance control requires robustness improvement.

### III. CONTROLLER DESIGN

#### 3.1. Disturbance Observer

DOB will be designed to decouple the input disturbance and minimize the chattering size of ISMC. The DOB design is based on the inverse system. From Eq.(4), the nominal plant is

\[ x(s) = \frac{1}{s^2}F_u(s) \] (10)

DOB is designed based on this transfer function.

The structure of the DOD is shown in the Fig.1 and the estimated disturbance is given by

\[ \hat{d}_{DOB} = P^{-1}Qe - Q\dot{F}_u \] (11)

where \( Q(s) = \sum_{i=0}^{n}a_3(s) \), \( a_3 = 1 \). Q filter is a low-pass filter designed to make the inverse of the system proper [15].

![Fig. 1 DOB structure](image)

Most DOB is usually designed in the joint space, but in this paper, it is designed in the task space for higher DOF robot.

By using DOB, the disturbance is considered as follows.

\[ d_r = \hat{d}_{DOB} - d_i \] (12)

where \( d_r \) denotes , the remaining bounded disturbance and uncertainties. This is expected to be much lower than the disturbance in Eq. (2).

DOB makes the ISMC have lower nonlinear gains, as it deals with lower disturbances and leads lower chattering.

\[ d_{\text{max}} \gg \| d_r \| \] (13)
3.2. Impedance-based Integral Sliding Mode Control

In this paper, the ISMC is designed to obtain the desired impedance without the effect of input disturbances. The \( F_{\text{ISMC}} \) is added to \( F_u \) as follows.

\[
F_u = A(x)(\ddot{x}_d - B \ddot{e} - Ke + F_{\text{ISMC}})
\]  

(14)

Then the error model Eq. (9) in the state space form is

\[
\dot{e}_z = Ae_z + B(F_{\text{ISMC}} + d_s)
\]

(15)

where \( e = e_1, \dot{e}_1 = e_z, A = \begin{bmatrix} 0 & I \\ -K & -B \end{bmatrix}, B = [0] I \).

The \( F_{\text{ISMC}} \) is used for ISMC.

In the SMC, the overall control dynamics is determined by the sliding mode dynamics. So, the desired impedance in Eq. (5) must be included in the sliding mode dynamics.

To achieve this, the following sliding surface is chosen.

\[
s = e_z + z
\]

(16)

where

\[
\dot{z} = -Ae_z
\]

(17)

If the error states are guaranteed to stay on the sliding surface, then \( s = 0 \) and \( \dot{s} = 0 \).

The \( s \) is calculated as follows.

\[
\dot{s} = \dot{e}_z - Ae_z
\]

(18)

Hence, the system has the desired impedance on the sliding surface.

In order to guarantee the existence of sliding surface, the following \( V \) must be Lyapunov function.

\[
V = \frac{1}{2} s^T s > 0
\]

(19)

and its time derivative has to be negative.

\[
\dot{V} = s^T s = s^T (Ae_z + B(F_{\text{ISMC}} + d_s) - Ae_z)
\]

(20)

The following input makes the above \( \dot{V} < 0 \) be negative.

\[
F_{\text{IBC}} = -d_{\text{max}} \frac{s^T B}{|s^T B|}
\]

(21)

The overall input consists of nominal control input, ISMC input and DOB output.

\[
F_{\text{all}} = A(x)(\ddot{x}_d - B \ddot{e} - Ke + F_{\text{ISMC}}) - d_{\text{DOB}}
\]

(22)

IV. SIMULATION

To show the performances of the proposed controller in robustness improvement and preserving the desired impedance, the computer simulation has been performed using the Stanford WBC software. This software provides the numerical robot dynamic model based on TAO dynamics engine library.

From the robot structure saved in the xml file, it numerically computes the Jacobian matrix, the inertia, Coriolis-centrifugal and gravity values.

The structure of the simulated robot is stored in a xml file. The robot has eight joint and 1 meter links. Their detail descriptions are in the following Table 1.

The software prepares the dynamic model Eq. (1) numerically.

Table. 1 Robot structure stored in the xml file

| Description                              | Value    |
|------------------------------------------|----------|
| Number of links                          | 8 [links]|
| Length of every link                     | 1 [meter]|
| Mass of every link                       | 1 [kg]   |
| Gravitational acceleration               | 9.81 [m/s²] |
| Center of mass of every link (basically at the middle of each link) | 0.5 [m] |

In the simulation, three cases are considered. First one is the nominal system with PD-type impedance
control, second one is the system with disturbances and pure impedance control and third one is the system with proposed controller for the system with disturbances. The third one must have the same time response with the first one even with disturbances.

The goal position is set in sinusoidal as follows.

\[
\begin{align*}
    x &= 2.5 \sin 0.2t \\
    y &= 2.5 \sin 0.37t
\end{align*}
\]  

(23)

The proposed controller is

\[
F_{\text{all}} = A(x)(\ddot{x}_d - B_K \dot{e} - Ke + F_{\text{ISMCE}}) - \tilde{d}_{\text{DOB}}
\]  

(24)

where \(B_K = 40, K = 400\) which determine the damping and stiffness.

The simulation result is shown in the following figures.

In Fig. 2 and 3, the time response of pure impedance control (red) is greatly affected by the external disturbance of \(500 \sin(t)\), while the proposed controller (blue) shows the considerably same as a system without disturbance (green).
V. CONCLUSIONS

A robust impedance controller is proposed using ISMC and DOB for high DOF robot. For disturbances, the proposed controller shows its robustness improvement compared to PD type impedance control. The time responses of proposed controller with disturbances are the same with the responses of the PD type controller without disturbances. The robustness is from ISMC characteristic. DOB is used decouple input disturbances and lowers the burden of ISMC and leads the 70% lower nonlinear gains. The proposed controller is considered for high DOF robot in task space where uncertainties are inevitable. The software used in the simulation can be used for the actual control of high DOF robots.

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