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Event-predictive Control for Energy Saving of Wireless Networked Control System

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Abstract—**This paper discusses on a new concept of Event-predictive control, which is an extension of the Event-triggered control. The aim of the research is to apply such asynchronous sampling control strategy to a wireless networked control system to save battery energy consumption in the wireless nodes. The key idea is to maximize the control interval, under the condition of appropriate control performance, to save communication energy cost for battery life of wireless network nodes incorporated in the control system. A heuristic new concept of "predictive event" is introduced which is pre-determined as a cross-point of future predictive response of the controlled system and the stable region trajectory named "admissible set trajectory" to ensure recoverability to stable region. Then the sleep and wake mode of the wireless node is controlled according to the predictive events. Some considerations on stability condition are discussed, which is extendable to a class of nonlinear plants under some assumptions. A numerical example is illustrated to show the effectiveness of the proposed method.**

I. Introduction

Recently the wireless network technology such as sensor network had rapidly progressed and attracted much attention and many applications in control engineering had been reported [1]. Wireless nodes such as the sensor network have merits such as easy to instrument and construction, applicable to moving target or multi-sensor information processing, etc.

On the contrary, the wireless nodes have weak points such as reliability and availability especially related to energy consumption, which cause shortage of buttery life.

Thus energy saving technologies is one of the important research areas in wireless network applications.

Fischione, et al. [2] proposed trade-off between wireless output power related to reliability and energy consumption. Where, a physical characteristic model was shown to reveal quantitative relations of communication outage probability. They also stresses to consider lower layer optimal protocol design considering application layer requirements.

On the other hand, we had discussed the optimal sleep mode control of the wireless network nodes, and introduced a new concept of the "communication cost" which corresponds to energy consumption in wireless nodes. Then we proposed a new wireless networked control strategy with a trade-off problem between control performance and communication cost, and also proposed a optimal control strategy considering both control performance and communication cost [3,4,5]. In the proposed method, the control period is optimized with minimization of a mixed type cost function of control performance and communication cost, in receding horizon control manner, to save communication cost aiming energy saving of the wireless nodes without loss of control performance. Though the proposed method is rather complicated and required real-time optimization of mixed integer programming. So a simpler control algorithm for wireless networked control system had been required.

On the while, the non-constant interval discrete system such as Lebesgue sampling theory [6] as well as event-triggered control [7,8] for control system is discussed. Here the control period goes long while the plant is stable, and once the plant is fluctuated, the control period becomes short. The point is that unnecessary rapid control action could be avoided while the closed loop system is stable. This concept is illustrated in fig.1.

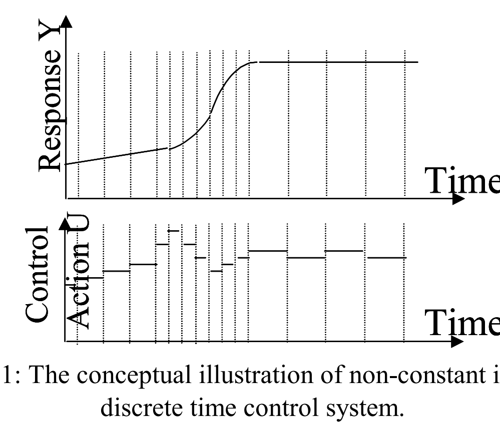

Fig.1: The conceptual illustration of non-constant interval discrete time control system.

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Motivation of this paper is, to apply the event-triggered control scheme to the wireless networked control system considering aforementioned minimization of communication cost. We newly introduce the "predictive event" because we need to determine the sleeping interval of the wireless nodes before future event occur when wireless communication should be wake up to activate control function. The predictive event is defined as a cross-point of future predictive response of the controlled system and the stable region trajectory named "admissible set trajectory" to ensure recoverability to stable region. Then the sleep and wake mode of the wireless node is controlled according to the predictive events. Some considerations on stability condition are discussed, which is extendable to a class of nonlinear plants under some assumptions. A numerical example is illustrated to show the effectiveness of the proposed method.

The remained sections are organized as follows. In section 2, general formulation of wireless networked control problem is defined to clarify the problem we discuss in this paper. In section 3, the main problem is formulated, where the concept of admissible set trajectory and the newly proposed "predictive event" is defined. Then the event predictive control algorithm for wireless networked control system is proposed. In section 4, some considerations on stability conditions of the closed system are discussed. Also an extension of the method to a class of nonlinear plants under some assumptions is discussed. A simple numerical example is illustrated in section 5. Finally this paper is concluded in Section 6.

II. Background of the Control Problem

In general, the sensor network means multiple sensor nodes. Though, to investigate properties of closed loop control system, hereafter we focus on a SISO closed loop system for simplicity without loss of generality. A general configuration of a wireless networked closed loop control system is illustrated in fig.2, which is composed of a process, a wireless sensor node, two functions of wireless controller nodes, namely a state estimator and a control calculator, and a wireless actuator node. The sensor node and the actuator node are supposed to be connected directly to the process. These components are basic elements in a general closed loop control system. Thus, three types of wireless communication paths I, II, III are possible, and corresponding three types of wireless networked control problems are defined as follows.

Type I: Wireless sensor networked control problem.

Type II: Wireless estimator networked control problem.

Type III: Wireless actuator networked control problem.

Type I is just the sensor network problem, while Type III is the controller or actuator node problem. Type II problem could be also defined such as Kalman-filter with wireless multi-sensor network.

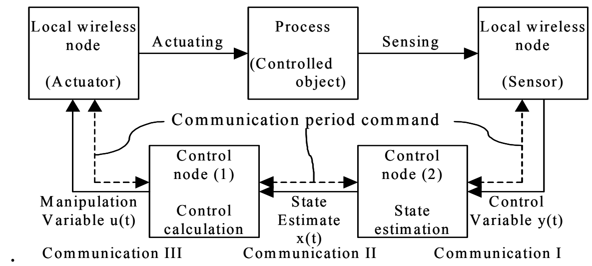


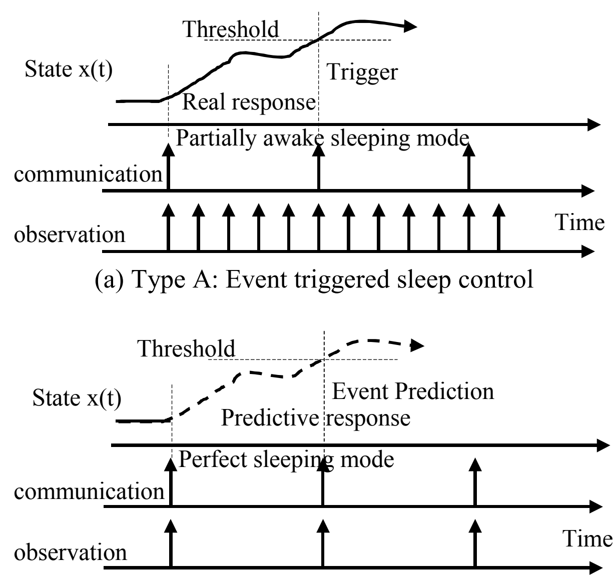
Fig.2: General configuration of wireless network based closed loop control system.

In wireless network application including wireless sensor network, energy saving problem considering battery life is one of the important issue in practical point of view. Many energy saving strategies are investigated such as C. Fischione et al.[2], where trade-off between power of wireless nodes and communication outage probability is discussed. Another effective strategy of energy saving is the sleep control of wireless nodes. Then two types of wireless network protocol for sleep control are defined as follows.

Type A: Event triggered sleep control; once switched to sleep mode, sleeping is continued until any event is triggered.

Type B: A priori time scheduled sleep control; before going to sleep mode in the wireless network, next awake time is scheduled a priori.

The two types of control action implemented to a wireless networked nodes are illustrated in Fig.3.



(a) Type A: Event triggered sleep control

(b) Type B: A priori time scheduled sleep control

Fig.3: Two types of event-triggered control with wireless networked control system.

Type A control strategy is the event-triggered control, which is investigated by such as M. Lemmon et al. [8], where the event trigger logic is proposed, as a function of state vector, which assure bounded control error against bounded disturbance in H-infinity sense.

Apparently type B approach is less energy consumption in the wireless nodes with perfect sleeping mode, while type A approach is rather energy consuming with partially awake sleeping mode to observe next event to wake up and activate the control system. In this paper we consider type B control strategy because our aim is to minimize the energy consumption of the wireless nodes, so we focus on optimization of trade-off between control performance and wireless energy consumption.

In order to realize a priori time scheduled sleep control, the prediction of future event to be awake and activate control system is required to schedule next communication time for control action. That is a reason to introduce the "predictive event" and to propose the "event predictive control".

The authors had proposed a kind of trade-off optimization based control strategy between control performance and communication energy saving [3,4,5]. Where, three types of trade-off optimization problems were defined.

A1: Control performance optimization with communication energy constraint; Control performance is minimized subject to any control constraints and the communication energy constraint.

min J(control performance)

s.t. communication cost < max-cost (1)

A2: Communication energy optimization with control performance constraint; Communication energy is minimized subject to the control performance constrained conditions.

min J(communication cost)

s.t. J(control performance) < worst admissible condition (2)

A3: Control performance and communication energy optimization; Control performance index and communication energy are combined and minimized simultaneously.

min J(control performance) + J(communication cost) (3)

In [3,4,5] the authors proposed a heuristic control method for A3 type optimization problem. In this paper the proposed control method is based on A2 type optimization problem.

III. Formulations

A. Formulation of the Event Predictive Control Problem

Here, the "Event Predictive" control problem is formulated.

The process is supposed to be a discrete time LTI system,

$$\tilde{x}(k+1) = \tilde{A}\tilde{x}(k) + \tilde{B}u(k)$$
$$y(k) = \tilde{C}\tilde{x}(k) \tag{4}$$

The state space model is augmented with integral factor for zero off-set tracking as follows.

$$x(k+1) = Ax(k) + B\Delta u(k)$$
$$y(k) = Cx(k) \tag{5}$$

where,

$$A = \begin{bmatrix} \tilde{A} & \tilde{B} \\ 0 & I \end{bmatrix}, \quad B = \begin{bmatrix} \tilde{B} \\ I \end{bmatrix}$$
$$C = \begin{bmatrix} \tilde{C} & 0 \end{bmatrix}, \quad x(k) = \begin{bmatrix} \tilde{x}(k) \\ u(k-1) \end{bmatrix}$$

and
$$\Delta u(k) = u(k) - u(k-1) \tag{6}$$

Then from 1 to Np steps predictor is formulated as follows, in general MPC formulation manner.

$$\begin{bmatrix} y(k+1) \\ \cdots \\ y(k+Np) \end{bmatrix} = G \begin{bmatrix} \Delta u(k) \\ \cdots \\ \Delta u(k+Nu-1) \end{bmatrix} + Fx(k)$$
$$\Rightarrow \quad Y(k) = G\Delta U(k) + Fx(k) \tag{7}$$

where,

$$G = \begin{bmatrix} CB & 0 & \cdots & 0 \\ CAB & CB & 0\cdots 0 & \\ \cdots & \cdots & & \\ CA^{Np-1}B \cdots CB & & & \end{bmatrix} \quad \text{and} \quad F = \begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^{Np} \end{bmatrix} \tag{8}$$

Future reference vector is denoted as follows,

$$Y^*(k) = [y^*(k+1), \cdots, y^*(k+Np)]^T \tag{9}$$

and a quadratic objective function

$$J = \sum_{i=1}^{Np} (y^*(k+i) - y(k+i))^2 + \lambda \sum_{j=1}^{Nu} \Delta u(k+i-1)^2 \tag{10}$$

is minimized. General linear control law is given as follows.

$$\Delta U(k) = [G^T G]^{-1} G^T (Y^*(k) - Fx(k))$$
$$u(k) = u(k-1) + \Delta u(k) \tag{11}$$

Also the general quadratic objective function

$$J = \sum_{i=1}^{Np} \{x^T(k+i)Qx(k+i) + \Delta u^T(k-1+i)R\Delta u(k-1+i)\} \tag{12}$$

where Nu=Np is applicable. Furthermore, some linear constraint conditions such as, state vector constraints and/or upper and lower limit for manipulation variable u(t) and their increments as follows.

$$Mx(k+i) \le \mathrm{I}, \quad \mathrm{I} = [1,1,\cdots,1]^T$$
$$u\min(k+i-1) \le u(k+i-1) \le u\max(k+i-1), \tag{13}$$
$$\Delta u\min(k+i-1) \le \Delta u(k+i-1) \le \Delta u\max(k+i-1),$$
$$i = 1,\cdots,Np$$

Then the quadratic objective function (10) or (12) subject to (13) is minimized with QP: quadratic programming optimization.

For the latter discussion, we introduce the bounded disturbance w(k) and v(k) as follows.

$$x(k+1) = Ax(k) + B\Delta u(k) + Dw(k)$$
$$y(k) = Cx(k) + Ev(k) \tag{5'}$$

B. Definition of admissible set trajectory for the Predictive Event

In order to define the "Predictive Event", a new concept of admissible set trajectory is introduced here. The admissible set for control system is proposed first by E. G. Gilbert et al. [11]. The maximal output admissible set χ_∞ means,

if once the state vector $x(k) \in \chi_\infty$ then

$x(k+i) \in \chi_\infty$ for all i, with a class of control strategy and constraint conditions such that

$$u(k+i) \in U, \quad w(k+i) \in W \text{ for all i.} \tag{14}$$

In this paper we suppose to require a loose stability condition "recoverable stability", which means: whenever we required, the control system can be recovered to a stable condition in finite time with in state vector being in the specified target set.

Then the "recoverable stability" region in the time-state space is illustrated in Fig.4. The region is a tube denoted by a series of admissible sets,

$$\chi_0, \chi_1, \chi_2, \cdots, \chi_{Np} = \chi_T \tag{15}$$

If the state vector is in the tube, whenever we can control the state into the specified target set χ_T, in finite time Np. How to calculate the series of admissible sets is as follows.

Step1: Define a target set χ_T at the end of prediction horizon so that future state vector x is included such as ,

$$x(k+i) \in \chi_T, \quad for\ \forall i \geq Np \tag{16}$$

then we can obtain the series of admissible sets by inverse direction step-by step calculation as follows,

$$\begin{aligned} &\chi_{k-1} = \{x(k-1)| \\ &\quad x(k-1) = \min_{w(k-1)\in W} \max_{u(k-1)\in U} \left[A^{-1}(x(k) - Bu(k-1) - Dw(k-1))\right], \\ &\quad x(k) \in \chi_k\} \quad for \quad k = Np, Np-1, \cdots, 0 \\ &x(Np) \in \chi_T \end{aligned} \tag{17}$$

Thus we obtain a series of admissible sets (15). Hereafter, we call them "admissible set trajectory".

Remark 1:

If the control system is globally asymptotically stable and no constraints are required to u(k) and x(k), then as Np goes infinity the admissible region χ_0 spreads to the hole space.

If the set U corresponds to the constrained condition of u(k) is finite, the series of admissible sets could be converged to a constant set

$$\chi_k = \chi_{k-1} = \chi_\infty \tag{18}$$

which is an invariant set.

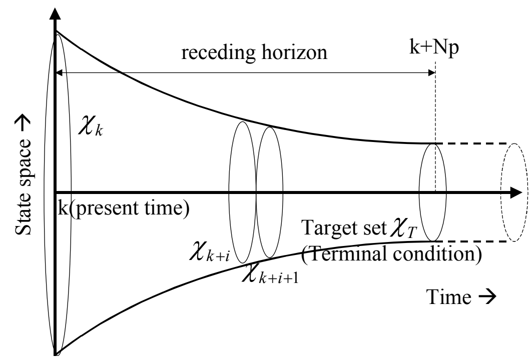


Fig.4: Concept of the admissible sets trajectory.

Remark 2:

If the target set is given as a polytope as defined Eq.(19) bellow, the admissible set trajectory (15) can be systematically calculated with linear equations. The calculation procedure is as follows.

Algorithm 1:

Let the admissible set χ_{k+i} is denoted as

$$\chi_{k+i} = \{x(k+i) \mid Mx(k+i) \leq \mathrm{I}\} \tag{19}$$

given $\chi_{k+Np} = \chi_T$

then χ_{k+i-1} for *i=Np,Np-1,…,1* is obtained as follows,

$$\begin{aligned} &\chi_{k+i-1} = \{x(k+i-1) \mid \\ &\quad MAx(k+i-1) + MB\Delta u(k+i-1) \leq \mathrm{I} - W^*)\} \\ &W^* = [w_1^*, w_2^*, \cdots, w_n^*]^T \\ &w_i^* = \max_{w\in W} M(i,:)Dw \end{aligned} \tag{20}$$

Remark 3:

The admissible set trajectory could be calculated off-line before starting control execution. The admissible set trajectory is calculated on the assumption of worst-case disturbance, so once we obtain it we always use it at each control stage.

Remark 4:

As more mathematical notation, the relationship between χ_{k+i} and χ_{k+i+1} is denoted as,

$$\chi_{k+i} = \chi_{k+i+1} \sim \{Dw(k+i) \mid w(k+i) \in W\} \tag{21}$$

where ~ is the Pontrryagin difference [12] defined as

$$Z_1 \sim Z_2 = \{z \mid z + z_2 \in Z_1\}\ . \tag{22}$$

C. Proposed Event Predictive Control strategy

The proposed Event Predictive Control algorithm is now formulated. The concept is illustrated in Fig.5. If the control loop become open with communication of wireless nodes goes sleeping mode, then present state vector x(k) will drift forward future direction. Until the predicted trajectory x(k+i) is included in the admissible sets trajectory

{ $\chi_k, \chi_{k+1}, \cdots \chi_{Np} = \chi_T$ } , the control system could be recovered after the communication waked up. So let's define the "Predictive Event" as the first cross point of prediction trajectory{ $x_k, x_{k+1}, \cdots x_{Np}$ } and the admissible sets trajectory { $\chi_k, \chi_{k+1}, \cdots \chi_{Np} = \chi_T$ } .

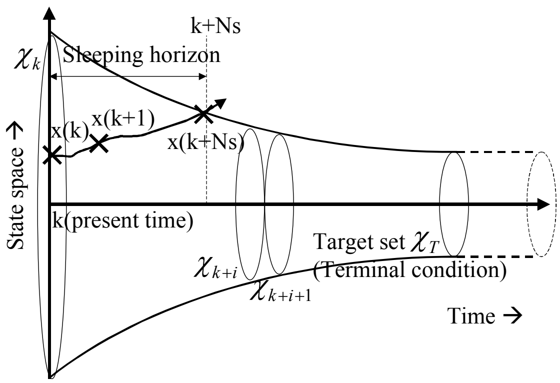


Fig.5: Definition of the "Predictive Event" for sleep control.

Thus the Event Predictive control strategy with admissible set trajectory { $\chi_k, \chi_{k+1}, \cdots \chi_{Np} = \chi_T$ } is defined us follows.

Algorithm 2:

Suppose the plant is denoted with equation (5'). Also suppose the system is observable and controllable and there exist a control strategy so that the closed loop is globally asymptotically stable, with constant control period.

With given admissible set trajectory

{ $\chi_0, \chi_{1,\cdots,}\chi_{Np} = \chi_T$ } calculated by Algorithm 1, the control method is denoted as follows.

At time t=k;

If $x(k) \notin \chi_0$ then,

Execute conventional control action with constant control period t=k,k+1,k+2,… until $x(k+i) \in \chi_0$.

Else if $x(k) \in \chi_0$ then,

Step 1: Execute current control calculation to obtain $\Delta u(k)$ and to manipulate the plant with

$$u(k) = u(k-1) + \Delta u(k). \tag{23}$$

Step 2: Estimate future response $x(k), x(k+1), \cdots x(k+Np)$ with

$$x(k+i) = A^i x(k) + A^{i-1} B \Delta u(k) \tag{24}$$

Step 3: Find Ns such that,

$$x(k+Ns) \in \chi_{Ns} \text{ and } x(k+Ns+1) \notin \chi_{Ns+1} \tag{25}$$

Step 4: Set the sleep timer of the communication sleep mode control and go to sleep.

These control strategies are illustrated in Fig.6.

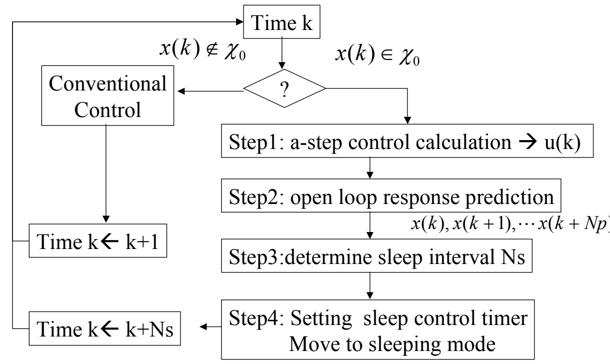


Fig.6: Control algorithm of the event predictive control.

Remark 5:

In this paper the actuator node in Fig.2 is supposed to have a zero-order holder, but we can also suppose an extended holder with holding series of future input { $\Delta u(k), \Delta u(k+1), \cdots, \Delta u(k+Np)$ } calculated by the Model Predictive Control algorithm with (11), (12) and (13). Then prediction model in Step 2 is slightly modified. During the wireless communication is sleeping, the actuator can output manipulation variables and the control performance is expected to be much improved. But no further formulation on this subject is discussed in this paper.

IV. Considerations on Stability

Here the condition of stability of the closed loop system is considered. Intuitively we can expect that the stability of the closed loop system with control strategy of algorithm 2, because the control strategy assures state vector x(k+i) to exist always in the trajectory tube of admissible sets $\chi_k, \chi_{k+1}, \cdots \chi_{Np} = \chi_T$ in Fig.5. It means after the controller wake-up at time t=k+Ns, at worst case, the controller could recover and achieve $x(k+Np) \in \chi_{Np} = \chi_T$ from the definition of the admissible set trajectory.

A general proof of the stability with Lyapunov function is considered as follows.

Theorem 1:

If the event predictive control is executed with Algorithm 2 in receding horizon manner, then state vector x(k) of the control system is bounded stable.

If the terminal of horizon t=Np is fixed, then

$$x(k+i) \rightarrow \chi_T \tag{26}$$

is achieved.

Proof:

First part is trivial because for the finite horizon Np and finite size of target set χ_T, the admissible set trajectory χ_i is bounded. From the Algorithm 2, state vector X(k) is always assured to be in the admissible set trajectory tube, so is bounded.

Second part is directory obtained because the admissible set trajectory goes to target set χ_T at t=Np, and state vector x(k) always in the admissible set goes into χ_T at t=Np.

Remark 6:

The predictive event and event predictive control algorithm only uses open loop response prediction and inverse-time calculation of the admissible sets. These procedures do not suppose the plant is restricted to be linear. So it is expected that the proposed event predictive control strategy is extendable to a class of nonlinear plants under some assumptions.

If the controlled object is denoted as following non-linear plant,

$$x(k+1) = f(x(k)) + g(\Delta u(k)) + h(w(k)) \tag{27}$$

then the calculation procedure of admissible set trajectory (17) is replaced with following non-linear version procedure.

$$\begin{aligned} &\chi_{k-1} = \{x(k-1) | \\ &\quad x(k-1) = \min_{w(k-1)\in W} \max_{u(k-1)\in U} f^{-1}(x(k) - g(u(k-1)) - h(w(k-1))), \\ &\quad x(k) \in \chi_k\} \quad for \quad k = Np, Np-1, \cdots, 0 \\ &x(Np) \in \chi_T \end{aligned} \tag{28}$$

and the future predictive response $x(k), x(k+1), \cdots x(k+Np)$ are calculated, instead of (24), with following non-linear version procedure.

$$\begin{aligned} &x(k+i) \\ &= f(\cdots(f(x(k) + g(\Delta u(k)))\cdots) + g(\Delta u(k+i-1)) \end{aligned} \tag{29}$$

A numerical example for nonlinear plant is illustrated in the next section.

V. Numerical Examples

In order to clarify the control procedure and visualize them, here a quite simple numerical example is illustrated. The plant is first order unstable system.

$$\begin{aligned} &x(k+1) = ax(k) + bu(k) + dw(k) \\ &a = 1.2, \quad b = 10.0, \quad d = 1.0, \quad Np = 10, \\ &u(k) \in U = [-2,2], \quad w(k) \in W = [-1,1] \end{aligned} \tag{30}$$

The control input u(k) is controlled with 1-step ahead predictive control. Disturbance w(k) is Gaussian white noise.

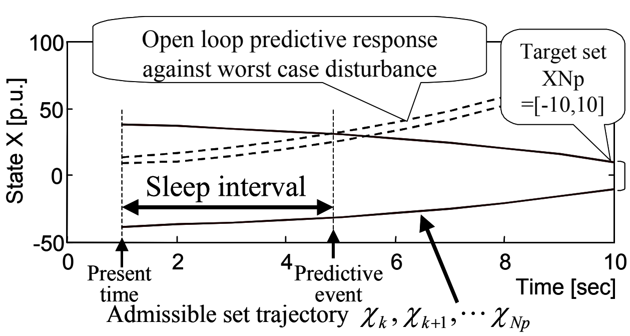


Fig.7 Trajectories of admissible sets and predicted x(k).

The trajectory of admissible sets $\{\chi_0, \chi_{1,\cdots,}\chi_{Np} = \chi_T\}$ and the prediction trajectory of $\{x(k), x(k+1), \cdots, x(k+Np)\}$ is plotted in Fig.7. The solid lines are trajectory of admissible sets trajectory for upper and lower band. While, the broken lines are the predicted trajectory of x(k) against worst-case disturbance w(k), also for upper and lower band.

The simulation result of the event predictive control system is shown in Fig.8. The control input u(k) is semi-periodically activated and the state variable x(k) is drifted but kept bounded. The numbers denoted in Fig.8 is the sleeping mode interval at each stage. The event predictive control procedure is executed in the receding horizon manner, and x(k) is almost kept in a target region of $\chi_T = [-10,10]$, but slightly disturbed with the persistent white noise disturbance.

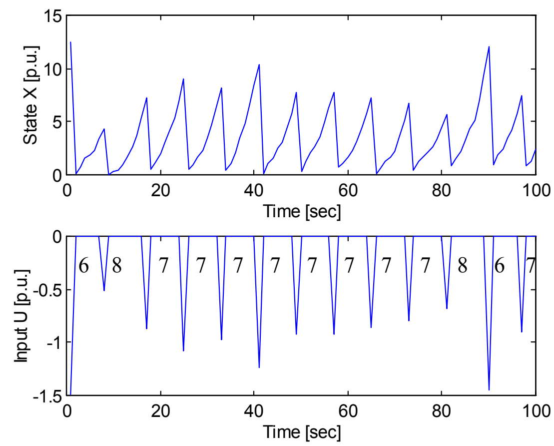


Fig.8 Simulation results of the event-triggered control system.

Next numerical example is for the nonlinear system case. The plant is first order nonlinear system.

$$\begin{aligned} &x(k+1) = a \cdot sign(x(k)) \cdot x(k)^2 + bu(k) + dw(k) \\ &a = 1.2, \quad b = 10.0, \quad d = 1.0, \quad Np = 10, \\ &u(k) \in U = [-5,5], \quad w(k) \in W = [-0.5,0.5] \end{aligned} \tag{31}$$

The control input u(k) is also controlled with 1-step ahead nonlinear predictive control. Disturbance w(k) is Gaussian white noise.

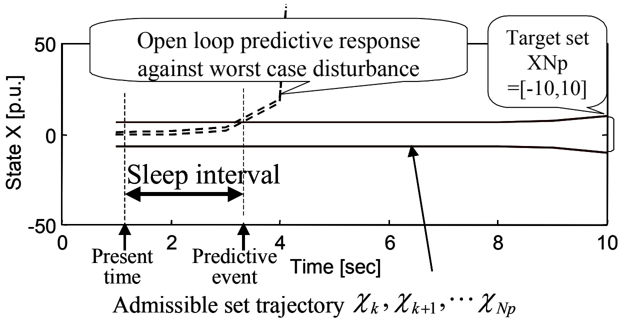


Fig.9 Trajectories of admissible sets and predicted x(k).

The trajectory of admissible sets $\{ \chi_0, \chi_{1,\cdot\cdot,} \chi_{Np} = \chi_T \}$ and the prediction trajectory of $\{ x(k), x(k+1), \cdots, x(k+Np) \}$ is plotted in Fig.9 as the same manner to Fig.7.

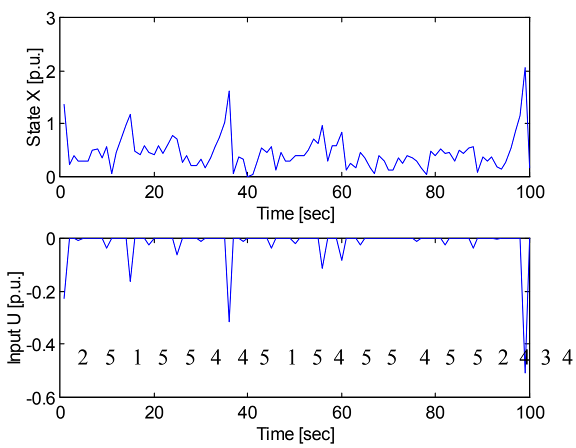


Fig.10 Simulation results of the event-triggered control system for a class of non-linear system.

The simulation result of the event predictive control system for the nonlinear system is shown in Fig.10. The control input u(k) is also semi-periodically activated and the state variable x(k) is drifted but kept bounded. The proposed method is shown to be effective for at least a class of nonlinear plant with numerical simulation. More strict formulations and stability considerations are future work.

VI. Conclusion

This paper discussed an energy saving strategy for the wireless networked control system. In order to save communication energy in wireless nodes, asynchronous control period is one of the effective control strategies. Then we focus on the event-triggered control strategy, and proposed the "Event Predictive Control". A heuristic new concept of "Predictive Event" is introduced, which is defined as the cross point of future predictive response and admissible set trajectory.

The features of the proposed method are as follows.

- The concept of "Predictive Event" with model predictive control framework and receding horizon control manner.
- The "Admissible set trajectory" defines the region of "recoverable stability" that is a kind of finite time attractive region.
- The "Admissible set" is calculated on the assumption of worst-case disturbance. So once it is calculated off-line we can use it at each control stage.

The predictive event enables a priori scheduling of sleeping mode control for wireless nodes that leads to the perfect sleeping mode to save the energy consumption.

Some considerations for stability condition and extension to a class of non-linear plants, was shown. Numerical examples showed the effectiveness of the proposed method. Further researches are expected on simplification of the control algorithm and evaluations on multi-variable plant or more general nonlinear plant cases.

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