

Received February 25, 2022, accepted March 15, 2022, date of publication March 21, 2022, date of current version March 28, 2022.

Digital Object Identifier 10.1109/ACCESS.2022.3161134

Time-Varying Transformation-Based Adaptive Tracking Control of Uncertain Robotic Systems With Event-Triggered Mechanism

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This work was supported in part by the Natural Science Foundation of Hunan Province under Project 2021JJ60067.

ABSTRACT In this paper, an adaptive global event-triggered control scheme for uncertain robotic systems, capable of guaranteeing adjustable tracking performance, is developed. Compared with most of the existing results, the proposed control exhibits some features. Firstly, to improve the transient tracking performance without the requirement of large control effort, a time-varying scaling diagonal matrix and an error transformation are constructed so that each element of the tracking error has its own convergence rate, which can be adjusted by selecting the design parameters. Secondly, due to the consideration of decreasing the consumption of network resources, some additional diagonal matrices embedded in the new closed-loop system make the new control gain matrix not symmetric and positive definite, then the stability analysis becomes rather more challenging. To solve this issue, an alternative Lyapunov function is constructed to circumvent the above obstacles. The effectiveness of the proposed approach is verified by a 2-DOF robotic manipulator.

INDEX TERMS Accelerated adaptive control, event-triggering mechanism, robotic systems, error transformation.

I. INTRODUCTION

In order to improve the quality of products in the manufacturing industry and to safely implement the dangerous yet significant tasks in the practical systems, the rigid robot manipulators have got a broad application in many fields [1]–[5]. Therefore, the study of uncertain robots has received great attention in both research and industry communities during the past decade. There are a lot of efficient methods in the literature, such as gravity-compensation control [6], adaptive control [7], computed torque control [8], [9], sliding mode control [10] and other control methods [11]. However, for the above existing literature, the corresponding methods for uncertain robotic systems are based on fixed periodic time-driven sampling. Noting that this fixed periodic form of sampling may procedure redundant control input, then it will result in the waste of communication resources. Hence, how to effectively use the communication bandwidth has been one of the most interesting topics in the field of robotic control.

The associate editor coordinating the review of this manuscript and approving it for publication was Okyay Kaynak¹.

Since the event-triggered-based strategy has the ability to decrease the consumption of network resources, there are many results on event-triggered control of nonlinear/linear systems [12]–[17]. In [12], by using the hybrid system tools, an event-triggered stabilization control for a class of nonlinear systems was developed. However, the precondition of corresponding stability analysis is that the considered system must satisfy the input-to-state stability (ISS), which is difficult to identify this point. To avoid the ISS condition, in [15] an adaptive backstepping control with event-triggered rules were designed simultaneously for a class of strict-feedback nonlinear systems. Inspired by the idea of event-triggering mechanism, some meaningful results for robotic systems have been proposed in the past decade. In [18], by utilizing the event-triggering strategy and some hybrid theory techniques, a tracking control method was proposed for mobile robots in the presence of malicious denial-of-service attacks. In [19], a neuro-adaptive event-triggered feedback control framework for uncertain robot manipulators was developed so that the system output tracks the predefined trajectory closely. Furthermore, to solve the problem of model

predictive control (MPC) optimization problem in online computation and communication resources, a novel MPC-based trajectory tracking controller for mobile robots was proposed in [20] by using the event-triggering mechanism. Nevertheless, how to improve the transient tracking performance of robotic systems is not considered in the above works.

Furthermore, some researchers focus on improving the transient tracking performance of uncertain robotic manipulators [7], [21], [22]. In [7], an improved prescribed performance control was developed for state-constrained robotic systems such that the tracking error converges to a pre-given region within a prescribed time. In [21], by relaxing the assumption on controllability of the system and the requirement for a priori knowledge on the reference trajectory, a novel prescribed performance fault-tolerant control strategy for Euler-Lagrange systems in the presence of output constraint and actuator faults was presented. In [22], by constructing an error-based transformation, an adaptive prescribed performance control approach for robotic manipulators was developed so that the tracking error is able to converge to a pre-specified residual set with a pre-given decay rate. However, the implementation of the works in [7], [21], and [22] must rely on the initial conditions and the corresponding results belong to semi-global results. If the reference signal or the initial state is changed, we must re-select the design parameters and re-implement the control algorithm. To relax the requirement on the initial condition, a filtered-error-based adaptive control scheme for uncertain robots was developed in [23], however, the issue of communication resources is not considered and only the transient performance for filter error (rather than the tracking error) is ensured.

Motivated by the above works, in this paper we propose an accelerated adaptive event-triggering control strategy for uncertain robotic manipulators. To improve the transient performance of the tracking error without involving large control effort, different from the normally employed filtered-error-based methods, we propose a time-varying scaling diagonal matrix and construct a novel error transformation to facilitate the control design. Moreover, to reduce the communication resources for signal transmit, an event-triggering mechanism is utilized for control design. The contributions of this paper are summarized as:

- To our best knowledge, it is the first time to design a global adaptive event-triggered control method for uncertain rigid robotic systems, which is able to guarantee the adjustable transient tracking performance without involving large initial control input;
- By imposing a time-varying diagonal matrix, with the aid of error transformation, the developed control not only ensures the global result but also guarantees that the tracking error converges to an adjustable region with a pre-specified convergence rate, which is at the user's disposal; and

- Due to the introduction of time-varying diagonal matrix and the event-triggering mechanism, the new virtual control gain matrix does not satisfy the positive definite property, which dramatically increases the difficulty of stability analysis. In this paper, by utilizing the information of available matrices, an alternative Lyapunov function candidate (rather than the quadratic one) is constructed, so that the stability of closed-loop systems is ensured.

The remaining of this paper is given as follows. In Section II, some preliminaries and the event-triggering mechanism, as well as the control goals, are introduced, respectively. To improve the transient tracking performance and to reduce the communication resources, an adaptive control scheme for uncertain robotic systems is developed in Section III, which ensures that all signals in the closed-loop systems are globally bounded. In Section IV, a simulation study on the 2-DOF robotic manipulator is carried out, which verifies the effectiveness of the developed control scheme. Finally, we conclude this paper in Section V.

Notation: R represents the set of real numbers, R_+ denotes the nonnegative real numbers, R^n is the set of n -dimensional real vectors, $R^{n \times n}$ represents the set of $n \times n$ real matrices, and Z_+ is the positive integer set. $\|\cdot\|$ represents the Frobenius norm of matrix \cdot and Euclidean norm of vector \cdot , respectively.

II. PROBLEM FORMULATION AND PRELIMINARIES

A. DYNAMICS MODEL

The dynamic model of rigid robotic systems is described in the following form:

$$H(x_1)\ddot{x}_1 + C(x_1, x_2)x_2 + G_g(x_1) + G_\tau(x_2) = u \quad (1)$$

where $x_1 \in R^m$ and $x_2 \in R^m$ denote the joint position and velocity vectors, respectively, $H(x_1) \in R^{m \times m}$ is the inertia matrix which is symmetric and positive definite, $C(x_1, x_2) \in R^{m \times m}$ represents the centripetal-coriolis matrix, $G_g(x_1) \in R^m$ is the gravitation vector, $G_\tau(x_2) = G_f + G_d$ with G_f being the static or dynamic frictional force and $G_d \in R^m$ being the external disturbance, and $u = [u_1, u_2, \dots, u_m] \in R^m$ is the control input.

Let $x_1 = [x_{11}, \dots, x_{1m}]^T \in R^m$ and $\dot{x}_1 = x_2 = [x_{21}, \dots, x_{2m}]^T \in R^m$, then (1) becomes

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = Mu + F(\cdot) \end{cases} \quad (2)$$

where $M(\cdot) = H^{-1}(x_1)$ and $F(\cdot) = M(-Cx_2 - G_g - G_\tau)$. Furthermore, the considered robot systems have the following well-known structural properties [8], [9], [24]:

Property 1: The inertia matrix H and its inverse matrix M are positive definite and symmetric. In addition, there exist some positive constants λ_{\max} and λ_{\min} such that

$$\lambda_{\min} \leq \|M\| \leq \lambda_{\max}, \quad (3)$$

$$\lambda_{\min} \|x\|^2 \leq x^T M x \leq \lambda_{\max} \|x\|^2, \quad \forall x \in R^m \quad (4)$$

Property 2: For any x_1 and x_2 , there exist some positive constants γ_1, γ_2 , and γ_3 such that

$$\begin{cases} \|H(x_1)\| \leq \gamma_1, \|G_g(x_1)\| \leq \gamma_2, \\ \|C(x_1, x_2)\| \leq \gamma_3 \|x_2\| \end{cases} \quad (5)$$

B. EVENT-TRIGGERING MECHANISM

To decrease the communication burden, motivated by the results in [15] and [25], we design an event-triggered mechanism in the controller-to-actuator channel, which is described as:

- Control input:

$$u_k(t) = v_k(t_{kj}), \quad \forall t \in [t_{kj}, t_{k,j+1}) \quad (6)$$

for $k = 1, \dots, m$.

- Event-triggering mechanism:

$$\begin{aligned} t_{k,j+1} &= \inf \{t \in R_+, \\ &|v_k(t) - u_k(t)| \geq \varpi_{1k}|u_k(t)| + \varpi_{2k}\} \end{aligned} \quad (7)$$

for $\forall j \in Z_+$, in which $0 < \varpi_{1k} < 1$ and $\varpi_{2k} > 0$ are design parameters, $t_{k,j+1}$ is the corresponding time of event triggering, $v_k(t)$ is the ‘‘virtual’’ control law which is a continuous signal, $\check{e}_k(t)$ is the measurement error between $v_k(t)$ and $u_k(t)$, i.e., $\check{e}_k(t) = v_k(t) - u_k(t)$, t_{kj} is the update time in the k -th actuator channel, namely, if (7) is triggered, the corresponding time instant will be marked as $t_{k,j+1}$ and the virtual signal $v_k(t_{k,j+1})$ will be transmitted to the k -th actuator. In all, for $\forall t \in [t_{kj}, t_{k,j+1})$, the control signal is always kept as a constant and no signal is transmitted from the controller to the actuator, i.e., $u_k(t) = v_k(t_{kj})$ for $\forall t \in [t_{kj}, t_{k,j+1})$.

As the value of control signal must be updated to $v_k(t_{kj})$ at the triggering time instant t_{kj} , it is seen from (7) that, for $\forall t \geq 0$, one has

$$|v_k(t) - u_k(t)| \leq \varpi_{1k}|u_k(t)| + \varpi_{2k} \quad (8)$$

When $u_k(t) \geq 0$, we have

$$-\varpi_{1k}u_k(t) - \varpi_{2k} \leq v_k(t) - u_k(t) \leq \varpi_{1k}u_k(t) + \varpi_{2k} \quad (9)$$

it is easily checked that

$$v_k(t) - u_k(t) = \rho_{1k}(t)\varpi_{1k}u_k(t) + \rho_{2k}(t)\varpi_{2k} \quad (10)$$

with $\rho_{1k}(t)$ and $\rho_{2k}(t)$ being time-varying continuous parameters and satisfying $|\rho_{1k}(t)| \leq 1$ and $|\rho_{2k}(t)| \leq 1$. Moreover, there exist some positive constants $\bar{\rho}_{1k}$ and $\bar{\rho}_{2k}$ such that $|\dot{\rho}_{1k}(t)| \leq \bar{\rho}_{1k}$ and $|\dot{\rho}_{2k}(t)| \leq \bar{\rho}_{2k}$. The similar result can also be ensured for the case $u_k(t) < 0$. Therefore, it is reduced that

$$v_k(t) = [1 + \rho_{1k}(t)\varpi_{1k}]u_k(t) + \rho_{2k}(t)\varpi_{2k} \quad (11)$$

which can be rewritten in another form:

$$u_k(t) = \frac{v_k(t)}{1 + \rho_{1k}(t)\varpi_{1k}} - \frac{\rho_{2k}(t)\varpi_{2k}}{1 + \rho_{1k}(t)\varpi_{1k}} \quad (12)$$

Then (12) becomes:

$$u(t) = \eta_1(t)v(t) + \eta_2(t) \quad (13)$$

where

$$\eta_1(t) = \text{diag} \left\{ \frac{1}{1 + \rho_{1k}(t)\varpi_{1k}} \right\} \in R^{m \times m}, \quad (14)$$

$$\eta_2(t) = \left[-\frac{\rho_{21}(t)\varpi_{21}}{1 + \rho_{11}(t)\varpi_{11}}, \dots, -\frac{\rho_{2m}(t)\varpi_{2m}}{1 + \rho_{1m}(t)\varpi_{1m}} \right]^T, \quad (15)$$

$$v(t) = [v_1(t), \dots, v_m(t)]^T \quad (16)$$

Substituting (13) into (2), one obtains

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = F + M\eta_1v + M\eta_2 \end{cases} \quad (17)$$

Remark 1: Note that $1 - \varpi_{1k} \leq 1 + \rho_{1k}(t)\varpi_{1k} \leq 1 + \varpi_{1k}$ and $|\rho_{2k}(t)\varpi_{2k}| \leq \varpi_{2k}$, then it follows that

$$\frac{1}{1 + \varpi_{1k}} \leq \frac{1}{1 + \rho_{1k}(t)\varpi_{1k}} \leq \frac{1}{1 - \varpi_{1k}}$$

which implies that η_1 is positive definite and η_2 is bounded, i.e., there exist positive constants $\underline{\eta}_1, \bar{\eta}_1$, and $\bar{\eta}_2$ such that $\underline{\eta}_1 \leq \|\eta_1\| \leq \bar{\eta}_1$ and $\|\eta_2\| \leq \bar{\eta}_2$.

C. OBJECTIVES AND ASSUMPTIONS

Define the position tracking error as

$$E = x_1 - y_d = [e_1, e_2, \dots, e_m]^T \quad (18)$$

where $y_d = [y_{d1}, y_{d2}, \dots, y_{dm}]^T \in R^m$ is the reference signal. The goal of this paper is to develop an event-triggered strategy for rigid robotic systems such that:

- 1) all signals of the closed-loop robot dynamics are globally bounded;
- 2) the tracking performance on tracking error can be improved by adjusting the design parameters; and
- 3) the Zeno behavior [26] can be avoided in the sense that there exists a finite time $t_k^* > 0$ so that the inter execution interval $t_{k,j+1} - t_{kj}$ is lower bounded by t_k^* , $\forall j \in Z_+$.

To achieve the above control goals, the following assumptions and lemma are imposed.

Assumption 1: The desired trajectory y_d and its time derivatives $y_d^{(i)}, i = 1, 2, 3$, are known, bounded, and piecewise continuous.

Assumption 2: The system states x_1 and x_2 are measurable.

Assumption 3: There exists an unknown positive constant γ_4 such that $\|G_\tau(x_2)\| \leq \gamma_4(1 + \|x_2\|)$.

Remark 2: We give a detailed explanation about Assumption 3. In this paper, $G_f \in R^m$ denotes the static and/or dynamic frictional force and $G_d(t) \in R^m$ is a bounded external disturbance. In the existing literatures for robotic systems, the frictional dynamic G_f covers the following several types [27], [28]:

$$G_f = \theta_1 x_2 + \theta_2 \text{sgn}(x_2) \quad (19)$$

$$G_f = \theta_1 \left(\theta_2 + e^{-\theta_3 \|x_2\|} + \theta_4 \|x_2\| \right) \text{sgn}(x_2), \quad \theta_3 > 0 \quad (20)$$

with θ_i ($i = 1, \dots, 4$) being unknown parameters. From the forms of friction in (19) and (20), it is obvious that

$$\|G_f\| \leq c_1 + c_2\|x_2\| \quad (21)$$

where c_i ($i = 1, 2$) are non-negative and bounded constants. As G_d is bounded, then there exists a positive constant c_3 so that $\|G_d\| \leq c_3$. Hence, G_τ can be upper bounded by

$$\|G_\tau\| \leq \|G_f\| + \|G_d\| \leq c_1 + c_2\|x_2\| + c_3 \leq \gamma_4(1 + \|x_2\|) \quad (22)$$

where $\gamma_4 = \max\{c_1 + c_3, c_2\}$ is an unknown parameter, which implies that Assumption 3 is reasonable.

Lemma 1 [29]: Considering the dynamic system with the positive constants γ , σ , and the non-negative function $h(t)$:

$$\dot{w}(t) = \gamma h(t) - \sigma w(t), \quad w(0) \geq 0 \quad (23)$$

then it is not difficult to prove that $w(t) \geq 0$ for $\forall t \geq 0$ and $w(0) \geq 0$.

III. MAIN RESULT

A. ERROR TRANSFORMATION

To improve the tracking performance of robotic systems, different from most existing works, by introducing a diagonal matrix β we construct the following error transformation:

$$\zeta = \beta E \quad (24)$$

where $\beta = \text{diag}\{\beta_i\} \in R^{m \times m}$ is a time-varying scaling matrix and the element of β is defined as

$$\beta_i(t) = \frac{1}{(1 - b_{if})\kappa_i(t) + b_{if}}, \quad i = 1, 2, \dots, m \quad (25)$$

with $0 < b_{if} < 1$ being a design parameter and the real function $\kappa_i(t) \in R$ satisfying the following properties:

- The initial value of $\kappa_i(t)$ is 1, i.e., $\kappa_i(0) = 1$;
- $\kappa_i(t) > 0$ is strictly monotonously decreasing with respect to (w.r.t.) time for $\forall t \in [0, \infty)$ and converges to zero as $t \rightarrow \infty$, i.e., $\lim_{t \rightarrow \infty} \kappa_i(t) = 0$.
- $\kappa_i^{(k)}(t)$, $k = 0, 1, 2, 3$, is known, bounded, and piecewise continuous; and
- $\lim_{t \rightarrow \infty} \kappa_i^{(k)}(t) = 0$ for $k = 1, 2, 3$.

It is not difficult to show that many functions satisfy the above properties, i.e., $\kappa_i = \exp(-t)$, $\frac{1}{1+t^2}$, $\frac{1}{1+t^2+t^3}$. With such a function κ_i , it is easy to prove that the time-varying function $\beta_i(t)$ has the following features:

- 1) The initial value of $\beta_i(t)$ is 1, i.e., $\beta_i(0) = 1$;
- 2) β_i is monotonically increasing w.r.t. time and converges to a positive constant $\frac{1}{b_{if}}$ as $t \rightarrow \infty$, namely, $\beta_i \in [1, 1/b_{if}]$; and
- 3) $\beta_i^{(k)}$ ($i = 1, 2, 3$) is known, bounded, and piecewise continuous for $\forall t \geq 0$.

Remark 3: According to the properties of $\beta_i(t)$, it is readily verified that the diagonal matrix $\beta(t)$ is positive definite and invertible, so is β^{-1} . Furthermore, its derivatives $\beta^{(k)}$, $k = 1, 2, 3$, are available for control design.

Noting that $E = x_1 - y_d$, then its time derivatives are

$$\dot{E} = \dot{x}_1 - \dot{y}_d = x_2 - \dot{y}_d \quad (26)$$

and

$$\ddot{E} = \dot{x}_2 - \ddot{y}_d \quad (27)$$

Then the derivatives of ζ as defined in (24) along (26) and (27) are

$$\dot{\zeta} = \dot{\beta}E + \beta\dot{E} = \dot{\beta}E + \beta(x_2 - \dot{y}_d) \quad (28)$$

and

$$\begin{aligned} \ddot{\zeta} &= \ddot{\beta}E + \dot{\beta}\dot{E} + \beta\ddot{E} + \beta(\dot{x}_2 - \ddot{y}_d) \\ &= \ddot{\beta}E + 2\dot{\beta}\dot{E} + \beta(\dot{x}_2 - \ddot{y}_d) \end{aligned} \quad (29)$$

To facilitate the control design, different from the normally employed tracking-error-based filtered error, we introduce the following ζ -based filtered error:

$$z = \lambda_1 \zeta + \dot{\zeta} \quad (30)$$

where $\lambda_1 > 0$ denotes a design parameter. Then the derivative of z along (28)-(29) is

$$\begin{aligned} \dot{z} &= \lambda_1 \dot{\zeta} + \ddot{\zeta} \\ &= \lambda_1 \dot{\zeta} + \ddot{\beta}E + 2\dot{\beta}\dot{E} + \beta(\dot{x}_2 - \ddot{y}_d) \end{aligned} \quad (31)$$

Substituting the expression of \dot{x}_2 as shown in (17) into (31), one has

$$\begin{aligned} \dot{z} &= \lambda_1 \dot{\zeta} + \ddot{\beta}E + 2\dot{\beta}\dot{E} - \beta\ddot{y}_d + \beta(F + M\eta_1 v + M\eta_2) \\ &= \beta M\eta_1 v + \beta(F + M\eta_2) + \Delta \end{aligned} \quad (32)$$

with

$$\Delta = \lambda_1 \dot{\zeta} + \ddot{\beta}E + 2\dot{\beta}\dot{E} - \beta\ddot{y}_d \quad (33)$$

being computable for control design.

B. CONTROL DESIGN

Due to the consideration of improving tracking performance and reducing communication burden, the diagonal matrices β and η_1 are imposed in the new system dynamics (32), it makes the normally employed quadratic function $\frac{1}{2}z^T z$ not applicable for stability analysis, then how to design an effective control algorithm and to select a proper Lyapunov function candidate to guarantee the stability is a challenging topic. This is because that, although the matrices β , M , and η_1 are all positive definite, the multiplication $\beta M\eta_1$ may not be positive definite, then the traditional control methods in [30]–[32] for MIMO nonlinear systems are no longer available.

To circumvent the obstacles caused by the event-triggering rule and the error transformation and to decrease the difficulty of control design, instead of $\frac{1}{2}z^T z$, we construct the following positive definite function

$$V_1 = \frac{1}{2}z^T \Omega z \quad (34)$$

as a part of Lyapunov function candidate, where Ω is defined as

$$\begin{cases} \Omega = \eta_1 \beta^{-1} = \text{diag}\{\omega_k\} \\ \omega_k = \eta_{1k} \beta_k^{-1} = \frac{(1 - b_{kf})\kappa_k(t) + b_{kf}}{1 + \rho_{1k} \varpi_{1k}} \end{cases}$$

Its derivative is

$$\dot{V}_1 = z^T \Omega \dot{z} + \frac{1}{2} z^T \Upsilon z \quad (35)$$

with $\Upsilon = \text{diag}\{\varepsilon_k\} = \frac{d}{dt} \Omega = \frac{d}{dt} (\eta_1 \beta^{-1})$, where

$$\varepsilon_k = \frac{d}{dt} (\eta_{1k} \beta_k^{-1}) = \frac{d}{dt} \left(\frac{(1 - b_{kf})\kappa_k(t) + b_{kf}}{1 + \rho_{1k} \varpi_{1k}} \right)$$

Noting that κ_k and its derivative $\dot{\kappa}_k$ are bounded, it is readily seen that ε_k is bounded, then it implies that there exist some positive constants $\bar{\varepsilon}_k$ and $\bar{\Upsilon}$ so that $|\varepsilon_k| \leq \bar{\varepsilon}_k$ and $\|\Upsilon\| \leq \bar{\Upsilon}$.

Substituting (32) into (35), one has

$$\dot{V}_1 = z^T \eta_1 M \eta_1 v + \mathcal{F} \quad (36)$$

where $\mathcal{F} = z^T \eta_1 (F + M \eta_2 + \beta^{-1} \Delta) + \frac{1}{2} z^T \Upsilon z$ is the lumped uncertainty.

According to the Properties 1-2 of robotic systems and Assumption 3, together with the definition of F , we have

$$\begin{aligned} \|F(\cdot)\| &\leq \lambda_{\max} \left[\gamma_3 \|x_2\|^2 + \gamma_2 + \gamma_4 (1 + \|x_2\|) \right] \\ &\leq \lambda_{\max} \max\{\gamma_2, \gamma_3, \gamma_4\} (2\|x_2\|^2 + 3) \\ &\leq a\phi \end{aligned} \quad (37)$$

where

$$a = \lambda_{\max} \max\{\gamma_2, \gamma_3, \gamma_4\}$$

is an unknown parameter and

$$\phi = 2\|x_2\|^2 + 3$$

is an available function for control design.

Upon using the Young's inequality, together with Remark 1, one has

$$z^T \eta_1 F \leq \|z\| \|\eta_1\| \|F\| \leq a^2 \bar{\eta}_1^2 \|z\|^2 \phi^2 + \frac{1}{4} \quad (38)$$

$$z^T \eta_1 M \eta_2 \leq \|z\| \bar{\eta}_1 \lambda_{\max} \bar{\eta}_2 \leq \bar{\eta}_1^2 \lambda_{\max}^2 \bar{\eta}_2^2 \|z\|^2 + \frac{1}{4} \quad (39)$$

$$\begin{aligned} z^T \eta_1 \beta^{-1} \Delta &\leq \|z\| \|\eta_1\| \|\beta^{-1} \Delta\| \\ &\leq \bar{\eta}_1^2 \|z\|^2 \|\beta^{-1} \Delta\|^2 + \frac{1}{4} \end{aligned} \quad (40)$$

Furthermore, note that

$$\frac{1}{2} z^T \Upsilon z \leq \frac{1}{2} \bar{\Upsilon} \|z\|^2 \quad (41)$$

Therefore, \mathcal{F} can be upper bounded by

$$\mathcal{F} \leq b \|z\|^2 \Phi + \frac{3}{4} \quad (42)$$

with

$$b = \max \left\{ \bar{\eta}_1^2, \bar{\Upsilon}, a^2 \bar{\eta}_1^2, \bar{\eta}_1^2 \lambda_{\max}^2 \bar{\eta}_2^2 \right\} \quad (43)$$

$$\Phi = \phi^2 + \|\beta^{-1} \Delta\|^2 + \frac{3}{2} \quad (44)$$

Then (36) becomes

$$\dot{V}_1 \leq z^T \eta_1 M \eta_1 v + b \|z\|^2 \Phi + \frac{3}{4} \quad (45)$$

The global adaptive event-triggered controller is designed as:

$$v = - \left(c + \hat{b} \Phi \right) z \quad (46)$$

where $c > 0$ denotes a design parameter, \hat{b} is the estimate of unknown parameter b and is updated by the following form:

$$\dot{\hat{b}} = \gamma \|z\|^2 \Phi - \sigma \hat{b}, \quad \hat{b}(0) \geq 0 \quad (47)$$

with γ and σ being positive design parameters. Furthermore, it must be emphasized that as $\gamma \|z\|^2 \Phi \geq 0$, with the aid of Lemma 1, it is guaranteed that $\hat{b}(t) \geq 0$ for $\forall t \in [0, \infty)$ and $\hat{b}(0) \geq 0$.

The stability analysis of the closed-loop robotic systems under the proposed adaptive controller (46)-(47) is summarized in the following theorem.

Theorem 1: Consider the uncertain robotic system (2) with event-triggering mechanism. Suppose Assumptions 1-3 hold, if the event-triggered adaptive control scheme as designed in (46)-(47) is applied, then it is ensured that:

- 1) all signals in the closed-loop robot dynamics are globally bounded;
- 2) the tracking performance can be improved by adjusting the design parameters; and
- 3) the Zeno behavior is avoided.

Proof: According to the definition of adaptive controller (46), it is seen that

$$z^T \eta_1 M \eta_1 v = - \left(c + \hat{b} \Phi \right) (\eta_1 z)^T M (\eta_1 z) \quad (48)$$

where the fact that $z^T \eta_1 = z^T \eta_1^T = (\eta_1 z)^T$ is utilized.

As M is positive definite, it leads to $(\eta_1 z)^T M (\eta_1 z) \geq \lambda_{\min} z^T \eta_1 \eta_1 z$. It is seen from Remark 1 that the diagonal matrix $\eta_1 \eta_1$ is also positive definite, then there exists a positive constant $\underline{\lambda}_\eta$ so that $z^T \eta_1 \eta_1 z \geq \underline{\lambda}_\eta \|z\|^2$, which implies from (48) that

$$z^T \eta_1 M \eta_1 v \leq -\underline{\lambda} \left(c + \hat{b} \Phi \right) \|z\|^2 \quad (49)$$

with $\underline{\lambda} = \lambda_{\min} \underline{\lambda}_\eta$. Thus, (45) becomes

$$\begin{aligned} \dot{V}_1 &\leq -\underline{\lambda} \left(c + \hat{b} \Phi \right) \|z\|^2 + b \|z\|^2 \Phi + \frac{3}{4} \\ &= -\underline{\lambda} c \|z\|^2 + \tilde{b} \|z\|^2 \Phi + \frac{3}{4} \end{aligned} \quad (50)$$

with $\tilde{b} = b - \underline{\lambda} \hat{b}$ being the parameter estimate error.

To prove the stability of the considered systems, we select the following form of Lyapunov function candidate:

$$V = V_1 + \frac{1}{2\underline{\lambda}\gamma} \tilde{b}^2 \quad (51)$$

with $\gamma > 0$. Then the time derivative of V along (50) yields

$$\dot{V} \leq -\underline{\lambda} c \|z\|^2 + \tilde{b} \|z\|^2 \Phi + \frac{3}{4} + \frac{1}{\underline{\lambda}\gamma} \tilde{b} \left(\dot{\tilde{b}} - \underline{\lambda} \dot{\hat{b}} \right) \quad (52)$$

Note that b is an unknown constant, it follows that $\dot{b} = 0$, then (52) further becomes

$$\dot{V} \leq -\underline{\lambda}c \|z\|^2 + \tilde{b}\|z\|^2\Phi + \frac{3}{4} + \frac{1}{\gamma}\tilde{b}(-\dot{\hat{b}}) \quad (53)$$

Invoking the adaptive law as given in (47) into (53), one has

$$\begin{aligned} \dot{V} &\leq -\underline{\lambda}c\|z\|^2 + \tilde{b}\|z\|^2\Phi + \frac{3}{4} + \frac{1}{\gamma}\tilde{b}(-\gamma\|z\|^2\Phi + \sigma\hat{b}) \\ &= -\underline{\lambda}c\|z\|^2 + \frac{3}{4} + \frac{\sigma}{\gamma}\tilde{b}\hat{b} \end{aligned} \quad (54)$$

As $\hat{b} = \frac{b-\tilde{b}}{\lambda}$, then it follows that

$$\frac{\sigma}{\gamma}\tilde{b}\hat{b} = \frac{\sigma}{\gamma\lambda}\tilde{b}(b-\tilde{b}) = \frac{\sigma}{\gamma\lambda}(\tilde{b}b - \tilde{b}^2) \quad (55)$$

By utilizing the Young's inequality, we have $\tilde{b}b \leq \frac{1}{2}\tilde{b}^2 + \frac{1}{2}b^2$, then

$$\frac{\sigma}{\gamma}\tilde{b}\hat{b} \leq \frac{\sigma}{2\gamma\lambda}(-\tilde{b}^2 + b^2) \quad (56)$$

which indicates that

$$\dot{V} \leq -\underline{\lambda}c\|z\|^2 - \frac{\sigma}{2\gamma\lambda}\tilde{b}^2 + \Theta \quad (57)$$

with $\Theta = \frac{3}{4} + \frac{\sigma}{2\gamma\lambda}b^2$ being an unknown positive constant.

As Ω is also positive definite and bounded, then there exist positive constants $\underline{\lambda}_\Omega$ and $\bar{\lambda}_\Omega$ such that

$$\underline{\lambda}_\Omega\|z\|^2 \leq z^T\Omega z \leq \bar{\lambda}_\Omega\|z\|^2 \quad (58)$$

it is checked that

$$-\bar{\lambda}_\Omega\|z\|^2 \leq -z^T\Omega z \quad (59)$$

which leads to

$$-\underline{\lambda}c\|z\|^2 \leq -\frac{\lambda c}{\lambda_\Omega}z^T\Omega z \quad (60)$$

Then (57) becomes

$$\dot{V} \leq -\frac{2\lambda c}{\lambda_\Omega}\frac{1}{2}z^T\Omega z - \frac{\sigma}{2\gamma\lambda}\tilde{b}^2 + \Theta \leq -\Gamma V + \Theta \quad (61)$$

where

$$\Gamma = \min\left\{\frac{2\lambda c}{\lambda_\Omega}, \sigma\right\} > 0$$

Solving the equation (61) on $[0, t]$, one has

$$V(t) \leq \frac{\Theta}{\Gamma} + \left(V(0) - \frac{\Theta}{\Gamma}\right)\exp(-\Gamma t) \quad (62)$$

Then we guarantee the following results.

We first prove that all signals in the closed-loop systems are bounded. It is from (62) seen that $V(t)$ is bounded, then from the definition of Lyapunov function candidate, one has z and \tilde{b} are bounded. As $\tilde{b} = b - \lambda_{\min}\hat{b}$ and b and λ_{\min} are positive constants, then it is shown that \hat{b} is also bounded. In addition, note that $z = \lambda_1\zeta + \dot{\zeta}$, then it is not difficult to prove that ζ and $\dot{\zeta}$ are bounded. According to the boundedness of β and $\dot{\beta}$, together with Assumption 2, it is ensured that

E and \dot{E} are bounded, which further implies that x_1 and x_2 are bounded. As the matrices η_1^{-1} and Υ are bounded, then the computational function Φ is also bounded, then from the definitions of control law and adaptive law as defined in (46)-(47), respectively, it follows that v and $\dot{\hat{b}}$ are bounded for $\forall t \geq 0$.

Next we analyze the tracking performance of each component of the tracking error. Denote $z = [z_1, \dots, z_m]^T \in R^m$ and $\zeta = [\zeta_1, \dots, \zeta_m]^T \in R^m$, then it follows from (30) that

$$\dot{\zeta}_i = -\lambda_1\zeta_i + z_i, \quad i = 1, \dots, m \quad (63)$$

Solving the above equation yields

$$\zeta_i(t) = \zeta_i(0)\exp(-\lambda_1 t) + \exp(-\lambda_1 t)\int_0^t \exp(\lambda_1 \tau)z_i(\tau)d\tau \quad (64)$$

Note that $|z_i| \leq \|z\| \leq \bar{z}$ with \bar{z} being a positive constant, then (64) becomes

$$|\zeta_i(t)| \leq |\zeta_i(0)|\exp(-\lambda_1 t) + \frac{\bar{z}}{\lambda_1} \leq |\zeta_i(0)| + \frac{\bar{z}}{\lambda_1} = B_i \quad (65)$$

As $E = [e_1, \dots, e_m]^T \in R^m$ and $\zeta_i = \beta_i e_i$, then $e_i = \beta_i^{-1}\zeta_i$, $i = 1, 2, \dots, m$, which further expresses as

$$\begin{cases} e_i(t) = \beta_i^{-1}(t)\zeta_i(t) = b_{if}\zeta_i(t) + (1 - b_{if})\kappa_i(t)\zeta_i(t) \\ |e_i(t)| \leq \beta_i^{-1}(t)|\zeta_i(t)| \leq b_{if}B_i + (1 - b_{if})\kappa_i(t)B_i \end{cases} \quad (66)$$

and

$$\begin{cases} e_i(t) = b_{if}\zeta_i(t) \text{ as } t \rightarrow \infty \\ |e_i(t)| \leq b_{if}|\zeta_i(t)| \leq b_{if}B_i \text{ as } t \rightarrow \infty \end{cases} \quad (67)$$

It is shown from (66) that the tracking error e_i includes two components: the first one is $b_{if}\zeta_i(t)$, it is seen from the above analysis that $b_{if}\zeta_i(t)$ is always within the residual region $b_{if}B_i$ during the whole control process. The second one is $(1 - b_{if})\kappa_i\zeta_i(t)$, the decay rate is not only governed by the term $\zeta_i(t)$, but more importantly influenced by the real function $\kappa_i(t)$. Here we must emphasize that this function κ_i is not only at user's disposal but also is independent of system initial conditions and any other design parameters. Hence, we have the freedom to choose the real function κ_i properly to improve the decay rate and mode for $(1 - b_{if})\kappa_i\zeta_i(t)$, so that the transient tracking performance of $e_i(t)$ can be significantly improved.

Furthermore, it is also seen from (67) that the steady-state performance of tracking error can be improved by decreasing the design parameter b_{if} and the size of B_i . Noting that the size of B_i relies on the design parameter λ_1 and the size of z_i , then it is shown that the size of z_i may effect the steady-state tracking performance. Noting that (57) can be expressed as $\dot{V} \leq -\underline{\lambda}c\|z\|^2 + \Theta$, then it is easily proved that z will enter into and remain within the compact set $\Omega_z := \left\{z \in R^m \mid \|z\| \leq \sqrt{\frac{\Theta + \mu}{\lambda c}}\right\}$, where μ is a small positive constant. As the size of z is proportional σ , and reversely proportional to c and γ , then increasing the design

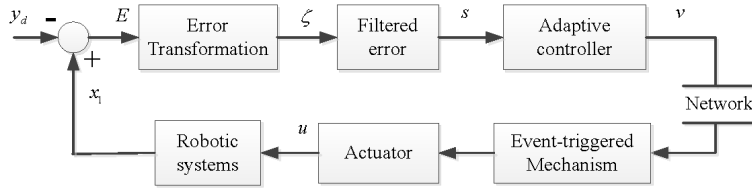


FIGURE 1. The diagram of control design procedure with event-triggered mechanism.

parameters c and γ and decreasing σ will lead to smaller z . In addition, it is seen from (65) that larger λ_1 may also lead to smaller ζ_i . Then increasing c , γ , λ_1 and decreasing σ may decrease the magnitude of z_i . However, larger c might lead to larger control effort. Therefore, certain compromise between control performance and control effort should be made in practice as with many other adaptive control methods.

Finally we show that the Zeno behavior [26] is avoided. As $\check{e}_k(t) = v_k(t) - u_k(t)$, it is deduced that:

$$\frac{d}{dt}|\check{e}_k| = \frac{d}{dt}(\check{e}_k * \check{e}_k)^{\frac{1}{2}} = \text{sign}(\check{e}_k)\dot{\check{e}}_k \leq |\dot{v}_k| \quad (68)$$

From the definition of $v(t)$ as shown in (46), we have $\dot{v}_k = \frac{\partial v_k}{\partial z_k}\dot{z}_k + \frac{\partial v_k}{\partial \Phi}\dot{\Phi} + \frac{\partial v_k}{\partial \hat{b}}\dot{\hat{b}}$. As \dot{z}_k , $\dot{\Phi}$, and $\dot{\hat{b}}$ are all continuous functions, then it is indicated that \dot{v}_k must be continuous. Noting that \dot{v}_k is a function of all bounded closed-loop signals, then there exists a constant $\chi_k > 0$ so that $|\dot{v}_k| \leq \chi_k$. According to the presented event-triggering mechanism, it follows that $\check{e}_k(t_{kj}) = 0$ and $\lim_{t \rightarrow t_{k,j+1}} \check{e}_k(t) = \omega_{1k}|u_k(t)| + \omega_{2k} > \omega_{2k}$, then we obtain that there exists a lower bound of inter-execution interval t_k^* and it satisfies $t_k^* \geq \frac{\omega_{2k}}{\chi_k}$. Therefore, the Zeno behavior is avoided. The proof is completed. \square

To recap the main design procedure, a control diagram that clearly illustrates the structure of the control loop is presented in Fig. 1.

Remark 4: If the error transformation (24) is not imposed, i.e., $\beta = I$, the proposed adaptive control scheme (46)-(47) reduces to

$$\begin{cases} \zeta = E \\ z = \lambda_1 \zeta + \dot{\zeta} \\ u = -(c + \hat{b}\Phi)z \\ \dot{\hat{b}} = \gamma \|z\|^2 \Phi - \sigma \hat{b}, \hat{b}(0) \geq 0 \\ \Phi = \phi^2 + \|\Delta\|^2 + \frac{3}{2}, \\ \phi = 2\|x_2\|^2 + 3, \Delta = \lambda_1 \dot{E} - \ddot{y}_d \end{cases} \quad (69)$$

then (69) is a special case of (46)-(47) and is referred to as the traditional event-triggered control method. Under this control scheme, although the boundedness of all signals in the closed-loop systems can be ensured, there is no any systematic guidance for improving the transient tracking performance. The normally method is to adjust the design parameters by the method of trial and error, however, this may lead to a

large magnitude of control law in the initial period. In this paper, by constructing a time-varying scaling matrix and introducing a meaningful error transformation, the proposed control not only ensures the boundedness of all signals but also achieves adjustable transient performance without involving large control inputs, which is very important for the control implementation in the practical engineering systems.

Remark 5: Compared with the [33]–[36] with or without event-triggered mechanism, the main difference is that in this paper the tracking transient performance is considered, which implies that the corresponding methods are no longer applicable. In this paper, by imposing a time-varying scaling function matrix in the control design, together with an event-triggered mechanism and an alternative form of Lyapunov function, the proposed method not only circumvents the obstacle caused by the event-triggered mechanism, but also guarantees the adjustable tracking performance for uncertain robotic manipulators.

Remark 6: Compared with the existing literature about the robotic control, the main contributions and the shortcoming of this study are discussed in the following:

- Due to the consideration of transient tracking performance, the original filtered-error-based control scheme is no longer applicable as the normally method on improving the transient performance is to adjust the design parameters by the method of trial and error, leading to a large magnitude of control input in the initial period and a adverse effort on the actuator. In this paper, in order to achieve the adjustable transient performance without involving large control law, by imposing a time-varying diagonal matrix, together with a error transformation, the developed global approach is able to ensure that the tracking error converges to an adjustable region with a adjustable decay rate without involving large control input;
- Noting that the diagonal matrices β and η_1 are imposed in the new system dynamics (32), it makes the control gain matrix $\beta M \eta_1$ not symmetric and positive definite at all, which further implies that the quadratic function $\frac{1}{2}z^T z$ is no longer applicable for stability analysis. Therefore, in this paper, different from the normally employed quadratic function, an alternative Lyapunov function candidate $\frac{1}{2}z^T \Omega z$ is constructed so that not only the difficulty caused by the time-varying diagonal matrix and the event-triggering mechanism is circumvented,

but also the stability of the closed-loop systems can be guaranteed.

- Although the proposed control of robotic control is able to achieve the global result with adjustable tracking performance, it is seen from (65) the control precision of tracking error depends on some unknown terms, which cannot be pre-specified by the control scheme. Therefore, we will focus on studying the global prescribed performance event-triggered control of uncertain robotic systems such that the control precision can be pre-assigned.

IV. SIMULATION VERIFICATION

To verify the effectiveness of the proposed event-triggered control method, we consider a 2-DOF robotic manipulator with the following detailed expressions:

$$\begin{aligned}
 H &= \begin{bmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{bmatrix}, \quad C = \begin{bmatrix} C_{11} & C_{12} \\ C_{21} & C_{22} \end{bmatrix} \\
 G_g &= [G_{g1}, G_{g2}]^T, \\
 G_f &= \theta_1(\theta_2 + \exp(-\theta_3 \|x_2\|) + \theta_4 \|x_2\|) \\
 G_d &= [\sin(t), \sin(t)]^T
 \end{aligned}$$

where

$$\left\{ \begin{aligned}
 H_{11} &= m_1 p_3^2 + m_2(p_1^2 + p_4^2 + 2p_1 p_4 \cos(x_{12})) \\
 &\quad + I_1 + I_2, \\
 H_{12} &= H_{21} = m_2(p_4^2 + p_1 p_4 \cos(x_{12})) + I_2, \\
 H_{22} &= m_2 p_4^2 + I_2, \\
 C_{11} &= -m_2 p_1 p_4 x_{22} \sin(x_{12}), \\
 C_{12} &= -m_2 p_1 p_4 x_{22}(x_{21} + x_{22}) \sin(x_{12}), \\
 C_{21} &= m_2 p_1 p_4 x_{21} \sin(x_{12}), \\
 C_{22} &= 0, \\
 G_{g1} &= (m_1 p_3 + m_2 p_1) g \cos(x_{11}) \\
 &\quad + m_2 p_4 g \cos(x_{11} + x_{12}), \\
 G_{g2} &= m_2 p_4 g \cos(x_{11} + x_{12}), \\
 \tau_{d1} &= p_5 \sin(x_{11}), \\
 \tau_{d2} &= p_6 \sin(x_{12}).
 \end{aligned} \right.$$

The system parameters are given as:

$$\begin{aligned}
 p &= [p_1, p_2, p_3, p_4, p_5, p_6] \\
 &= [1, 1, 0.5, 0.5, 0.5, 0.5], \\
 [\theta_1, \theta_2, \theta_3, \theta_4] &= [0.5, 0.6, 0.8, 0.3], \\
 I_1 = I_2 &= 0.5 \text{ kg} \cdot \text{m}^2, \\
 m_1 = m_2 &= 1 \text{ kg}, \quad g = 9.81 \text{ m/s}^2.
 \end{aligned}$$

The objective in the simulation is to utilize the proposed event-triggered control scheme (46)-(47) for the 2-DOF robotic systems such that the system output x_1 tracks the known reference signal $y_d(t) = [1.2 \sin(t), 0.5 \sin(t)]^T$ (rad) with excellent transient tracking performance. To show the effectiveness of the proposed control, the initial conditions are given as: $x_{11}(0) = 1.3$ (rad), $x_{12}(0) = 1$ (rad),

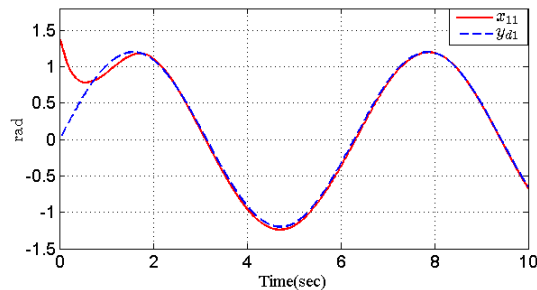


FIGURE 2. The evolutions of x_{11} and y_{d1} .

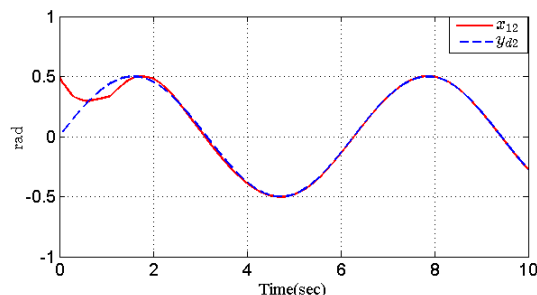


FIGURE 3. The evolutions of x_{12} and y_{d2} .

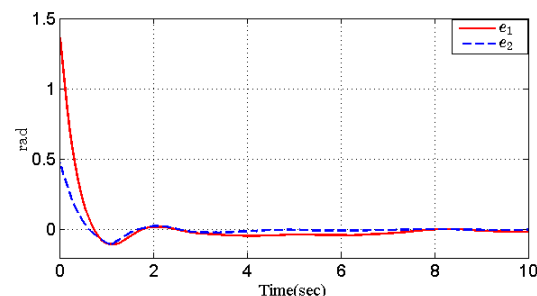


FIGURE 4. The evolutions of e_{11} and e_{12} .

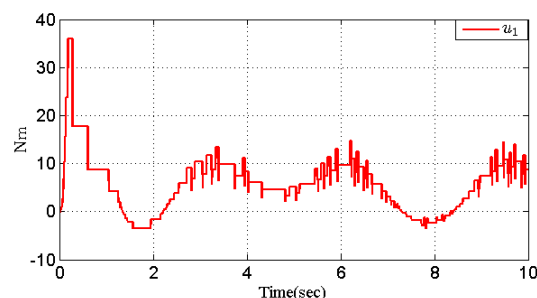


FIGURE 5. The evolution of control input u_1 .

$x_{21}(0) = -1$ (rad/s), $x_{22}(0) = -1$ (rad/s), and $\hat{b}(0) = 0$. The design parameters for the proposed control are given as $c = 1$, $\lambda_1 = 1.5$, $\gamma = 0.001$, $\sigma = 0.1$, $b_{if} = 0.08$, and $\kappa_i = \exp(-t)$, $i = 1, 2$.

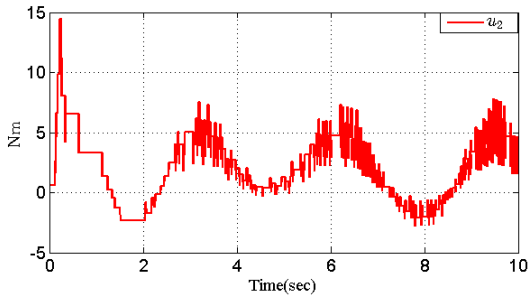


FIGURE 6. The evolution of control input u_2 .

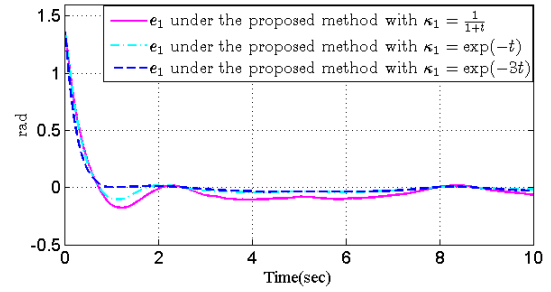


FIGURE 10. The evolutions of tracking error e_1 with different real function κ_1 .

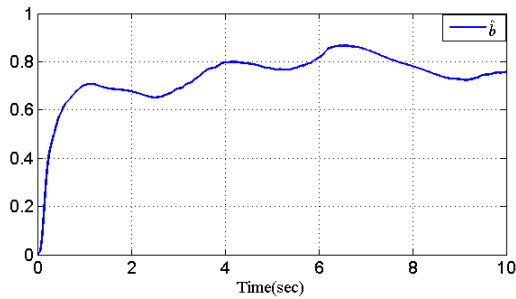


FIGURE 7. The evolution of parameter estimate \hat{b} .

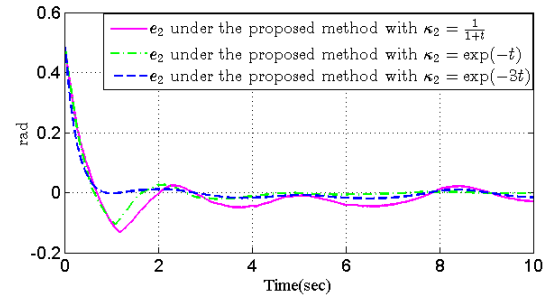


FIGURE 11. The evolutions of tracking error e_2 with different real function κ_2 .

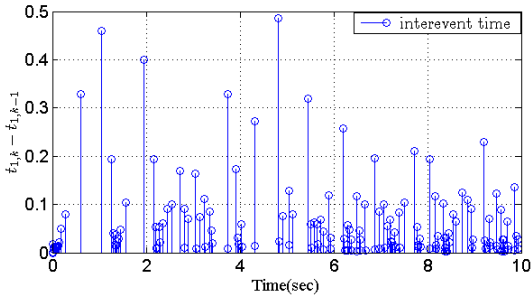


FIGURE 8. Time interval of triggering event for control law u_1 .

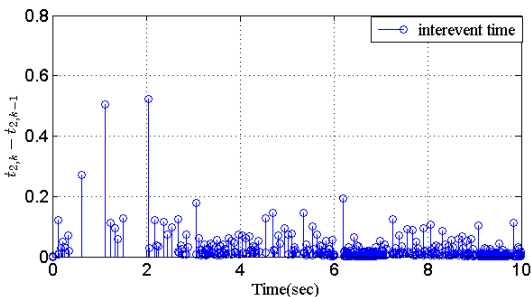


FIGURE 9. Time interval of triggering event for control law u_2 .

The simulation results are shown in Fig. 2-Fig. 9. The evolutions of x_{1k} and y_{dk} are plotted in Fig. 2-Fig. 3, respectively. The trajectories of tracking errors e_{11} and e_{12} are shown in Fig. 4, from which it is seen that under the proposed control, the tracking error exhibits good tracking

performance. In addition, the evolutions of control inputs u_1 and u_2 are plotted in Fig. 5 and Fig. 6, respectively. The trajectory of parameter estimate \hat{b} is given in Fig. 7. It is seen that all signals are bounded for $\forall t \geq 0$. Furthermore, the event triggered times for the event-triggering mechanism in the controller-to-actuator channels are shown in Fig. 8 and Fig. 9, respectively, from which it is checked that the numbers of events triggered within 10s are 133 and 431.

Furthermore, to verify that the proposed control is able to adjust the transient tracking performance by choosing different real function $\kappa_i(t)$, three different functions for κ_i ($i = 1, 2$) are considered, i.e., $\kappa_i(t) = \frac{1}{1+t}$, $\exp(-t)$, and $\exp(-3t)$. For fair comparison, all shared parameters and the initial values of the developed control scheme are set to be the same, the simulation results are shown in Fig. 10 and Fig. 11, from which it is seen that different $\kappa_i(t)$ can produce different tracking performance and the evolutions of tracking error can be adjusted, which confirms our theoretical analysis.

V. CONCLUSION

In this paper, we have developed a novel adaptive event-triggered control strategy for uncertain robotic systems with adjustable transient tracking performance. With the aid of diagonal matrix β , the tracking error-based transformation is employed so that the tracking performance caused by the event triggering mechanism is compensated and successfully

improved. Furthermore, the proposed control has also ensured the global boundedness of all closed-loop signals in robot dynamics.

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