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Event-Triggered Discrete Higher-Order SMC for Networked Control System having Network Irregularities

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. ***Abstract*—This paper presents a discrete-time higher-order sliding mode controller for Networked Control System (NCS) using event-triggered approach and time delay compensation to overcome the network abnormalities like communication delay, congestion, and network utilization that degrade the performance of the NCS. First, a novel event-triggered sliding variable is constructed with time delay compensation using Thiran's approximation followed by discrete-time super-twisting algorithm in which control actions are updated based on the event generation. The event generator block in feedback channel results in an increase of communication rate efficiency and reduction in network congestion. The stability of closed-loop system is addressed using the Lyapunov technique which guarantees the finite convergence of system states within the designed sliding band. Further, the proposed controller is validated on a laboratory set up of serial flexible joint robotic manipulator. The simulation and experimental results show that the proposed controller outperforms the controller with reaching law approach.**

***Index Terms*—Networked control system, Event-triggered controller, Super-twisting sliding mode control, Gao's reaching law, Random communication delay and Network congestion.**

I. Introduction

WHEN any conventional control system with feedback channel is closed through some communication network it is defined as a Networked Control System (NCS). The existence of network medium in NCS, suffers from various challenges such as deterministic or random time delay, data packet loss, data packet disordering, bandwidth sharing, network utilization (number of transmissions of packets) and security which deteriorate the output performance of the system [1]. In spite of these challenges, NCS has received much attention from the researchers worldwide in control domain due to its various advantages such as lower cost, reduced weight, ease of installation, easier maintainence, and high reliability [2]. These advantages lead to great potential for NCS in industrial applications such as process industries, automobile sectors, medical sectors, aircraft industries, and robotic applications.

In the past few decades, sliding mode control (SMC) theory has received much attention in the networked domain due to its robustness with respect to the disturbances applied at the input side of the channel (matched uncertainty) [3]. In NCS, the communication processes are divided into two categories: time-driven communication approach and event-driven communication approach. In spite of wide research, in the case of limited communication resources (such as network utilization and network congestion) which are the major concerns in NCS, the time-driven communication process is less preferable because of unwanted data transmissions within the network (see e.g. [4]-[8] and references therein).

In order to overcome this drawback, recently an event-driven communication [9] approach has come into existence for NCS with a hope to avoid unnecessary data transmission in the network. In event-driven communication technique, the data packets are transmitted through the network in aperiodic manner. This, leads to a reduction of network utilization and an increase in the efficiency of communication rate. The event triggered mechanism consists of two parts: (i) error which is computed based on the difference of current measurement data and past measurement data transmitted over the network, and (ii) threshold conditions. The designing of threshold conditions decide the efficiency of the communication rate in NCS. Various approaches are proposed to avoid Zeno behaviour considering the fixed threshold condition (see e.g. [10]-[13] and references therein). The major drawback of the fixed threshold condition is, it does not guarantee the efficiency of communication rate. Thus, there is need of designing some novel threshold condition in NCS that can regulate the frequency of data packets in the network which results in improvement of communication rate.

In recent years various control strategies (state and output feedback) for linear and non-linear systems are proposed using event-triggered approach due to its aperiodic transmission of data packets (see e.g. [14]-[17] and references therein). Many researchers ([18]-[24]) have also proposed the design methods of conventional and optimal control strategies for NCS using event-triggered and time-triggered approach. Very few research works ([25]-[26]) discussed about the robust control strategy such as SMC in the discrete-time domain for NCS using the event-triggered approach in the presence of random networked delay and matched uncertainty. Very

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recently ([27]-[28]), the Discrete time Higher Sliding Mode Control (DHOSMC) strategy is proposed that ensures the reduced quasi-sliding mode band which makes it more robust. However, this strategy is not yet explored by the researchers in time-triggered or event-triggered NCS with time delay compensation scheme in the discrete-time domain. Moreover, designing of sliding mode control using event-triggered approach is considered to be a new era for industrial system as it increases the overall throughput of the system in the presence of network non-idealities. These research gaps in event-triggered NCS motivated the authors to design a novel type of event-triggered super-twisting sliding mode control in discrete-time domain that compensates the effect of random networked delay and develop an event-triggered mechanism that reduces the network congestion problem and increases the efficiency of communication rate in the presence of network non-idealities such as random networked delay, flow rate of data packets and matched uncertainty.

The brief layout of the paper is as follows: Section II describes the event-based networked control system with time delay compensation. Section III presents the problem formulation followed by event-triggering mechanism. The design of novel type of sliding surface with event-triggered approach and Thiran's approximation is presented in Section IV followed by mathematical modelling of random fractional delay based on Poisson's distribution function. Section V presents the design of ST-SMC using proposed sliding surface followed by derivation of the sliding band. Section VI discusses stability criteria derived using proposed control law with Lyapunov approach for closed-loop NCS. Simulation results and comparative analysis with Gao's reaching law on 2-DOF robotic arm are discussed in Section VII. Section VIII highlights the concluding remarks and possible furture extension of the proposed work.

A. Contributions

The major contributions of the paper are:

- Design of novel sliding surface in the discrete-time domain using event-triggered approach and Thiran's approximation technique that nullifies the effect of random fractional delay in the feedback and forward channel;
- Design of event-triggered mechanism with the relative threshold approach that controls the flow of data packets in the network and avoids the Zeno behaviour;
- Design of discrete-time super-twisting sliding mode control (ST-SMC) that encompasses the effect of random fractional delay, network congestion, and network utilization problems;
- Analysis of sliding band for the proposed event-triggered sliding mode control algorithm such that the sliding variable remains within the specified band in the presence of network non-idealities;
- The closed-loop stability of NCS with proposed discrete-time ST-SMC;
- Implementation of the proposed protocol on a 2-DOF robotic arm and thoroughly verified in a series of tests.

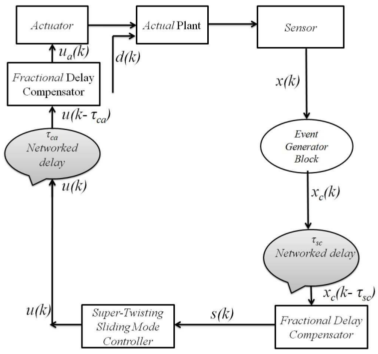

Fig. 1: Event-Triggered NCS with Time Delay Compensation

II. Event-Triggered Networked Control System

Fig. 1 shows the schematic block diagram of event-triggered NCS with time delay compensation. As shown in the block diagram, the event generation block updates the state information $x(k)$ measured at the sensor side when the event-triggering condition is satisfied otherwise it retains the current state information. The state information signal generated at event generation block is transmitted to the controller through network medium and experiences the sensor to controller random fractional delay τ'_{sc}. The delayed signal $x(k-\tau'_{sc})$ is first compensated in the fractional delay compensation block before sending it to the controller block. The controller computes the control signal using Discrete Higher Order SMC technique presented in this paper. The control signal generated at the controller side experiences the controller to actuator random fractional delay τ'_{ca} due to network medium. The delayed control signal $u(k-\tau'_{ca})$ is compensated in the fractional delay compensation block at the actuator side.

III. Problem Formulation

Consider the linear time invariant SISO (Single Input Single Output) system with network induced fractional delay and matched uncertainty in discrete form as

$$x(k+1) = Fx(k) + G(u(k-\tau') + d(k)) \quad (1)$$

$$y(k) = Cx(k) \quad (2)$$

where $x \in R^n$ is system state vector, $u \in R^m$ is control input, $y \in R^p$ is system output, $F \in R^{n\times n}$, $G \in R^{n\times m}$, $C \in R^{p\times n}$, are the matrices with appropriate dimensions, τ' is total network induced delay in discrete-time domain, $d(k)$ is the matched uncertainty with bounded disturbance applied at input side of channel given by

$$d(k) = \int_0^h e^{At} Bd((k+1)h - t)dt \in O(h). \quad (3)$$

Remark 1: For simplicity, it is considered that $d(k)$ is slowly time varying matched disturbance and remains constant from kh to $(k+1)h$ for the given instant.

In NCS, the total network induced delay τ consists of two components (i) combination of forward channel delay and feedback channel delay τ_t (ii) system delays τ_s which consist of processing delays at actuator and sensor side and computational delay that occurs at the controller side.

When these delays are transformed in the discrete-time domain, they posseses non-integer type of values which are defined as fractional delays. The behaviour of these fractional delays is either deterministic or random in nature depending on the type of communication medium. Thus, the fractional form of total network induced delay is given as

$$\tau' = \tau'_t + \tau'_s \tag{4}$$

where $\tau' = \frac{\tau}{h}$, $\tau'_t = \frac{\tau_t}{h}$ and $\tau'_s = \frac{\tau_s}{h}$.

Remark 2: Observing Eqn. (4), it can be referred that the units of τ', τ'_t and τ'_s are dimensionless since the fractional values of these delays are computed by sampling interval h.

Assumption 1: In real-time communication medium, it is assumed that the effect of system delays is negligible as compared to the feedback and forward channel delay. So without loss of generality, the total network induced fractional delay is given as

$$\tau' = \tau'_t \tag{5}$$

where $\tau'_t = \tau'_{sc} + \tau'_{ca}$. τ'_{sc} is the fractional form of sensor to controller delay and τ'_{ca} is the fractional form of controller to actuator delay.

Assumption 2: It is assumed that total network induced fractional delay mentioned in Eqn. (5) is random and bounded in nature, thus, satisfying the following condition

$$\tau'_l \leq \tau' \leq \tau'_u \tag{6}$$

where τ'_l and τ'_u indicates the lower and upper bound of total network induced fractional delay.

Problem Statement: To design an event-triggered discrete-time higher order sliding mode controller using discrete super-twisting algorithm for networked control system having network non-idealities such as random fractional delay, network congestion and matched uncertainties.

A. Event-Triggering Condition

The event-triggered condition at the sensor side is mathematically defined as

$$||x(k_i) - x(k)|| \geq \sigma_s ||x(k)||, \tag{7}$$

for all $k \in \mathbb{Z}$ and $k \in [k_i, k_{i+1})$.

Where σ_s is positive real constant (σ_s>0) which decides the threshold value for triggering action. When $\sigma_s = 0$ in Eqn. (7), the corresponding event-triggered mechanism reduces to the conventional time-triggered system.

Remark 3 It may be noted that the state variable $x(k)$ is updated only at the event-triggering instant k_i and held constant up to next $k_i + 1$ instant for every $k \in [k_i, k_{i+1})$ event-triggering instant. However, $k_i + 1$ is not necessarily equal to $k + 1$.

IV. Event-Triggered Sliding Variable with Time Delay Compensation

The design of discrete-time sliding mode control law involves: (i) design of sliding variable, and (ii) selection of reaching law that steers the system states on the sliding surface defined by equating this variable to zero. In this section, a novel sliding variable is proposed in **Lemma 1** below using event-triggered and time delayed states. The delay is compensated by Thiran's approximation method [29] that compensate the effect of flat group of transport delay occurring in discrete-signal.

Lemma 1 The event-triggered time-delay compensated sliding variable in the presence of sensor to controller random fractional delay and matched uncertainty is given by

$$s(k_i) = C_s x(k_i) - \alpha C_s x(k_i - 1) \tag{8}$$

where $s(k_i)$ is the compensated sliding variable computed at triggering instant k_i, C_s is the sliding gain computed using discrete LQR approach, α is the parameter that compensates the effect of sensor to controller random fractional delay τ'_{sc_i}, $x(k_i)$ is the state information signal that is received at controller side at triggering instant k_i and $x(k_i - 1)$ is the past state information signal that is received at controller side at triggering instant k_i.

Proof : The sliding variable that compensates the effect of sensor to controller random fractional delay τ'_{sc_i} at triggering instant k_i is given as

$$s(k_i) = C_s x_c(k_i), \forall k \in [k_i, k_{i+1}) \tag{9}$$

where $x_c(k_i)$ is the communicated state variable available from the output of event-generator block at triggering instant k_i. Mathematically, it is represented as

$$x_c(k_i) = x(k_i - \tau'_{sc_i}) \tag{10}$$

where $x(k_i - \tau'_{sc_i})$ is the delayed state variable at triggering instant k_i and τ'_{sc_i} is random sensor to controller fractional delay for the triggering instant k_i.

In case of real-time networks, the total network induced fractional delay is random in nature. Hence, sensor to controller random fractional delay τ'_{sc_i} in feedback channel generated at each triggering instant k_i is modeled using Poisson's distribution. In this distribution, the dynamic variables of random nature having smaller values are modeled as per the events generated over the specified interval of time [30].

The mathematical representation of sensor to controller fractional delay $\{\tau'_{sc_i}\}$ using Poisson's distribution that takes the values in a finite set, that is, $\tau'_{sc_i} \epsilon \{\nu_1, \nu_2, ..., \nu_q\}$ with probabilities is given by

$$Pr\{\tau'_{sc_i} = \nu_v\} = E\{\nu_v\} = \beta_v, v = 1, 2, ..., q$$

where β_v is the positive scalar quantity and $\Sigma_{v=0}^{q} \beta_v = 1$, $E\{\nu_v\}$ is the expectation of the stochastic variable ν_v. The mathematical form of β_v using Poisson's distribution is given by

$$\beta_v = \frac{\lambda^w \kappa^{-\lambda}}{w!} w = 0, 1, 2, 3, ... \tag{11}$$

where w denotes the number of trials, λ indicates average number of events per interval and κ indicates the Euler's number.

Applying Z-Transform to Eqn. (10), we get

$$x_c(k_i) = x(z_i) z^{-\tau'_{sc_i}}, \forall z \in [z_i, z_{i+1}, ...) \tag{12}$$

where $\tau'_{sc_i} = N = \frac{\tau_{sc_i}}{h}$.
Considering $\tau'_{sc}<1$, $z^{-\tau'_{sc_i}}$ is approximated [29] as

$$z^{-\tau'_{sc_i}} = \Sigma_{c=0}^{1}(-1)^c \binom{n}{c} \Pi_{d=0}^{1} \frac{2\tau'_{sc_i}+d}{2\tau'_{sc_i}+c+d} z^{-c}. \quad (13)$$

The above Eqn. (13) represents the first-order approximation of random sensor to controller fractional delay in discrete-time domain for each sampling instant.
Assumption 3: The sensor to controller random network delay τ_{sc} and controller to actuator random network delay τ_{ca} are always lesser than sampling interval.
On further simplification, we get

$$z^{-\tau'_{sc_i}} = 1 - \alpha z^{-1} \quad (14)$$

where $\alpha = \frac{\tau'_{sc_i}}{\tau'_{sc_i}+1}$.
Substituting Eqn. (14) into (10),

$$x_c(z_i) = x(z_i)(1 - \alpha z^{-1}). \quad (15)$$

Applying inverse Z-Transform, the compensated sliding variable in Eqn. (9), is computed as

$$s(k_i) = C_s x(k_i) - \alpha C_s x(k_i - 1). \quad (16)$$

From Eqn. (16), it is observed that the effect of fractional part of sensor to controller delay at each sampling instant is compensated through the difference of current state information and past state information. It may also be noticed that the α also varies with the delay which compensates the negative influence of delay. However, the value of α would also be smaller than the feedback channel delay as it is the ratio of sensor to controller and total fractional delay. Thus it can be extended that, the negative influences of the delay would be suppressed through parameter α at each sampling instant. Moreover, it can also be noticed that the sliding variable is updated based on the event-triggered mechanism generated at instant k_i.

V. Event-Triggered ST-SMC for Networked Control System

Theorem 1: The event-triggered discrete-time super-twisting sliding mode controller for the system (1), (2) in the presence of sensor to controller fractional delay τ'_{sc_i} at triggering instant k_i is given as

$$u(k_i) = -(C_s G)^{-1}[C_s F x(k_i) - \alpha C_s x(k_i) + \theta_1 \sqrt{|s(k_i)|} \, sgn(s(k_i)) - w(k_i - 1) + h\theta_2 sgn(s(k_i - 1))] \quad (17)$$

where $\theta_1>0$, $\theta_2>0$ and $w(k_i - 1) = w(k_i) + h\theta_2\phi_2$.
Proof: Let us consider the discrete form of super-twisting algorithm [31] at triggering instant k_i as

$$s(k_i + 1) = -\theta_1\phi_1(s(k_i)) + w(k_i), \quad (18)$$

$$w(k_i + 1) = w(k_i) - h\theta_2\phi_2 \quad (19)$$

where $\phi_1(s(k_i)) = |s(k_i)|^{\frac{1}{2}} sgn(s(k_i))$, $\phi_2(s(k_i)) = sgn(s(k_i))$.
The simplified form of Eqn. (18) is given by,

$$s(k_i + 1) = -\theta_1 \sqrt{|s(k_i)|} sgn(s(k_i)) + w(k_i - 1) - h\theta_2 sgn(s(k_i - 1)). \quad (20)$$

Substituting the value of $s(k_i + 1)$ from Eqn. (16) into Eqn. (20), it is simplified as follows

$$C_s x(k_i + 1) - \alpha C_s x(k_i) = -\theta_1 \sqrt{|s(k_i)|} sgn(s(k_i)) + w(k_i - 1) - h\theta_2 sgn(s(k_i - 1)). \quad (21)$$

Using Eqn. (1), Eqn. (21) is given as

$$C_s[Fx(k_i) + Gu(k_i - \tau')] - \alpha C_s x(k_i) = -\theta_1 \sqrt{|s(k_i)|} \, sgn(s(k_i)) + w(k_i - 1) - h\theta_2 sgn(s(k_i - 1)). \quad (22)$$

Remark 4: In this work, the fractional delays existing in forward and feedback channels are compensated seperately. Thus, the control signal in Eqn. (22) is transformed to

$$u(k_i - \tau') = u(k_i). \quad (23)$$

Further expanding Eqn. (22) using Eqn. (23), we have

$$C_s F x(k_i) + C_s G u(k_i) - \alpha C_s x(k_i) = -\theta_1 \sqrt{|s(k_i)|} \, sgn(s(k_i)) + w(k_i - 1) - h\theta_2 sgn(s(k_i - 1)). \quad (24)$$

Thus, the event-based super-twisting control law at instant k_i is expressed as

$$u(k_i) = -(C_s G)^{-1}[C_s F x(k_i) - \alpha C_s x(k_i) + \theta_1 \sqrt{|s(k_i)|} \, sgn(s(k_i)) - w(k_i - 1) + h\theta_2 sgn(s(k_i - 1))]. \quad (25)$$

The control signal computed in Eqn. (25) for triggering instant k_i at controller side suffers from controller to actuator random fractional delay τ'_{ca}. Thus, using the concept of Thiran's approximation the compensated control signal received at the actuator side at triggering instant k_i is

$$u_a(k_i) = u(k_i) + \beta u(k_i - 1) \quad (26)$$

where $\beta = \frac{\tau'_{ca_i}}{1+\tau'_{ca_i}}$.

A. Sliding Mode Band

To derive the quasi-sliding mode band (QSMB), let us consider the sliding variable and control input at k^{th} instant which includes the k_i^{th} instant. The QSMB is presented as **Theorem 2** below.
Theorem 2: Let $\sigma_s>0$ be the given positive real constant, then the practical quasi-sliding mode band for system (1), (2) with designed control law (25) is given as

$$|\Omega e(k)| < \sigma_s, \forall k \in \mathbb{Z} \geq 0 \quad (27)$$

where $\Omega = C_s F - \alpha C_s$ and $e(k) = x(k_i) - x(k)$ is the error due to the implementation of the controller (25) aperiodically.
Proof : Let us consider the compensated sliding variable given by

$$s(k + 1) = C_s x(k + 1) - \alpha C_s x(k) \quad (28)$$

Substituting $x(k + 1)$ into (28), we have

$$s(k + 1) = C_s[Fx(k) + G(u(k) + d(k))] - \alpha C_s x(k). \quad (29)$$

Referring to Eqn. (17), Eqn. (29) is expressed as

$$s(k + 1) = C_s F x(k) + C_s G\{-(C_s G)^{-1}[C_s F x(k_i) - \alpha C_s x(k_i) + \theta_1 \sqrt{|s(k_i)|} sgn(s(k_i)) - w(k_i - 1) + h\theta_2 sgn(s(k_i - 1))]\} + C_s G d(k) - \alpha C_s x(k). \quad (30)$$

Further simplification of Eqn. (30) gives

$$\begin{aligned} s(k+1) = C_sFx(k) - C_sFx(k_i) + \alpha C_s x(k_i) - \\ \theta_1\sqrt{|s(k_i)|}sgn(s(k_i)) + w(k_i-1) - h\theta_2 \\ sgn(s(k_i-1)) + C_sGd(k) - \alpha C_s x(k). \end{aligned} \quad (31)$$

Solving further, we have

$$\begin{aligned} s(k+1) = -\Omega e(k) - \theta_1\sqrt{|s(k_i)|}sgn(s(k_i)) + \\ w(k_i-1) - h\theta_2 sgn(s(k_i-1)) + C_sGd(k). \end{aligned} \quad (32)$$

Let us denote $C_sGd(k) = \hat{d}$ for simplicity. Referring to Eqn. (1), it is considered that $d(k)$ is bounded in nature with $O(h)$ and remains constant for interval kh to $(k+1)h$. So, without loss of generality, $\hat{d}$ is also bounded in nature with $O(h)$ and remains constant for the specified interval. Thus using relation (27), the above Eqn. (32) is written as

$$\begin{aligned} |s(k+1)|<\sigma_s - \theta_1\sqrt{|s(k_i)|}sgn(s(k_i)) + w(k_i-1) \\ -h\theta_2 sgn(s(k_i-1)) + \hat{d}. \end{aligned} \quad (33)$$

Once the system states computed at event triggering instant k_i reach to practical QSMB, for all $k \in [k_i, k_{i+1})$ we have $s(k) = 0$. So, as per the definition of quasi-sliding mode control Eqn. (33) can be reduced to

$$|s(k)|<\sigma_s + \hat{d}, \forall k \in \mathbb{Z}\geq 0. \quad (34)$$

Thus, the practical QSMB is given by

$$\Upsilon = \{x \in R^n : |s(k)|<\epsilon_2\} \quad (35)$$

where $\epsilon_2 = \sigma_s + \hat{d}$.

It may be noted that the practical QSMB condition in (35) is not satisfied at the event occurring instant. However, the control input $u(k_i)$ ensures that the sliding variable reaches to the practical QSMB.

VI. Stability Analysis

Theorem 3 : The trajectories of the closed loop system (1), (2) are asymtotically stable for the designed control law (25) and sliding variable (16), if the following condition in (41) holds true

$$\Psi_s<s^T(k)s(k). \quad (36)$$

Proof : Selecting the Lyapunov function as

$$V_s(k) = s^T(k)s(k). \quad (37)$$

Writing forward difference of the above equation

$$\Delta V_s(k) = s^T(k+1)s(k+1) - s^T(k)s(k). \quad (38)$$

Substituting $s(k+1)$ in Eqn. (38) we get

$$\begin{aligned} \Delta V_s(k) = [C_s x(k+1) - \alpha C_s x(k)]^T[C_s x(k+1) - \\ \alpha C_s x(k)] - s^T(k)s(k). \end{aligned} \quad (39)$$

Further substituting $x(k+1)$ and $u(k)$, the simplified form of the above equation is given by

$$\Delta V_s(k) = \Psi_s - s^T(k)s(k) \quad (40)$$

where $\Psi_s = [-\theta_1\sqrt{|s(k)|}sgn(s(k)) + w(k-1) - h\theta_2 sgn(s(k-1)) + \hat{d}]^T[-\theta_1\sqrt{|s(k)|}sgn(s(k)) + w(k-1) - h\theta_2 sgn(s(k-1)) + \hat{d}]$.

At $k = k_i$, the above Eqn. (40) is transformed as

$$\Delta V_s(k_i) = \Psi_{s_i} - s^T(k)s(k) \quad (41)$$

where $\Psi_{s_i} = [-\theta_1\sqrt{|s(k_i)|}sgn(s(k_i)) + w(k_i-1) - h\theta_2 sgn(s(k_i-1)) + \hat{d}]^T[-\theta_1\sqrt{|s(k_i)|}sgn(s(k_i)) + w(k_i-1) - h\theta_2 sgn(s(k_i-1)) + \hat{d}]$.

Remark 5 It is considered that the sliding variable and control signal computed at k^{th} instant includes the k_i^{th} instant. Moroever, observing Eqns. (40) and (41) it can be noticed that Ψ_s and Ψ_{s_i} both are tuned by the same parameters θ_1 and θ_2. So without loss of generality, the overall stability of the closed loop system is proved at k^{th} instant which also includes k_i^{th} instant.

Thus, from Eqn. (40) it can be noticed that tuning $'\Psi_s'$ close to zero by properly selecting the parameters θ_1 and θ_2 we have, $s^T(k)s(k)$ larger than Ψ_s. Thus for any small parameter β', we have $\Psi_s - s^T(k)s(k)<\beta' s^T(k)s(k)$.

By tuning the parameter θ_1 and θ_2, we have

$$\Delta V_s(k)<\beta' s^T(k)s(k) \quad (42)$$

which guarantees the finite time convergence of $\Delta V_s(k)$.

VII. Application to a 2-DOF Serial Flexible Joint Robot

The simulation and experimental results are carried out on a laboratory setup of 2-DOF serial flexible joint (SFJ) robotic arm as described and shown in Fig. 2. The results are also compared with the DSMC derived using Gao's reaching law. The robotic system consists of two rigid bars having two joints namely joint-1 and joint-2 which are serially interconnected through a common link.The first bar is connected to the drive through flexible joint. At the other end of the first bar, second drive is connected which rotates the second bar through another flexible joint. The movement of both the flexible joints is controlled through DC motors and the position of each joint is measured by the quadrature optical encoders [32].

Fig. 2: Test-Bed platform of 2-DOF Flexible Joint Robot

The simulation and experimental results are carried out for two stages for joint-1 and joint-2 respectively. The results are carried out with MATLAB/Simulink as front end and QUARC software for real-time interface with sensors and actuators.

The mathematical model of the system is given in the [32]. The system matrices for joint-1 and joint-2 discretized at sampling rate of $h = 2msec$ are as under

- Flexible Joint-1

$$F=\begin{bmatrix}0.9997 & 0.0002696 & 0.001865 & 1.818e-07\\ 7.81e-05 & 0.9999 & 5.028e-08 & 0.001999\\ -0.2634 & 0.2634 & 0.868 & 0.0002695\\ 0.07809 & -0.07809 & 7.45e-05 & 0.9993\end{bmatrix},$$

$$G=\begin{bmatrix}0.0002673\\ 3.545e-09\\ 0.2612\\ 7.042e-06\end{bmatrix}, C=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}.$$

- Flexible Joint-2

$$F=\begin{bmatrix}0.9979 & 0.002078 & 0.001739 & 1.416e-06\\ 0.0007443 & 0.9993 & 4.63e-07 & 0.001994\\ -1.983 & 1.983 & 0.7499 & 0.002075\\ 0.7433 & -0.7433 & 0.0006783 & 0.994\end{bmatrix},$$

$$G=\begin{bmatrix}0.0004521\\ 5.827e-08\\ 0.4315\\ 0.0001149\end{bmatrix}, C=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}.$$

The results are discussed in four sections. (i) Figs. 3 to 10 depict the simulation results of the flexible joint robotic system in terms of state variables, sliding variable, control efforts, and interexecution event time computed at controller side with proposed event-triggered DHSMC with time delay compensation (ii) Figs. 11 to 13 depict the simulation results of flexible joint robotic system for stage-1 in context with state variable, sliding variable, and control efforts at the actuator side for the DSMC derived using Gao's reaching law with time delay compensation (iii) Figs. 14 to 19 depict the simulation results of flexible joint robotic system in the terms of state variables, sliding variable and control efforts without time delay compensation and (iv) Figs. 20 to 25 depict the experimental results of flexible joint robot in the terms of tracking response and interexecution event time for stage-1 and stage-2 respectively.

A. Simulation results with the proposed Event-triggered DHSMC law with network delay compensation

For developing the proposed event-triggered DHSMC given in Eqn. (25), the sliding gain is computed to be $C_s=[76.57 \quad 81.55 \quad 2.86 \quad 23.02]$ using LQR method with tuning parameters $Q=diag(1500,0)$ and $R=2$. The other parameters chosen for simulation are $\theta_1=1.1$, $\sigma_s=0.08$, $\theta_2=1$, $\hat{d}=0.0015$ (stage-1) and $\hat{d}=0.0025$ (stage-2). The sliding band computed on the basis of above parameters for stage-1 is $|s(k)|<0.0815$ and stage-2 is $|s(k)|<0.0825$. According to Poission's distribution, it is assumed that the probability of networked delay lesser than sampling interval with the single trial is $p'=0.67$. Thus the total random network induced delay in both the cases is computed to be $0.1msec \leq \tau \leq 1.8msec$. The fractional part of computed random networked delay with sampling interval of $h=2msec$ is $0.05 \leq \tau' \leq 0.9$. Figs. 3 and 4 show the results of state variables for stage-1 and stage-2 of flexible joint robotic arm with initial condition $x(0)=[0.1 \quad 0.2 \quad 0.3 \quad 0.4]^T$ respectively. It is noticed that the state variables converge to the zero from specified initial condition in both the cases in the presence of random fractional delay and matched uncertainty. The magnified windows in Figs. 3 and 4 show the effect of time delay approximation technique on the state variables.

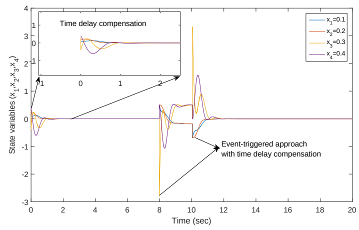

Fig. 3: State variables of SFJ for stage-1

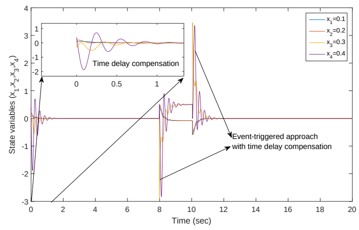

Fig. 4: State variables of SFJ for stage-2

In both the cases, it is observed that all the state variables are computed from first sampling interval in the presence of random fractional delay. Thus, it can be concluded that the random fractional delay in both the feedback and forward channel is compensated by the proposed approximation technique. To show the effect event occurrence, events are generated at $t=8sec$ and $t=10sec$ at the plant side as shown in Figs. 3 and 4. From the results it can be noticed that each state variable is controlled at each event triggering instants. In case, if the events are not generated the state variables remain in their previous state till the next triggering instant. Figs. 5 and 6 show

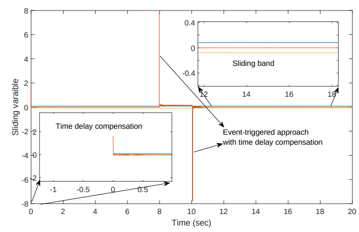

Fig. 5: Sliding variable of SFJ for stage-1

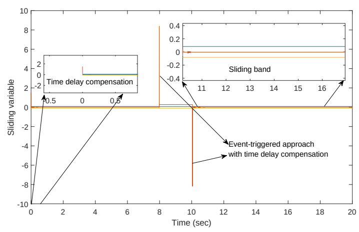

Fig. 6: Sliding variable of SFJ for stage-2

the sliding variable for both the stages of flexible joint robotic arm respectively. It can be observed that, the sliding mode is achieved in finite time and the sliding variable remains within the practical quasi-sliding mode band even in the presence of random fractional delay and matched uncertainty. Figs. 7 and 8 show the control signal at the actuator side for both the stages of flexible joint robotic arm. The magnified results show the

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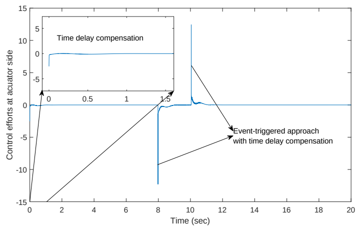

Fig. 7: Control efforts at actuator side of SFJ for stage-1

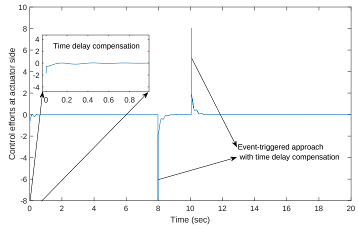

Fig. 8: Control efforts at actuator side of SFJ for stage-2

compensation of network delay. Further, from the results, it is noticed that, when the events are generated at the plant side (i.e. at $t = 8sec$ and $t = 10sec$), the control efforts are updated at the controller side. However, it is observed that the control effort remains constant until the occurrence of next triggering instant. Figs. 9 and 10 show the interexecution event time of

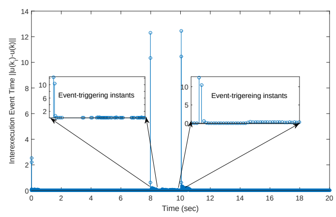

Fig. 9: Interexecution event time of SFJ for stage-1

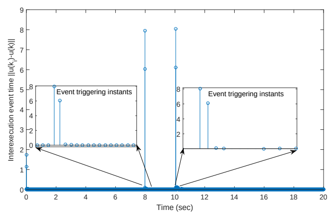

Fig. 10: Interexecution event time of SFJ for stage-2

control signal computed at controller side for both the stages. It can be observed that the control effort is updated at the time of event.

B. Simulation results with the DSMC law derived using Gao's reaching law with network delay compensation

In this section, the simulation results for stage-1 of flexible joint robotic system using DSMC derived with Gao's reaching law are presented to compare the performance of the proposed event-triggered DHSMC with network delay compensation. The event-triggered DSMC using Gao's reaching law [33] with

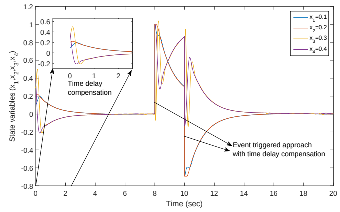

Fig. 11: State variables of SFJ for stage-1 using DSMC with Gao's reaching law

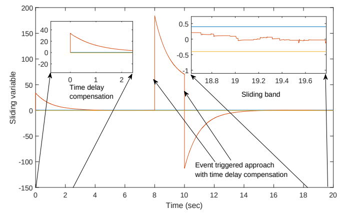

Fig. 12: Sliding variable of SFJ for stage-1 using DSMC with Gao's reaching law

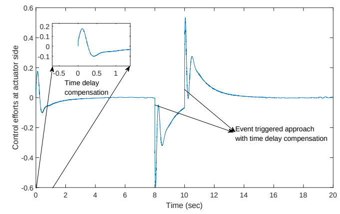

Fig. 13: Control signal computed at actuator side of SFJ for stage-1 using DSMC with Gao's reaching law

network delay compensation for system (1), (2) is given as

$$\begin{aligned} u(k_i) = -(C_sG)^{-1}[C_sFx(k_i) - (1-qh)(s(k_i)) \\ -\alpha C_sx(k_i) + \epsilon hsgn(s(k_i))]. \end{aligned} \tag{43}$$

The parameters used in to carry out the simulation are $\epsilon = 150$, $\sigma_s = 0.08$, and $q = 10$. The quasi sliding mode band computed is $|s(k)|<0.386$.

Figs. 11 to 13 depict the simulation results of system state variable at the plant side, sliding variable and control efforts at the actuator side. The initial condition assumed to be $x(0) = [0.1 \quad 0.2 \quad 0.3 \quad 0.4]^T$ and random network delay $0.1msec \le \tau \le 1.8msec$.

Comparing the results shown in Figs. 11, 12, and 13 with Figs. 3, 5 and 7, it can be noticed that the proposed event-triggered DHSMC algorithm shows less chattering and reduced band size. Moreover, the control effort is less in the proposed control algorithm when the events are generated at the plant side for $t = 8sec$ and $t = 10sec$.

C. Simulation results with the proposed event-triggered DHSMC law without network delay compensation

The proposed event-triggered DHSMC law is also checked without delay compensation to show the adverse effect of network delay in the system response.

Figs. 14 to 19 show the simulation results of state variables, sliding variable and control efforts without time delay compensation for stage-1 and stage-2 respectively. From the results, it

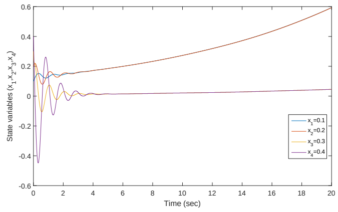

Fig. 14: State variables of SFJ for stage-1

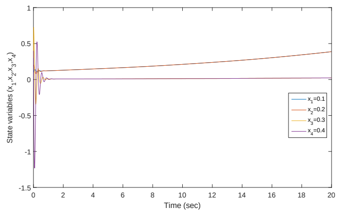

Fig. 15: State variables of SFJ for stage-2

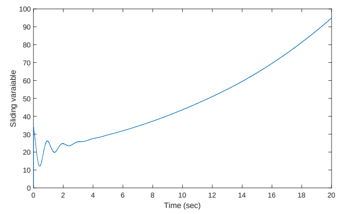

Fig. 16: Sliding variable of SFJ for stage-1

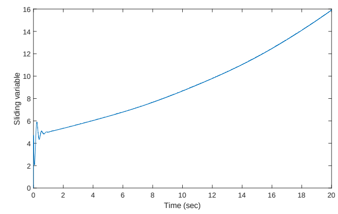

Fig. 17: Sliding variable of SFJ for stage-2

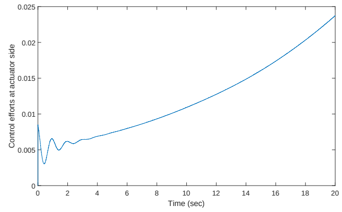

Fig. 18: Control efforts at actuator side of SFJ for stage-1

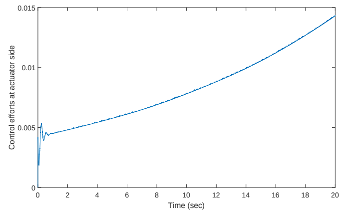

Fig. 19: Control efforts at actuator side of SFJ for stage-2

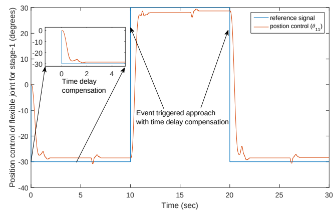

Fig. 20: Postion control of SFJ for stage-1

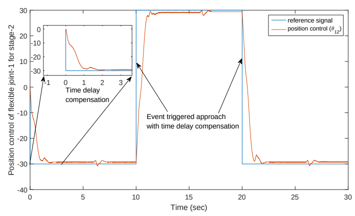

Fig. 21: Postion control of SFJ for stage-2

is observed that the system variables (states, sliding variable and control efforts) do not converge to the origin and slide towards infinite region. This results in the degradation of the overall system performance in the presence of network non-idealities. Thus, it is extended that the super-twisting algorithm without time delay compensation does not perform efficiently in the presence of network delay.

D. Experimental results with proposed Event-triggered DHSMC law with network delay compensation

The proposed event-triggered DHSMC law with network delay compensation is further implemented on the experimental set up to show the efficacy. The experimental results were carried out for stage-1 and stage-2 in the presence of network irregularities. The sliding gain is computed to be $C_s = [80.65 \quad 101.25 \quad 5.93 \quad 26.5]$ using LQR gains $Q = diag(1000, 0)$ and $R = 1$. The system parameters and controller parameters are chosen as $\theta_1 = 5.3$, $\sigma_s = 4.05$, $\theta_2 = 5$, $\hat{d} = 0.0015$ (stage-1) and $\hat{d} = 0.0025$ (stage-2). The sliding band computed on the basis of above parameters for stage-1 is $|s(k)|<4.0515$ and stage-2 is $|s(k)|<4.0525$. According to Poission's distribution, the total random network induced delay in both the cases is computed to be $0.1msec \leq \tau \leq 1.8msec$. The fractional part of computed random networked delay with sampling interval of 2msec is $0.05 \leq \tau' \leq 0.9$.

Figs. 20 to 25 show the experimental results of tracking response and interexecution event time of control signal for stage-1 and stage-2 respectively. It is observed that the position of robotic arm is controlled at the occurrence of the events at the plant side for both the stages. To create the event in this case, the reference signal is varied at particular instant. It is observed that for each event generation the effect of feedback and forward channel delay is compensated in the presence of network non-idelities. Further observing Figs. 24 and 25, it is also noticed that control signal is updated when the events are generated. For all other cases, the control signal at controller side is computed based on the previous state information signal.

Thus, from all the above results, it is concluded that the proposed event-triggered DHSMC with network delay compensation technique is more robust, having less chattering and also compensates the effect of random fractional delay in

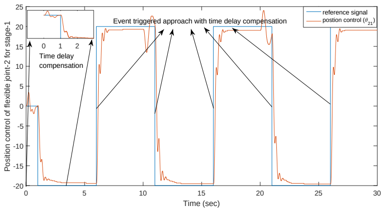

Fig. 22: Position control of SFJ for stage-1

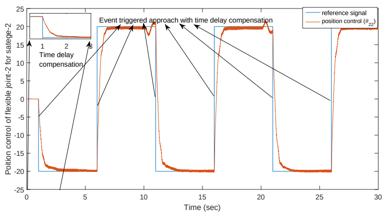

Fig. 23: Position control of SFJ for stage-2

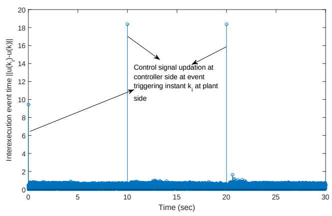

Fig. 24: Interexecution event time of SFJ for stage-1

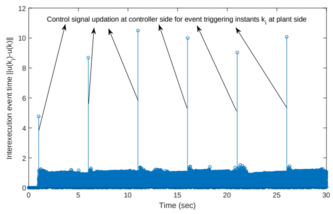

Fig. 25: Interexecution event time of SFJ for stage-2

the presence of system uncertainties. Moreover, the proposed controller acts only when the event occurs and thus reduces the network resources like bandwidth and congestion. This increases the efficiency of the communication rate in the presence of network abnormalities.

VIII. Conclusion

In this paper, a super-twisting type higher order discrete-time sliding mode controller is designed using a novel event-based sliding surface. The proposed controller ensures that the system states remain within the specified band over a finite interval of time under the influence of network abnormalities and system uncertainties. The random fractional delay in the forward and feedback channel is modeled using Poission's distribution and compensated using Thiran's approximation technique. The event generation block is designed at the plant side such that the state information is updated when the triggering condition is satisfied otherwise it retains the current state information. The stability of the closed-loop system with proposed controller is assured through Lyapunov approach. The proposed controller is applied and also compared with DSMC law derived using Gao's reaching law on 2-DOF flexible joint robot system. From simulation and experimental results, it is inferred that the proposed control strategy designed using event-triggered approach is robust and it also compensates the effect of random fractional delay, reduces network congestion problem and increases the efficiency of communication rate in the presence of network non-idealities. In future, the analysis can be extended for single or multiple packet loss in discrete-time domain for networked control system.

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