Decentralized Intermittent Feedback Adaptive Control of Non-Triangular Nonlinear Time-Varying Systems

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Abstract—This note investigates the decentralized stabilization problem for a class of interconnected systems in the presence of non-triangular structural uncertainties and time-varying parameters, where each subsystem exchanges information only with its neighbors and only intermittent (rather than continuous) states and input are to be utilized. Thus far to the best of authors' knowledge, no solution exists prior to this work, despite its high prevalence in practice. Two globally decentralized adaptive control schemes are presented based on the backstepping technique: the first one is developed in a continuous fashion by combining the philosophy of the modified congelation of variables-based approach with the special treatment of non-triangular structural uncertainties, which avoids the derivative of time-varying parameters and eliminates the limitation of the triangular condition, thus largely broadens the scope of application. By making use of the important property that the partial derivatives of the constructed virtual controllers in each subsystem are all constants, the second scheme is developed through directly replacing the states in the preceding scheme with the triggered ones. Consequently, the non-differentiability issue of the virtual controllers stemming from intermittent state feedback is completely obviated. The internal signals under both schemes are rigorously shown to be globally uniformly bounded with the aid of several novel lemmas, while the stabilization performance can be enhanced by appropriately adjusting design parameters. Moreover, the intervene intervals are ensured to be lower bounded by a positive constant. Finally, numerical simulation verifies the benefits and efficiency of the proposed method.

Index Terms—Backstepping, decentralized adaptive control, event-triggering, non-triangular uncertain systems.

I. INTRODUCTION

Large-scale uncertain complex interconnected systems are frequently encountered [1]. Communication network is necessary for signal transmission in large-scale nonlinear control systems owing to networked control systems with advantages of lower cost, easier maintenance, and higher reliability [2]. However, there is a gap between decentralized control and control over networks under such framework, because the sensor data cannot be transmitted/updated in real time on account of limited communication bandwidth and channels, which potentially degrades the control performance of large-scale nonlinear systems. To preserve a tradeoff between communication resource usage and control performance, the emergence of event-triggered control is stimulated as an appealing method for saving energy and communication resources, which enables communication only when certain predefined condition is triggered (see, e.g., [3], [4], and the references therein). Considerable achievements on event-triggered control have been made for both linear systems [5], [6] and nonlinear systems [7] over the past few decades. However, the closed-loop dynamic is required to be input-to-state stable (ISS) in the pioneering work [7]. Such limitation is removed in [8] by co-designing an event-triggered control algorithm, while the system model considered in [8] is exactly known. To handle the uncertainties for nonlinear systems, some event-triggered adaptive control schemes are advocated via the backstepping design procedure [9], [10]. Nonetheless, those results are dedicated to the case where only the actuator input is intermittently transmitted over the network while continuous feedback of plant states are required.

Control design via intermittent state feedback has stirred an increasing amount of attention these last years, due to its more efficient usage of available limited resources. In this direction, two types of strategies should be highlighted. The first one is the state-triggered control using intermittent output only. The results in [11] focus on developing a state-triggered output feedback solution for nonlinear systems subject to exogenous inputs. The problem of decentralized adaptive backstepping-based output feedback control is addressed for nonlinear interconnected systems in [12]. The second one is the state-triggered control via intermittent full-state feedback. For this scenario, some efforts have been made in [13] and [14] by applying backstepping-based adaptive control, wherein the models are in low-order form [13] or in normal form [14]. With respect to more general systems, a fully distributed adaptive state-triggered control algorithm is recently developed in [15] for networked nonlinear systems with mismatched and nonparametric uncertainties. The results in [16] solve the problem of stabilizing large-scale interconnected systems by distributed state-triggered controllers built on the ISS condition. Nevertheless, the approaches in [11], [12], [13], [14], [15], and [16] are tailored for nonlinear systems in triangular form. Meanwhile, the plant parameters involved in the abovementioned results are all restricted to constants. In most applications, however, plant parameters may vary with time rapidly [17]. For instance, traffic-free speed is considered as a time-varying parameter in freeway traffic systems control, since changes in weather, air pressure, and wind speed, etc., can strongly influence free speed; in automatic train control problems, the mass changes in weather, air pressure, and wind speed, etc., can strongly influence free speed.

Motivated by the aforementioned discussion, in this work, we develop a decentralized event-triggered adaptive backstepping control...
method for nonlinear interconnected systems with non-triangular structural uncertainties and unknown time-varying parameters. Under such setting, it is actually nontrivial to achieve this goal, this is because two major technical difficulties are present in control design and stability analysis. First, the models of the subsystems are all in nontrivial non-triangular time-varying forms with nonlinear coupling interactions that directly challenges the traditional backstepping design procedure, a tailored technique for triangular systems with constant parameters. Second, with intermittent feedback signals arising from event triggering, the underlying problem becomes even more complicated when carrying out backstepping design because the repetitive differentiation of virtual control signals (with respect to the triggering state signals) is no longer feasible (literally undefined due to the nature of the state-triggering). In this work, we propose two globally decentralized adaptive backstepping control design approaches for the cases with and without event-triggering setting, respectively. The first one is developed in a continuous fashion that successfully removes the triangular-form-limitation imposed on the system model by properly treating the non-triangular structural uncertainties for the backstepping design, which simultaneously restrains the effects of the parameter-induced perturbation by freezing the time-varying parameters at the centers, thus avoiding the derivative of time-varying parameters. It is shown that the partial derivatives of virtual controllers in each subsystem with respect to states are constants. With such property, the second control scheme is then constructed by replacing the states in the first control strategy with the triggered ones, thus circumventing the aforementioned non-differentiability issue in a global manner. Several lemmas are established to facilitate the authentication of the global uniform boundedness of all the closed-loop signals in both strategies with the stabilization performance improvable by appropriately adjusting design parameters. Moreover, a strictly positive lower bound on the inter transmission times is enforced by the proposed event-triggering mechanism (ETM), thus the notorious Zeno phenomenon is avoided. Finally, the results are extended to more general systems with multiple mismatched time-varying parameters. To the best of authors’ knowledge, this is the first adaptive backstepping control solution for interconnected nonlinear systems under intermittent state feedback that is able to tolerate non-triangular structural uncertainties and unknown time-varying parameters.

II. PROBLEM FORMULATION

Consider the following nonlinear system consists of $N$ interconnected subsystems, with the $i$th subsystem modeled as:

\begin{equation}
\dot{x}_{i,k} = x_{i,k+1} + \sum_{j=1}^{N} f_{ij,k}(x_j, u_j, t), \quad k = 1, \ldots, n_i - 1
\end{equation}

\begin{equation}
\dot{x}_{i,n_i} = u_i + \varphi^T_i(x_i) \theta_i(t) + \psi_i(x_i) + \sum_{j=1}^{N} f_{ij,n_i}(x_j, u_j, t)
\end{equation}

\begin{equation}
y_i = x_{i,1}, \quad i = 1, \ldots, N
\end{equation}

where $x_{i,k} \in \mathbb{R}^P (k = 1, \ldots, n_i)$ is the system state, with $x_1 = [x_{1,1}, \ldots, x_{1,n_i}]^T$, $u_i \in \mathbb{R}$ and $y_i \in \mathbb{R}$ are the control input and the output, respectively, $\varphi_i(x_i) \in \mathbb{R}^P$ and $\psi_i(x_i) \in \mathbb{R}$ are known functions with $\varphi_i(0) = 0$, $\theta_i(t) \in \mathbb{R}^F$ is an unknown time-varying parameter vector, and $f_{ij,k}(x_j, u_j, t) \in \mathbb{R}$ denotes the nonlinear coupling interaction from the $j$th subsystem for $j \neq i$, or the modeling error of the $i$th subsystem for $j = i$.

The objective of this work is to develop the globally decentralized adaptive backstepping control scheme for system (1) using only locally intermittent feedback signals, such that: i) the global uniform boundedness of the closed-loop signals is ensured, while all the subsystem outputs are steered into an assignable residual set around zero; and ii) the Zeno behavior is precluded.

To move on, we make the following assumptions.

Assumption 1: The unknown nonlinear function $f_{ij,k}(x_j, u_j, t)$ satisfies the following linearly growing condition [18], [19]:

\begin{equation}
|f_{ij,k}(x_j, u_j, t)| \leq h_{ij,k} \|x_i\| + \epsilon_{ij,k}, \quad k = 1, \ldots, n_i
\end{equation}

III. DECENTRALIZED CONTINUOUS ADAPTIVE BACKSTEPPING CONTROL

In this section, a decentralized adaptive backstepping control scheme is developed using locally continuous state signals, which can be regarded as the basis of the control scheme under intermittent state feedback in the next section. To this end, we carry out the following change of coordinates:

\begin{equation}
z_{i,1} = x_{i,1}
\end{equation}

\begin{equation}
z_{i,k} = x_{i,k} - \alpha_{i,k-1}, \quad k = 2, \ldots, n_i
\end{equation}

The decentralized adaptive backstepping control scheme under continuous state feedback is designed as follows:

\begin{equation}
\alpha_{i,1} = - c_{i,1} z_{i,1} - \sum_{j=1}^{N} \left( \frac{1}{4 \epsilon_{ij,k,1}} + \frac{1}{4 \epsilon_{ij,k,2}} \right) z_{j,1}
\end{equation}

\begin{equation}
\alpha_{i,k} = - c_{i,k} z_{i,k} - \sum_{j=1}^{N} \left( \frac{1}{4 \epsilon_{ij,k,1}} + \frac{1}{4 \epsilon_{ij,k,2}} \right) z_{j,k}
\end{equation}

\begin{equation}
- z_{i,k-1} + \sum_{l=1}^{k-1} \epsilon_{ij,k-1,l} x_{j,l+1}, \quad k = 2, \ldots, n_i
\end{equation}

\begin{equation}
u_i = \alpha_{i,n_i} - \varphi^T_i(x_i) \theta_i - \psi_i(x_i)
\end{equation}
where $c_{i,k}, \varpi_{ijk,k,1},$ and $\varpi_{ijk,k,2}$ ($k = 1, \ldots, n_i$) are some positive design parameters, and $\xi_{k-1,i,j}(k = 2, \ldots, n_i, l = 1, \ldots, k)$ is the partial derivative of $\alpha_{j,k-1}$ to $x$ for $l$, which is a constant that relies on $c_{i,k}, \varpi_{ijk,k,1},$ and $\varpi_{ijk,k,2}$. The updating law of $\hat{\theta}_i$ is designed as follows:

$$\dot{\hat{\theta}}_i = \Gamma_i \left[ -\sigma_i \hat{\theta}_i + \varphi_i(x_i) \right] z_{i,n_i}$$

(10)

where $\sigma_i$ is some positive design parameter, $\Gamma_i$ is some positive definite design matrix, and $\hat{\theta}_i$ is the estimate of an unknown bounded constant vector $k_{\theta,i}$ that will be defined later. At this stage, the following lemma is introduced.

**Lemma 1 (see [18]):** The state vector $x_i$ and its transformation vector $z_i = [z_{i,1}, \ldots, z_{i,n_i}]^T$ obey the following relationship:

$$\|x_i\| \leq \|A_{i-1}B_{i}\|_{F} \|z_i\|, i = 1, \ldots, N$$

(11)

where $A_i$ and $B_i$ are constant matrices defined in (61) and (62).

**Proof:** See Appendix A.

**Theorem 1:** Consider the interconnected nonlinear non-triangular system (1) under Assumptions 1–3, if using the decentralized adaptive controller (9), with the adaptive law (10), it holds that: i) the global uniform boundedness of the closed-loop signals is ensured, and ii) all the subsystem outputs are steered into a residual set around zero, yet the stabilization performance can be improved with some proper choices of the design parameters.

**Proof:** The proof is composed of the following $n_i$ steps.

**Step 1:** Consider the Lyapunov function $V_{i,1} = \frac{1}{2} z_{i,1}^2$. In light of Assumption 1, we can obtain that

$$\left\| z_{i,1} \right\| \leq \sum_{j=1}^{N} \left( \frac{1}{4 \varpi_{i,j,k,1}} z_{i,j,k}^2 + \varpi_{i,j,k,1} \varpi_{i,j,k,2} \left\| x_j \right\|^2 \right.$$ \( + \frac{1}{4 \varpi_{i,j,k,2}} z_{i,j,k}^2 + \varpi_{i,j,k,2} z_{i,j,k}^2 \right) \). \(12)\)

By utilizing (1), (5), (6), (7), and (12), $V_{i,1}$ is expressed as follows:

$$\dot{V}_{i,1} \leq -c_{i,1} z_{i,1}^2 + z_{i,1} z_{i,2} + \varpi_{i,1,1} \varpi_{i,1,2} \left\| x_2 \right\|^2 + \varpi_{i,1,1} \varpi_{i,1,2} \left\| x_1 \right\|^2$$

$$+ \sum_{j=1}^{N} \left( \varpi_{i,j,1,1} \varpi_{i,j,1,2} \left\| x_j \right\|^2 + \varpi_{i,j,1,2} \left\| x_j \right\|^2 \right) \). \(13)\)

**Step k ($k = 2, \ldots, n_i - 1$):** Consider the Lyapunov function $V_{i,k} = V_{i,k-1} + \frac{1}{2} z_{i,k}^2$. Recalling Assumption 1, it is seen that

$$\left\| z_{i,k} \right\| \leq \sum_{j=1}^{N} \left( \frac{1}{4 \varpi_{i,j,k,1}} z_{i,j,k}^2 + \varpi_{i,j,k,1} \varpi_{i,j,k,2} \left\| x_j \right\|^2 \right.$$ \( + \frac{1}{4 \varpi_{i,j,k,2}} z_{i,j,k}^2 + \varpi_{i,j,k,2} \varpi_{i,j,k,2} \right) \).

$$+ \sum_{j=1}^{N} \sum_{l=1}^{N} \left( \varpi_{i,j,l,1} \varpi_{i,j,l,2} \left\| x_l \right\|^2 + \varpi_{i,j,l,2} \varpi_{i,j,l,2} \left\| x_l \right\|^2 \right) \). \(14)\)

Synthesizing (1), (6), (8), (13), (14), and (15) results in

$$\dot{V}_{i,k} \leq \sum_{t=1}^{N} c_{i,1} z_{i,1}^2 + z_{i,k} z_{i,k+1} + \sum_{t=1}^{N} \sum_{j=1}^{N} \left( \varpi_{i,j,t,1,2} \left\| x_j \right\|^2 + \varpi_{i,j,t,2,2} \right) \).

(16)

**Step $n_i$:** Consider the following Lyapunov function:

$$V_{i,n_i} = V_{i,n_i-1} + \frac{1}{2} z_{i,n_i}^2 + \frac{1}{2} (k_{\theta,i} - \hat{\theta}_i)^T (k_{\theta,i} - \hat{\theta}_i)$$

(17)

where $k_{\theta,i}$ is an unknown bounded constant vector. As opposed to [9], [13], and [14], here we construct the adaptive parameter estimation term $\frac{1}{2} (k_{\theta,i} - \hat{\theta}_i)^T \Gamma_i^{-1} (k_{\theta,i} - \hat{\theta}_i)$ instead of $\frac{1}{2} (\hat{\theta}_i - \hat{\theta}_i)^T \Gamma_i^{-1} (\hat{\theta}_i - \hat{\theta}_i)$, which restrains the effects of the parameter-induced perturbation via freezing the time-varying parameters at the centers. Notice that such replacement is one of the key steps to avoid the appearance of term $\hat{\theta}_i$ while ensuring stability of the closed-loop system, as detailed in the sequel. By using (1), (6), (9), (16), and (17), $V_{i,n_i}$ becomes

$$V_{i,n_i} \leq -\sum_{t=1}^{N} c_{i,1} z_{i,1}^2 + \sum_{t=1}^{N} \sum_{j=1}^{N} \left( \varpi_{i,j,t,1,2} \left\| x_j \right\|^2 \right.$$ \( + \frac{1}{2} \frac{1}{2} (k_{\theta,i} - \hat{\theta}_i)^T (k_{\theta,i} - \hat{\theta}_i) + \Delta \).

(22)
It immediately follows that $\dot{V} \leq -AV + \Delta$, where $c_j = \varepsilon_j - \frac{1}{2}\beta_j\|B_j\|^2 + \sum_{\tau=1}^{\infty} \sum_{i=1}^{N} \varpi_{i,j}({\tilde x}_{i,j})^2\|A_j^T B_j\|^2 > 0$ by choosing $\varepsilon_j$ large enough, with $\varepsilon_j = \min\{c_{j,1}, \ldots, c_{j,n}\}$, $\sigma_i = \frac{1}{2}\tau_j > 0$, $\Lambda = \min\{2c_1, \ldots, 2c_N, 2\varepsilon_{\text{max}}(N)\}$, and $\Delta = \sum_{\tau=1}^{\infty} \sum_{i=1}^{N} \sum_{j=1}^{N} \varpi_{i,j}({\tilde x}_{i,j})^2 + \sum_{\tau=1}^{\infty} \frac{1}{2}\|\kappa_{\tau}\|^2$. In what follows, we prove that the results in Theorem 1 hold.

**Stability analysis:** It is readily seen from the abovementioned analysis that $V(t) \in L_{\infty}$, which guarantees that $x_i, \dot{\theta}_i \in L_{\infty}$. From (5)–(8), it is established that $x_i$ ($k = 1, \ldots, n_i$) is bounded, which, combined with (9), yields the boundedness of $u_i$. Therefore, all signals in the closed-loop system are globally uniformly bounded.

**Performance analysis:** According to the definition of $\kappa_{\tau}$, one can obtain $|z_{i,1}| \leq \sqrt{2(V(0) - \frac{N}{2})} e^{-\Lambda t} + 2 \frac{\kappa_{\tau}}{\tau}$, which implies that $z_{i,1}$ attenuates to a residual set around zero. Besides, the upper bound of $|z_{i,1}|$ can be decreased by increasing design parameters $c_i$, $\varpi_{i,j}$, and $\Gamma_i$, or decreasing $\varpi_{i,j}$ and $\varpi_{i,j,2}$, $k = 1, \ldots, n_i$.

### IV. DECENTRALIZED EVENT-TRIGGERED ADAPTIVE BACKSTEPPING CONTROL

In this section, a decentralized adaptive backstepping control scheme under the event-triggering setting is constructed upon the previous scheme, which inherits the ability of coping with non-triangular structural uncertainties and time-varying parameters in the continuous scheme while evading the non-differentiability issue.

**A. Event-Triggering Mechanism (ETM)**

Inspired by the ETM presented in [9] and [13], we denote $\bar{x}_{i,k}$, $\bar{x}_{j,k}$, and $u_i$, $i, j = 1, \ldots, N$ ($j \neq i$), $k = 1, \ldots, n_i$, as the local states information, other subsystem states information, and the actuation signal information, respectively, which broadcast their information according to the devised ETM. As $t_{k,i}^0$, $t_{k,i}^l$, and $t_{k,i}^l$ denote the $l$th event times at which the subsystem $i$, other subsystem $j$ and actuation broadcast their information accordingly; it follows that $\bar{x}_{i,k}$, $\bar{x}_{j,k}$, and $u_i$ remain unchanged as $\bar{x}_{i,k}(t) = x_{i,k}(t)$, $\bar{x}_{j,k}(t) = x_{j,k}(t)$, $\bar{u}_i(t) = u_i(t)$, $l = 1, 2, \ldots, N$.

Now we propose the following triggering conditions that only depend on locally available information:

\[ t_{k,i}^0 = \inf \{ t > t_{k,i}^0 \mid |x_{i,k}(t) - \bar{x}_{i,k}(t)| > \Delta x_{i,k} \} \quad (23) \]

\[ t_{k,i}^l = \inf \{ t > t_{k,i}^l \mid |x_{i,k}(t) - \bar{x}_{i,k}(t)| > \Delta x_{i,k} \} \quad (24) \]

\[ t_{k,i}^l = \inf \{ t > t_{k,i}^l \mid |v_i(t) - u_i(t)| > \Delta u_i \} \quad (25) \]

where $\Delta x_{i,k}$, $\Delta x_{j,k}$, and $\Delta u_i$ are positive triggering thresholds, and $t_{k,i}^0$, $t_{k,i}^l$, and $t_{k,i}^l$ denote the first instants when (23)–(25) are fulfilled, respectively.

**B. Controller Design**

Since only the locally intermittent state signals $\bar{x}_{i,k}$ are available in controlling the system in the case of state-triggering, we modify the coordinate transformations (5) and (6) into the following form:

\[ \bar{x}_{i,k} = \bar{x}_{i,1} \quad (26) \]

\[ \bar{x}_{i,k} = \bar{x}_{i,k} - \bar{x}_{i,k-1}, \quad k = 2, \ldots, n_i. \quad (27) \]

Under intermittent state feedback, the decentralized event-triggered adaptive backstepping control scheme is constructed as follows:

\[ \alpha_{i,1} = - c_i \bar{x}_{i,1} - \sum_{j=1}^{N} \left( \frac{1}{4\varpi_{i,j,1,1}} + \frac{1}{4\varpi_{i,j,1,2}} \right) \bar{x}_{i,1} \quad (28) \]

![Fig. 1. Block diagram of closed-loop systems with continuous control scheme and the corresponding event-triggered control scheme.](image-url)

\[ \bar{\alpha}_{i,k} = - c_i \bar{x}_{i,k} - \sum_{j=1}^{N} \left( \frac{1}{4\varpi_{i,j,1,1}} + \frac{1}{4\varpi_{i,j,1,2}} \right) \bar{x}_{i,k} - \sum_{j=1}^{N} \int_{t_{k,i}^0}^{t_{k,i}^l} \left( \frac{c_i}{4\varpi_{i,j,1,1}} + \frac{c_i}{4\varpi_{i,j,1,2}} \right) \bar{x}_{i,k} \quad (29) \]

\[ v_i = \bar{\alpha}_{i,n_i} - \varphi_i \left( \bar{x}_{i,1} \right) \bar{\theta}_i - \varphi_i \left( \bar{x}_{i,1} \right) \bar{z}_{i,1} \quad (30) \]

where $c_i$, $\varpi_{i,j}$, $\varpi_{i,j,2}$, and $\varpi_{i,j,2}$ ($k = 1, \ldots, n_i$) are some positive design parameters. The updating law of $\bar{\theta}_i$ is designed as follows:

\[ \bar{\theta}_i = \Gamma_i \left[ -\sigma_i \bar{\theta}_i + \varphi_i \left( \bar{x}_{i,1} \right) \bar{z}_{i,1} \right] \quad (31) \]

where $\sigma_i$ is some positive design parameter, $\Gamma_i$ is some positive definite design matrix, and $\bar{\theta}_i$ is the estimate of an unknown constant vector $\kappa_{\tau}$. The proposed two globally decentralized adaptive backstepping control strategies and their relationship are conceptually shown in Fig. 1.

To ensure the global uniform boundedness of all the closed-loop signals, we establish the following lemma.

**Lemma 2:** The effects of event-triggering are bounded as follows:

\[ |z_{i,k} - \bar{z}_{i,k}| \leq \Delta z_{i,k} \quad (32) \]

\[ |\alpha_{i,k} - \bar{\alpha}_{i,k}| \leq \Delta \alpha_{i,k} \quad (33) \]

for $k = 1, \ldots, n_i$, where $\Delta z_{i,k}$ and $\Delta \alpha_{i,k}$ are some positive constants that depend on the triggering thresholds $\Delta x_{i,k}$, $\Delta x_{j,k}$, and $\Delta u_i$, and the design parameters $c_i$, $\varpi_{i,j,1}$, and $\varpi_{i,j,2}$. The proof of Lemma 2 is similar to the proof of Lemma 1.

**Remark 5:** Thanks to the proposed modified congelation of variables-based approach and a special treatment on non-triangular uncertainties, the partial derivatives $\xi_{k,1}(k = 2, \ldots, n_i, l = 1, \ldots, k)$ in each subsystem are all ensured to be constants. Such property ensures that the impacts of event-triggering are bounded by constants, as detailed in Lemma 2. It is not trivial to derive such property, especially in the presence of serious uncertainties and time-varying parameters. Specifically, in the available adaptive state-triggered results, such as [14] and [15], only systems in norm form exhibit this property [14]; for nonlinear strict-feedback systems [15], one can only prove that the triggering errors are bounded by some time-varying functions, while requiring the exploitation of dynamic filtering technique (which can only obtain a semi-global result). Therefore, it is even more challenging to retain such property for the non-triangular nonlinear time-varying interconnected systems actually considered here.

We are in the position to state the following theorem.

**Theorem 2:** Consider the interconnected nonlinear non-triangular system (1) under Assumptions 1–3, if using the decentralized adaptive controller (30), with the adaptive law (31) and triggering conditions (23)–(25), it holds that:

i) The global uniform boundedness of the closed-loop signals is ensured.
ii) All the subsystem outputs are steered into a residual set around zero, yet the stabilization performance can be improved with some proper choices of the design parameters.

iii) The Zeno phenomenon is precluded.

Proof: The proof consists of the following \( n_i \) steps.

Step 1: Consider the Lyapunov function \( V_{i,1} = \frac{1}{2} z_{i,1}^2 \). From (1), (5), (6), (7), and (12), \( V_{i,1} \) is expressed as follows:

\[
\dot{V}_{i,1} \leq -c_i \cdot z_{i,1}^2 + \varpi_{i,1} \cdot z_{i,2} + \varpi_{i,2} \cdot z_{i,1}^2 + \varpi_{i,2} \cdot z_{i,1}^2 
+ \sum_{j \neq i} \varpi_{i,j} \cdot \| z_{j,1} \|^2 + \sum_{j \neq i} \varpi_{i,j} \cdot z_{i,1} \cdot z_{i,2} \cdot z_{i,1} \cdot z_{i,2}.
\tag{34}
\]

Step 2: \( k(k = 2, \ldots, n_i - 1) \): Consider the Lyapunov function \( V_{i,k} = V_{i,k-1} + \frac{1}{2} z_{i,k}^2 \). By using (1), (6), (8), (14), and (34), we have

\[
\dot{V}_{i,k} \leq -c_i \cdot z_{i,1}^2 + z_{i,k} \cdot z_{i,k+1} + \sum_{j \neq i} \varpi_{i,j} \cdot \| z_{j,1} \|^2 + \varpi_{i,j} \cdot z_{i,1} \cdot z_{i,2},
\tag{35}
\]

Step 3: \( n_i \): Consider the Lyapunov function \( V_{i,n_i} = V_{i,n_i-1} + \frac{1}{2} z_{i,n_i}^2 \). Note that the control law in (30) can be rewritten as

\[
v_i = \alpha_{i,n_i} - \varphi_1 \cdot (x_i) + \theta_i \cdot (x_i) + \varphi_2 \cdot (x_i) \cdot \theta_i \cdot z_{i,n_i} \]

\[+ \varphi_3 \cdot (x_i) - \varphi_4 \cdot (x_i) \cdot \hat{\theta}_i \cdot (x_i) \cdot \hat{\theta}_i \cdot z_{i,n_i} \]

From (1), (6), (35), and (36), \( \dot{V}_{i,n_i} \) is expressed as follows:

\[
\dot{V}_{i,n_i} \leq - c_i \cdot z_{i,n_i}^2 + \sum_{j \neq i} \varpi_{i,j} \cdot \| z_{j,n_i} \|^2 + \varpi_{i,j} \cdot z_{i,n_i} \cdot z_{i,n_i+1} + \sum_{j \neq i} \varpi_{i,j} \cdot z_{i,n_i} \cdot z_{i,n_i+1}.
\tag{37}
\]

Substituting (31) and (37) yields

\[
\dot{V}_{i,n_i} \leq - c_i \cdot z_{i,n_i}^2 + \sum_{j \neq i} \varpi_{i,j} \cdot \| z_{j,n_i} \|^2 + \sum_{j \neq i} \varpi_{i,j} \cdot \| z_{j,n_i} \|^2 + \varpi_{i,j} \cdot z_{i,n_i} \cdot z_{i,n_i+1} + \sum_{j \neq i} \varpi_{i,j} \cdot z_{i,n_i} \cdot z_{i,n_i+1}.
\tag{38}
\]

Notice from (39) and (40), and invoking Lemma 1, it holds that

\[
\Delta \Xi_i \leq k_i \cdot \| z_i \|^2 + \| \theta_i - \hat{\theta}_i \|^2 \cdot \| \delta_1 \| \cdot \| z_i \|^2 + \delta_2 \frac{1}{2} \| \delta_1 \| \cdot \| z_i \|^2
\leq \| \delta_1 \| \cdot \| z_i \|^2 + \| \delta_2 \| \cdot \| z_i \|^2 + \| \theta_i - \hat{\theta}_i \|^2 + \Delta_{\alpha}
\tag{41}
\]

where \( \lambda_i = \frac{1}{2} (\lambda_1 + \lambda_2) \), \( \delta_i = \frac{1}{2} (\delta_1 + \delta_2) \), and \( \Delta_{\alpha} = \frac{1}{2} (\lambda_1 + \lambda_2) \). With \( \lambda_i = \Delta \alpha_{\alpha} + \Delta \alpha_{\beta} + \Delta \alpha_{\gamma} + \Delta \alpha_{\delta} \), where \( \delta_i = \lambda_i \cdot \| z_i \|^2 + \| \theta_i - \hat{\theta}_i \|^2 + \Delta_{\alpha} \).

From (42) and replacing \( \sum_{j = 1}^{n_i} \| z_j \|^2 \) for clear presentation, it holds that

\[
\nabla \leq - \sum_{j = 1}^{n_i} \| z_j \|^2 + \sum_{j = 1}^{n_i} \| z_j \|^2.
\tag{43}
\]

Then \( \sum_{j = 1}^{n_i} \| z_j \|^2 \) for clear presentation, it holds that

\[
\nabla \leq - \sum_{j = 1}^{n_i} \| z_j \|^2 + \sum_{j = 1}^{n_i} \| z_j \|^2.
\tag{44}
\]

Now we show that results i)-iii) in Theorem 2 hold. By following the similar lines to the proof of Theorem 1, the results i) and ii) can be drawn. Next, we show that the result (3) holds. Define \( m_{i,i}(t) = x_{i,i}(t) - x_{i,i}(t) \) \( \forall t \in [t_k+1, t_{k+1}] \), it follows that \( \| m_{i,i}(t) \| \leq \| m_{i,i}(t = 0) \| \). As \( x_{i,i}(t) \) remains unchanged for \( t \in [t_k+1, t_{k+1}] \), one can obtain

\[
\| m_{i,i}(t) \| \leq \| m_{i,i}(t = 0) \| \leq \| m_{i,i}(t = 0) \|.
\tag{45}
\]

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V. EXTENSION TO MORE GENERAL SYSTEMS WITH MULTIPLE MISMATCHED TIME-VARYING PARAMETERS

To address the more general systems with multiple mismatched time-varying parameters, we modify system (1) following one with time-varying parameters in each differential equation:

\[ \dot{x}_{i,k} = x_{i,k+1} + \varphi_{i,k}^{T}(\tilde{x}_{i,k}) \theta_{i,k}(t) + \sum_{j=1}^{N} f_{ij,k}(x_{j}, u_{j}, t) \]

\[ \dot{y}_{i} = x_{i,1}, \quad i = 1, \ldots, N \]

for \( k = 1, \ldots, n_{i} - 1 \), where \( \theta_{i,k}(t) \in \mathbb{R}^{p} \) is an unknown time-varying parameter vector, \( \varphi_{i,k}(\tilde{x}_{i,k}) \in \mathbb{R}^{p} \) is a known function, with \( \tilde{x}_{i,k} = [x_{i,1}, \ldots, x_{i,k}]^{T} \) and \( \varphi_{i,k}(0) = 0 \), and \( f_{ij,k}(\cdot) \) are defined before, for all \( k = 1, \ldots, n_{i} \).

First, we introduce the following change of coordinates:

\[ \tilde{x}_{i,k} = \bar{x}_{i,1}, \quad \bar{x}_{i,k} = \bar{x}_{i,k-1} - \bar{z}_{i,k}, \quad k = 2, \ldots, n_{i} \]

\[ \tilde{y}_{i,k} = \bar{x}_{i,k} - \bar{z}_{i,k}, \quad k = 2, \ldots, n_{i} \]

where \( \bar{x}_{i,k} = \theta_{i,k} \bar{z}_{i,k} + \bar{z}_{i,k} = \bar{x}_{i,k-1} - \bar{z}_{i,k} \). We determine the following filter:

\[ \dot{\theta}_{i,k} = \hat{\theta}_{i,k}(\tilde{x}_{i,k}) \]

Following Assumption 4, the time-varying parameter vector \( \theta_{i,k}(t) \) is piecewise continuous and belongs to a compact convex set \( \Omega_{\theta_{i,k}} := \{ \theta_{i,k} : \| \theta_{i,k} \| \leq \bar{\theta}_{i,k} \} \), where \( \bar{\theta}_{i,k} \) is some positive constant.

**Assumption 5:** The functions \( \varphi_{i,k}(\tilde{x}_{i,k}) \) and \( \varphi_{i,k}^{T}(\tilde{x}_{i,k}) \) satisfy the following Lipschitz continuity condition such that:

\[ \| \varphi_{i,k}(\tilde{x}_{i,k}) - \varphi_{i,k}(\hat{\tilde{x}}_{i,k}) \| \leq L_{\varphi_{i,k}} \| \tilde{x}_{i,k} - \hat{\tilde{x}}_{i,k} \|, \quad k = 1, \ldots, n_{i} \]

\[ \| \varphi_{i,k}^{T}(\tilde{x}_{i,k}) - \varphi_{i,k}^{T}(\hat{\tilde{x}}_{i,k}) \| \leq L_{\varphi_{i,k}} \| \tilde{x}_{i,k} - \hat{\tilde{x}}_{i,k} \|, \quad k = 1, \ldots, n_{i} \]

where \( L_{\varphi_{i,k}} \) is some unknown bounded positive constants.

Based on coordinate transformations (45) and (46), we develop the following decentralized adaptive backstepping control scheme:

\[ \hat{\theta}_{i,k} = \hat{\theta}_{i,k}(\tilde{x}_{i,k}) \]

where \( \hat{\theta}_{i,k} \) is the estimate of an unknown bounded constant vector \( \theta_{i,k} \).\( \hat{\theta}_{i,k} \) is a projection operator to ensure that \( \hat{\theta}_{i,k} \) is always in the set \( \| \hat{\theta}_{i,k} \| \leq \bar{\theta}_{i,k} + \epsilon \leq \epsilon \bar{\theta}_{i,k} \) and \( \gamma_{i,k} = \theta_{i,k} \) is an arbitrary positive constant, and \( \Gamma_{i,k} \) is some positive definite design matrix.

The following two lemmas are useful for the control development.

**Lemma 3:** Define \( y_{i,k} = \alpha_{i,k} - \theta_{i,k} \) \((k = 2, \ldots, n_{i})\), where \( \alpha_{i,k} \) is the output of (47) under constant state feedback, then the state vector \( x_{i} \), the transformation vector \( z_{i} = [x_{i,1}, \ldots, x_{i,n}]^{T} \), and \( y_{i} = [0, y_{i,2}, \ldots, y_{i,n}]^{T} \) obey the following relationships:

\[ \| x_{i} \| \leq \| A_{i}^{-1} B_{i}^{T} \| \| y_{i} \| + \| A_{i}^{-1} C_{i}^{*} \| \| y_{i} \| \]

where \( A_{i}, B_{i}, \) and \( C_{i}^{*} \) are constant matrices that depend on constants \( c_{i,r}, \varpi_{i,j,k}, c_{i,r}, \varpi_{i,j,k}, c_{i,r}, \varpi_{i,j,k}, \) and \( \gamma_{i,m} \) is the constant parameter in the design parameters \( \alpha_{i,k}, \varpi_{i,j,k}, \alpha_{i,k}, \varpi_{i,j,k}, \) and \( \gamma_{i,m} \) is the Lipschitz constant in \( \varpi_{i,j,k}, \gamma_{i} = 1, \ldots, N \).

**Lemma 4:** The effects of event-triggering are bounded as follows:

\[ |\bar{z}_{i,k} - \bar{z}_{i,k}| \leq \Delta \bar{z}_{i,k} \]

\[ |\bar{z}_{i,k} - \bar{z}_{i,k}| \leq \Delta \bar{z}_{i,k} \]

for \( k = 1, \ldots, n_{i} \), where \( \Delta \bar{z}_{i,k} \) and \( \Delta \bar{z}_{i,k} \) are some positive constants that depend on the triggering thresholds \( \Delta \bar{z}_{i,k}, \Delta \bar{z}_{i,k}, \) and \( \gamma_{i,m} \), the design parameters \( \varpi_{i,j,k}, \varpi_{i,j,k}, \) and \( \gamma_{i,m} \), and the Lipschitz constant in \( \varpi_{i,j,k}, j = 1, \ldots, N \).

**Proof:** By applying the projection operator technique, the proofs of Lemmas 3 and 4 can be done following the lines similar to those of Lemmas 1 and 2.

The following theorem states the result.

**Theorem 3:** Consider the interconnected nonlinear non-triangular system (44) under Assumptions 1, 4, and 5, if using the decentralized adaptive controller (52), with the adaptive law (53) and triggering conditions (23)–(25), it holds that:

1) The signals in the closed-loop system are all semi-globally uniformly bounded.

2) All the subsystem outputs are steered into a residual set around zero, yet the stabilization performance can be improved with some proper choices of the design parameters.

3) The Zeno phenomenon is ruled out.

**Proof:** Using Lemmas 3 and 4, the proof of Theorem 3 can be done following the lines similar to those of Theorems 1 and 2.

**Remark 4:** Since the traditional backstepping design procedure, a tailored technique for triangular systems, is not applicable here, a special treatment is presented exclusively for dealing with the non-triangular structural uncertainties. For the first part, by constructing a nonlinear compensation term \( -\sum_{j=1}^{N} \frac{x_{i,j}^{T} x_{i,j}}{x_{i,j}^{T} x_{i,j}} \), we naturally offset the terms related to \( x_{i,k} \) in (14) and (15), whereas in the second part, the nonlinear interaction exists among different subsystems throughout the entire interconnected system and that the interaction for each subsystem is allowed to depend on the states of all the other systems, which is even more challenging to handle. Inspired by the ideas in [18], we first keep all terms associated with \( \| x_{i} \|^{2} \) \((j = 1, \ldots, N)\) in each recursive step, and then handle them in the final step by applying Lemma 1. Notice that what is considered here is an entirely different and more difficult implementation scenario than the one in [18].

On the one hand, the continuous state signals and the continuous actuator signal can be directly used for the controller design in [18] since neither state-triggering nor input-triggering is involved. On the other hand, the work in [18] concerns unknown constant parameters only, which, therefore, are able to be handled easily by employing adaptive parameter estimation methods. Moreover, the developed solution can be further extended to more general systems with multiple mismatched time-varying parameters which is not addressed in [18].

**Remark 5:** To overcome the non-differentiability issue, we first develop a decentralized adaptive backstepping control scheme (7)–(10) in a continuous fashion with a special treatment of the non-triangular structural uncertainties, and simultaneously restrains the effects of the parameter-induced perturbation via freezing the time-varying parameters at the centers. A decentralized event-triggered adaptive backstepping control scheme (28)–(31) is then proposed based upon the preceding scheme by replacing the states in the preceding scheme with the triggered ones, in which one key property utilized is that the partial derivatives \( \xi_{i-1}(k) (k = 2, \ldots, n_{i}, i = 1, \ldots, k) \) in each subsystem are all ensured to be constants. Finally, the crucial Lemmas 1 and 2 are elaborately deduced with rigorous proofs for establishing stability condition under such replacement.

**Remark 6:** It is noteworthy that we construct the adaptive parameter estimation term \( \frac{1}{2}(\hat{\theta}_{i,k} - \hat{\theta}_{i,k})^{T} \Gamma_{i,k}^{-1}(\hat{\theta}_{i,k} - \hat{\theta}_{i,k}) \) instead of \( \frac{1}{2}(\hat{\theta}_{i,k} - \hat{\theta}_{i,k})^{T} \).
Comparative results under different control schemes. (a) State $x_{1,k} (k = 1, 2)$ under case 1. (b) State $x_{2,k} (k = 1, 2)$ under case 1. (c) Control input $u_i$. (d) Adaptive estimated parameter $\hat{\theta}_i$. (e) State $x_{1,k} (k = 1, 2)$ under case 2. (f) State $x_{2,k} (k = 1, 2)$ under case 2. (g) Triggering times of $x_{1,k} (i, k = 1, 2)$ for different triggering thresholds. (h) Triggering times of $x_i (i, k = 1, 2)$ for different triggering thresholds.

We set the initial states $x_{1,1} (0) = x_{1,2} (0) = 0.2$ and $x_{2,1} (0) = x_{2,2} (0) = 0.1$, the design parameters $c_{1,1} = 0.5$, $c_{1,2} = 0.3$, $c_{2,1} = 1.8$, $c_{2,2} = 1.5$, $\sigma_1 = 0.001$, $\Gamma_1 = 0.5$, and $\varpi_{i,j,k,l} = 1$, the time-varying $\hat{\theta}_i(t) = 0.1 + 0.1 \sin(0.0t)$ and $\theta_i(t) = 0.1 + 0.1 \cos(0.2t)$, and the functions $\varphi_i = 0.2(x_{i,1}^2 + x_{i,2}) + 3 \cos(x_{i,1}, x_{i,2})$, $f_{11,1} = 0.1 \sin(u_i u_2) \Theta_1$, $f_{12,1} = 0.15 \Theta_2$, $f_{11,2} = 0.1 \Theta_1$, $f_{12,2} = 0.15 \sin(\Theta_2)$. $f_{21,1} = f_{21,2} = 0.15 \Theta_1$, and $f_{22,2} = 0.1 \ln(1 + \Theta_2)$, with $\Theta_1 = \sqrt{x_{1,1}^2 + x_{1,2}^2}$ and $\Theta_2 = \sqrt{x_{2,1}^2 + x_{2,2}^2}$ for all $i, j, k, l = 1, 2$.

First, to verify the advantages of our method in saving communication resources, fair comparison with the method in [18] is provided. Second, to test the effect of triggering thresholds on the system performance, two sets of triggering thresholds are chosen for comparison with the other design parameters remaining the same, that is: case 1) $\Delta x_{1,1} = 0.001$, $\Delta x_{2,1} = \Delta x_{2,2} = 0.002$, and $\Delta u_1 = \Delta u_2 = 0.01$, and case 2) $\Delta x_{1,1} = 0.002$, $\Delta x_{2,1} = \Delta x_{2,2} = 0.005$, $\Delta u_1 = \Delta u_2 = 0.003$, and $\Delta u'_1 = \Delta u'_2 = 0.03$.

The comparative results under different control schemes are presented in Fig. 2. Fig. 2(a) and (b) shows the evolutions of states $x_{1,k}$ and $x_{2,k} (k = 1, 2)$ under case 1, respectively, from which it is seen that the system performance under both schemes is undistinguishable. Besides, since only a small amount of sensor data and actuation signal need to be transmitted under the event-triggering setting, our approach greatly saves communication resources as compared with [18]. Fig. 2(c) and (d) depicts the boundedness of the control input $u_i$ and the estimated parameter $\hat{\theta}_i$, respectively. Fig. 2(e) and (f) illustrates the evolutions of states $x_{1,k}$ and $x_{2,k} (k = 1, 2)$ under case 2, respectively. The triggering times of $x_{1,k} (i, k = 1, 2)$ and $u_i$ are presented in Fig. 2(g) and (h), respectively. It can be observed from Fig. 2(a), (b), (e), (f), (g), and (h) that the larger the triggering thresholds, the smaller the triggering times, and thus more communication resources are saved, while the system performance is degraded to some extent.

VII. CONCLUSION

This work presents two globally decentralized adaptive backstepping control schemes for non-triangular nonlinear time-varying systems with and without event-triggering setting, respectively. The major technical challenge in the control design is to obviate the non-differentiability issue arising from intermittent state feedback, while coping with the non-triangular structural uncertainties and time-varying parameters. By using the results established in the lemmas, it is shown that the closed-loop signals are globally uniformly bounded without Zeno behavior, and at the same time, all the subsystem outputs are steered into an assignable residual set around zero. In addition, the results are extended to more general systems with multiple mismatched time-varying parameters. An interesting topic for future research is the consideration of dynamic triggering mechanisms for such system.
**APPENDIX A**

*Proof of Lemma 1:* From (5), (6), (7), and (8), it is seen that

\begin{align}
\dot{z}_{i,1} &= x_{i,1} \\
\dot{z}_{i,2} &= x_{i,2} + c_{i,1}z_{i,1} + \sum_{j=1}^{N} \left( \frac{1}{4\pi ij,1,1} + \frac{1}{4\pi ij,1,2} \right) z_{j,1} \\
\dot{z}_{i,k} &= x_{i,k} + c_{i,k-1}z_{i,k-1} - \sum_{l=1}^{k-2} \xi_{l,k-2,l}x_{i,l+1} + z_{i,k-2} + \sum_{j=1}^{N} \sum_{l=1}^{N-j} \left( \frac{\xi_{l,k-2,l}^2}{4\pi ij,k-1,1} + \frac{\xi_{l,k-2,l}^2}{4\pi ij,k-1,2} \right) z_{j,k-1} \\
&\quad + \sum_{j=1}^{N} \left( \frac{1}{4\pi ij,k,1} + \frac{1}{4\pi ij,k,2} \right) z_{i,k-1},
\end{align}  

for \( k = 3, \ldots, n_i \). Then, it can be derived that

\[ A_i(c_i, r, \varpi, i, r, \varpi, i, r, 2) x_i = B_i(c_i, r, \varpi, i, r, 1, \varpi, i, r, 2) z_i, \]

with

\[ A_i = \begin{pmatrix}
1 & 0 & 0 & \cdots & 0 \\
0 & 1 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & -\xi_{n_i-2,2} & \cdots & \cdots & 1
\end{pmatrix}
\]

and

\[ B_i = \begin{pmatrix}
B_{i,1,2} & 0 & 0 & \cdots & 0 \\
\vdots & \ddots & \ddots & \ddots & \vdots \\
0 & 0 & \cdots & \cdots & \cdots \\
0 & 0 & \cdots & -1 & B_{i,n_i,1}
\end{pmatrix}, \]

where \( B_{i,1,2} = -c_{i,1} - \sum_{j=1}^{N} \frac{1}{4\pi ij,1,1} \left( \frac{\xi_{1,1}^2}{4\pi ij,1,1} + \frac{\xi_{1,1}^2}{4\pi ij,1,2} \right) \) and

\[ B_{i,n_i,1} = \begin{pmatrix}
1 & 0 & 0 & \cdots & 0 \\
0 & 1 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \ddots & \vdots \\
0 & -\xi_{n_i-2,2} & \cdots & \cdots & 1
\end{pmatrix}, \]

and \( c_{i,1} = \sum_{j=1}^{n_i-2} \xi_{j+1,j} \). It is readily seen that \( A_i \) and \( B_i \) are constant matrices consisting of \( c_{i,1}, r, \varpi, i, r, 1, \varpi, i, r, 2, r = 1, \ldots, n_i \). Since \( A_i \) is an invertible matrix, we can obtain \( x_i = A_i^{-1}B_i z_i \), then it holds that \( \|x_i\| \leq \|A_i^{-1}B_i\| \cdot \|z_i\| \).

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