Robust Anti-Disturbance Coordinated Control for Multiple Manipulators

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Abstract

In this paper, the anti-disturbance coordinated control is investigated for the multiple mobile manipulators with disturbances. Some disturbances are induced by the random white noise; the others are assumed to be described by an external system. These disturbances are rejected and attenuated based on the disturbance-observer-based-control (DOBC) method and the adaptive control approach. Subsequently, a robust adaptive antidisturbance coordinated control strategy is proposed for the multiple mobile manipulators based on the back-stepping control scheme. In accordance with Lyapunov stability theory and the stochastic control theory foundation, the tracking error systems are guaranteed to be exponentially practically stable in mean square. Finally, an example is used to verify the effectiveness of the presented control method.

Index Terms

Disturbance-observer-based-control, adaptive control, multiple manipulators, stochastic system.

I. INTRODUCTION

The manipulator is a common control system, which has been widely used in many different domains, such as in robots, protheses and manufacturing. In recent years, the intelligent robot has permeated into many aspects of life with the development of such control systems. Hence, the control performances of the manipulator system have attracted much attention. The theoretical foundation of the manipulator system has been summarized in some authoritative and state-of-the-art publications in this subject matter in [1] and [2]. Furthermore, many meaningful research results for various manipulator control systems have also been published. In particular, the coordinated multi-manipulator systems was studied using the adaptive control scheme in [3]. Combining the neural-network control and the adaptive control methods, the problem of two robotic arms manipulating an object with relative motion was resolved in [4], and the designed control scheme proposed was unquestionably classical. The coordinated control issues were further discussed in [5], [6] by the adaptive control method. In [7], the second-order sliding mode controller is designed for the nonlinear system with output constraint, which is an effective method for manipulator systems. In the last few years, the manipulator control system has been a hot topic in the intelligent control field. The extreme learning machine control scheme was used for handling the haptic identification issue of the uncertain manipulator system in the works of [8]. Based on the neural network technology, the adaptive control method and the input control saturation scheme, the uncertain robotic dynamics systems were discussed in [9]. Kong et al. [10], used the adaptive fuzzy control scheme to investigate the coordination control problem of multiple robots systems with varying degrees of output feedback. In the above study, the disturbances are considered as an indispensable part of control methods. The anti-disturbance control methods are used in the manipulator system which would improve the quality of control.

Disturbances are the important components of the control system modeling. However, many of the disturbances are not completely unknown in designing the controller. Some information can be obtained, such as the continuity and the slow time-varying. Based on these known information, the DOBC
scheme is applied in [11]–[14]. Combining the traditional control approaches, the composite anti-disturbance control schemes are presented consecutively. In [15], the $H_{\infty}$ control theory was united with the DOBC method to reject and attenuate the influence of the multiple disturbances, which was a heuristic control idea for the anti-disturbance control issue. The sliding model control, adaptive neural control and DOBC methods are applied in [16] to discuss a class of uncertain discrete-time systems. The event-triggered control problem of semi-Markovian jump nonlinear systems was discussed via using DOBC scheme in the works of [17]. In [18], the fixed-time attitude tracking control was investigated for the spacecraft industry with input quantization by fixed-time disturbance observer control method. Combining the resilient $L_2 - L_{\infty}$ control theory and the DOBC method, the Markovian jump nonlinear systems were studied under the partly unknown transition probabilities and multiple disturbances [19]. The presented results focusing on the anti-disturbance control issues indicate that the DOBC scheme is an outstanding control method for dealing with the common disturbances. As the development of the actual system, the requirement of the control accuracy is becoming a hot topic on the control domain. The random disturbances are arousing many scholars’ concern.

Random systems have generated much interest since the Itô’s stochastic differential theory was established [20]. Various excellent theories of the stochastic control system have been published, such as [21]–[24]. These publications have promoted the development of the stochastic control theory. Based on the above researches, many practical application systems were developed based on the stochastic system models. In [25], a class of stochastic Lagrangian control systems were investigated as stochastic systems via the adaptive tracking control methods. The stochastic nonlinear Markovian switching systems was handled by the adaptive backstepping tracking controller in the works of [26]. The full state constraints issue was discussed for a class of stochastic nonlinear systems using the adaptive control-based barrier Lyapunov functions technology in [27]. In the works of [28], showed that a class of non-triangular stochastic nonlinear systems gave positive results with robust adaptive output feedback control. The nonlinear stochastic system and the stochastic Markovian jump system were discussed based on the DOBC scheme to deal with the anti-disturbance problem in the works of [29] and [30]. As such, based on the above research, in order to improve control performance of the manipulators, the random disturbances had been considered in the present paper.

In this paper, the anti-disturbance control issue is discussed for the manipulators systems. The contributions of the proposed control method are presented as follows:

- The coordinated control issue is studied for manipulators control systems under multiple disturbance issues, especially for the random disturbances.
- The anti-disturbance adaptive control method is used manipulators control systems. The common time-varying disturbances are removed by the disturbance observer control method; the other part disturbances induced by the random white noise are cut off via the adaptive control scheme. The robustness of the closed-loop systems would be enhanced under the proposed controller.

Finally, a numerical example is given to verify the validity of the designed controller.

This paper is organized as follows: In Section 2, the system description and mathematical preliminaries are given in details. The main results are presented in Section 3. A simulation is shown in Section 4. Section 5 is the conclusion.

II. PROBLEM STATEMENT

A. SYSTEM DESCRIPTION

In the paper, the coordinated control issue is discussed for multiple mobile manipulators. The main control task is that an appropriate controller is designed such that the $m$ manipulators cooperatively work to track the commanded trajectory. The dynamic of the manipulators in joint space is considered as [1]:

$$M_q(q(t))\ddot{q}(t) + C_q(q(t), \dot{q}(t))\dot{q}(t) + G_q(q(t)) = \tau(t),$$

where $q(t) = \left( q_1^T(t), \ldots, q_m^T(t) \right)^T$ is position vector in joint space, $m$ is the number of the robots, and $q_i(t) \in \mathbb{R}^n$, for $i = 1, 2, \ldots, m$. $M_q(q(t))$ is the positive definite joint quality inertia matrix. $C_q(q(t), \dot{q}(t))$ is the joint Coriolis and centrifugal matrix. $G_q(q(t))$ denotes the joint gravitational forces. $\tau(t) = \left( \tau_1^T(t), \ldots, \tau_m^T(t) \right)^T$ is the sum of the external forces, for $i = 1, 2, \ldots, m$, which include the control input, external contact forces and disturbances. The detailed structure functions can be found in the reference [1], which are ignored in this paper.

Indeed, the relationship between the actual trajectory of the manipulators end-effectors $x(t) = \left( x_1^T(t), \ldots, x_m^T(t) \right)^T$ and $q(t)$ satisfy:

$$\dot{x}(t) = J(q(t))\dot{q}(t),$$

where $J(q(t)) \in \mathbb{R}^{m \times mn}$ is the Jacobian matrix between $x(t)$ and $q(t)$, which is an invertible matrix as a common assumption.

The dynamic of the object is described as following:

$$M_o(x_o(t))\ddot{x}_o(t) + C_o(x_o(t), \dot{x}_o(t))\dot{x}_o(t) + G_o(x_o(t)) = \tau_o(t),$$

where $x_o(t) \in \mathbb{R}^n$ is the position vector of the object. $M_o(x_o(t))$ is the positive definite inertia matrix. $C_o(x_o(t), \dot{x}_o(t))$ is the Coriolis and centrifugal matrix. $G_o(x_o(t))$ denotes the gravitational forces. $\tau_o(t) \in \mathbb{R}^n$ is the sum of the external forces, which include the control input, result forces and disturbances.

According to the work of [6], the relationship between $x$ and $x_o$ is shown as follows:

$$\dot{x}(t) = J_o(x_o(t))\dot{x}_o(t),$$
where \( J_{\tau o}(x_o(t)) \in \mathbb{R}^{m \times n} \) is the Jacobian matrix between \( x(t) \) and \( x_o(t) \).

In order to improve the control performance, the disturbances of the manipulators system and the object system are considered in the controller designed, therefore, the sum of the external forces \( \tau \) and \( \tau_{\omega o} \) is denoted as:

\[
\tau(t) = \tau_o(t) - J^T(q)\tau_e + d(t) + \Lambda_1(x(t))\xi(t),
\]
\[
\tau_{\omega o}(t) = \tau_o(t) + \Lambda_2(x_o(t))\xi(t),
\]
where \( \tau_o(t) \) is the control force. \( \tau_e \) and \( \tau_{\omega o}(t) \) denote the contact force and the result force, and they satisfy \( J_{\tau o}^T(x_o(t))\tau_e = \tau_o(t) \).

According to [3], the contact force \( \tau_e \) can be represented as:

\[
\tau_e = J_{\tau o}^+T(x_o(t))\tau_o(t) + \tau_l(t),
\]

where \( J_{\tau o}^+T(x_o(t)) \) is the pseudo inverse matrix of \( J_{\tau o}^T(x_o(t)) \), and \( \tau_l(t) \) is an addition vector which belongs to the nuclear space of the \( J_{\tau o}^T(x_o(t)) \), i.e. for any vector \( \nu_n \) in the nuclear space of the \( J_{\tau o}^T(x_o(t)) \), satisfying \( J_{\tau o}^T(x_o(t))\nu_n = 0 \).

\( d(t) \) is the time-varying disturbance, which can be described as the following external system:

\[
d(t) = Mw(t),
\]
\[
\dot{w}(t) = Ww(t),
\]
where \( M \) and \( W \) are the disturbance system parameters, and \( w(t) \) is the internal variable. \( \Lambda_1(x(t))\xi(t) \) and \( \Lambda_2(x_o(t))\xi(t) \) are the random disturbances induced by the random white noise \( \xi(t) \), and \( \Lambda_1(x(t)) \) and \( \Lambda_2(x_o(t)) \) are unknown functions and satisfy the locally Lipschitz condition.

From (3), (5) and (6), we deduce

\[
J_{\tau o}^T(q)\tau_e = J^T(q)J_{\tau o}^+T(x_o(t))\tau_o(t) + J^T(q)\tau_l(t),
\]
\[
= J^T(q)J_{\tau o}^+T(x_o(t))\left(M_{\omega o}(x_o(t))\dot{x}_o(t) + C_{\omega o}(x_o(t), \dot{x}_o(t))\dot{x}_o(t) + G_{\omega o}(x_o(t))\right) - \Lambda_2(x_o(t))\xi(t) + J^T(q)\tau_l(t).
\]

Noting the relationship of (2) and (4), and \( J(q) \) is an invertible matrix, we have

\[
\dot{q} = J^{-1}(q)Ju_o(x_o(t)),
\]
\[
\ddot{q} = \frac{d}{d\tau} \left(J^{-1}(q)Ju_o(x_o(t))\right)\dot{x}_o + J^{-1}(q)Ju_o(x_o(t))\ddot{x}_o.
\]

Noting (5) and (8), the dynamic of the multiple manipulators (1) is shown as follows:

\[
M_{\dot{q}}(q(t))\ddot{q}(t) + C_{\ddot{q}}(q(t), \dot{q}(t))\ddot{q}(t) + G_{\ddot{q}}(q(t)),
\]
\[
= \tau_o(t) + d(t) + \Lambda_1(x(t))\xi(t) + J^T(q)J_{\tau o}^+T(x_o(t))\left(M_{\omega o}(x_o(t))\dot{x}_o(t) + C_{\omega o}(x_o(t), \dot{x}_o(t))\dot{x}_o(t) + G_{\omega o}(x_o(t))\right) - \Lambda_2(x_o(t))\xi(t) + J^T(q)\tau_l(t).
\]

According to (9) and (10), both sides of the equation (8) multiply \( J_{\tau o}^T(x_o(t))J^{-T}(q(t)) \), we obtain

\[
M(x_o(t))\ddot{x}_o(t) + C(x_o(t), \dot{x}_o(t))\dot{x}_o(t) + G(x_o(t)) = u(t) + D(x_o(t))d(t) + \Lambda(x_o(t))\xi(t),
\]

where

\[
D(x_o(t)) = J_{\tau o}^T(x_o(t))J^{-T}(q(t)),
\]
\[
M(x_o(t)) = D(x_o(t))M_{\omega o}(q(t))D^T(x_o(t)) + M_{\omega o}(x_o(t)),
\]
\[
C(x_o(t)) = D(x_o(t)) \left( M_{\omega o}(q(t)) \right) \left( \frac{d}{dt} \left( D^T(x_o(t)) \right) \right) + C_{\omega o}(x_o(t), \dot{x}_o(t))
\]
\[
+ G_{\omega o}(x_o(t)) = D(x_o(t))G_{\omega o}(q(t)) + G_{\omega o}(x_o(t)),
\]
\[
u(t) = D(x_o(t))\tau_{\omega o}(t),
\]
\[
\Lambda(x_o(t)) = D(x_o(t))(\Lambda_1(x(t)) + \Lambda_2(x_o(t))\xi(t).
\]

Noting the forms of the functions \( \Lambda(x_o(t)) \), \( \Lambda_1(x(t)) \) and \( \Lambda_2(x_o(t)) \) satisfying the locally Lipschitz condition, the unknown function \( \Lambda(x_o(t)) \) is assumed to satisfy the following inequations:

\[
||\Lambda(x_o(t))||^2 \leq \phi_1(x_o(t))\phi_1(t),
\]
\[
||\Lambda(x_o(t)) - \Lambda'(x_o'(t))||^2 \leq \phi_2(x_o(t), x_o'(t))||x_o(t) - x_o'(t)||^2 \phi_2(t),
\]

where \( \phi_1 > 0 \) and \( \phi_2 > 0 \) are unknown parameters, \( \phi_1(x_o(t)) \) and \( \phi_2(x_o(t), x_o'(t)) \) are known functions.

**Remark 1:** The manipulators systems discussed in our paper are modeled based on Lagrangian equations, the modeling process can be acquired from the reference [1]. Because the detailed dynamic equations would occupy much space of this paper, and which do not affect the control method design. Hence, we ignore the detailed dynamic equations of manipulators systems.

**Remark 2:** The disturbance \( d(t) \) is assumed to be described as the system (7). In the actual system, many disturbances can be denoted as the system (7), such as the harmonic disturbances, the constant disturbances and so on. Based on the working experience, the frequencies of these disturbances are often able to be obtained during the design of the controller. These input are necessary as a part of the control algorithm to enhance the robustness of the closed-loop system. Moreover, according to the Fourier series theory, any continuous functions can be estimated by a sum of sinusoidal functions. Hence, the system (7) is an universal disturbance form.

**B. MATHEMATICAL PRELIMINARIES**

For convenience, the following stochastic nonlinear system is considered:

\[
d\vartheta(t) = f(\vartheta(t), t)dt + g(\vartheta(t), t)dW(t),
\]

where \( \vartheta(t) \) is the state, \( f(\vartheta(t), t) \) and \( g(\vartheta(t), t) \) are piece-wise continuous functions, which satisfy the local Lipschitz condition. \( W(t) \) is an one_dimensional independent standard Wiener process.
Definition 1 [22]: A function $V(\vartheta(t), t)$ is a continuously twice differentiable in $x \in \mathbb{R}^n$ and once differentiable in $t \in \mathbb{R}$, the infinitesimal generator of $V(\vartheta(t), t)$ is given by

$$\mathcal{L}V(\vartheta(t), t) = V_t(\vartheta(t), t) + V_\vartheta(\vartheta(t), t)f(\vartheta(t), t) + \frac{1}{2}\text{Tr}\left(g^T(\vartheta(t), t)V_{\vartheta\vartheta}(\vartheta(t), t)g(\vartheta(t), t)\right),$$

(14)

where $\text{Tr}$ denotes the trace of a matrix, and

$$V_t(\vartheta(t), t) = \frac{\partial V(\vartheta(t), t)}{\partial t},$$
$$V_\vartheta(\vartheta(t), t) = \left(\frac{\partial V(\vartheta(t), t)}{\partial \vartheta_1}, \ldots, \frac{\partial V(\vartheta(t), t)}{\partial \vartheta_n}\right),$$
$$V_{\vartheta\vartheta}(\vartheta(t), t) = \left(\frac{\partial^2 V(\vartheta(t), t)}{\partial \vartheta_i \partial \vartheta_j}\right)_{n \times n}.$$

Definition 2 [25]: The system (13) is said to be $p$th moment exponentially stable if there exist positive constants $\lambda$, $d$ and a function $\kappa(||\bullet||) \in \mathbb{C}$ such that

$$E[|\vartheta(t)||]^p \leq \kappa(||\vartheta_0||)e^{-\lambda t} + d, \quad t \geq t_0, \vartheta_0 \in \mathbb{R}^n.$$  

(15)

When $p = 2$, we also say that it is exponentially stable in mean square.

Lemma 1 [25]: For system (13), assume that there exist a function $V(\vartheta(t), t)$ is a continuously twice differentiable in $\vartheta \in \mathbb{R}^n$ and once differentiable in $t \in \mathbb{R}$, with some positive constants $k_i$, $k'_i$, $p_i$, $p'_i$, $c$ and $d_c$, such that

$$\sum_{i=1}^{n} k_i |\vartheta_i|^p_i \leq V(\vartheta(t), t) \leq \sum_{i=1}^{n} k'_i |\vartheta_i|^p'_i,$$  

(16)

$$\mathcal{L}V(\vartheta(t), t) \leq -\lambda V(\vartheta(t), t) + d_c.$$  

(17)

Then, there exists a unique strong solution $\vartheta(t) = \vartheta(t; \vartheta_0, t_0)$ of system (13) for each $\vartheta_0 \in \mathbb{R}^n$ and the system (13) is $p$th moment exponentially stable, where $p = \min\{p_1, \ldots, p_n\}$.

Lemma 2 (Young’s Inequality) [25]: For any vectors $x, y \in \mathbb{R}^n$ and any scalars $\epsilon > 0, p > 1$, there holds $x^T y \leq \frac{\epsilon^p}{p} |x|^p + \frac{1}{q \epsilon^{p-1}} |y|^q$ where $q = \frac{p}{p-1}$.

III. CONTROLLER DESIGN

The tracking task is that construct a proper controller such that the predefined tracking signal $x_d(t)$ could be tracked in a reasonable range. Moreover, the derivative of $x_d(t)$ is known for the anti-disturbance controller design. The controller designed process is shown as the Figure 1.

According to above discussing, the stochastic form of the system (11) can be written as:

$$dx_1(t) = x_2(t),$$
$$dx_2(t) = M^{-1}(x_1(t))( - C(x_1(t))x_2(t) - G(x_1(t)) + u(t) + D(x_1(t))d(t))dt + M^{-1}(x_1(t))\Lambda(x_1(t))d\mu(t),$$  

(18)

where $x_1(t) = x_1(t), x_2(t) = x_2(t), \mu(t)$ is an one-dimensional independent standard Wiener process. Note that the random disturbance $\Lambda(x_1(t))d\mu(t)$ is induced from the white noise $\xi(t)$, from [21], $\xi(t)$ can be replaced by $\frac{d\mu(t)}{dt}$.

In the following, combining the backstepping control method, the disturbance observer based control and the adaptive control, a random adaptive anti-disturbance control scheme is proposed. Define the tracking error $e_1(t) = x_1(t) - x_d(t), e_2(t) = x_2(t) - \dot{x}_d(t)$, and $\dot{x}_d(t)$ is a virtual control law, which is

$$\alpha_1(t) = -k_1 e_1(t) + \dot{x}_d(t).$$  

(19)

Then, the dynamic of the tracking error is written as:

$$de_1(t) = (-k_1 e_1(t) + e_2(t))dt.$$  

(20)

where $k_1 > 0$ is a positive parameter.

Choose a Lyapunov function candidate $V_1(t)$ as:

$$V_1(t) = \frac{1}{4}(e_1^T(t)e_1(t))^2.$$  

(21)

The infinitesimal generator of $V_1(t)$ along with (20) is presented as:

$$\mathcal{L}V_1(t) = -k_1 (e_1^T(t)e_1(t))^2 + e_2^T(t)e_1(t)e_2(t).$$  

(22)

From Lemma 2, there exists a parameter $\epsilon_1 > 0$, such that

$$e_1^T(t)e_1(t)e_2(t) \leq \frac{3\epsilon_1^4}{4}(e_1^T(t)e_1(t))^2 + \frac{1}{4\epsilon_1^4}(e_2^T(t)e_2(t))^2,$$  

(23)

Then, (22) can be written as:

$$\mathcal{L}V_1(t) \leq -\left(k_1 - \frac{3\epsilon_1^4}{4}\right)(e_1^T(t)e_1(t))^2 + \frac{1}{4\epsilon_1^4}(e_2^T(t)e_2(t))^2.$$  

From (19) the dynamic of the tracking error $e_2$ is given as:

$$de_2(t) = M^{-1}(x_1(t))(-C(x_1(t))x_2(t) - G(x_1(t)) + u(t) + D(x_1(t))d(t))dt + M^{-1}(x_1(t))\Lambda(x_1(t))d\mu(t)$$

$$-k_1^2 e_1(t) + k_1 e_2(t)dt - \dot{x}_d(t)dt.$$  

(24)
The controller $u(t)$ is designed as

$$u(t) = -(k_2 + k_1)M(x_1(t))e_2(t) + C(x_1(t))x_2(t) + G(x_1(t)) - D(x_1(t))\hat{d}(t) + M(x_1(t))u_d(t) + \dot{k}_2^2M(x_1(t))e_1(t) + M(x_1(t))\bar{e}_2(t),$$

where $u_d(t)$ is an addition controller to be designed, $\hat{d}(t)$ is the estimation of disturbance $d(t)$, which is generated from the following disturbance observer to be constructed.

Then, we have

$$de_2(t) = \left(-k_2e_2(t) + u_d(t) + M^{-1}(x_1(t))D(x_1(t))Me_u(t)\right)dt + M^{-1}(x_1(t))\Lambda(x_1(t))d\mu(t),$$

where $e_u(t) = w(t) - \hat{w}(t)$ is the estimate error, and $\hat{w}(t)$ is the estimation of $w(t)$. Based on (26), the disturbance observer is designed as [15]:

$$\hat{d}(t) = M\hat{w}(t),$$

$$\hat{w}(t) = \sigma(t) + \beta(e_2(t)), $$

$$\sigma(t) = W\hat{w}(t) - \frac{d\beta}{de_2} \left(-k_2e_2(t) + u_d(t)\right).$$

The dynamic of the estimate error is shown as:

$$de_u(t) = Ww(t) - \sigma(t) - \frac{d\beta}{de_2} \hat{e}_2(t),$$

$$= We_u(t) - \frac{d\beta}{de_2} \left(M^{-1}(x_1(t))D(x_1(t))Me_u(t)dt + M^{-1}(x_1(t))\Lambda(x_1(t))d\mu(t)\right).$$

Let $\frac{d\beta}{de_2} = LD^+(x_1(t))M(x_1(t))$, and choose $L$ such that $W - LM$ is a Hurwize matrix by pole assignment method, and there exists a parameter $l > 0$ such that $-l \geq \text{max}\{\text{eig}(W - LM)\}$. The system (28) can be rewritten as:

$$de_u(t) = (W - LM)e_u(t)dt - LD^+(x_1(t))\Lambda(x_1(t))d\mu(t).$$

Equation (30) obviously satisfies the locally Lipschitz condition, thus, we have

$$||LD^+(x_1(t))\Lambda(x_1(t)) - LD^+(x_d(t))\Lambda(x_d(t))||^2 \leq \phi_2^2(x_1(t), x_d(t))(||e_1(t)||^2 + \theta_2^2(t)), $$

where $\theta_2 > 0$ is an unknown parameter, $\phi_2^2(x_1(t), x_d(t))$ is a known function.

Define $\hat{\theta}_1(t) = \theta_1 - \hat{\theta}_1(t)$ and $\hat{\theta}_2(t) = \theta_2 - \hat{\theta}_2(t)$ are the estimation error of $\theta_1$ and $\theta_2$, and $\hat{\theta}_1(t)$ and $\hat{\theta}_2(t)$ is the estimation of $\theta_1$ and $\theta_2$ to be desined in the following steps.

Then, choose a Lyapunov function candidate $V_2(t)$ as:

$$V_2(t) = \frac{1}{4}(e_2^T(t)e_2(t))^2 + \frac{1}{4}(e_u^T(t)e_u(t))^2 + \frac{1}{2\lambda_1}\hat{\theta}_1^2(t) + \frac{1}{2\lambda_2}\hat{\theta}_2^2(t).$$

The infinitesimal generator of $V_2(t)$ along with (26) and (29) is presented as:

$$\mathcal{L}V_2(t) = -k_2(e_2^T(t)e_2(t)) + e_2^T(t)e_2(t)M^{-1}(x_1(t))D(x_1(t))Me_u(t) + e_u^T(t)e_u(t) + \frac{1}{2} Tr \left(\Lambda^T(x_1(t))M^{-T}(x_1(t))\Lambda(x_1(t))\right) + e_u^T(t)e_u(t) + \frac{1}{2\lambda_1}\hat{\theta}_1^2(t) + \frac{1}{2\lambda_2}\hat{\theta}_2^2(t) + \frac{1}{2} Tr \left(\Lambda^T(x_1(t))D^+(x_1(t))\Lambda(x_1(t))\right).$$

According to Lemma 2, for some parameters $\varepsilon_2 > 0$, $\varepsilon_3 > 0$ and $\varepsilon_4 > 0$, the following inequations hold:

$$e_2^T(t)e_2(t)M^{-1}(x_1(t))D(x_1(t))Me_u(t) \leq \frac{3\varepsilon_2^2}{4}||M^{-1}(x_1(t))D(x_1(t))M||^2(e_2^T(t)e_2(t))^2,$$

$$+ \frac{1}{4\varepsilon_2^2}||e_u(t)||^2,$$

$$\frac{1}{2} Tr \left(\Lambda^T(x_1(t))M^{-T}(x_1(t))\Lambda(x_1(t))\right) \leq \frac{3}{2}||e_2(t)||^2||M^{-1}(x_1(t))\Lambda(x_1(t))||^2,$$

$$\frac{3}{2}||e_2(t)||^2||M^{-1}(x_1(t))||^2\phi_1(x_1(t))\hat{\theta}_1(t) + \frac{3}{2}||e_2(t)||^2||M^{-1}(x_1(t))||^2\phi_1(x_1(t))\hat{\theta}_1(t),$$

$$\frac{3}{4}||M^{-1}(x_1(t))||^2\phi_2^2(x_1(t), x_d(t))(e_2^T(t)e_2(t))^2,$$

$$+ \frac{3}{4\varepsilon_3^2}||e_2(t)||^2||M^{-1}(x_1(t))||^2\phi_1(x_1(t))\hat{\theta}_1(t),$$

$$\frac{3}{2} Tr \left(\Lambda^T(x_1(t))D^+(x_1(t))\Lambda(x_1(t))\right) \leq \frac{3}{2}||e_u(t)||^2||LD^+(x_1(t))\Lambda(x_1(t))||^2,$$

$$\frac{3}{2}||e_u(t)||^2||LD^+(x_1(t))\Lambda(x_1(t)) - LD^+(x_d(t))\Lambda(x_d(t))||^2 + ||LD^+(x_d(t))\Lambda(x_d(t))||^2.$$
\[
\dot{\theta}_2(t) + \frac{3\varepsilon_2^2}{4} (e_w^T(t) e_w(t))^2 + \frac{3}{4\varepsilon_3} \delta_0^2,
\]

where \(\delta_0 \geq ||LD^+(x_d(t))\Lambda(x_d(t))||^2\) is a positive parameter. Substituting (33) into (32), we have

\[
\mathcal{L} V_2(t) \leq \left( -k_2 + \frac{3\varepsilon_2^2}{4} ||M^{-1}(x_1(t))D(x_1(t))M||^2 \right)
\]
\[
+ \frac{3\varepsilon_2^2}{4} ||M^{-1}(x_1(t))||^4 \phi^2_1(x_1(t))\dot{\theta}_1^2(t) e_2(t)^2
\]
\[
+ \frac{3}{4\varepsilon_3} \phi^2_2(x_1(t), x_d(t))(e_1^T(t)e_1(t))^2 \dot{\theta}_2(t)
\]
\[
+ \frac{3}{2} ||e_2(t)||^2 ||M^{-1}(x_1(t))||^2 \phi_1(x_1(t)) \dot{\theta}_1(t)
\]
\[
+ \left( -l + \frac{1}{4\varepsilon_4} + \frac{3\varepsilon_2^2}{4} \right) (e_w^T(t)e_w(t))^2
\]
\[
+ \frac{1}{2\lambda_1} \dot{\theta}_1(t) + \frac{1}{2\lambda_2} \dot{\theta}_2(t) + \frac{3}{4\varepsilon_3} \delta_0^2.
\]

Design the addition control law and the adaptive laws as:

\[
u_a(t) = \left( -k_2 + \frac{3\varepsilon_2^2}{4} ||M^{-1}(x_1(t))D(x_1(t))M||^2 \right)
\]
\[
+ \frac{3\varepsilon_2^2}{4} ||M^{-1}(x_1(t))||^4 \phi^2_1(x_1(t))\dot{\theta}_1^2(t) \right) e_2(t),
\]
\[
\dot{\theta}_1(t) = -3\lambda_1 ||M^{-1}(x_1(t))||^4 \phi_1(x_1(t)) \dot{\theta}_1(t) e_2(t),
\]
\[
\dot{\theta}_2(t) = -\frac{3\lambda_2}{2\varepsilon_4} \phi^2_2(x_1(t), x_d(t))(e_1^T(t)e_1(t))^2.
\]

Based on (35) and (36), yields:

\[
\mathcal{L} V_2(t) \leq -k_2(e_2^T(t)e_2(t))^2 + \left( -l + \frac{1}{4\varepsilon_4} + \frac{3\varepsilon_2^2}{4}
\right)
\]
\[
+ \frac{1}{2\lambda_1} \dot{\theta}_1(t) + \frac{1}{2\lambda_2} \dot{\theta}_2(t) + \frac{3}{4\varepsilon_3} \delta_0^2.
\]

Combining (19), (25) and (35), the backstepping anti-disturbance adaptive controller is given as:

\[
a_1(t) = -k_1 e_1(t) + \dot{s}_d(t),
\]
\[
u(t) = F_m(t)e_2(t) + C(x_1(t))x_d(t) + G(x_1(t))
\]
\[
- \lambda D(x_1(t)) \dot{\theta}_d(t) + k_1^2 M(x_1(t)) e_1(t)
\]
\[
+ M(x_1(t)) \ddot{x}_d(t).
\]

where

\[
F_m(t) = M(x_1(t)) \left[ - (k_2 + k_1) + \frac{3\varepsilon_2^2}{4} ||M^{-1}(x_1(t))D(x_1(t))M||^2
\right]
\]
\[
+ \frac{3\varepsilon_2^2}{4} ||M^{-1}(x_1(t))||^4 \phi^2_1(x_1(t))\dot{\theta}_1(t) \right)
\]

From (20), (26), (28), (35) and (36), the composite closed-loop system is shown as:

\[
de_1(t) = (-k_1 e_1(t) + e_2(t)) dt,
\]
\[
de_2(t) = \left( \left( -k_2 - \frac{3\varepsilon_2^2}{4} ||M^{-1}(x_1(t))D(x_1(t))M||^2 \right)
\right)
\]
\[
- \frac{3\varepsilon_2^2}{4} ||M^{-1}(x_1(t))||^4 \phi_1(x_1(t)) \dot{\theta}_1(t) e_2(t)
\]
\[
+ M^{-1}(x_1(t))D(x_1(t)) M e_w(t) dt
\]
\[
- M^{-1}(x_1(t)) \Lambda(x_1(t)) d\mu(t),
\]
\[
\delta_f(t) = (W - LM)v(t) dt - LD^+(x_1(t)) \Lambda(x_1(t)) d\mu(t),
\]
\[
\dot{\delta}_1(t) = -3\lambda_1 ||M^{-1}(x_1(t))||^4 \phi_1(x_1(t)) e_2^T(t)e_2(t),
\]
\[
\dot{\delta}_2(t) = -\frac{3\lambda_2}{2\varepsilon_4} \phi^2_2(x_1(t), x_d(t))(e_1^T(t)e_1(t))^2.
\]

Based on the above discussing, we conclude the main result in the following theorem to state a sufficient condition that guarantees the composite closed-loop system is exponentially practically stable in mean square.

**Theorem 1:** Consider stochastic multiple manipulators systems (18), the backstepping adaptive anti-disturbance controller (38), the disturbance observer (27) and the adaptive laws (36), the composite closed-loop system (40) is exponentially practically stable in mean square. If there exist parameters \(\varepsilon_1 > 0, \varepsilon_2 > 0, \varepsilon_3 > 0, \varepsilon_4 > 0, \varepsilon_5 > 0, \lambda_1 > 0\) and \(\lambda_2 > 0\), such that \(k_1 - \frac{3\varepsilon_2^2}{4} > 0, k_2 - \frac{1}{4\varepsilon_4} > 0, \) and \(\frac{1}{4\varepsilon_4} + \frac{3\varepsilon_2^2}{4} + \frac{3\varepsilon_2^2}{4} < l \leq -\max\{\text{eig}(W - LM)\}).

**Proof:** Choose the Lyapunov function \(V(t)\) as

\[
V(t) = V_1(t) + V_2(t),
\]
\[
= \frac{1}{4} (e_1^T(t)e_1(t))^2 + \frac{1}{4} (e_2^T(t)e_2(t))^2 + \frac{1}{4} (e_w^T(t)e_w(t))^2
\]
\[
+ \frac{1}{2\lambda_1} \dot{\theta}_1(t) + \frac{1}{2\lambda_2} \dot{\theta}_2(t).
\]

According to (23) and (37), the infinitesimal generator of \(V(t)\) along with (40) satisfies:

\[
\mathcal{L} V(t) \leq \left( - \left( k_1 - \frac{3\varepsilon_2^2}{4} \right) (e_1^T(t)e_1(t))^2
\right)
\]
\[
- k_2 - \frac{1}{4\varepsilon_4} (e_2^T(t)e_2(t))^2
\]
\[
- \left( l - \frac{1}{4\varepsilon_4} - \frac{3\varepsilon_2^2}{4} \right) (e_w^T(t)e_w(t))^2
\]
\[
+ \frac{3}{4\varepsilon_3} \delta_0^2.
\]
where $c_m = \min \left\{ 4 \left( k_1 - \frac{3 \varepsilon_1}{\varepsilon_1^2} \right), 4 \left( k_2 - \frac{1}{4 \varepsilon_2^2} - \frac{3 \varepsilon_2}{\varepsilon_2^2} \right) \right\}$, and $d_m(t) = \frac{c_p}{2} \theta_0^2(t) + \frac{c_p}{2} \theta_0^2(t) \frac{3}{4 \varepsilon_3} + \frac{3}{4 \varepsilon_3} \delta_0^2$.

Note that $\dot{\theta}_1(t) = \theta_1 - \dot{\theta}_1(t)$ and $\dot{\theta}_2(t) = \theta_2 - \dot{\theta}_2(t)$, and according to (40), we confirm $\dot{\theta}_1(t) \leq 0$ and $\dot{\theta}_2(t) \leq 0$. Thus, $\ddot{\theta}(t)$ is a bounded for any initial value $\ddot{\theta}(t_0)$. Which means that

$$LV(t) = -c_m V(t) + D, \quad (44)$$

where $D \geq d_m(t)$.

Noting Lemma 1, the Lyapunov function $V(t)$ and its the infinitesimal generator $LV(t)$ satisfy the conditions (16) and (17), respectively. Therefore, the composite closed-loop system (40) is exponentially practically stable in mean square. The proof is completed.

**IV. SIMULATION**

In this section, an actual multiple mobile manipulators example is borrowed from the reference [1] to illustrate the control performance of our designed control method. The two robotic arms manipulators systems model is shown as Figure 2. The structure functions of manipulators systems are cited from the Simulation Example 8.5.3 of the reference [1], which are ignored in our paper. The predefined control signals are chosen as:

$$x_{od}(t) = \begin{pmatrix} -0.25 \cos(\pi t) + 0.25 \sin(1.5 \pi t) \\ 0.75 - 0.25 \cos(\pi t) + 0.25 \cos(0.75 \pi t) \\ 0.1 \sin(\pi t) \end{pmatrix}. \quad (45)$$

The parameters are also borrowed from the reference [1]: $m_1 = 1 \text{kg}, m_2 = 1 \text{kg}, m_o = 1 \text{kg}, g = 9.8 m/s^2, l_{11} = l_{21} = 1m, l_{12} = l_{22} = 0.2m, l_{13} = l_{23} = 1m$ and $p_1 = p_2 = (4.81 \ 1.29 \ 0.05 \ 0.05 \ 1.30 \ 0.12 \ 3.62 \ 1.29 \ 0.05)^T \text{kgm}^2$. The system parameters of the disturbances $d(t)$ is set as:

$$W = \begin{pmatrix} 0 & -2.5 & 0 & 0 \\ 2.5 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix},$$

$$M = \begin{pmatrix} -0.5 & -0.7 & 1 & 1.5 \\ -1 & -1 & 1 & 1.5 \\ -0 & -0.7 & 0 & 1.5 \\ -0.5 & -0.7 & 1 & 1.5 \\ -0 & -2 & 1 & 1.5 \\ 0.3 & -1 & 0.2 & 1 \end{pmatrix}.$$  

The time-varying parameter of the random disturbance is chosen as

$$\Lambda(x_o) = \begin{pmatrix} m_1 g (\cos(q_{11}))^2 \\ m_2 g (\cos(q_{11}))^2 \\ m_2 g (\cos(q_{11}))^2 \end{pmatrix}.$$  

The functions $\phi_1(t)$ and $\phi_2(t)$ are given as $\phi_1(t) = 10(\cos(q_{11}(t)))^2$ and $\phi_2(t) = 10(\cos(q_{11}(t)))^2$. The initial values of the object system are set as $x_{o}(t) = (-0.15 \ 0.65 \ -0.1)$.  

The simulations are presented in the Figure 3-12. The tracking errors of the closed-loop system are shown in Figure 3 and Figure 4, the results manifest the object system could track the predefined state trajectories under the designed controller in a reasonable range, and the bounded of the tracking errors is controlled in $10 \times 10^{-4}$ under the random disturbances. The state trajectories of the object system are given in Figure 5-7, the predefined trajectories are given.
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FIGURE 7. The state $x_{od}(t)$ trajectory of the object system.

FIGURE 8. The controller curves of multiple mobile manipulators.

FIGURE 9. The adaptive laws of the control system.

FIGURE 10. The disturbance $d_1(t)$ and its estimation.

FIGURE 11. The disturbance $d_2(t)$ and its estimation.

FIGURE 12. The disturbance $d_3(t)$ and its estimation.

as (45), obviously, the predefined state trajectories $x_{od}(t)$ are rapidly tracked with a peaceful process, even though subject to the time-varying disturbances and the random disturbances. The controller $\tau_u(t)$ are presented in Figure 8, due to the random disturbances existing in the multiple mobile manipulators, the control curves have some impulse spots, while the control signals still maintain in proper magnitude ranges. The adaptive laws are given in Figure 9. The unknown bounds of the weight time-varying parameters are estimated by using the adaptive laws. In Figures 10-12, we show the disturbances and their estimations, which imply the disturbances can be rejected by using our proposed controller designed method. In conclusion, these simulation results show that the multiple manipulators systems have been well controlled by using the proposed control strategy.

V. CONCLUSION

This paper discusses the coordinated control problem of multiple manipulators via adaptive anti-disturbance control scheme. The DOBC method and adaptive control technology are used to rejected the common time-varying disturbances and random disturbances, respectively. The control performance of the tracking error system is guaranteed via the stochastic control theory thus ensuring a robust and definitive outcome. Finally, the effectiveness of the proposed control method is verified via a numeral simulation.

In the further, we will consider the states constraint and input saturation issues to enhance the practicability of the anti-disturbance controller for the multiple manipulators systems.

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