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ISMC와 IDA-PBC를 이용한 유연관절로봇의 강인제어

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Robust Control of Flexible Joint Robot Using ISMC and IDA-PBC

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요 약

본 논문은 유연관절로봇의 추종성능과 정합과 비정합 외란 모두에 대한 강인성을 향상시키기 위한 강인한 제어기를 제안한다. 제안된 제어기는 백스테핑 외란관측기(DOB), 수동성기반 제어기(PBC)와 적분슬라이딩모드 제어기(ISMC)가 백스테핑기법 형태로 구성되어 있다. 백스테핑 DOB는 링크측의 비정합 외란을 고려하는데 사용되며 모터측의 기준입력을 제공하는 역할을 한다. IDA-PBC는 모터측의 추종제어를 수행하며 적분슬라이딩모드제어와 결합될 때 공칭제어기의 역할을 하며 전체 공칭제어시스템의 안정도를 보장받도록 한다. 반면에 적분슬라이딩모드제어는 정합조건을 만족시키는 모터측의 외란의 영향을 제거하는데 사용된다. 링크측의 제어기를 설계하는데 있어서는 PD타입의 임피던스제어기와 DOB가 결합됨으로써 강인한 제어특성과 함께 모터측의 기준입력에 적합한 연속적인 입력의 제공이 가능하도록 하였다.

ABSTRACT

This paper proposes a robust controller for flexible joint robots to achieve tracking performance and to improve robustness against both matched and mismatched disturbances. The proposed controller consists of a disturbance observer(DOB), passivity-based controller, and integral sliding mode controller(ISMC) in a backstepping manner. The DOB compensates the mismatched disturbance in the link-side and formulates the reference input for the motor-side controller. Interconnection and damping assignment passivity-based controller (IDA-PBC) performs tracking control of motor-side, and it is integrated to nominal control of ISMC to guarantee the over-all stability of the nominal system, while, matched disturbances are decoupled by the discontinuous control of ISMC. In the design of the link-side controller, PD type impedance controller is designed with DOB and this leads the continuous control input which is suitable to the reference input for the motor-side.

키워드 : 유연관절로봇, 수동성, 적분슬라이딩모드제어, 비정합조건 외란, 외란관측기

Key word : Flexible joint robot, Passivity, Integral Sliding Mode, Mismatched Disturbance, Disturbance Observer

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Ⅰ. INTRODUCTION

Nowadays, the variety of robotic field is increasing and the flexible joint robots(FJR) are used frequently like series elastic actuator, belt-pulley transmission and harmonic drives. Hence, more researches for the control of FJR are needed to achieve better performances and robustness. Until now, problems such as non-linearity, stability issues, mismatched disturbance due to environment contact, and robustness improvement must still be collectively addressed. Numerous researches such as passivity-based control [1-3], sliding mode control [4], adaptive control [5], backstepping [6, 7] and other robust control [8, 9]. These researches failed to collectively address these issues, especially mismatched disturbance which is a vital consideration in control of flexible joint robot.

This paper proposes to integrate the robust ISMC to PBC to improve robustness of this method.

Passivity-based control is a non-linear control which aims to shape the energy function of a system and incorporates system's physical considerations into design, energy shaping not only guarantee stability but also improve the control performance. There are two methodologies of PBC which are the classical PBC and IDA-PBC [10, 11]. IDA-PBC aims to shape the energy function by assigning interconnection and damping to a passive system. IDA-PBC for flexible joint robot is proposed in [2, 3]. This paper shows stable performance but robustness against disturbances is not considered.

System robustness is the main concern of sliding mode controllers [4, 12]. Among SMCs, ISMC has no reaching phase, guarantees robustness against matched disturbances, and preserves the nominal performance. ISMC consists of nominal control that controls the disturbance-free system and switching control that guarantees system stability in the presence of matched disturbances [13]. In this paper, PBC is chosen as the nominal controller of ISMC. Certainly, there are ideas that combine PBC and SMC [14-18]. Usually, the concept of passivity is used in stability analysis of SMC [13, 15]. In [18], a passivity-based ISMC is proposed but mismatched disturbance is not considered. It is well-known that SMCs cannot address mismatched disturbance. Practically, flexible joint robots are affected by these mismatched disturbances, hence, this is important to include it into control considerations. Some papers proposed a method to address mismatched perturbations problem [19-21]. But in [20], they concluded that any attempts to compensate for mismatch disturbances will just increase the norm of the equivalent disturbance. In [7], the backstepping approach is proposed to address the mismatched disturbance of flexible joint robot. However, the performance is degraded by the chattering caused by link-side ISMC.

The proposed controller combines three different control schemes. First, a DOB [22] is used to control the link-side to compensate the mismatched disturbance, and then, the control input formulated for the link-side is realized as the motor-side reference input like in a backstepping approach. Second, IDA-PBC is combined with the ISMC for the motor-side. IDA-PBC is designed by assigning the desired energy function that injects proper energy to perform the reference tracking on the motor-side. The passivity is used to guarantee the over-all stability of the nominal system. Lastly, ISMC encases the IDA-PBC and its discontinuous control to assure stability under matched disturbance.

The novelty of this paper is in the decoupling of mismatched disturbance in the motor-side by backstepping-like approach and using IDA-PBC and ISMC to perform motor-side tracking while guaranteeing the over-all stability.

This paper is organized as follows: problem formulation is given in chapter II and controller design including the proposed controller is described in chapter III. Chapter IV shows the simulation results and chapter V gives the conclusion of this paper.

Ⅱ. PROBLEM FORMULATION

The dynamical model of one-link flexible joint robot is proposed in [1].

$$\begin{aligned} &M\ddot{q}+g(q)=\tau+\tau_{ext} && (link-side) \\ &B\ddot{\theta}+\tau=\tau_m+\tau_f && (motor-side) \\ &\tau=K(\theta-q)+D(\dot{\theta}-\dot{q}) && \end{aligned} \qquad (1)$$

where the parameter description is in the Table 1.

Table. 1 Flexible Joint Robot parameters

Denotation	Name
$q\in R^n$, $\theta\in R^n$	Link Angle and Motor Angle Vector
$M, g(q)$	Inertial, & Gravity Matrices
τ, τ_{ext}, τ_m and τ_f	Joint, External, Motor and Friction Torque
K, D	Stiffness & Damping Matrices
B	Motor Inertia Matrix

As proposed in [1], it is preferable to reduce the motor inertia from B to B_θ by using the following feedback law

$$\tau_m = BB_\theta^{-1}u_m+(I-BB_\theta^{-1})\tau \qquad (2)$$

Applying this feedback law, the motor side equation will be

$$B_\theta\ddot{\theta}+\tau=u_m+\tau_f \qquad (3)$$

Aside from the dynamical system model, the formulation of IDA-PBC needs the state-space model of the flexible joint robot which can be written as

$$\dot{x}=F(x)+G(x)(\tau_m+\tau_f)+G_d(x)d_u \qquad (4)$$

where

$$\begin{aligned} &x=[q\ \dot{q}\ \theta\ \dot{\theta}]^T \\ &F(x)=[\dot{q}\quad M^{-1}\tau\quad \dot{\theta}\quad -B_\theta^{-1}\tau)]^T \\ &G(x)=[0\ \ 0\ \ 0\ \ B_\theta^{-1}]^T \\ &G_d(x)=[0\ \ M^{-1}\ \ 0\ \ 0]^T \\ &d_u=\tau_{ext}-g(q) \end{aligned} \qquad (5)$$

The form of $G(x)$ and $G_d(x)$ shows the mismatched condition of the link-side disturbance. Also, Gravity compensation will be treated as mismatched disturbance compensation to ease the control formulation of the nominal non-linear system.

Ⅲ. Controller Design

3.1. Robust Control Using DOB

The angle of the motor is considered as the input to the link-side system.

A linear controller is designed with in backstepping manner to control the link-side and to compensate for mismatched disturbances d_u: external torques and gravity torques. Consider the link-side equation in (1), the following transfer function describes the nominal dynamics of the link-side.

$$G_{LSn}(s)=\frac{q}{\theta}=\frac{Ds+K}{Ms^2+Ds+K} \qquad (6)$$

In the above transfer function, the motor-side variable is considered as the input.

$$u_b=\theta \qquad (7)$$

DOB is used for the robust controller [21]. To obtain the output of DOB that will compensate for disturbance of the link-side, consider

$$u_b=[G_{LSn}(s)^{-1}Q(s)-Q(s)] \qquad (8)$$

where

$$Q(s)=\frac{\omega}{(s+\omega)^m} \qquad (9)$$

is low-pass filter with m as the filter's order and ω as the cut-off frequency. It is well-known that the order of DOB must be higher than the order of the plant's order to make the $G_{LSn}(s)^{-1}Q(s)$ term of DOB implementable.

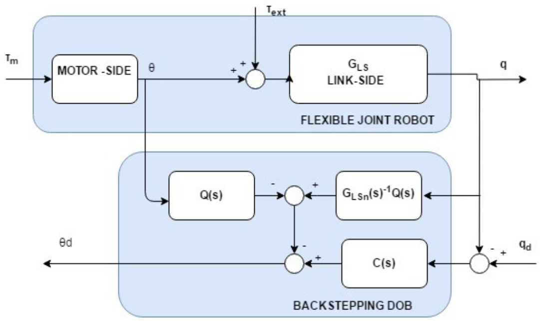

Fig. 1 Backstepping DOB

As proposed in [7], the input u_b is realized as the reference input of the motor-side.

$$\theta_d = u_b \tag{10}$$

In this way, the actuation signal that will make the link-side subsystem track the link-side variable is formulated, and this will be the reference signal of the motor-side control. The introduction of DOB into the backstepping technique is one of the main idea of this paper.

Hence, this reference signal must be unchattered so that the motor-side control can adequately track this reference signal. Therefore, we strongly advice to not use SMC as the robust linear controller to compensate for link-side disturbance.

The structure of the proposed backstepping DOB is shown in Fig. 1. The block $C(s)$ is used as the link-side tracking controller. The error dynamics of $C(s)$ is

$$e_q = q - q_d \tag{11}$$

3.2. IDA Passivity Based Control

The design objectives of passivity based control are to shape the energy function of a system into a desired one and to incorporates system's physical considerations into design. Passive systems satisfy the following conditions.

For a storage function of $H(x)$,

$$\dot{H} \le y^T u \tag{12}$$

where y is the chosen output of the system and u is the input of the system. IDA-PBC uses Port-controlled Hamiltonian systems (PCH) which incorporates system's physical consideration into design. PCH systems have following form.

$$\dot{x} = (J - R)\frac{\partial H(x)}{\partial x} + G(x)u \qquad y = G^T(x)\frac{\partial H(x)}{\partial x} \tag{13}$$

where $H(x)$ is the system's total energy function, $J \in R^{nxn}$, and $R \in R^{nxn}$ are the system's interconnection and damping matrices, respectively. The interconnection and damping matrices follow the following condition.

$$J = -J^T \qquad R = R^T > 0 \tag{14}$$

In IDA-PBC, the desired closed-loop energy function $H_d(x)$ and the system's desired interconnection $J_d \in R^{nxn}$ and damping $R_d \in R^{nxn}$ are determined via partial differential equation (PDE) which can be expressed as

$$G(x)^L F(x) = G(x)^L (J_d - R_d)\frac{\partial H_d(x)}{\partial x} \tag{15}$$

where $G(x)^L$ is the left annihilator of $G(x)$ ($G(x)^L G(x) = 0$).

The desired energy function $H_d(x)$ is chosen by considering the open-loop energy function $H(x)$, and then solve for equivalent interconnection and damping assignment using (15).

The final objective of IDA-PBC is to make the closed-loop dynamics as

$$\dot{x} = (J_d - R_d)\frac{\partial H_d(x)}{\partial x} \tag{16}$$

Equating (13) and (15), the control input that achieves the closed-dynamics is

$$\beta(x) = (G(x)^T G(x))^{-1} G(x)^T \times [(J_d - R_d)(\frac{\partial H_d(x)}{\partial x}) - F(x)] \tag{17}$$

As discussed in [14], the stability of the closed-loop system is proven by choosing $H_d(x)$ as the Lyapunov candidate function.

$$\dot{H}_d = -\left[\frac{\partial H_d(x)}{\partial x}\right]^T R_d \frac{\partial H_d(x)}{\partial x} \le 0 \tag{18}$$

For flexible joint robot, the followings are for PCH system description.

$$G(x)^L = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{19}$$

and

$$J_d = \begin{bmatrix} 0 & J_1 & J_2 & J_3 \\ -J_1 & 0 & J_4 & J_5 \\ -J_2 & -J_4 & 0 & J_6 \\ -J_3 & -J_5 & -J_6 & 0 \end{bmatrix} \quad R_d = \begin{bmatrix} r_1 & 0 & 0 & 0 \\ 0 & r_2 & 0 & 0 \\ 0 & 0 & r_3 & r_5 \\ 0 & 0 & r_5 & r_4 \end{bmatrix} \tag{20}$$

The desired energy function $H_d(x)$ is chosen first and then J_d and R_d are determined.

The open-loop energy function of flexible joint robot in (1) can be written as

$$H(x) = H_{link}(q) + H_{motor}(\theta) \tag{21}$$

The link energy function $H_{link}(q)$ describes the passive mapping $(\tau \rightarrow \dot{q})$ and this can be written as

$$H_{link} = 0.5\,\dot{q}^T M(q)\dot{q} + V_g(q) \tag{22}$$

On the other hand, the motor energy function $H_{motor}(\theta)$ describes the passive mapping $(\dot{q} \rightarrow \tau)$

$$H_{motor} = 0.5\dot{\theta}^T B_\theta \dot{\theta} + 1/2(\theta - q)^T K(\theta - q) \tag{23}$$

Considering the total energy function in (21) , in this paper, the desired energy function for reference tracking is chosen as

$$H_d = 0.5\dot{q}^T M\dot{q} + 0.5\dot{\theta}^T B_\theta \dot{\theta} + 0.5(\theta - q)^T K(\theta - q) + H_{rt}(\theta) \tag{24}$$

where an injected energy $H_{rt}(\theta)$ is added to perform the reference tracking and this can be expressed as

$$H_{rt}(\theta) = 0.5(\theta - \theta_d)^T K_p(\theta - \theta_d) \quad K_p > 0 \tag{25}$$

In this way, the main objective of IDA-PBC; motor-side reference tracking, and the over-all stability of the system is guaranteed. As mentioned above, the θ_d is provided by the link-side robust controller expressed in (8).

Using the PDE in (15), J_d and R_d can be found as

$$J_d = \begin{bmatrix} 0 & M^{-1} & 0 & 0 \\ -M^{-1} & 0 & 0 & M^{-1}B_\theta^{-1}D \\ 0 & 0 & 0 & B_\theta^{-1} + r_5 \\ 0 & -M^{-1}B_\theta^{-1}D & -B_\theta^{-1} - r_5 & 0 \end{bmatrix} \tag{26}$$

$$R_d = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & M^{-1}D & 0 & 0 \\ 0 & 0 & 0 & r_5 \\ 0 & 0 & r_5 & r_4 \end{bmatrix}$$

where $r_4 > 0$, $r_5 > 0$ assign the desired damping. Lastly, the control input is determined as folllows.

$$\beta(x) = (-r_4 B_\theta^2 + D)\dot{\theta} + (1 - 2r_5)K_p(\theta - \theta_d) - 2r_5 K(\theta - q) \tag{27}$$

Let $K_p{}' = (1 - 2r_5)K_p < 0 \quad K_d = -r_4 B_\theta^2 + D \ < 0$ and $K_f = -2r_5 K < 0$.

The following Fig. 2 shows the overall control scheme proposed in this paper.

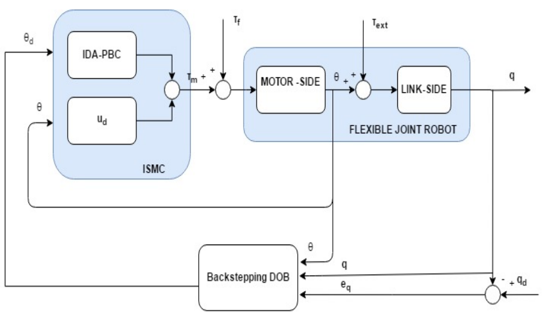

Fig. 2 Proposed Control Scheme

3.3. Integral Sliding Mode Control with PBC

The control input of SMC is separated into two parts

$$u = u_0 + u_d \tag{28}$$

where u_0 is the nominal controller which is the PBC formulated in the previous section and u_d is the control input to make the state go to the sliding surface. Fig. 2 shows the control stucture of the proposed controller.

The sliding surface is chosen as

$$s = x - z \tag{29}$$

where the nominal dynamics z is expressed as

$$\dot{z} = F(x) + G(x)u_0 \tag{30}$$

The derivative of the sliding surface is given as

$$\dot{s} = \dot{x} - \dot{z} = F(x) + G(x)(u+d) - (F(x) + G(x)u_0) = G(x)(u_d + d) \tag{31}$$

Lyapunov candidate function is chosen as

$$V = 0.5s^2 \tag{32}$$

and its derivative is

$$\dot{V} = s^T \dot{s} = s^T [G(x)(u_d + d)] \le 0 \ . \tag{33}$$

To guarantee stability, $\dot{V}$ must be negative and the following discontinuous control must be chosen.

$$u_d = -d_{\max} \times sign(s^T G(x)) \tag{34}$$

where $d_{\max} > |d|$.

Ⅳ. SIMULATION RESULTS

A one-link flexible joint robot is controlled by the proposed cnotroller and it is simulated in MATLAB with parameters as shown in Table 2. The control parameters are chosen as $K_p' = -10\,Nm/rad$, $K_d = -5$, $K_f = -5\,Nms/rad$, $B_\theta = 0.11\,kgm^2$, and $dmax = 110\,Nm$.

Table. 2 Flexible Joint Robot Parameter Values

Name	Values
Link-side position reference	$q_d = 1rad$
Inertial & Gravity Matrix	$M(q) = 0.441kgm$, $g(q) = mgl\sin q = 41.16\sin q N$
Stiffness & Damping Matrix	$K = 100\,Nm/rad$ $D = 1.232\,Nms/rad$
Motor Inertia Matrix	$B = 0.55\,kgm^2$

The matched disturbance introduced to the system is $\tau_f = 100\sin 5t$. The comparison between IDA-PBC with and without matched disturbance, and the proposed control is shown in Fig. 3.

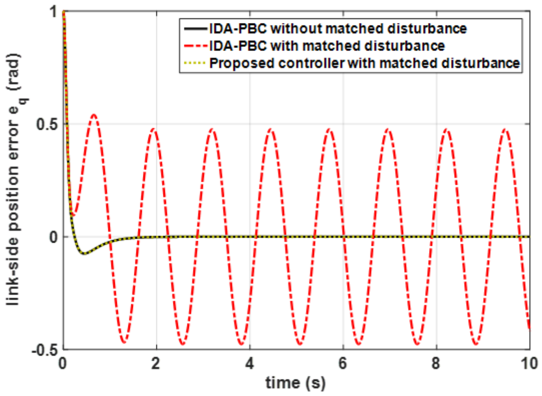

Fig. 3 Error Response of FJR with Matched Disturbance

The disturbed system controlled only by IDA-PBC shows deteriorated control performance. On the other hand, the proposed controller shows robustness against matched disturbance.

Fig. 4 shows the results to compare the proposed controller and IDA-PBC when the system is affected by mismatched disturbance. The mismatched disturbance that is introduced to the system is $\tau_{ext} = 10\sin 5t$.

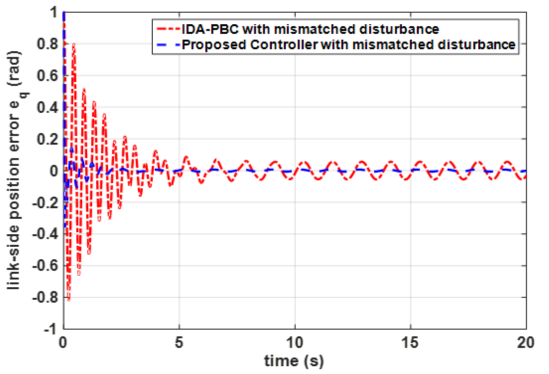

Fig. 4 Error Response of FJR with Mismatched Disturbance

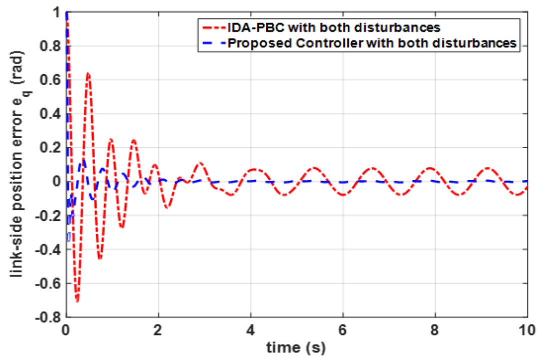

Fig. 6 Error Response of FJR with both Matched and Mismatched Disturbances

The proposed controller shows desirable tracking. On the other hand, the IDA-PBC controlled system shows disturbed performance. Fig. 5 shows the motor-side reference signal formulated by the robust linear controller.

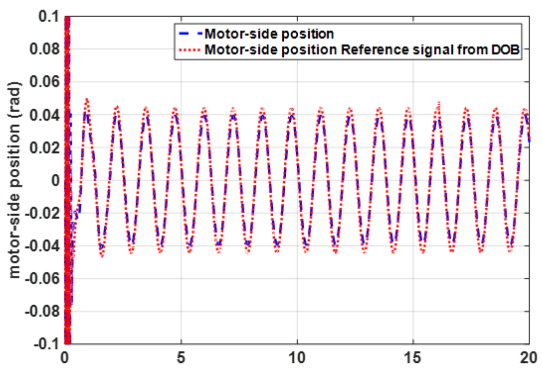

Fig. 5 Comparison of Motor-side reference signal θ_d and θ

The tracking of IDA-PBC with varying reference is shown to be satisfactory. Also, it is shown to be unchattered. This is desirable for motor-side tracking.

Fig. 6 shows the performance comparison of the proposed controller and IDA-PBC when the system is disturbed by both matched and mismatched disturbances.

The results show that the proposed controller is robust when the both disturbances are present.

Fig. 7 shows the motor torque of proposed controller.

In Fig. 8, the sliding surface comparison between the proposed controller with matched disturbance, and proposed controller with mismatched disturbance is shown.

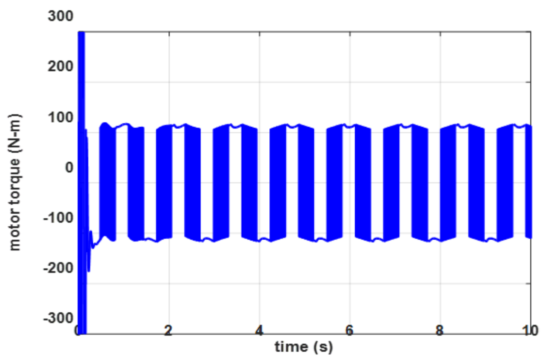

Fig. 7 Input motor torque

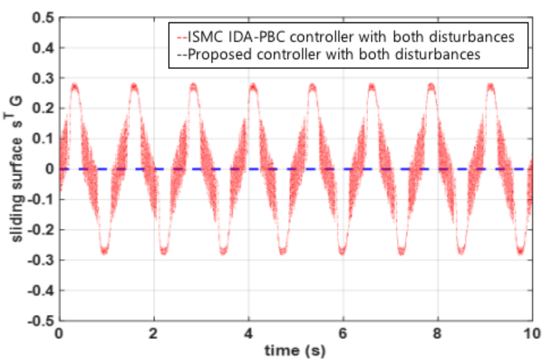

Fig. 8 Sliding Function

In Fig. 8, the sliding surface of the proposed controller with unmatched disturbance is close to zero, while, the sliding surface of IDA-PBC with only ISMC is affected by mismatched disturbance. This shows that the DOB used in the proposed ccontroller decouples the mismatched disturbance.

Ⅴ. CONCLUSIONS

The proposed controller is robust for the matched and mismatched disturbances. The performance of PBC, the robustness of the SMC for the matched disturbances and the disturbance decoupling of DOB for the mismatched disturbances are properly combined. Their combinations are introducing ISMC and backstepping technique. The PBC guarantees the overall stability of the nominal system and ISMC guarantees the overall stability for the system with disturbances. The DOB decouple the disturbance to improve the control performances.

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