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REVIEW

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The event-based strategies have recently received considerable research attention due primarily to their irreplaceable superiority in resource-constrained systems. Compared with the widely adopted time-driven schemes, such novel event-based schemes have advantages of improving the efficiency in resource utilization in many real applications. Event-based strategies represent an effective way of generating sporadic executions, where an execution is generated only when a specific event (e.g. a certain signal exceeds a prescribed threshold) arises. In this survey, we aim to summarize the results available in the literature on event-based strategies so as to promote the related research in this realm. The progress of the event-based design and analysis strategies is systematically reviewed in both control and estimation domains. Specifically, the event-based control strategies have been discussed for networked control systems, multi-agent systems and other systems, and the event-based estimation schemes have been highlighted according to the send-on-delta and send-on-area concepts. Some potential future research directions are finally pointed out for event-based strategies.

Keywords: optimal control; feedback control; networked control

1. Introduction

The past few decades have seen rapid developments of computer technologies. As a result, the discrete-time systems are becoming increasingly important especially after the emergence of embedded microprocessors. Compared with the traditional analog equipment, such small and flexible digital microprocessors have the advantages of decreasing the energy consumption and the installation cost. As such, they are gradually forming an essential part of many diverse applications. As is well known, in discrete-time systems, only the samples of signals at discrete-time instants can be employed. A crucial issue is that how to choose the appropriate sampling intervals. In the widely used sample data or time-driven control, the signals are sampled equidistantly in a periodic manner. This periodic strategy is a good one for its simplicity in analysis and design. On the other hand, in some small-sized but high-integrated embedded systems, the space for power modules is limited and the energy supply could not be inexhaustible. Hence, it is of both theoretical significance and practical importance to improve the energy efficiency during the running time of embedded systems for the sake of extending their service lives.

In the traditional time-driven control scheme, the system adjusts the actuator state at every sampling instant. Such a time-triggered mechanism would inevitably cause frequent changes of the actuator state and therefore leads to unnecessary energy consumption as well as actuator attrition. For this reason, some researchers have started to resort to the event-based approaches in order to overcome these disadvantages. Specifically, in event-based strategies, the actuators are modulated only when certain conditions are satisfied in event-based strategies. A nice feature of event-based approaches is that it could guarantee both stable performance and energy utilization efficiency in the target systems. To see an implementation of such an event-based mechanism, we refer the reader to a simple example of event-based proportional-integral-derivative control in the work (Årzén, 1999).

Since the real-time status of controlled systems is always changing during operations, an aperiodic schedule, which adjusts control signals based on the current information of systems, seems more appropriate than a periodic one. Actually, the event-based approach is one of the aperiodic scheduling mechanisms, which aim to decrease the execution rate by impelling systems operated in an open-loop manner during execution intervals until the next update comes (Åström & Bernhardsson, 2002). Let us consider a simple event-based control problem, in which we desire to keep the plant state in a specified area when time tends to infinity. To be more specific, the control signals are triggered/updated to be modulated only when the states leave the prescribed area, otherwise system dynamics remains unchanged. This way, the state is forced back into the desirable area by relatively fewer adjustments. However, when the system state approaches its equilibrium point, the execution instants may be too close to each

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other. This highly undesirable phenomenon is called Zeno-sampling, and it will force the system to sample excessively fast (Ames, Tabuada, & Sastry, 2006; Lemmon, 2010). Consequently, to make the event-based control strategies applicable, the existence of lower bound of executions should be guaranteed. Moreover, a difference always exists between the actual input signals and the triggering ones because event-based approach only updates the signals at triggering instants, which results in some difficulties in control or estimator synthesis. Despite its superiority over the time-driven approach, the event-based scheme actually abandons many dispensable executions to avoid the consumption of resources. In other words, certain control/estimation performance would have to be sacrificed to meet the reasonable resource allocation. Therefore, the primary challenge of event-based approach is to co-design the control law and event triggering criteria so as to balance both system performance and employment of limited resources.

2. Theoretical analysis of event-based control

In this section, we will recall the theoretical developments of event-based control in the recent years from various aspects including networked control systems (NCSs) and multi-agent systems.

2.1. Networked control systems

A NCS is a digital control system whose components, such as actuators, sensors and controllers, are spatially distributed. Among system components, the information is transmitted in the form of successive data packets through communication networks. In recent years, NCSs have become increasingly prevalent due to their advantages of high reliability, low installation, maintenance costs, etc. Although the network infrastructure brings us numerous benefits, some highly undesirable network-induced phenomena are encountered in the communication process, such as time delays in the information transmission, randomly occurring dropped packets, quantization distortions, etc. For this reason, one of the performance indices in NCSs is to minimize the adverse influences induced by the network and reduce the occupancy of network bandwidth by designing a control scheme with possible long execution intervals in order to spare the resource for other purposes. As a result, novel event-based approaches in NCSs have received considerable research attention and many results have been reported in recent years. Particularly, many results derived in embedded systems under event-based control could be regarded as a special case of NCSs from the aspect of underlying design methodologies, and therefore they will not be discussed separately in this survey.

In Wang and Lemmon (2008, 2011a) the authors have presented preliminary results of control synthesis for systems with event-based schemes, where the controllers have been designed to ensure the asymptotic/exponential stability of the closed-loop systems under the assumption of input-to-state stability with respect to measurement errors. In Garcia and Antsaklis (2011), a schedule called fixed threshold strategy (FTS) has been proposed to guarantee the bounded-input bounded-output stability of the controlled system, where the switching boundary is determined a priori as a fixed positive constant. When the boundary is set to zero, the event-based approach will reduce to the time-driven one. Furthermore, a relative threshold strategy has been investigated to adjust the diameter of the boundary in proportion to the norm of the system state. It is clear that the controlled system is asymptotically stable and the plant state will be driven to a decreasing area. Many established results referring to event-triggering schemes are in the framework of continuous-time systems, while some results have been extended to control discrete-time systems, see Eqtami, Dimarogonas, and Kyriakopoulos (2010). In fact, such a discrete-time controlled system does has its inherent benefit, for instance, the lower bound of execution intervals would be no shorter than the sampling period. However, for those continuous-time systems, the desired lower bound on execution interval (if it exists) is rather difficult to design under the complicated impacts of the system parameter settings.

To deal with event-based control strategies for linear NCSs, several different analysis approaches have been proposed in Heemels, Donkers, and Teel (2012) and Heemels and Donkers (2013) as follows: (1) an impulsive system approach; (2) a discrete-time piecewise linear (PWL) system approach and (3) a discrete-time perturbed linear (PL) system approach. The impulsive system approach exactly reveals the inter-sample behaviors of event-based control, and the PWL system approach models the controlled system as piecewise functions. The PL system approach regards the control errors introduced by events as a disturbance of the nominal system, and thus it naturally resorts to the perturbation method for further analysis (Khalil, 2002). Most of the existing results have been based on the PL approach, see, e.g. Tabuada (2007), Meng and Chen (2012), Garcia and Antsaklis (2013) and so on. However, it is still noteworthy that, compared with the first two approaches, this PL system approach usually establishes a more conservative stability condition. In addition, in the works Hu and Yue (2012a) and Yue, Tian, and Han (2013), for the convenience of analysis and synthesis, a delay system method has been proposed to investigate the NCSs with transmission delays under the event-based scheme. Unlike the aforementioned works (Garcia & Antsaklis, 2013; Meng & Chen, 2012; Molin & Hirche, 2013; Tabuada, 2007), the event generator monitors the triggering condition in a discrete-time manner instead of a continuous one. Since the lowest execution intervals are determined by discrete-time supervision instants, there is neither accumulation point nor Zeno-sampling phenomenon during the running process of the system. In addition, another nice feature lies in the fact

that this discrete-time event generator can be conveniently implemented by a digital embedded device.

Sometimes, there are a large number of data packets competing to pass through the network with constrained bandwidth, which gives rise to some adverse network-induced factors including randomly occurring packet losses, communication delays, etc. These network-induced phenomena inevitably degrade the system performance or even result in instability. In such situations, the time delays and packet losses have been taken into consideration in Wang and Lemmon (2009, 2011b) under the framework of event-based approaches. These works have predicted the allowable upper bound of transmission delays and the maximal number of successive dropouts by a distributed algorithm. In particular, only the local information of subsystems has been utilized, which makes the algorithm applicable in practical application. In Premaratne, Halgamuge, and Mareels (2013), the event-triggered adaptive differential modulation has been proved to be robust to packet droplets. These works (Meng & Chen, 2012; Tabuada, 2007) have considered the time delays between the measuring and updating process in embedded microprocessors. In fact, certain event-based control schemes could naturally compensate time delays induced by the communication network in the case that the prior knowledge about time-delay statistics is provided. Additionally, another important factor in digital networks that should be investigated is the quantization effect, which may influence both process output and control input. Some original results have been reported in Premaratne et al. (2013), Garcia and Antsaklis (2013) and Hu and Yue (2012a). For example, in Hu and Yue (2012a), linear matrix inequalities (LMIs) have been utilized to analyze and synthesize the network control systems with quantized measurements. Besides, with regard to differential modulation technique for NCSs, the event-based ideology has also been adopted to trigger sampling executions if the step size exceeds the prefixed threshold to reduce traffic reduction, see Premaratne et al. (2013).

In addition, it is worth mentioning that there usually exist model parameter uncertainties in many practical applications. Therefore, in Garcia and Antsaklis (2012, 2013) and Hu, Yin, Zhang, and Tian (2012), some researchers have proposed model-based periodic event-based control strategies for discrete-time linear plants subject to disturbances and model uncertainties. The model-based technologies, which construct model-based predictors running both at the sensor and the controller system, have been well recognized as an effective method in reducing the impact of model uncertainties in the absence of continuous feedback signals. Compared with the traditional open-loop event-based control, in this case, continuous close-loop signals for real-time control can be generated using predictors with aperiodic updates. Furthermore, in Heemels and Donkers (2013) the authors have investigated the model-based periodic event-triggered mechanism under two general analysis frameworks of PL systems and PWL systems.

Over the past 10 years or so, event-based control of distributed NCSs has gained increasing attention from researchers. It is obvious that, in the centralized triggering schemes, the global information is demanded for event generators to determine synchronous execution instants, which may lead to the overburden of communication networks as well as a waste of energy. Some alternative event-based distributed strategies have been proposed to alleviate the occupation of network, see, for example, the works in Heemels et al. (2012), Wang and Lemmon (2008), Wang, Sun, and Hovakimyan (2012), Mazo and Tabuada (2011) and Donkers and Heemels (2012). Nevertheless, we can see that the decentralized triggering conditions are more conservative than the centralized ones, namely, the average execution intervals are usually shorter in the decentralized case. Consequently, a zero-sum set of on-line adaptation parameters scheme has been proposed to reduce this conservation (Mazo & Tabuada, 2011).

2.2. Multi-agent systems

Very recently, the cooperation of multi-agents has been an increasingly popular topic for its potential prospects in variety realms such as military, industry, etc. Up to now, numerous results concerning the formulation, rendezvous and leader-following problems in multi-agent systems have been reported. Essentially, the multi-agent systems constitute a subset belonging to the distributed systems, where each intelligent agent utilizes the available information from not only itself but also its neighboring agents for the purpose of collectively performing certain tasks or actions (Olfati-Saber & Murray, 2004). A paramount problem is how to appropriately design the distributed algorithms for both communication protocol and control scheme. In general, these distributed agents are equipped with small but high-integrated microprocessors. These mini-processors guarantee the regular communication between neighbor agents and calculate the control signals for the actuators. In terms of traditional distributed strategies, signal transmissions and updates should be executed at every sampling instant. It increases the risk of some undesired phenomena, including communication congestion as well as frequent modulation of actuators, which might have a destructive impact on the network environments and damage the lifespan of actuators, respectively. Motivated by the discussion above, an alternative aperiodic approach named event-based consensus protocol has been introduced into multi-agent systems with limited resources. In this framework, plenty of redundant executions would be abandoned because the actuators are modulated only when some specific events happen. Hence, it is natural that event-based approaches are more favorable than time-driven ones for actual multi-agent systems.

Generally, the consensus protocol for multi-agent systems calls for the information exchanging between neighboring agents in a periodic mechanism (Olfati-Saber &

Murray, 2004). An important aspect in the implementation of event-based strategies lies in the communication and control schemes. There are two event-based consensus protocols in the existing literature: (1) centralized event-based consensus control and (2) decentralized event-based consensus control. In terms of centralized event-based approaches, there is only a single-event generator determining the global triggering instants for each agent to broadcast the local information and update control input at the same time. On the other hand, decentralized approaches require every smart agent to equip event generators in order to transmit their local information to neighborhoods in asynchronous instants rather than the synchronous ones. Besides, after receiving the broadcast, the agents only need to update the corresponding control input from the message sources. It is obvious that the decentralized event-based approaches own the inherent advantages since they do not demand a triggering center to guide the behaviors of the multi-agent systems.

In Teixeira, Dimarogonas, Johansson, and Sousa (2010), an event-based communication strategy has been proposed to ensure the target configuration of vehicles, whose motion can be described as a single-integrator with external disturbances. Concerning centralized event-based approaches with the global information, some conclusions have been reached, see Tang, Liu, and Chen (2011), Chen and Hao (2012) and Hu (2012). In Tang et al. (2011), the formulation control of multi-agent systems has been addressed. In Chen and Hao (2012), LMIs have been utilized to investigate the average consensus problem in discrete-time systems with the predefined event generator condition. For second-order multi-agent systems, an event-based mechanism has been presented to guarantee the stability of systems under limited resources in Hu (2012). However, despite the fact that centralized triggering approaches are relatively simple to implement, every agent has to know the global information in order to decide the next triggering instant. Consequently, to address the challenges of reasonable bandwidth allocation, a decentralized event-based control mechanism has been introduced in Hu et al. (2011a, 2011b), Dimarogonas, Frazzoli, and Johansson (2012) and Liu, Chen, and Yuan (2012). To be specific, the authors have considered the second-order leader-following multi-agent systems with partial observations in Hu et al. (2011a). The velocity of the active leader remains unknown but could be estimated for the following agents. Based on the framework of Hu et al. (2011a, 2011b), the event-based control problem has been addressed with partial observations and communication delays, where some partially uncertain acceleration exists in the dynamic system of the active leader. Insights on event-based control for multi-agent systems in a fixed undirected network topology has been proposed in Dimarogonas et al. (2012), where both centralized and decentralized manners are applied to a first-order agreement problem. Additionally, a self-triggered strategy has been explored to calculate the next sampling instant in the absence of the system state. In Liu et al. (2012), the authors have discussed the event-based average consensus problem under the assumption of directed and weighted communication topology.

However, it is worth mentioning that, for many established decentralized event-based approaches, the event generator located in each agent utilizes real-time information from its neighboring agents, such that each agent has to broadcast the states at every sampling period to keep all its neighbors informed about its local information. This framework may result in the additional energy consumption of agents and go against the original intentions of event-based approaches. Some appropriate triggering conditions have been established to avoid this unreasonable requirement. Specifically, in Fan, Feng, Wang, and Song (2012), the rendezvous problem has been solved by a distributed event-based method, and then an iterative algorithm has been proposed to deal with the continuous measurements of the neighbor states. A novel triggering strategy independent of the real-time state of neighbors has been further investigated in Seyboth, Dimarogonas, and Johansson (2012) for both single-integrator and double-integrator agents, and therefore the continuous monitoring is no longer needed. Nevertheless, a drawback of this strategy is that the global network topology should be available to each agent in order to appropriately design the distributed event generator strategies. Moreover, the consensus problem of discrete-time heterogeneous multi-agent systems of single-integrator and double-integrator agents has been explored under distributed event-based control in Yin, Yue, and Hu (2013). Based on the Kronecker product and Lyapunov functional method, the feedback gain matrices have been designed to guarantee the agreement. Furthermore, in Yin and Yue (2013), the event-based control of discrete-time heterogeneous multi-agent systems with Markov communication delays has been addressed.

2.3. Other aspects

The T–S fuzzy model approach plays an important role in the study of nonlinear systems since it could give an approximation of a class of nonlinear systems. By a set of If–Then rules, they could exactly describe nonlinear systems' characteristics with a linear representation (Takagi & Sugeno, 1985). A discrete-time event-based communication protocol and a parallel distribution compensation controller have been appropriately co-designed as to trade-off communication bandwidth utilization and stability of controlled continuous-time T–S fuzzy system in Peng, Han, and Yue (2013). Similar with Yue et al. (2013), the system with transmission delays under the event-based mechanism is transferred into a time-delay description to simplify the further analysis.

Trajectory tracking control problems, which guarantee the system state to track a prescribed time-varying reference trajectory, have significant importance in diverse

applications such as industrial manufacture, economics, etc. Recently, for the sake of reducing unnecessary waste of resources, some traditional time-driven works on tracking control have been extended into event-based ones. On the basis of the delay system approach, the work (Hu, Zhang, & Du, 2012) has addressed the H_∞ tracking control with an event-based scheme for networked systems with time-varying delays. Moreover, in Tallapragada and Chopra (2013), the event-based condition and control law have been designed to guarantee the uniform ultimate boundedness of the tracking error for nonlinear systems.

3. Event-based estimation

Filtering or estimation problems have received lots of attention over the past decades. They have been widely brought into practical applications to restore the state vector of the plant from observations with external disturbances. In traditional filtering algorithms (e.g. Kalman filter, Welch & Bishop, 2001), the synchronous innovations are required in every iteration cycle, so that the fixed sampling period should be designed under the worst conditions. Moreover, with the development of network technologies, nowadays many industrial manufacturers have introduced the networked environment infrastructures due to their capability of reducing the implementation difficulties and increasing the equipment reliability. System parameters (e.g. temperature and pressure) are usually transmitted to data centers via communication channels to solve the filtering problems in networked systems. However, the waste of bandwidth arises from the transmission of unnecessary information in the time-driven strategy. It is well known that the event-based estimation is a highly effective alternative scheme aiming to enlarge the execution intervals, which has both engineering significance and practical importance. As a result, it has recently become a hot research topic and has attracted an increasing interest in constrained resources systems.

In Miskowicz (2006), the triggering mechanism is based on a send-on-delta (SOD) regulation, namely, only when the measurement values change more than a predetermined threshold Δ, the sensors transmit their sampling data to data centers for processing. Besides, the advantages of the SOD concept over a time-driven one have been fully discussed. After that, in Le and McCann (2007), an event-based approach has been investigated to estimate the system states with intermittent measurements by a modified Kalman filter. Furthermore, in Nguyen and Suh (2007) and Suh, Nguyen, and Ro (2007), the authors have considered the hybrid update strategy to reduce the filtering error of the remote filters without real-time innovations. When there are no new measurements, it can recognize that the difference between the present and the latest measurement values is limited within a bounded subset of the measurement space. Furthermore, the posterior probability of estimation can be updated with such bounded subset. One major issue

of the SOD scheme pointed out in Miskowicz (2007) is that this FTS cannot detect the steady-state error or small state oscillation, which undesirably reduces the estimation performance. Additionally, since these methods are sensitive to the process noise, which will frequently cause unnecessary triggering, a send-on-area triggering approach has been proposed in Nguyen and Suh (2008) to overcome these disadvantages by utilizing the integral of such difference instead.

Based on the fundamental ideas above, some papers use standard probability density function to set up a general mathematical description of this event-based hybrid update scheme, see Sijs and Lazar (2009, 2012) and Wu, Jia, Johansson, and Shi (2013). Not confined to the traditional SOD scheme, a more general bounded Borel set in discrete-time measurement space is under consideration to denote the triggering area (Sijs & Lazar, 2009, 2012). Moreover, a summation of Gaussians has been employed to approximate its probability distribution function so that one can minimize the computational complexity. In Li, Lemmon, and Wang (2010), a remote estimator has been put forward to minimize the mean square error by a sequence of special measurements satisfying triggering rules. Other works that have presented the minimum mean-squared error (MMSE) estimator with an event-based scheme can be found in Sijs and Lazar (2009) and Wu et al. (2013). Similarly, an approximation technique from nonlinear filtering is exploited to derive an approximate MMSE estimator for computational convenience. Concerning nonlinear systems, the event-based particle filtering and vector quantization methods have been proposed to estimate the plant's state in Cea and Goodwin (2012).

Recently, some results about event-based estimation have been reported under the framework of event-based methods. For networked systems, H_∞ filtering problems have been addressed to estimate the state of the plant in Hu and Yue (2012b), where the new measurements are triggered in an aperiodic manner and transmitted over a bandwidth-limited network with communication delays. The LMIs have been employed to appropriately design the filter parameters that guarantee both the exponential stability and the noise energy attenuation at a certain level. The results have been extended to solve state estimation in delayed recurrent neural networks in Li (2012). It is well worth mentioning that the triggering mechanism of these two papers is quite different from existing SOD schemes. Since the threshold figuring the triggering area is tuned according to an adaptive value, one can see that this threshold will decrease along with the decline of estimation errors. Obviously, such an adaptive threshold will ultimately eliminate the negative influences of steady-state error and small state oscillations.

Moreover, the event-based scheme has been further utilized in fault diagnosis in the literature (Li, Sauter, & Xu, 2011), where the authors presented a modified fault

isolation filter (FIF) for discrete-time NCSs with multiple faults. Unlike the traditional time-driven FIFs, the measurements are available for the modified filter in this paper only when the prescribed events are triggered.

4. Conclusions and future work

Throughout the paper, we have presented an overview of the recent progress on novel event-based strategies available in the current literature, which can be divided into two main domains as control and filtering. In fact, they share the identical standpoint in terms of event-based approaches, that is, to reduce the unnecessary executions on the premise of prescribed performance. However, there are some essential differences between event-based control problems and estimation or filtering problems. In the controlled systems, when considering the event-based scheme, the event generation function generally relies on the difference between the current system state and the latest updated one. It can be seen that the plant state would have impacts on the output of triggering function in return. Hence, the design of such a function plays an important role in the stability of controlled systems. On the contrary, in terms of estimation or filtering problem, the filtering system stability apparently has no correlation with the values of the event-generation function. Consequently, researchers should focus on how to define an appropriate sampling mechanism to catch the significant change of the state of target systems.

Finally, based on the literature review, we conclude this paper with some related directions for the further research works as follows:

(1) As we know, the intrinsic design methodology of the proposed event-based approach is to provide a trade-off between the system performance and the resource utilization efficiency, thereby it would be a promising research topic to analyze and synthesize an event-based strategy with a comprehensive evaluation index, where few related works have been published in this realm.

(2) In the current literature, the majority of event-based control problems usually make the prior assumption that event generator functions are established in advance and then the suitable control laws are calculated in order to ensure the stability of the original system. Therefore, it will be interesting to seek a novel method to co-design both the controller laws and the event generator condition with certain index.

(3) Moreover, the event generator conditions available in most current works are conservative, in other words, some loose conditions could be easily found to guarantee the stability of practical systems with similar performance but better resource utilization. Future works may be involved in studying how to construct an exact mathematical description of event-based systems and find an appropriate analysis technology to obtain less conservative event generator conditions.

(4) Furthermore, modified event generator mechanisms should be considered for stochastic systems to prevent frequent event triggering that results from external disturbances, especially, for the systems whose event-triggering thresholds trend to a small positive value as time goes on.

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