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Event-based Control and Filtering of Networked Systems: A Survey

Lei Zou[1] Zi-Dong Wang[1, 2] Dong-Hua Zhou[1, 3]

[1]College of Electrical Engineering and Automation, Shandong University of Science and Technology, Qingdao 266590, China
[2]Department of Computer Science, Brunel University London, Uxbridge, Middlesex, UB8 3PH, UK
[3]Department of Automation, Tsinghua National Laboratory for Information Science and Technology, Tsinghua University, Beijing 100084, China

Abstract: In recent years, theoretical and practical research on event-based communication strategies has gained considerable research attention due primarily to their irreplaceable superiority in resource-constrained systems (especially networked systems). For networked systems, event-based transmission scheme is capable of improving the efficiency in resource utilization and prolonging the lifetime of the network components compared with the widely adopted periodic transmission scheme. As such, it would be interesting to 1) examining how the event-triggering mechanisms affect the control or filtering performance for networked systems, and 2) developing some suitable approaches for the controller and filter design problems. In this paper, a bibliographical review is presented on event-based control and filtering problems for various networked systems. First, the event-driven communication scheme is introduced in detail according to its engineering background, characteristic, and representative research frameworks. Then, different event-based control and filtering (or state estimation) problems are categorized and then discussed. Finally, we conclude the paper by outlining future research challenges for event-based networked systems.

Keywords: Event-triggered transmission, networked systems, event-based control, event-based filtering, event-triggered distributed state estimation, distributed control with event-based protocol.

1 Introduction

1.1 Engineering background

With the progress in networked communication technology the data transmissions among system components in a wide range of applications are implemented via communication networks. Such systems are known as networked systems and they possess many advantages including low cost, simple installation, reduced system wiring, ease of maintenance, high flexibility and reliability. Hence, networked systems have gained ever-increasing research attention in the past few decades. Related to this core area are the control and filtering problems which have attracted considerable research interest[1−8].

The main difference between traditional systems (non-networked systems) and networked systems is the communication process. Data exchanges between components (e.g., signal transmissions between sensors and the controller) are implemented via point-to-point communication in which the components are connected by their corresponding communication channels. However, in networked systems, all signals of various components are transmitted via a shared network (or shared networks). Generally speaking, the communication processes of networked systems could be divided into two categories: time-driven communication and event-driven (or event-based) communication. Time-driven communication is a widely used communication strategy in which the signal transmissions are always implemented in a periodic manner. Such a manner does have the advantages of easy implementation and good predictability. However, in the case that the communication resources (e.g., bandwidth of the network) are the major concern, time-driven communication becomes less preferable since such a communication manner would lead to unnecessary data transmissions. This is particularly true for large scale networked systems with limited communication bandwidth and computation capacity. As such, the event-driven communication appears with the hope to avoid unnecessary signal transmissions[9, 10]. Such a communication scheme is capable of improving the efficiency in communication resource utilization and prolonging the lifetime of network components.

In event-driven communication scheme, transmission instants are determined by the so-called "event generator" by which the signal transmission is triggered only when certain triggering condition (i.e., event-triggering condition) is achieved. The triggering condition could be regarded as an index indicating whether the system performance under

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consideration is getting worse than the requirement (e.g., the system becomes unstable). As such, the event-driven communication could provide a trade-off between the system performance and the communication bandwidth utilization. Compared with the time-driven communication scheme, the event-driven communication possesses the features such as aperiodic transmission manner, high communication utilization efficiency and energy saving. So far, the analysis and synthesis issues for networked systems with event-driven communication scheme have gained a great deal of research attention, see e.g., [11–21] and the references therein.

1.2 Theoretical frameworks

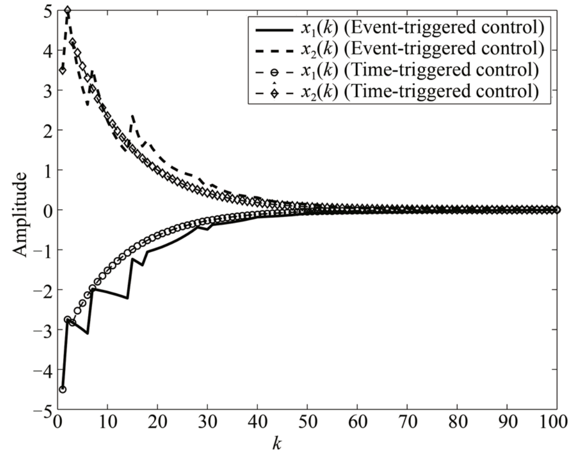
Event-triggering conditions play an important role in the analysis and synthesis issues of event-driven networked systems. An event-triggering condition is composed of two parts: the error-based part which contains the difference between the current measurement data and the previously transmitted measurement data, and the threshold part. According to the utilization of threshold part in event-triggering mechanisms, there are two different types of event-triggering conditions widely investigated in the literature: the fixed threshold condition[22−28] and the relative threshold condition[11, 12, 16, 17]. Specifically speaking, let $y(t)$ and t_k be the current measurement and the time of the k-th triggering instant, respectively. In most of the literature, the error-based part δ_e is always constructed by $\delta_e \triangleq (y(t)-y(t_k))^{\mathrm{T}}Q(y(t)-y(t_k))$ where Q is the weight matrix, the threshold parts ρ_t of the fixed threshold condition and the relative threshold condition are constructed by $\rho_t \triangleq r$ and $\rho_t \triangleq ry^{\mathrm{T}}(t_k)Qy(t_k)$ (where r is the triggering parameter), respectively. Then, the $(k+1)$-th triggering instant would be determined by $t_{k+1} \triangleq \{t|t>t_k, \delta_e \geq \rho_t\}$. Obviously, the parameter r could regulate the transmission frequency (or communication rate) of the event-triggering mechanism. When r is set to be zero, the corresponding event-driven system reduces to the conventional time-driven one.

Remark 1. Different event-triggering conditions would lead to different control (or filtering) performance. For example, the event-triggering mechanism with a fixed threshold condition (also called "send-on-delta" strategy) is more suitable for the state estimation problem proposed in [24]. Based on the Luenberger estimator and the fixed threshold condition, the estimation error dynamics could be described by an autonomous system, while the relative threshold condition would lead to a non-autonomous system. On the other hand, as shown in [16], the event-triggering mechanism with the relative threshold condition is more suitable for control problems. A properly designed relative threshold condition could guarantee the global asymptotical stability of the closed-loop system.

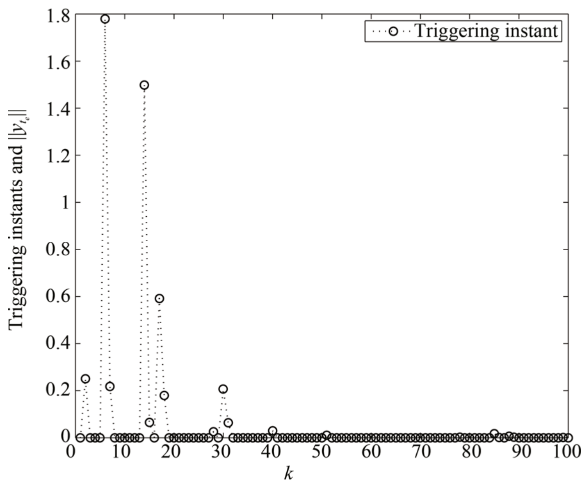
For the purpose of demonstrating the effectiveness of the event-driven communication, a comparative example of event-triggered control and time-triggered control is presented as follows. The plant is a second-order system which is described by

$$\begin{cases} x_{k+1} = \mathrm{diag}\{1.1, 0.8\}x_k + \begin{bmatrix}1 & 1\end{bmatrix}^{\mathrm{T}} u_k \\ y_k = \begin{bmatrix}1 & 0.5\end{bmatrix} x_k. \end{cases}$$

In time-triggered control scheme, the control input is set to be $u_k = -0.8y_k$. In event-triggered control scheme, the control input and the event-triggering condition is selected as $u_k = -0.8y_k$ and $\|y_k - y_{t_s}\| \geq 0.8\|y_k\|$, respectively. Fig. 1 (a) shows the control performance of event-triggered control and time-triggered control. Fig. 1 (b) describes the transmission instants of the event-driven communication. Obviously, the event-triggering mechanism trades off the communication rate and control performance.



(a) Control performance of different communication schemes



(b) Transmission instants of the event-driven communication

Fig. 1 A comparative example of event-triggered control and time-triggered control

For a networked system with event-based communication mechanism, the dynamics analysis would be inevitably complicated. Traditional approaches are not competent to handle the analysis issue of a networked system with event-based communication. This is mainly due to the aperiodicity of the event-triggered transmission scheme which would

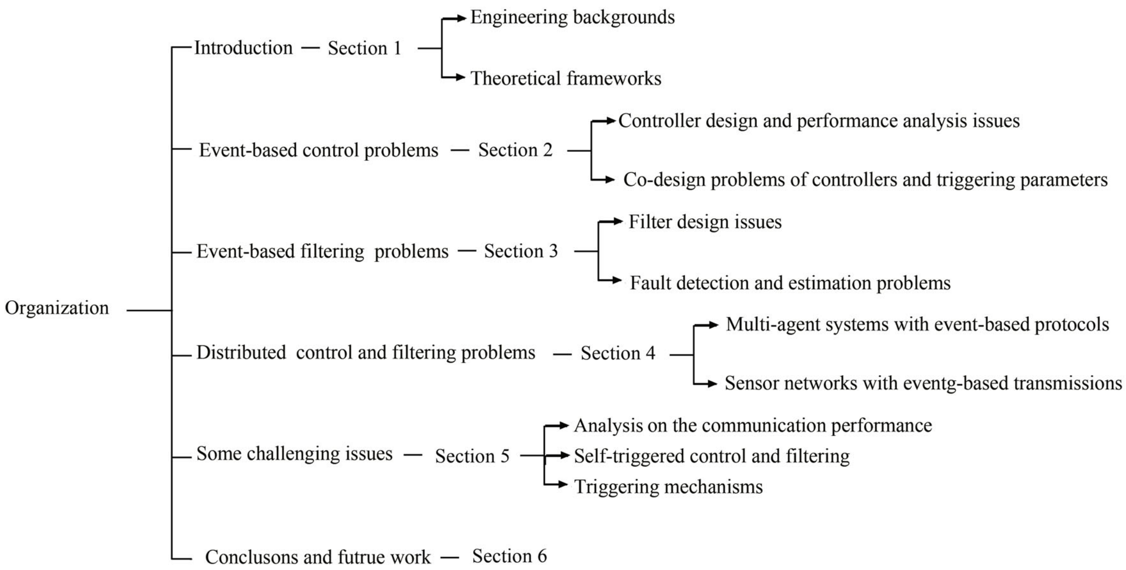


Fig. 2 Organization of this survey

greatly affect the system performance such as the stability and H_∞ performance of the closed-loop system. In order to deal with such a system, one should consider the system dynamics and the impact of event-based communication simultaneously. More specifically, the corresponding theoretical framework should demonstrate the systems dynamics and the effect induced by the event-triggering condition. Nowadays, three arguable representative theoretical frameworks (e.g., the Lyapunov stability based approach[14, 17, 29], hybrid system based approach[11, 12] and input-to-state stability (ISS) based method[16, 30, 31]), have been widely applied to deal with the analysis and synthesis problems with event-based communication schemes for networked systems.

Lyapunov stability based approach has been widely employed in the performance analysis and controller (or filter) design. Based on such an approach, the event-triggering condition could be regarded as a nonlinear constraint. Hence, we can embed this nonlinear constraint into the calculation of Lyapunov function or functional. Obviously, such an approach could be considered as the "robustness-based" method. On the other hand, by substituting the error-based part into the system dynamics, the event-driven system could be reformulated as a dynamical system with an input $(y(t)-y(t_k))$ satisfying the bounded constraint induced by the utilized event-triggering condition. Then, the ISS based method could be applied to cope with the analysis and synthesis issues for the reformulated system. Compared with the Lyapunov stability based approach and the ISS based method, hybrid system based approach is introduced based on the fact that the event-driven system could be reformulated by a dynamical system with the impulsive behavior. Hence, we can analyze the dynamical behaviors of such a system via the hybrid system based approach.

This survey aims to provide a timely review on the recent advances of the event-based control and filtering problems for networked systems. The references discussed in this paper include, but are not limited to the following aspects of networked systems: 1) stability analysis problem of networked systems with event-based communication, 2) methods and algorithms to design event-based controller and event-based filter for networked systems, 3) robustness analysis issue of event-driven networked systems, and 4) distributed control and state estimation problems with event-based transmission scheme. The organization of this survey could be summarized by Fig. 2. In the following sections, the developments of the distributed event-based control for multi-agent systems (MASs) and the distributed event-based state estimation for sensor networks (SNs) are systematically reviewed as follows.

2 Event-based control problems

Typical event-driven networked control systems (NCSs) could be categorized into two groups, which are demonstrated by Fig. 3. In this section, we will recall the theoretical developments of event-based control issues in the recent years from various aspects including the controller design and performance analysis, and the co-design issues of controllers and triggering parameters.

Remark 2. In NCSs, both the sensor-to-controller channel and the controller-to-actuator channel could be implemented via communication networks. For example, in [32], the stabilization problem has been studied for NCSs with both-sides networks. Hence, in order to reduce the communication burden of both-sides networks, the event-triggering mechanism could be utilized in both the sensor-to-controller channel and the controller-to-actuator channel (e.g., [33, 34]). On the other hand, when the network resource of the sensor-to-controller channel is the only concern, the paradigm shown in Fig. 3 (b) is more suitable for the NCS.

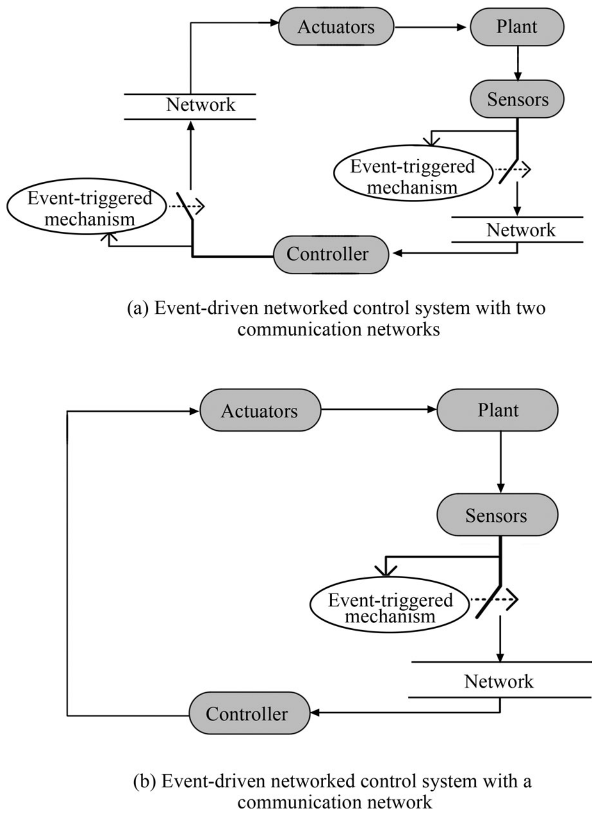


Fig. 3 Two typical event-driven networked control systems

2.1 Controller design and performance analysis issues

H_∞ control is one of the most investigated control problems due to its wide applications in various control systems. A rich body of literature has appeared on the H_∞ controller design issue subject to time-driven communication. With respect to the analysis and design issue of controller subject to event-triggered transmission scheme, the time-triggered controllers are extremely difficult to handle the control task with the satisfactory performance. As such, a great deal of research attention has been devoted to the event-based H_∞ control issue in recent years, e.g., [35–38]. In [39], the H_∞ control problem has been investigated for a class of NCSs based on event-time-driven model. By reformulating the considered systems into a class of switched delay systems including an unstable subsystem, the switching controller has been designed in terms of linear matrix inequalities (LMIs). The H_∞ control issue has been studied in [40] for a class of discrete-time linear parameter-varying systems with network-induced delays. In [41], the H_∞ tracking control design problem has been studied for a class of continuous-time NCSs with event-triggered sampling scheme. With respect to the control problem with communication delay, we mention some representative work as follows. In [29], a delay system model has been firstly constructed for the analysis of NCSs with event-triggered communication. Note that the presented event-triggered communication is implemented based on the sampled data of sensors. A combined event-triggering condition and controller-feedback-gain design approach has been presented in [17] for NCSs, where the communication delay and packet loss phenomenon have been taken into consideration. Hu et al.[42] illustrated the event-triggered H_∞ stabilization (in mean square sense) problem for NCSs with multiplicative noise and network-induced delays. Markov jump system has a wide range of application because of its capacity of capturing the abrupt mode changes of the plant. In [43], the event-based H_∞ control problem has been dealt with for discrete Markov jump systems based on a time interval analysis approach. The event-triggered H_∞ controller design problem has been investigated in [44] for nonlinear NCSs with time delay and uncertainties, where the uncertainties in networked Takagi-Sugeno (T-S) fuzzy model have been modeled by the parallel distributed compensation fuzzy control rules.

L_∞ control has long been a hot topic in control theory. In [11], the stability and L_∞-performance have been studied for event-triggered control systems with dynamical output-based controllers and decentralized event-triggering mechanisms via an impulsive system based method. The stabilization of the event-based networked systems subject to both quantization and time-varying network induced delay has been address in [45] where both fixed threshold condition and relative threshold condition have been considered simultaneously. In [46], a novel event-triggered control strategy called rollout event-triggered control has been developed which is capable of guaranteeing a performance improvement over traditional periodic control for cyber-physical systems. The main results established in that paper have quantified the performance improvements for quadratic average cost problems. The event-based pinning control problem for the synchronization of complex networks has been investigated in [47] where the considered networks have been modeled by time-varying weighted graphs and featuring generic linear interaction protocols. The event-based sampled-data model predictive control problem has been studied in [48] based on the non-monotonic Lyapunov function approach for continuous-time systems with disturbances. With respect to the spatially distributed system, in [49], an event-based model predictive networked control scheme has been proposed for a traffic control system (which has been modeled as a spatially distributed system). As it is well known, the distributed parameter systems could be modeled by partial differential equations (PDEs). The event-triggered control problem has been studied in [50] for parabolic systems (a class of distributed parameter systems) governed by semi-linear diffusion PDEs with transmission delays and signal quantization.

Optimal control is another hot topic in control theory dealing with the problem of finding a control law for a given system such that a certain optimality criterion is achieved. A local event-based approach has been developed in [51] for the optimal control of the heating, ventilation, and airconditioning (HVAC) systems, where decisions were made only when certain events occurred. On the other hand, the suboptimal event-triggered control problem has been considered in [52] for delay linear systems where the performance considered has included a linear quadratic cost function for quantifying the control performance and average event times. In [53], the fault-tolerant control problem has been discussed for networked systems with dynamic quantization and event-triggered transmission scheme. The semi-global stabilization problem has been studied in [54] for null controllable systems with actuator saturation and event-triggered transmission scheme via Riccati equations. In [55], a novel approximation-based event-triggered control scheme has been proposed for multi-input multi-output uncertain nonlinear continuous-time systems in affine form. A nonzero positive lower bound of the inter-event times is guaranteed to avoid the Zeno behavior (i.e., the occurrence of an infinite number of events in finite time).

2.2 Co-design of controllers and triggering parameters

The main idea of the co-design problem of event-based control and triggering condition is to design the desired controller parameters and certain parameters of the event-triggering mechanism simultaneously. Up to now, such a problem has received a great deal of research interest in the literature. In [12], the co-design problem has been presented for a linear time-invariant continuous-time system with the periodic event-triggered controller. Both the static state-feedback and dynamical output-based controllers have been considered. Furthermore, three different approaches (e.g., impulsive system based approach, piecewise linear system based method, and perturbed linear system based method) to cope with such a problem have been presented and discussed. The model-based event-triggered predictive control problem has been investigated in [56] for discrete-time linear systems with time-varying communication delays, where the co-design problems of the controller and the event-triggering parameter have been discussed in terms of the linear matrix inequality approach and the Lyapunov functional method. Al-Areqi et al.[57, 58] studied the co-design problems of event-based control and scheduling for networked embedded control systems (NECSs) in which multiple control loops closed over a communication network have been implemented on embedded processors. By modeling the considered systems as discrete-time switched linear systems, the co-design issues have then been formulated as certain LMI optimization problems with associated quadratic cost functions. A novel event-triggering mechanism (dynamic triggering mechanism) has been introduced in [59]. The co-design problem addressed there was to design the corresponding event-triggering parameters and feedback controller so that the resulting closed-loop systems could keep stable.

The co-design problem of dynamic output feedback controller and event-triggering parameters have been proposed in [60] with data quantization. Two design approaches have been presented for both event-triggered sampled output-feedback case and periodic event-triggered output feedback case via a hybrid system model based framework. The small-gain approach has been applied in [61, 62] to cope with the design problems of event-triggering parameters for networked nonlinear systems. First, the closed-loop system under consideration has been reformulated as two subsystems. Based on the reformulation, the Lyapunov-based small-gain theorems have been utilized to design the triggering conditions. In [63], the co-design problem of output tracking controller and event-triggering parameters has been studied for a T-S fuzzy system. The resulting system has been modeled as an asynchronous threshold-error-dependent T-S fuzzy system with time-varying delay. The co-design problems of event-triggering parameters and controllers for sampled-data systems have been discussed in [64, 65]. Specifically, in [64], the L_2 control problem has been studied and criteria have been derived for the system analysis and synthesis by using the saw tooth structure characteristic of an artificial delay. In [65], the event-triggered transmission scheme has been considered in both sensor-to-controller network and controller-to-actuator network. Furthermore, both static output feedback control and dynamic output feedback control have been studied simultaneously. In [66], a non-fragile control system approach has been employed to design the event conditions in event-triggered control systems. It has been shown that the designed event condition would be less conservative and leads to larger inter-event times than the event conditions in some existing works.

3 Event-based filtering problems

State estimation and filtering problems are widely used in real engineering applications to reconstruct the system state of the plant from measurements with external disturbances. A typical event-driven filtering system is shown in Fig. 4. In this section, we will review the developments of the event-based filtering and state estimation as follows.

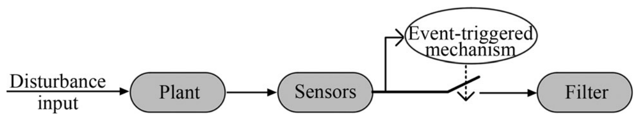


Fig. 4 A typical event-driven filtering system

3.1 Filter design issues

Recursive filtering technology is an effective tool for estimating the states of a system and has attracted significant research attention due to the widespread success of the Kalman filter in industrial applications (especially in aerospace application). In [67], an event-based sensor data scheduler has been proposed. Then, a modified recursive filter (i.e., minimum mean-squared error (MMSE) estimator) has been derived as well as an approximate estimator under the event-based sensor data scheduler. The networked estimation problem with modified send-on-delta transmission method has been investigated in [25]. In the proposed transmission method, an event-based sampling has been utilized combined with a time-triggered sampling scheme to detect packet dropouts. The structure of such a recursive filter has also been studied in [68] based on the event-based sampling scheme. The corresponding estimation performance has been analyzed under such a sampling scheme. In [69], the optimal sensor fusion problem has been studied based on the hybrid measurement information provided by a sequence of sensors.

Different from previous triggering mechanisms, a novel event-triggering mechanism called variance-based triggering scheme has been developed in [70], where the event-based state estimation problem has been considered for a stochastic linear time-invariant system. In [71], the event-based sampling strategies (e.g., send-on-delta and matched sampling) have been introduced in detail. Then, the set-membership property of the proposed triggering criteria has been derived. A modified state estimator has been developed based on the proposed set-membership measurement information. In [72], an event-based recursive filter has been developed for discrete time-varying systems with fading channels, randomly occurring nonlinearities and multiplicative noises via the recursive linear matrix inequality approach. In [73], the properties of set-valued Kalman filters with multiple sensor measurements have been explored. Furthermore, the obtained results have been applied to the event-based estimation, which could be regarded as the event-based MMSE estimation algorithm.

Recursive filtering (e.g., Kalman filtering and extended Kalman filtering) is capable to deal with the state estimation tasks with Gaussian noise. However, sometimes, accurate system models are not as readily available and the noise in many practical filtering problems is non-Gaussian. In this case, a variety of filtering algorithms have been proposed to cope with such problems. One of the most investigated one is the H_∞ filtering approach. In [74], the H_∞ filtering problem has been investigated for networked systems with an event-triggered scheme. The online scheduling strategy has been proposed based on a novel middleware in which two modules (e.g., information selection module and congestion avoidance module) have been developed. The event-based H_∞ filtering problem has been studied in [14] for networked systems with communication delay, where a new model of filtering error system has been established via a novel delay system approach with simultaneous consideration of communication delay and event-triggered scheme. By applying the Lyapunov-Krasovskii functional method combined with free weighting matrix approach, in [75], a periodic event-triggered H_∞ filter design approach has been provided for a discrete linear system. In the proposed periodic event-triggered communication scheme, the sensor has been time-triggered and the transmitter has been event-triggered in a periodic manner with the known sampling period. Then, the H_∞ filtering analysis criterion and stabilization criterion are obtained in terms of LMIs. The communication and filtering parameters have been acquired based on a co-design algorithm in a unified framework.

With respect to the sampled data systems, the event-based H_∞ filtering problem has been examined in [76, 77]. An event-based bounded real lemma has been formulated to co-design the H_∞ filters and the event parameters for the sampled-data system by employing the Lyapunov-Krasovskii functional approach. In [78], the event-based filtering problem has been studied for discrete time-varying systems in a finite-horizon. Based on the predefined event-triggered scheme, the corresponding structure of the time-varying filter has been introduced. The adaptive event-based H_∞ filtering problem has been studied in [79] for a class of T-S fuzzy systems with time delay, where the threshold of the event-triggering mechanism could be adaptively adjusted. In [80], the problem of event-triggered H_∞ filtering for networked Markovian jump system has been investigated where a dynamic discrete event-triggered scheme has been designed. A co-design scheme for the H_∞ filter and event-triggering parameters has been proposed. The event-triggered H_∞ filtering issue has been addressed in [81] for networked T-S fuzzy systems with the asynchronous constraints of the membership functions. It could be observed that the asynchronous constraints on membership functions could reduce the conservativeness of the filter design and achieve a better H_∞ performance.

3.2 Fault detection and estimation

The study on fault diagnosis is an important and challenging problem in a variety of communities including chemical engineering, nuclear engineering and automotive systems. Generally speaking, there are three different research areas for fault diagnosis: 1) fault detection (FD), 2) fault isolation (FI), and 3) fault estimation. The aim of FD is to design a residual generator based on which a decision can be made to judge whether a fault occurred. Because of the rapid developments in networked control systems (NCSs), increasing research attention has been devoted to the FD problem subject to networked environment. In [82], the event-based FD problem has been examined for a class of networked systems subject to communication delay and nonlinear perturbation. A novel event-triggered transmission scheme has been introduced with the hope to reduce the communication load. Under the proposed event-triggered transmission scheme, the event-based FD model has been developed with the consideration of network transmission delay. The general structure of the event-triggered FD algorithm has been introduced for networked control systems in [83] where the proposed event-triggered FD algorithm was compatible with various event-triggered schemes. Then, the proposed algorithm has been applied for FD of the NCS under the mixed event-triggering mechanism. Furthermore, a similar design problem has been considered where the FD algorithm was co-implemented with the control algorithm on the same processor. Finally, some concluding remarks have been drawn and some possible future research directions have been pointed out. In [84], the problem of event-triggered FD filter and controller coordinated design has been investigated for a continuous-time NCS with biased sensor faults based on the combined mutually exclusive distribution and Wirtinger-based integral inequality approach.

FI is the next step of FD process. The aim of FI is to determine the location of the fault. In the FI process, in order to enhance the isolability of the faults, the residuals should be generated with directional properties in response to a particular fault. The FI problem subject to event-triggered sampling scheme has been studied in [85] for linear stochastic systems with multiple faults. According to the proposed send-on-delta sampling scheme, a modified fault isolation filter has been developed based on a particular form of the Kalman filter. For the purpose to provide an estimation of the faults, an event-triggered fault estimator has been designed in [86] for a class of nonlinear systems. For the purpose of characterizing the features of communication network, the event-triggered transmission scheme and missing measurements phenomenon have been considered simultaneously. The corresponding fault estimator has been implemented in the form of extended Kalman filter by which the fault and states can be jointly estimated. The required parameters to be designed have been derived by solving two recursive matrix equations which are suitable for online applications.

4 Distributed control and state estimation problems

Nowadays, most of the real-world large-scale systems could be modeled as networked agent systems, where examples include biological systems, multi-vehicle systems, and distributed sensor systems. For such systems, it might be no longer valid to deal with them via centralized control or centralized state estimation schemes due to the huge requirements on communication resources and computation capability[87, 88]. As such, distributed control and state estimation schemes become necessary to deal with such systems. For distributed control and state estimation problems, nodes could exchange their information according to the underlying connection links, in which the event-triggered transmission scheme would lead to certain dynamical behaviors. A typical networked agent system with event-based communication is described by Fig. 5. In this

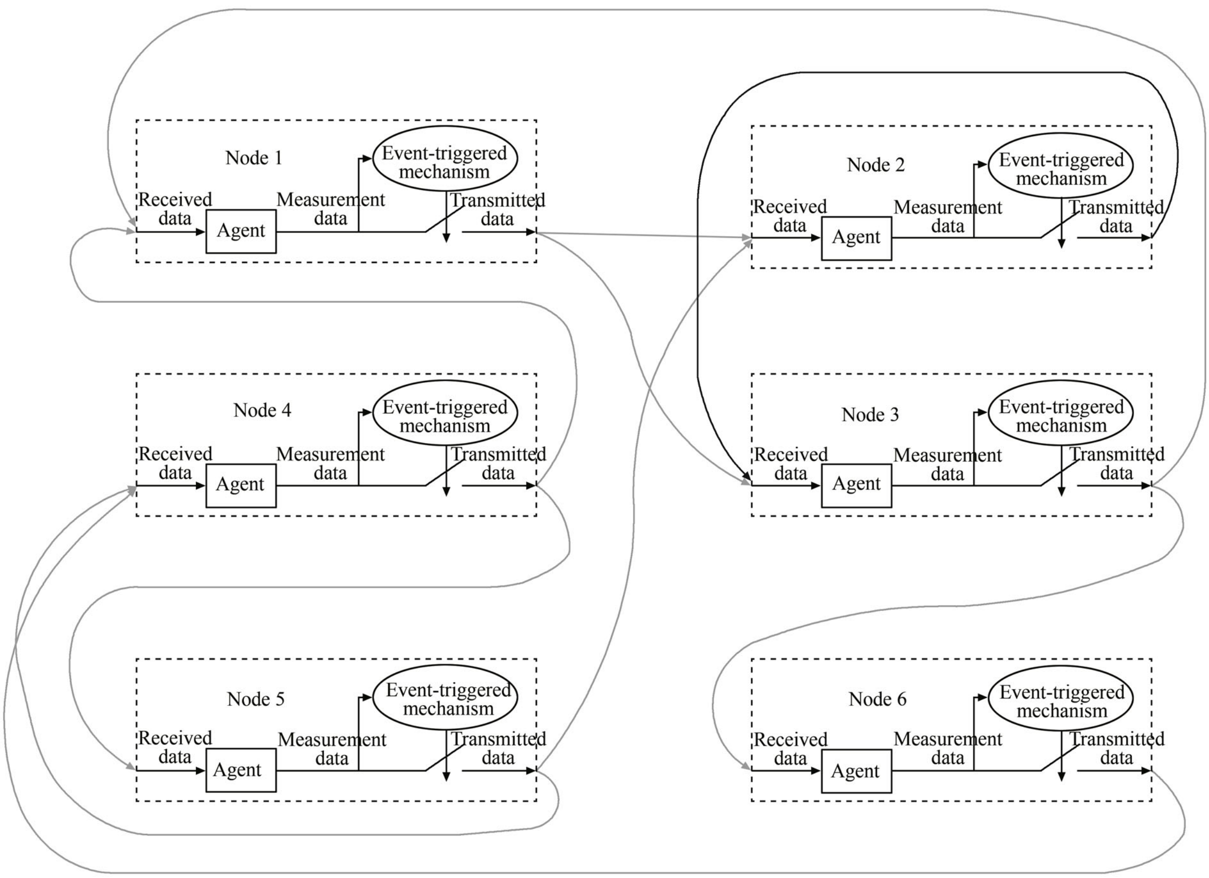


Fig. 5 An event-driven networked agent system with six nodes (RD: received data, MD: measurement data, TD: transmitted data, E-T M: event-triggered mechanism)

section, the developments of the distributed event-based control for multi-agent systems (MASs) and the distributed event-based state estimation for sensor networks (SNs) are systematically reviewed as follows.

4.1 Multi-agent systems with event-based protocols

Consensus problem for MASs has received intensive research attentions in the past decade due primarily to their practical application insights in a variety of fields[89]. Chen and Hao[90] investigated the event-triggered and self-triggered consensus control schemes for discrete-time MASs, where the event-triggering condition proposed was related to the measurement error and the disagreement vector. The distributed rendezvous problem has been studied in [91] for MASs with event-triggered controllers where a combinational measurement approach has been proposed in the event-based controller design algorithm. Based on such a design, the control of each agent is only triggered at its own event-time which could reduce the amount of signal transmissions between controllers. The event-based consensus control issue with time-dependent triggering conditions has been proposed in [92] in which the asymptotic convergence to average consensus was guaranteed and Zeno behavior was excluded. In [93], an event-based control algorithm has been proposed to achieve the consensus performance for MASs with fixed topology via sampled data. The consensus problem has been studied in [94] for discrete-time heterogeneous MASs with random communication delays represented by a Markov chain and event-triggered control protocols, where the mean square stability of the closed-loop MASs has been studied analyzed based on the Lyapunov functional method and the Kronecker product technique. In [95], the event-triggered transmission scheme has been examined for distributed control systems with packet loss and transmission delays. Intensive analysis has taken place for both linear and nonlinear subsystems via ISS design technology and LMI technology. Sampled data control scheme is a widely used method in networked control systems. In [96], the event-triggered sampled-data consensus problem has been investigated for MASs with directed graph. The MAS-based event-triggered hybrid control problem has been considered in [97] for intelligently restructuring the operating mode of a micro-grid (MG) to ensure the energy supply with high security, stability and cost effectiveness.

In MASs, asynchronous sampling means that the sampling of each agent does not happen at the same time. In [98], the consensus problem has been investigated for first-order MASs under linear asynchronous decentralized event-triggered control scheme, where both the undirected and directed topologies have been considered. The consensus problem has been studied in [99] for MASs with randomly occurring nonlinear dynamics and time-varying delay based on stochastic analysis approach and Kronecker product technique. Both centralized and distributed event-triggered cooperative control strategies have been proposed in [100] for MASs with linear dynamics based on output feedback control scheme. The leader-following event-triggered asynchronous sampling scheme has been studied in [101] for second-order multi-agent systems. It has been shown that the inter-event intervals are lower bounded by a strictly positive constant, which could exclude the Zeno-behavior. The leader-follower flocking problem has been proposed in [102] for MASs via a new hybrid control algorithm where the signal transmissions are governed by a distributed event-triggering mechanism. In [103], the finite-time distributed event-triggered consensus control problem has been investigated for MASs based on the finite-time stability theory. The event-triggered leader-follower tracking control problem has been studied in [104] for MASs with general linear dynamics for both undirected and directed follower graphs. In [105], the consensus problem has been considered for second-order MASs where the data is sampled randomly and transmitted based on the event-triggering mechanism according to the topology governed by a directed spanning tree. The obtained results have been further extended to other practical control applications where the agents have been equipped with limited capability microprocessor.

4.2 Sensor networks with event-based transmissions

In the past few decades, a rich body of literature has appeared on the distributed state estimation problems for sensor networks (SNs) due mainly to the insight of their engineering applications, see [106−108] and the references therein. It is worth mentioning that the research on event-based state estimation problem is of great importance for SNs since it is usually crucial to ensure the efficient communication and energy consumption. This is particularly true for wireless SNs, where the sensors are battery-operated and communication resources are often a concern. In this case, event-based transmission scheme serves as a natural alterative for the smooth operation of the SNs. In [109], the event-triggered distributed H_∞ state estimation problem has been investigated for a class of discrete-time stochastic nonlinear systems with packet dropouts in a SN, where the innovation information of each sensor node has been transmitted only when certain triggering condition has been violated. The event-based distributed state estimation problem has been addressed in [110] for nonlinear discrete-time delayed systems over SNs with event-triggered communication scheme. Different from the innovation-based triggering condition proposed in [109], the event-triggering mechanism of [110] is implemented based on the local measurement of each sensor node (i.e., measurement-based triggering mechanism). Based on the innovation-based triggering mechanism, the distributed H_∞ consensus filtering problem has been studied in [111] for mobile SNs via sampled measurement. A unified co-design algorithm for the filter gains and triggering parameters has been given. In [112], the distributed state estimation algorithms have been established for linear time-varying discrete-time systems with event-triggered transmission scheme over wireless SNs. Corresponding stability analysis has been proposed. The event-triggered distributed state estimation problem for uncertain stochastic systems with state-dependent noises has been considered in [113], where the norm-bounded uncertainty has been supposed to be occurred in a random way, which has been modelled by the Bernoulli distributed white sequences with known conditional probabilities.

The event-based distributed filtering problem for continuous-time Itô stochastic systems has been investigated in [114] over the wireless SNs subject to finite resources and stochastic measurement fading. An adaptive algorithm for determining the triggering parameter has been developed, by which the intelligent sensors have been allowed to tune the boundary of a local event domain in an online manner. In [115], the recursive distributed filtering technology has been developed for a class of discrete time-varying systems with event-based communication scheme, where the upper bound for filtering error covariance could be computed recursively by solving a Riccati-like matrix equation. The distributed event-based H_∞ filtering problem has been studied in [116] for continuous-time linear time-invariant systems over SNs with communication delays. In [117], the event-triggered distributed state estimation problem has been considered for a class of discrete nonlinear stochastic systems with time-varying delays, randomly occurring uncertainties and randomly occurring nonlinearities. The estimator has been designed by constructing a Lyapunov-Krasovskii functional and employing the delay-fractioning approach. The Kalman consensus filter has been developed in [118] for linear time-varying systems over SNs with event-triggered transmission scheme in which the triggering decision was based on the send-on-delta data transmission mechanism. The event-based distributed set-membership filtering problem has been investigated in [119] for time-varying nonlinear systems over SNs subject to saturation effects. In [120], the event-triggered distributed filtering algorithm has been presented for non-Gaussian systems over wireless SNs. The boundedness of the presented distributed filter parameter has then been analyzed. In [121], the distributed estimation problem is examined for networked systems with network-induced delays and dropouts as well as the event-based communication scheme. The estimator′s structure of each agent is designed based on local Luenberger-like observers with consideration of consensus strategies. The event-triggered distributed state estimation problem is examined in [122] for large-scale systems over a wireless network. A global event-based communication policy is introduced to minimize the weighted function of the network energy consumption and the number of transmissions. The proposed minimization problem is solved based on a distributed 1-step greedy heuristic.

5 Some challenging issues

In the past decade, we have witnessed significant progress on the event-based control and filtering issues for various networked systems, and a large number of results have been reported on such topics. In this section, we highlight some challenging problems with respect to these topics.

5.1 Analysis on the communication performance

The main idea of event-triggering mechanism is to reduce the signal transmission frequency while guaranteeing a satisfactory system performance. The signal transmission frequency is largely dependent on the threshold of the event-triggering condition. Generally speaking, a big threshold would lead to a low signal transmission frequency. However, it is still difficult to evaluate the exact communication performance of an event-driven networked system. In other words, the "average transmission rate" and the "maximum transmission rate" are still difficult to derive for a networked system with the known event-triggering condition. Shi et al.[123] considered the event-triggered state estimation in the framework of maximum likelihood estimation. Furthermore, for the one-step problem, the calculation of upper and lower bounds of the transmission rates from the process side has also been briefly analyzed. In [73], the event-based state estimation problem has been studied where the triggering conditions could be designed by considering requirements on performance and transmission rates. In [67], a minimum mean-squared error estimator has been developed. Moreover, an illustrative relationship between the transmission rate and the estimation quality has been achieved. It should be pointed out that, up to now, the corresponding results concerning the analysis on communication performance are very scattered for event-driven networked systems with different networked-induced effects (e.g., communication delays, quantization effects) due primarily to the difficulty in the mathematical analysis on the effects induced by the event-triggering mechanism.

5.2 Self-triggered control and filtering

Event-triggering mechanism is implemented based on the generation of the "event", which requires special hardware to detect the measurement output frequently. The hardware could be realized by application-specific integrated circuits (ASIC) of field-programmable gate array (FPGA) processors. Hence, event-triggering mechanism would inevitably lead to additional cost of energy in order to keep the sensor awake and computing unceasingly. As such, the self-triggered strategy has been explored to "calculate" the transmission instant in the absence of continuous monitoring of the measurement output. The self-triggered mechanism represents a model-based emulation of the event-triggering mechanism by replacing the detection task by certain admissible "prediction", which could be computed by the software. More specifically, the next triggering instant is precomputed by the previously transmitted data and the knowledge of the system dynamics. In [124], an introductory overview on the event-triggered and self-triggered control problems has been presented. Some existing results on networked systems with self-triggered mechanisms have been reported in [125−128]. However, the corresponding results concerning self-triggered control and filtering problems are very scattered for nonlinear systems and complex systems with various networked-induced phenomena. Furthermore, how to predict the triggering instant with less conservatism is another challenging topic.

5.3 Triggering mechanisms

As we introduced in Section 1.2, there are two triggering mechanisms widely adopted in the literature: the fixed threshold triggering and the relative threshold triggering. One of the main difficulties for event-driven networked systems is to design suitable event-triggering mechanism guaranteeing that a positive minimum inter-event time existed (Zeno behavior could be avoided). In [59], a novel event-triggering mechanism named dynamic triggering mechanism has been introduced where an internal dynamic variable satisfying certain differential equation is employed to generate the event-triggering condition. In such a triggering condition, the information about the error-based part from the previous transmission instant to the current time instant has been considered. Such a triggering mechanism has been improved in [129] in which an auxiliary parameter has been added to provide a lower bound on the minimum inter-event time. In [27], a new integral-based event-triggering mechanism has been developed for a class of nonlinear systems. It has been shown that the event-driven system with such a triggering mechanism is more efficient and less conservative than the corresponding system introduced in [16]. So far, the corresponding results concerning other triggering mechanisms (excluding the fixed threshold triggering and the relative threshold triggering) are very scattered. How to develop other suitable triggering mechanism is a challenge topic worthy of further investigation.

6 Conclusions and future work

In this paper, we have discussed and reviewed results, mostly from relatively recent work, on the problems of event-based control and filtering for networked systems. Various event-based control problems and event-based filtering (or state estimation) problems have been surveyed in great detail for different networked systems. Based on the literature review, some related topics for the future research work are listed as follows.

1) The main purpose to design the event-based controllers or event-based filters is to provide a trade-off between the system performance and the communication utilization efficiency. Hence, it would be a promising research topic to analyze the relationship between the system performance and the "average transmission rate" induced by the event-triggering mechanism.

2) So far, two event-triggering mechanisms have been widely studied, e.g., fixed threshold triggering (or send-on-delta triggering) mechanism, and relative threshold triggering mechanism. Some modified event-triggering mechanisms could be further considered (e.g., dynamic triggering mechanism introduced in [59]).

3) Event-triggering mechanism should be implemented based on certain component called "event generator" which would increase the cost of networked systems. As such, self-triggering mechanism becomes an alternative scheme to improve the communication utilization efficiency. Therefore, it leads to a particularly attractive area for developing controllers and filters based on self-triggered transmission schemes.

4) The nonlinearities addressed have some constraints that may bring somewhat conservative results. A trend for future research is to study the co-design problems of event-triggering conditions and controllers (or filters) parameters for nonlinear stochastic systems.

5) Another future research direction is to discuss the applications of the established theories and methodologies to some practical engineering problems such as smart grids and mobile robots.

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Lei Zou received the B. Sc. degree in automation from Beijing Institute of Petrochemical Technology, China in 2008, the M. Sc. degree in control science and engineering from China University of Petroleum (Beijing Campus), China in 2011, and the Ph. D. degree in control science and engineering from Harbin Institute of Technology, China in 2016. From October 2013 to October 2015, he was a visiting Ph. D. student with the Department of Computer Science, Brunel University London, UK. He is a very active reviewer for many international journals.

His research interests include nonlinear stochastic control and filtering, as well as networked control under various communication protocols.

E-mail: zouleicup@gmail.com
ORCID iD: 0000-0002-0409-7941

Zi-Dong Wang received the B. Sc. degree in mathematics from Suzhou University, China in 1986, the M. Sc. degree in applied mathematics in 1990 and the Ph. D. degree in electrical engineering in 1994, both from Nanjing University of Science and Technology, China. He is currently a professor of dynamical systems and computing in the Department of Computer Science, Brunel University London, UK. From 1990 to 2002, he held teaching and research appointments in universities in China, Germany and UK. He has published more than 300 papers in refereed international journals. He is a holder of the Alexander von Humboldt Research Fellowship of Germany, the JSPS Research Fellowship of Japan, William Mong Visiting Research Fellowship of Hong Kong. He is a fellow of the IEEE. He is serving or has served as the editor-in-chief for *Neurocomputing*, an associate editor for 12 international journals, including *IEEE Transactions on Automatic Control*, *IEEE Transactions on Control Systems Technology, IEEE Transactions on Neural Networks, IEEE Transactions on Signal Processing*, and *IEEE Transactions on Systems, Man, and Cybernetics-Systems*. He is also a fellow of the Royal Statistical Society and a member of program committee for many international conferences.

He research interests include dynamical systems, signal processing, bioinformatics, control theory and applications.

E-mail: Zidong.Wang@brunel.ac.uk (Corresponding author)
ORCID iD: 0000-0002-9576-7401

Dong-Hua Zhou received the B. Eng., M. Sc., and Ph. D. degrees in electrical engineering from Shanghai Jiaotong University, China in 1985, 1988, and 1990, respectively. He was an Alexander von Humboldt research fellow with the University of Duisburg, Germany from 1995 to 1996, and a visiting scholar with Yale university, USA from 2001 to 2002. He joined Tsinghua University, China in 1997, and was a professor and the head of the Department of Automation, Tsinghua University, China from 2008 to 2015. He is now the vice president of Shandong University of Science and Technology, China. He has authored and coauthored over 140 peer-reviewed international journal papers and 6 monographs. He is a member of the IFAC Technical Committee on Fault Diagnosis and Safety of Technical Processes, a senior member of IEEE, an associate editor of *the Journal of Process Control*, the associate chairman of Chinese Association of Automation.

His research interests include fault diagnosis, fault-torrent control, process control, networked control and filtering, and reliable control.

E-mail: zdh@mail.tsinghua.edu.cn