Reduced-Order GPIO Based Dynamic Event-Triggered Tracking Control of a Networked One-DOF Link Manipulator Without Velocity Measurement

Jiankun Sun, Jun Yang, *Senior Member, IEEE*, and Shihua Li, *Fellow, IEEE*

***Abstract*—In networked robot manipulators that deeply integrate control, communication and computation, the controller design needs to take into consideration the limited or costly system resources and the presence of disturbances/uncertainties. To cope with these requirements, this paper proposes a novel dynamic event-triggered robust tracking control method for a one-degree of freedom (DOF) link manipulator with external disturbance and system uncertainties via a reduced-order generalized proportional-integral observer (GPIO). By only using the sampled-data position signal, a new sampled-data robust output feedback tracking controller is proposed based on a reduced-order GPIO to attenuate the undesirable influence of the external disturbance and the system uncertainties. To save the communication resources, we propose a discrete-time dynamic event-triggering mechanism (DETM), where the estimates and the control signal are transmitted and computed only when the proposed discrete-time DETM is violated. It is shown that with the proposed control method, both tracking control properties and communication properties can be significantly improved. Finally, simulation results are shown to demonstrate the feasibility and efficacy of the proposed control approach.**

***Index Terms*—Dynamic event-triggering mechanism (DETM), external disturbance and system uncertainties, networked robot manipulator, reduced-order generalized proportional-integral observer (GPIO), robust control.**

I. Introduction

WITH the many applications of robot manipulators in different fields including advanced medical, space and defense, modern industries, etc., the control issues of manipulators have captured tremendous attention from industrial and academic communities [1], [2]. Meanwhile, the last two decades have witnessed a significant increase in interest in the area of networked control systems (NCS) due to the advances in network infrastructure, communication architecture and computer technology [3]–[8]. For the control issues of networked robot manipulators, many works have been published where the use of a network is essential for receiving the sensor signal and transmitting the control signal [9], [10]. For example, networked are used in the coordination control of multiple manipulators [11], telerobotic control systems [12], and so on.

Typically, a NCS is composed of five basic components including sensors, controllers, actuators, plants, and a shared communication network [13]–[15]. Those components need to exchange sensor and controller signals to achieve control tasks. For instance, the control input is transmitted and the sensor signal is received from a distance in telerobotic control systems [12]. The information is transported from one agent to another such that some complex tasks can be accomplished by multiple manipulators [11]. For NCSs, low energy consumption and computation are sought, with communication being costly due to the limited energy, computation and communication bandwidth. Even though many researchers have devoted themselves to the networked control manipulators [16]–[21], little attention has been paid to the communication constraint, which motivates us to develop a resource-efficient control method for the networked control manipulator.

To improve the resource efficiency while guaranteeing desirable control performance, event triggered control has been proposed in recent two decades as a kind of communication protocol where the control tasks are executed only when it is necessary [22]–[29]. In contrast to more commonly used periodic transmission schemes (i.e., time-triggering mechanism (TTM)), event triggered control tends to execute the control tasks that are sporadic in nature, rather than during a certain period of time as in the conventional TTMs [30]–[37]. Some experimental results have demonstrated that the event triggered control can significantly save the communication resource compared with the conventional TTMs with comparable performance [38]. Some survey papers on event triggered control can be found in [13], [39], [40].

In practical applications, it is hard to obtain the exact dynamics of robot manipulators due to the inevitable existence

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J. K. Sun is with the School of Automation, Southeast University, Nanjing 210096, China (e-mail: bssdemail@163.com).

J. Yang and S. H. Li are with the School of Automation, Southeast University, Key Laboratory of Measurement and Control of CSE, Ministry of Education, Nanjing 210096, China (e-mail: j.yang84@seu.edu.cn; lsh@seu.edu.cn).

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of lumped disturbances including external disturbances, load variation, friction, and system uncertainties [19], [20], [41]–[44]. Lumped disturbances not only deteriorate control properties, but also result in a waste of system resources, since even small disturbances may lead to increased transmission times [38], [45]. In addition, velocity measurements are generally unknown in most commercially available robot manipulators in order to decrease the manufacturing costs [16], [17], [21]. Therefore, designing a robust output feedback control method to attenuate the undesirable influence of lumped disturbances is essential and contributes to the improvement of both control properties and communication properties of event-triggered systems, which is another motivation of the current study.

In this paper, a novel dynamic event-triggered tracking control method is proposed for a one-degree of freedom (DOF) link manipulator subject to external disturbances and system uncertainties via the reduced-order generalized proportional-integral observer (GPIO) when only a sampled-data position measurement is available. By using a sampled-data position measurement and the control input, a new reduced-order GPIO is first proposed to estimate the velocity information and the lumped disturbance information, and the robust dynamic event-triggered controller is simultaneously designed by employing the technique of disturbance estimation/compensation to attenuate the undesirable influence of lumped disturbances on communication properties and tracking control properties. In the proposed control method, system information is transmitted via a communication network only when a well-designed dynamic event-triggering mechanism (DETM) is violated, such that a better tradeoff can be achieved between communication resource utilization and tracking control performance. In the proposed DETM, the threshold parameter is dynamically adjusted following an adaptive rule. Under the proposed event-triggering control method, it is shown that tracking errors asymptotically converge to a bounded region, and the bound can be set to be arbitrarily small by choosing appropriate parameters. The major merits of the proposed robust dynamic event-triggered tracking control method in this paper are fourfold:

1) The proposed tracking control method does not need the velocity measurement, and the values of the lumped disturbance and the velocity can be accurately estimated by the proposed reduced-order GPIO. Compared with the full-order GPIO, the reduced-order observer has one less parameter to be regulated.

2) The parameters of the proposed DETM can be adaptively updated according to a defined error, such that the communication resources can be significantly saved while guaranteeing a satisfactory tracking control performance.

3) By the virtue of the technique of disturbance estimation/compensation, the proposed robust control method can attenuate the undesirable influence of the lumped disturbance on communication properties and tracking control properties in the framework of the DETM.

4) Compared with some results on DETM [46], [47], where the triggering mechanisms are continuous-time, the proposed control method in the paper is more suitable for digital applications, since both the proposed robust output feedback tracking controller and the novel DETM are in discrete-time form.

The remainder of this paper is organized as follows: Section II describes the manipulator model and the problem statement. The proposed robust tracking controller and the novel DETM are shown in Section III. The stability analysis with some conditions on the existence of the proposed controller are given in Section IV. Then, Section V depicts the numerical simulation result to verify the efficiency of the proposed controller. Finally, the main conclusions are summarized in Section VI.

II. Preliminaries

A. Notations

Throughout this paper, let $\mathbb{N}$ and $\mathbb{N}^+$ represent the sets of non-negative and positive integers, respectively. $\mathbb{R}$ and $\mathbb{R}_0^+$ stand for the sets of real and non-negative real numbers, respectively. For a given $r \in \mathbb{R}$, its absolute value is denoted by $|r|$. Given a set $a = (a_1, \dots, a_n)$, where $a_i \in \mathbb{R}$ for each $i = 1, \dots, n$, $\mathrm{diag}(a)$ denotes a diagonal matrix with the entries of a on the main diagonal. The superscript T represents the transpose. $\|\cdot\|$ denotes the Euclidean norm of a vector and the corresponding induced matrix norm. For a positive and symmetric matrix P, $\lambda_M(P)$ and $\lambda_m(P)$ denotes the maximum and minimum eigenvalues of P.

B. System Model and Problem Description

Consider the dynamics of a one-DOF link manipulator as follows:

$$D\ddot{\theta} + C\dot{\theta} + G = \tau + d \tag{1}$$

where θ and τ are the output angle and the control torque, $D = 4ml^2/3$ is the moment of inertia, m is the mass of the manipulator, l is the distance from the centroid to the center of connecting rod rotation, C is the viscous friction coefficient, $G = mgl\cos\theta$ is the gravity of the manipulator, g is the gravitational acceleration and d is the external disturbance. The reference signal of the angle θ is denoted by θ_d.

In this paper, system uncertainties are taken into account since system parameters can not be accurately known in practical applications. We define m_0, g_0, l_0, and C_0 as the nominal values of m, g, l, and C, respectively.

Defining a scale parameter $L \geq 1$, with the help of the new denotations $y(t) = x_1(t) = \theta(t) - \theta_d(t)$, $x_2(t) = \dot{x}_1(t)/L$ and $u(t) = \tau(t)/L^2$, we represent (1) by

$$\begin{cases} \dot{x}_1(t) = Lx_2(t) \\ \dot{x}_2(t) = La_0u(t) + \dfrac{w(t, x(t), u(t), d(t), \dot{\theta}_d(t))}{L} \\ y(t) = x_1(t) \end{cases} \tag{2}$$

where $a_0 = 3/4m_0l_0^2$ can be regarded as the nominal parameter of (2). $w(t, x(t), u(t), d(t), \dot{\theta}_d(t)) = -\dfrac{3C}{4ml^2}\dot{\theta}(t) - \dfrac{3g}{4l}\cos(\theta(t)) + \left(\dfrac{3}{4ml^2} - \dfrac{3}{4m_0l_0^2}\right)u(t) + \dfrac{3}{4ml^2}d(t) + \dot{\theta}_d(t)$ denotes the lumped disturbance including system uncertainties, the external disturbance and the desired velocity. For simplicity, $w(t)$ is defined as the shorthand of $w(t,x(t),u(t),d(t),\dot{\theta}_d(t))$ in the rest of the paper.

Inspired by most of the results on disturbance rejection control [42], [43], a common assumption on the lumped disturbance $w(t)$ is given as follows:

Assumption 1: The lumped disturbance $w(t)$ is assumed to satisfy $|\dot{w}(t)| \le w_1$ and $|\ddot{w}(t)| \le w_2$ for all $t \in \mathbb{R}$, where w_1 and w_2 are two positive constants.

Remark 1: It should be mentioned that the hypothesis on disturbances given in Assumption 1 is general and has been utilized in several existing works on disturbance rejection approaches [42], [43]. From a practical point of view, it is reasonable to assume that the lumped disturbance or its derivative are bounded since the external disturbance, the system uncertainties, and the desired velocity are all bounded in practice. The proposed method still works when the disturbance is piecewise continuous, since it can be viewed that the proposed observer is reset at every discontinuous instant.

Due to the finite rate digital communication channel between the sensor and the controller, the event-triggering mechanism is employed to reduce transmission times while a desirable trajectory tracking error can be guaranteed. In the presence of the lumped disturbance, trajectory tracking performance is inevitably deteriorated, and more communication times are probably generated if the disturbance is not properly handled. Therefore, to improve both the communication properties and trajectory tracking properties, this paper develops a new DETM for a robust output feedback controller via the reduced-order GPIO for the robot manipulator dynamics (1).

The structure of the proposed event-triggered method is shown in Fig. 1, where the signals are transmitted continuously along the solid lines, periodically along the dashed line, and intermittently based on the events along the dotted line. In the proposed control method, we only know the sampled-data position information at the sampling instant $\{kT\}_{k\in\mathbb{N}}$ with a constant sampling period T. By using sampled-data, a reduced-order GPIO is first designed to estimate the unknown velocity and the disturbance information. To save communication resources, the output and the estimates are transmitted only when the pre-designed discrete-time DETM is triggered at certain sampling instants. The control input is updated once the latest output and estimates are received; otherwise, it remains the same.

Without the loss of generality, we assume the first event happens at $t_0 = 0$, the sequence $\{t_k\}_{k\in\mathbb{N}}$ stands for the set of event-triggering instants, where t_k denotes the $(k+1)$th event-triggering instant. The proposed triggering condition is detected at every sampling instant $\{kT\}_{k\in\mathbb{N}}$. Therefore, there exists some integer $i_k \in \mathbb{N}$, such that $t_k = i_kT$ holds with $i_0 = 0$ and $i_k < i_{k+1}$. Defining $d_k = i_{k+1} - i_k - 1$, one has $d_k \ge 0$ since $t_k < t_{k+1}$. It is obvious that the inter-event interval $[t_k, t_{k+1})$ can be written as $[t_k, t_{k+1}) = \bigcup_{j=0}^{d_k} I_j^k$, where $I_j^k = [t_k + jT, t_k + (j+1)T)$, $j = 0, \ldots, d_k$.

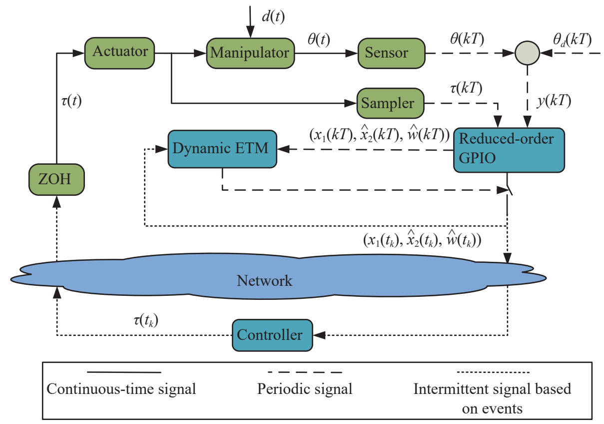

Fig. 1. The structure of the proposed event-triggered control method.

III. Event-Triggered Output Feedback Control Design via Reduced-Order GPIO

A. Reduced-Order GPIO-Based Controller

With the help of the sampled-data output, we design a new reduced-order GPIO for (2) in the time interval I_j^k, $k \in \mathbb{N}$, $j = 0, \ldots, d_k$ as follows:

$$\begin{cases} \dot{z}_1(t) = -L\beta_1(z_1(t)+\beta_1 y(t_k+jT)) + L(z_2(t)+\beta_2 y(t_k+jT)) \\ \qquad + La_0u(t) \\ \dot{z}_2(t) = -L\beta_2(z_1(t)+\beta_1 y(t_k+jT)) + L(z_3(t)+\beta_3 y(t_k+jT)) \\ \dot{z}_3(t) = -L\beta_3(z_1(t)+\beta_1 y(t_k+jT)) \\ \hat{x}_2(t) = z_1(t)+\beta_1 y(t),\ \hat{w}(t) = L^2(z_2(t)+\beta_2 y(t)) \\ \hat{\dot{w}}(t) = L^3(z_3(t)+\beta_3 y(t)) \end{cases} \tag{3}$$

where $z_i(t), i = 1,2,3$ are the internal variables. $\hat{x}_2(t)$, $\hat{w}(t)$ and $\hat{\dot{w}}(t)$ are the estimates of the state $x_2(t)$, the disturbance $w(t)$ and its derivative $\dot{w}(t)$, respectively. $y(t_k + jT)$ is the sampled-data output at the sampling instant $t_k + jT$. β_i, $i = 1,2,3$ are the observer gains to be designed.

It should be pointed out that the proposed reduced-order GPIO (3) is in continuous-time form, and such a design form is convenient for stability analysis, but not suitable for practical applications in digital computers. To cope with that, we give an accurate discretized version of (3). Firstly, (3) can be rewritten as follows:

$$\dot{Z}(t) = L\underbrace{\begin{bmatrix} -\beta_1 & 1 & 0 \\ -\beta_2 & 0 & 1 \\ -\beta_3 & 0 & 0 \end{bmatrix}}_{\Pi_1} Z(t) + L\underbrace{\begin{bmatrix} a_0 \\ 0 \\ 0 \end{bmatrix}}_{\Pi_2} u(t)$$
$$+ L\underbrace{\begin{bmatrix} -\beta_1^2+\beta_2 \\ -\beta_1\beta_2+\beta_3 \\ -\beta_1\beta_3 \end{bmatrix}}_{\Pi_3} y(t_k+jT) \tag{4}$$

where $Z(t) = [z_1(t), z_2(t), z_3(t)]^T$.

Then, by integrating $Z(t)$ from $t_k + jT$ to $t_k + (j+1)T$, an accurate discretized version of (4) can be obtained by

$$
\begin{aligned}
Z(t_k+(j+1)T) &= e^{L\Pi_1 T}Z(t_k+jT)+\int_0^T e^{L\Pi_1 s}ds \\
&\quad \times (L\Pi_2 u(t)+L\Pi_3 y(t_k+jT)) \\
&= \bar{\Pi}_1 Z(t_k+jT) \\
&\quad +\bar{\Pi}_2 u(t_k+jT)+\bar{\Pi}_3 y(t_k+jT) \qquad (5)
\end{aligned}
$$

where $\bar{\Pi}_1 = e^{L\Pi_1 T}$, $\bar{\Pi}_2 = L\int_0^T e^{L\Pi_1 s}ds\Pi_2$ and $\bar{\Pi}_3 = L\int_0^T e^{L\Pi_1 s}ds\Pi_3$.

Let $e(t) = [e_1(t), e_2(t), e_3(t)]^T$ denotes the estimation error vector, where $e_1(t) = x_2(t)-\hat{x}_2(t)$, $e_2(t) = (w(t)-\hat{w}(t))/L^2$ and $e_3(t) = (\dot{w}(t)-\hat{\dot{w}}(t))/L^3$. Then, with system (2) and observer (3) in mind, one obtains the following estimation error system

$$
\begin{cases}
\dot{e}_1(t) = -L\beta_1 e_1(t)+Le_2(t)+L(\beta_1^2-\beta_2)(y(t_k+jk)-y(t)) \\
\dot{e}_2(t) = -L\beta_2 e_1(t)+Le_3(t)+L(\beta_1\beta_2-\beta_3)(y(t_k+jk)-y(t)) \\
\dot{e}_3(t) = -L\beta_3 e_1(t)+L\beta_1\beta_3(y(t_k+jk)-y(t))+\dfrac{\ddot{w}(t)}{L^3}.
\end{cases} \qquad (6)
$$

Combining (3) and (5), we can get $x_1(t_k)$, $\hat{x}_2(t_k)$ and $\hat{w}(t_k)$. Then, an event-triggered robust controller is designed by

$$
\begin{aligned}
u(t) = u(t_k) &= -\frac{1}{a_0}\left(k_1 x_1(t_k)+k_2\hat{x}_2(t_k)+\frac{\hat{w}(t_k)}{L^2}\right), \\
& t\in[t_k, t_{k+1}),\ k\in\mathbb{N} \qquad (7)
\end{aligned}
$$

where k_1 and k_2 are the feedback controller gains to be designed.

The event-triggered controller (7) can be further redescribed by

$$
\begin{aligned}
u(t) = u(t_k) &= -\frac{1}{a_0}\left(k_1 x_1(t)+k_2 x_2(t)+\frac{w(t)}{L^2}\right) \\
&+\frac{1}{a_0}(k_2 e_1(t)+e_2(t))+\frac{k_1}{a_0}(x_1(t)-x_1(t_k+jT)) \\
&+\frac{k_2}{a_0}(x_2(t)-x_2(t_k+jT))+\frac{1}{L^2 a_0}(w(t)-w(t_k+jT)) \\
&-\frac{k_2}{a_0}(e_1(t)-e_1(t_k+jT))-\frac{1}{a_0}(e_2(t)-e_2(t_k+jT)) \\
&+\frac{k_1}{a_0}(x_1(t_k+jT)-x_1(t_k))+\frac{k_2}{a_0}(\hat{x}_2(t_k+jT)-\hat{x}_2(t_k)) \\
&+\frac{1}{L^2 a_0}(\hat{w}(t_k+jT)-\hat{w}(t_k)), \\
& t\in I_j^k,\ k\in\mathbb{N},\ j=0,\ldots,d_k \qquad (8)
\end{aligned}
$$

where the last five items $\frac{k_2}{a_0}(e_1(t)-e_1(t_k+jT))$, $\frac{1}{L^2a_0}(e_2(t)-e_2(t_k+jT))$, $\frac{k_1}{a_0}(x_1(t_k+jT)-x_1(t_k))$, $\frac{k_2}{a_0}(\hat{x}_2(t_k+jT)-\hat{x}_2(t_k))$ and $\frac{1}{L^2a_0}(\hat{w}(t_k+jT)-\hat{w}(t_k))$ can be viewed as those caused by the DETM to be designed. When $d_k = 0$ for all $k\in\mathbb{N}$, the proposed controller (7) is reduced to a periodic sampled-data controller with a zero-order holder.

B. Dynamic Event-Triggering Mechanism

With the help of denotation $\varepsilon(t_k+jT) = [x_1(t_k+jT)-x_1(t_k), \hat{x}_2(t_k+jT)-\hat{x}_2(t_k), \hat{w}(t_k+jT)-\hat{w}(t_k)]$, $k\in\mathbb{N}$, $j=0,\ldots,d_k$ and defining $\bar{\varepsilon}(qT) = \sigma(qT)\|y(qT)\|+\sigma_1-\sqrt{\varepsilon^T(qT)\Phi\varepsilon(qT)}, q\in\mathbb{N}$, we can design a novel discrete-time DETM by

$$
t_{k+1} = \min_{q\in\mathbb{N}}\{qT \mid \bar{\varepsilon}(qT)\le 0 \wedge qT\ge t_k\} \qquad (9)
$$

where σ_1 is a non-negative constant, Φ is a positive definite and diagonal weight matrix, and $\sigma(qT)$ is a dynamic parameter, which updates according to the following adaptive law.

$$
\begin{aligned}
\sigma(qT) &= e^{-\alpha_1 T}\sigma((q-1)T)+\frac{\alpha_2\left(1-e^{-\alpha_1 T}\right)}{1+\bar{\varepsilon}((q-1)T)}, \\
& t\in[(q-1)T, qT),\ q\in\mathbb{N}^+ \qquad (10)
\end{aligned}
$$

with $\alpha_1\ge 0$ and $\alpha_2\ge 0$, $\sigma(0)\ge 0$ is the initial condition.

From the proposed DETM (9), it can be easily deduced that $\sqrt{\varepsilon^T(t_k+jT)\Phi\varepsilon(t_k+jT)}\le\sigma(t_k+jT)|y(t_k+jT)|+\sigma_1$, $\forall k\in\mathbb{N}$, since no event happens in the inter-event interval $[t_k, t_{k+1})$.

Remark 2: In the proposed DETM (9), there are three key parameters to be regulated. Firstly, we can choose a different weight matrix Φ, such that the different entry of the vector $\varepsilon(qT)$ has a different weight. For example, the first entry of Φ can be regulated to be quite large when the tracking error $x_1(qT)$ is considered. Secondly, the relative threshold $\sigma(qt)$ can be adaptively regulated according to the error function $\bar{\varepsilon}((q-1)T)$, which means the larger the error function $\bar{\varepsilon}((q-1)T)$ is, the smaller the threshold parameter $\sigma(qT)$ is and the larger the possibility for the event-triggering condition to be violated, and vice versa. The last parameter σ_1 is the absolute threshold to be regulated to avoid the frequent communication. Therefore, a better balance between the communication properties and the control properties can be guaranteed under the proposed DETM (9) compared with most of the results on the event-triggering mechanisms [48]–[50].

Remark 3: It should be highlighted that the reduced-order GPIO (3) can be accurately discretized, the robust controller (7) is in the form of discrete-time, and the proposed DETM (9) is detected with a constant period as well. Hence, the proposed dynamic event-triggered control method is suitable for the implementation in digital computers.

Lemma 1: Consider the adaptive law (10) with a given initial condition $\sigma(0)\ge 0$. If $\alpha_1\ge 0$ and $\alpha_2\ge 0$, then $0\le\sigma(qT)\le\bar{\sigma}$, $\forall q\in\mathbb{N}$ with $\bar{\sigma} = \max\{\sigma(0), \alpha_2\}$.

Proof: Firstly, by (10), we have that $\sigma(qT)>0$, $\forall q\in\mathbb{N}$. When $\alpha_1 = 0$, it is easily obtained from (10) that $\sigma(qT) = \sigma(0)$, $\forall q\in\mathbb{N}$. Otherwise, by (10), we find that

$$
\begin{aligned}
\sigma(qT) &\le e^{-\alpha_1 T}\sigma((q-1)T)+\alpha_2\left(1-e^{-\alpha_1 T}\right) \\
&\le e^{-q\alpha_1 T}\sigma(0)+\alpha_2\left(1-e^{-\alpha_1 T}\right)\frac{1-e^{-q\alpha_1 T}}{1-e^{-\alpha_1 T}} \\
&= (\sigma(0)-\alpha_2)e^{-q\alpha_1 T}+\alpha_2. \qquad (11)
\end{aligned}
$$

Therefore, it can be easily deduced from (11) that $\forall q\in\mathbb{N}$, $\sigma(qT)$ is upper-bounded by $\bar{\sigma} = \max\{\sigma(0), \alpha_2\}$, if $\alpha_1>0$, $\alpha_2\ge 0$ and $\sigma(0)\ge 0$. As a conclusion, one has that $\sigma(qT)\ge 0$, and is upper-bounded by $\bar{\sigma}$, $\forall q\in\mathbb{N}$. ■

IV. Main Results

Firstly, to develop the stability analysis of the event-triggered control systems, we introduce an important lemma as follows:

Lemma 2 [38]: Consider the following dynamics:

$$\dot{\zeta}(s) = F(\zeta(s),\zeta(s_k)),\quad \forall s \in [s_k, s_{k+1}),\ s_k = kT,\ k \in \mathbb{N} \tag{12}$$

where F: $\mathbb{R}^n \times \mathbb{R}^n \to \mathbb{R}^n$. If $F(\zeta(s),\zeta(s_k))$ satisfies

$$\|F(\zeta(s),\zeta(s_k))\| \le \rho_1(\|\zeta(s)-\zeta(s_k)\| + \|\zeta(s_k)\|) + \rho_2 \tag{13}$$

where ρ_1 and ρ_2 are two positive constant, then it follows that

$$\|\zeta(s)-\zeta(s_k)\| \le \left(\|\zeta(s_k)\| + \frac{\rho_2}{\rho_1}\right)\left(e^{\rho_1(s-s_k)} - 1\right),$$
$$\forall s \in [s_k, s_{k+1}),\ k \in \mathbb{N}.$$

Then, with the help of (2), (6) and (7), a closed-loop system can be finally obtained in the time interval I_j^k, $k \in \mathbb{N}$, $j = 0,\ldots,d_k$ as follows:

$$\begin{cases}
\dot{x}_1(t) = Lx_2(t)\\
\dot{x}_2(t) = -Lk_1x_1(t) - Lk_2x_2(t) + Lk_2e_1(t) + Le_2(t)\\
\qquad + Lk_1(x_1(t) - x_1(t_k+jT)) + Lk_2(x_2(t) - x_2(t_k+jT))\\
\qquad + \dfrac{(w(t) - w(t_k+jT))}{L} - Lk_2(e_1(t) - e_1(t_k+jT))\\
\qquad - L(e_2(t) - e_2(t_k+jT)) + Lk_1(x_1(t_k+jT) - x_1(t_k))\\
\qquad + Lk_2(\hat{x}_2(t_k+jT) - \hat{x}_2(t_k)) + \dfrac{(\hat{w}(t_k+jT) - \hat{w}(t_k))}{L}\\
\dot{e}_1(t) = -L\beta_1e_1(t) + e_2(t) + L(\beta_1^2 - \beta_2)(y(t_k+jk) - y(t))\\
\dot{e}_2(t) = -L\beta_2e_1(t) + e_3(t) + L(\beta_1\beta_2 - \beta_3)(y(t_k+jk) - y(t))\\
\dot{e}_3(t) = -L\beta_3e_1(t) + L\beta_1\beta_3(y(t_k+jk) - y(t)) + \dfrac{\ddot{w}(t)}{L^3}.
\end{cases} \tag{14}$$

Defining a new variable vector $\omega(t) = [x_1(t), x_2(t), e_1(t), e_2(t), e_3(t)]^T$, we can represent (14) by

$$\dot{\omega}(t) = L\underbrace{\begin{bmatrix} 0 & 1 & 0 & 0 & 0\\ -k_1 & -k_2 & k_2 & 1 & 0\\ 0 & 0 & -\beta_1 & 1 & 0\\ 0 & 0 & -\beta_2 & 0 & 1\\ 0 & 0 & -\beta_3 & 0 & 0\end{bmatrix}}_{A}\omega(t)$$
$$+L\begin{bmatrix} 0\\ k_1(x_1(t) - x_1(t_k+jT))\\ +k_2(x_2(t) - x_2(t_k+jT))\\ -k_2(e_1(t) - e_1(t_k+jT))\\ -(e_2(t) - e_2(t_k+jT))\\ (\beta_1^2 - \beta_2)(y(t_k+jT) - y(t))\\ (\beta_1\beta_2 - \beta_3)(y(t_k+jT) - y(t))\\ \beta_1\beta_3(y(t_k+jT) - y(t))\end{bmatrix}$$
$$+\begin{bmatrix} 0\\ Lk_1(x_1(t_k+jT) - x_1(t_k))\\ +Lk_2(\hat{x}_2(t_k+jT) - \hat{x}_2(t_k))\\ +\dfrac{(\hat{w}(t_k+jT) - \hat{w}(t_k))}{L}\\ 0\\ 0\\ 0\end{bmatrix} + \begin{bmatrix} 0\\ \dfrac{w(t) - w(t_k+jT))}{L}\\ 0\\ 0\\ \dfrac{\ddot{w}(t)}{L^3}\end{bmatrix}. \tag{15}$$

By Lemma 1, we have $0 \le \sigma(qT) \le \bar{\sigma}$, $\forall q \in \mathbb{N}$. Hence, with (9) in mind, one obtains $\|\varepsilon(t_k+jT)\| \le \frac{1}{\sqrt{\lambda_m(\Phi)}}(\sigma(t_k+jT)$ $|y(t_k+jT)| + \sigma_1) \le \frac{1}{\sqrt{\lambda_m(\Phi)}}(\bar{\sigma}|y(t_k+jT)| + \sigma_1)$, $\forall k \in \mathbb{N}$, $j = 0,\ldots,d_k$. Then, one obtains

$$\left\|\begin{bmatrix} 0\\ Lk_1(x_1(t_k+jT) - x_1(t_k))\\ +Lk_2(\hat{x}_2(t_k+jT) - \hat{x}_2(t_k))\\ +\dfrac{(\hat{w}(t_k+jT) - \hat{w}(t_k))}{L}\\ 0\\ 0\\ 0\end{bmatrix}\right\|$$
$$\begin{aligned}
&\le L|k_1||x_1(t_k+jT) - x_1(t_k)| + L|k_2||\hat{x}_2(t_k+jT) - \hat{x}_2(t_k)|\\
&\quad + \frac{|\hat{w}(t_k+jT) - \hat{w}(t_k)|}{L}\\
&\le c_1\|\varepsilon(t_k+jT)\|\\
&\le \frac{c_1}{\sqrt{\lambda_m(\Phi)}}(\bar{\sigma}|y(t_k+jT)| + \sigma_1)
\end{aligned} \tag{16}$$

where $c_1 = \sqrt{3}\max\left\{L|k_1|, L|k_2|, \dfrac{1}{L}\right\}$.

By Lemma 2 and Assumption 1, one gets

$$\left\|\begin{bmatrix} 0\\ k_1(x_1(t) - x_1(t_k+jT))\\ +k_2(x_2(t) - x_2(t_k+jT))\\ -k_2(e_1(t) - e_1(t_k+jT))\\ -(e_2(t) - e_2(t_k+jT))\\ (\beta_1^2 - \beta_2)(y(t_k+jT) - y(t))\\ (\beta_1\beta_2 - \beta_3)(y(t_k+jT) - y(t))\\ \beta_1\beta_3(y(t_k+jT) - y(t))\end{bmatrix}\right\| \le c_2\|\omega(t_k+jT) - \omega(t)|$$
$$\le c_2(\|\omega(t_k+jT)\| + b_1) \times\left(e^{b_2T} - 1\right) \tag{17}$$

where c_2, b_1 and b_2 are three positive constants.

According to Assumption 1, one gets

$$\left\|\begin{bmatrix} 0\\ \dfrac{(w(t) - w(t_k+jT))}{L}\\ 0\\ 0\\ \dfrac{\ddot{w}(t)}{L^3}\end{bmatrix}\right\| \le \tilde{w} \tag{18}$$

where $\tilde{w} = \sqrt{\dfrac{w_1^2T^2}{L^2} + \dfrac{w_2^2}{L^6}}$.

Obviously, the system matrix A can be designed to be Hurwitz, when the parameters k_i, $i = 1,2$ and β_i, $i = 1,2,3$ are chosen such that both of $\lambda^2 + k_2\lambda + k_1$ and $\lambda^3 + \beta_1\lambda_2 + \beta_2\lambda + \beta_3$ are Hurwitz polynomials. Therefore, one can see that there exists a positive definite matrix $P = P^T \in \mathbb{R}^{5\times5}$ such that $A^TP + PA = -I$.

Constructing a candidate Lyapunov function $V(\omega(t)) =$

$\omega^T(t)P\omega(t)$ for (15) in the time interval I_j^k, $k\in\mathbb{N}$, $j=0,\ldots,d_k$, one takes the time derivative of $V(\omega(t))$ along (15), and integrates (16)–(18) into $\dot{V}(\omega(t))$ as follows:

$$\begin{aligned}\dot{V}(\omega(t))\leq&-L\|\omega(t)\|^2+2Lc_2\|P\|\|\omega(t)\|(\|\omega(t_k+jT)\|+b_1)\\&\times\left(e^{b_2T}-1\right)+\frac{2c_1}{\sqrt{\lambda_m(\Phi)}}\|P\|\|\omega(t)\|\\&\times(\bar{\sigma}\|\omega(t_k+jT)\|+\sigma_1)+2\tilde{w}\|\omega(t)\|.\end{aligned}\tag{19}$$

Noticing that $\|P\|=\lambda_M(P)$, since P is positive definite matrix, we can determine

$$\begin{aligned}\dot{V}(\omega(t))\leq&-\gamma_1V(\omega(t))+\gamma_2\sqrt{V(\omega(t))V(\omega(t_k+jT))}\\&+\gamma_3\sqrt{V(\omega(t))}\end{aligned}\tag{20}$$

where $\gamma_1=\dfrac{L}{\lambda_M(P)}$, $\gamma_2=\dfrac{2Lc_2\lambda_M(P)\sqrt{\lambda_m(\Phi)}\left(e^{b_2T}-1\right)+2c_1\bar{\sigma}\lambda_M(P)}{\lambda_m(P)\sqrt{\lambda_m(\Phi)}}$ and

$$\gamma_3=\frac{2c_2b_1\lambda_M(P)\sqrt{\lambda_m(\Phi)}\left(e^{b_2T}-1\right)+2c_1\sigma_1\lambda_M(P)+\tilde{w}\sqrt{\lambda_m(\Phi)}}{\sqrt{\lambda_m(P)}\sqrt{\lambda_m(\Phi)}}.$$

Since $\gamma_1>0$, it can be obtained from (20) that

$$\frac{d}{dt}\sqrt{V(\omega(t))}\leq-\frac{\gamma_1}{2}\sqrt{V(\omega(t))}+\frac{\gamma_2}{2}\sqrt{V(\omega(t_k+jT))}+\frac{\gamma_3}{2}.\tag{21}$$

Integrating $\sqrt{V(\omega(t))}$ from t_k+jT to $t_k+(j+1)T$ yields

$$\begin{aligned}\sqrt{V(\omega(t_k+(j+1)T))}\leq&\left(e^{-\frac{\gamma_1}{2}T}+\left(1-e^{-\frac{\gamma_1}{2}T}\right)\frac{\gamma_2}{\gamma_1}\right)\\&\times\sqrt{V(\omega(t_k+jT))}+\left(1-e^{-\frac{\gamma_1}{2}T}\right)\frac{\gamma_3}{\gamma_1}\\=&\gamma_4\sqrt{V(\omega(t_k+jT))}+\left(1-e^{-\frac{\gamma_1}{2}T}\right)\frac{\gamma_3}{\gamma_1}\end{aligned}\tag{22}$$

where $\gamma_4=\left(e^{-\frac{\gamma_1}{2}T}+\left(1-e^{-\frac{\gamma_1}{2}T}\right)\frac{\gamma_2}{\gamma_1}\right)$.

Noticing that $\bar{\sigma}=\max\{\sigma(0),\alpha_2\}$, it obtains that the condition

$$\bar{\sigma}<\frac{L\lambda_m(P)\sqrt{\lambda_m(\Phi)}}{2c_1\lambda_M^2(P)}\tag{23}$$

can be satisfied by choosing appropriate parameters $\sigma(0)$, α_2 and L. When the sampling period T is selected to satisfy the following condition:

$$T<\frac{1}{b_2}\ln\left(\frac{L\lambda_m(P)\sqrt{\lambda_m(\Phi)}-2c_1\bar{\sigma}\lambda_M^2(P)}{2Lc_2\lambda_M^2(P)\sqrt{\lambda_m(\Phi)}}+1\right)\tag{24}$$

we have $\gamma_4<1$. Therefore, by (22), it has that for any bounded $\omega(0)$, $\omega(t_k+jT)$ is uniformly bounded $\forall k\in\mathbb{N}$, since $\left(1-e^{-\frac{\gamma_1}{2}T}\right)\frac{\gamma_3}{\gamma_1}$ is bounded. As t_k+jT approaches infinity, $\omega(t_k+jT)$ converges to the following bounded region $\mathcal{R}_1$

$$\mathcal{R}_1=\left\{\omega\,|\,\|\omega\|\leq\frac{\gamma_3\left(1-e^{-\frac{\gamma_1}{2}T}\right)}{\sqrt{\lambda_m(P)}\gamma_1(1-\gamma_4)}\right\}.\tag{25}$$

Furthermore, by (17), it has

$$\|\omega(t)\|\leq\|\omega(t_k+jT)\|e^{b_2T}+b_1\left(e^{b_2T}-1\right).\tag{26}$$

Since $\omega(t_k+jT)$ is uniformly bounded, we have from (26) that for any $\omega(0)$, $\omega(t)$ is also uniformly bounded $\forall t\geq0$, and converges to the bounded region $\mathcal{R}_2$

$$\mathcal{R}_2=\left\{\omega\,|\,\|\omega\|\leq\frac{\gamma_3\left(1-e^{-\frac{\gamma_1}{2}T}\right)}{\sqrt{\lambda_m(P)}\gamma_1(1-\gamma_4)}e^{b_2T}+b_1\left(e^{b_2T}-1\right)\right\}\tag{27}$$

as t approaches infinity.

It can be observed that the bounded region $\mathcal{R}_2$ in (27) can be regulated to be arbitrarily small when the scale gain L is large enough, and the absolute threshold σ_1 and the sampling period T are small enough. Finally, we give the following theorem as a conclusion.

Theorem 1: Under the proposed dynamic event-triggered control method (3), (7) and (9). If the controller parameters are chosen to satisfy the conditions (23) and (24), then, the state variables of the closed-loop system (15) asymptotically converge to the bounded region $\mathcal{R}_2$ in (27). And the radius can be adjusted to be arbitrarily small by selecting appropriate parameters L, σ_1, and T.

V. Simulation Results

This section presents the simulation results on a single-link robot manipulator. For simplicity, the shorthand of the proposed event-triggered control method is denoted by DETM with compensation. In order to demonstrate the performance of the proposed control method, we conduct simulations under TTM. Meanwhile, we consider another simulation case where the lumped disturbance is not estimated and compensated in the dynamic event-triggered control method (we call the method as DETM without compensation), such that the benefit of disturbance estimation/compensation can be proven to improve both communication properties and tracking control performance.

The DETM without compensation means that the lumped disturbance is not estimated and compensated in the dynamic event-triggered control method. Specifically, for the DETM without compensation, the reduced-order observer is reduced to a first-order system as follows:

$$\begin{cases}\dot{z}_1(t)=-L\beta_1(z_1(t)+\beta_1y(t_k+jT))+La_0u(t)\\\hat{x}_2(t)=z_1(t)+\beta_1y(t),\forall t\in I_j^k,k\in\mathbb{N},j=0,\ldots,d_k\end{cases}\tag{28}$$

where $z_1(t)$ is the internal variable. $\hat{x}_2(t)$ is the estimate of the state $x_2(t)$. $y(t_k+jT)$ is the sampled-data output at t_k+jT. β_1 is the observer gain to be designed.

The event-triggered controller without disturbance

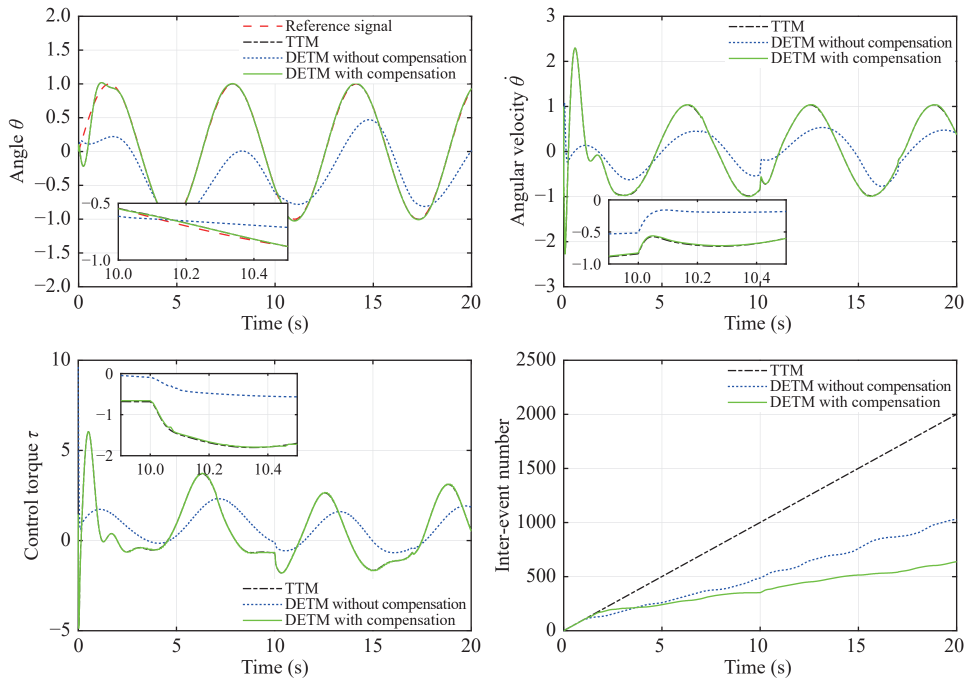

Fig. 2. The trajectories of the angle θ, the velocity $\dot{\theta}$, the control torque τ, and the execution number under the TTM, the DETM with compensation and the DETM without compensation.

compensation becomes

$$u(t) = u(t_k) = -\frac{1}{a_0}\left(k_1 x_1(t_k) + k_2 \hat{x}_2(t_k)\right), t \in [t_k, t_{k+1}), k \in \mathbb{N} \quad (29)$$

where k_1 and k_2 are the feedback control gains to be designed. And the error function $\varepsilon(t_k + jT)$ is redefined as $\varepsilon(t_k + jT) = [x_1(t_k + jT) - x_1(t_k), \hat{x}_2(t_k + jT) - \hat{x}_2(t_k)], k \in \mathbb{N}, j = 0, \ldots, d_k$. The remainder of the design of the DETM without compensation is same as the proposed dynamic event-triggered control method, and the stability analysis is very similar with that of the DETM with compensation, hence we omit them.

The nominal values of the parameters of (1) are chosen as follows: $g_0 = 9.81\ \mathrm{m/s^2}$, $l_0 = 0.25$ m, $C_0 = 2.0\ \mathrm{N \cdot m \cdot s/rad}$, $m_0 = 1.00$ kg. Assume that $g = g_0$, $l = l_0$, where the disturbance $d(t)$ and the uncertainties of other parameters in the simulations are described as follows:

$$d(t) = \begin{cases} 1, & t \in [0, 10) \\ 2, & t \in [10, 20) \end{cases}$$

$$C(t) = \begin{cases} 2, & t \in [0, 5) \\ 2 + 0.2(t-5), & t \in [5, 7) \\ 2.2, & t \in [7, 20] \end{cases}$$

$$m(t) = \begin{cases} 1, & t \in [0, 15) \\ 1 + 0.2(t-5), & t \in [15, 17) \\ 1.2, & t \in [17, 20]. \end{cases}$$

In the simulations, the sampling frequency is set as 100 Hz and the scale gain L is selected as 1. For the TTM and the DETM with compensation, the controller parameters and the initial states are the same, and set as follows: $[k_1, k_2] = [49, 14]$, $[\beta_1, \beta_2, \beta_3] = [42, 588, 2744]$ and the initial states $[0.1;\ -2;\ -10;\ 0;\ 0]$. The controller parameters and the initial states for the DETM without compensation $[k_1, k_2] = [49, 14]$, $\beta_1 = 14$, and the initial states are selected as $[0.1; -2; -10]$. For the DETMs without and with compensation, the parameters of DETMs are the same, and chosen as $\alpha_1 = 0.7$, $\alpha_2 = 0.08$, $\sigma_0 = 0.03$ and $\sigma_1 = 0.08$. Let the weight matrix $\varPhi = \mathrm{diag}(100, 80)$ for the DETM without compensation, and $\varPhi = \mathrm{diag}(100, 80, 0.01)$ for the DETM with compensation.

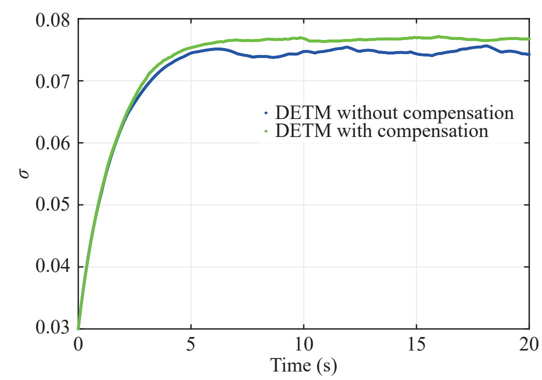

Fig. 3. The cures of variable σ designed in the proposed DETM.

Using each of the three different control methods, the response curves of the states, the control torque, and the event numbers are depicted in Fig. 2. From Fig. 2, we can see that the event numbers generated by the TTM and the DETMs with and without compensation are 2000, 639, and 1031 times, respectively. Among the three control methods, the closed-loop system under the proposed DETM with compensation has the least communication times but has comparatively increased tracking performance compared with TTM. In contrast with the DETM without compensation, the proposed DETM with compensation has less communication times but can guarantee better tracking performance since the reduced-

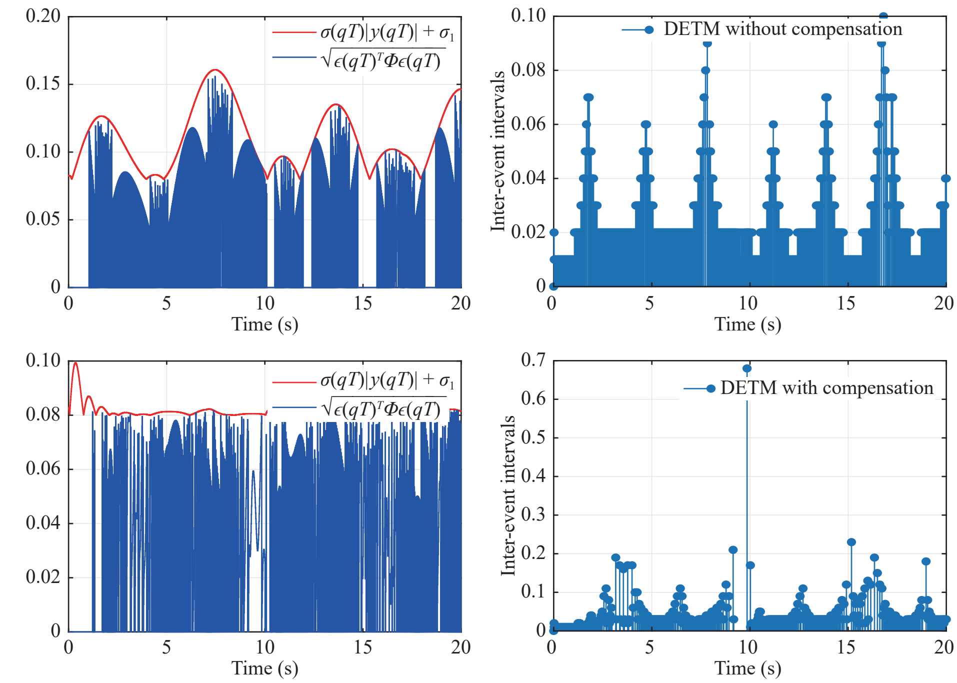

Fig. 4. The results under the DETM without compensation (top) and the proposed DETM with compensation (bottom). The left two figures show the curves of $\sqrt{\varepsilon^T(qT)\Phi\varepsilon(qT)}$ and $\sigma(qT)|y(qT)|+\sigma_1$ under the two DETMs; The right two figures show the event-triggering instants and the inter-event intervals under the two DETMs.

order GPIO based control can improve both the tracking control properties and communication properties.

The results of using variable σ designed in the DETMs with and without compensation are displayed in Fig. 3. Fig. 4 shows the results using three triggering mechanisms. It can be concluded that the proposed dynamic event-triggered control method can save communication resources while guaranteeing a desirable tracking control performance.

VI. Conclusion

In this paper, we have considered the problem of robust output feedback tracking control design for a networked one-DOF robot manipulator without velocity measurement in the presence of disturbance/uncertainties and resource constraints. A novel reduced-order GPIO based dynamic event-triggered robust control method has been proposed to achieve a better balance of communication properties and tracking control performance. By using the sampled-data position measurement and the control signal, a reduced-order GPIO has been first proposed to estimate the velocity information and the lumped disturbance information. By the virtue of the disturbance estimation/compensation technique, the proposed control method can not only obtain the desired tracking performance, but also improve communication properties. The proposed control method is in the form of discrete-time, and only uses the sampled-data position signal, thereby being more suitable for practical applications. The results of the simulation of a one-DOF robot manipulator have been presented to demonstrate the effectiveness of the proposed control method.

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Jiankun Sun is a Ph.D. candidate at the School of Automation, Southeast University. He received the B.S. degree in mathematics from Southeast University in 2013. His current research interests include networked control systems, event-triggered control, nonlinear control, disturbance/uncertainty estimation, and compensation.

Jun Yang (M'11–SM'18) received the B.Sc. degree from the Department of Automatic Control, Northeastern University in 2006, and the Ph.D. degree in control theory and control engineering from the School of Automation, Southeast University in 2011. He is currently an Associate Professor with the School of Automation, Southeast University. His current research interests include disturbance estimation and compensation, advanced control theory, and its application to flight control systems and motion control systems. Dr. Yang is an Associate Editor of the *Transactions of the Institute of Measurement and Control.* He received the ICI Prize for Best Paper of *Transactions of the Institute of Measurement and Control* in 2016.

Shihua Li (M'05–SM'10–F'19) received the bachelor, master, Ph.D. degrees in automatic control from Southeast University in 1995, 1998, and 2001, respectively. Since 2001, he has been with the School of Automation, Southeast University, where he is currently a Professor and the Director of the Mechatronic Systems Control Laboratory. He has authored or co-authored over 200 technical papers and 2 books. His current research interests include modeling, analysis, and nonlinear control theory with applications to mechatronic systems. Prof. Li is the Vice Chairman of the *IEEE CSS Nanjing Chapter*. He serves as an Associate Editor or Editor of the *International Journal of Robust and Nonlinear Control, IET Power Electronics, International Journal of Control, Automation and Systems, International Journal of Electronics*, and *Journal of Power Electronic*, and the Guest Editor of the *IEEE Transactons on Industrial Electronics, International Journal of Robust and Nonlinear Control,* and *IET Control Theory and Applications.*