ALGORITHMS OF NETWORKED CONTROL SYSTEM DESIGN

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Abstract: This paper discusses design of Networked Control Systems (NCS). NCS are distributed control systems whose sensors, actuators and controllers are interconnected by shared industrial network. The major NCS problem is network-induced delays. These delays caused by the sharing of communication medium can be constant, bounded, or even random and can degrade system's performance. The main goal of the paper is to present the methodology of NCS design and the behaviour algorithms for individual NCS nodes. Finally, the control methods suitable for NCS are shortly presented.

Keywords: control system, control design, communication networks, delay compensation, algorithms

1. INTRODUCTION

Industrial networks and their applications have been developing rapidly in the last two decades. On the side of automation, new requirements for control systems which include modularity, control decentralization, integrated diagnostics, fast and easy operation and easy maintenance limit the use of traditional analogue way of interconnection in industrial control. Thus use of industrial networks in area of high performance control and automation is promising application and research task. Feedback control systems wherein the control loops are closed through the industrial network are called Networked Control Systems (NCS). This implementation of a network into the control loop has several advantages as lower cabling price in comparison with the analogue connection, easier installation and maintenance, easy diagnostics of system, increasing of control architecture flexibility, increasing of system reconfiguration etc. But this network interconnection has also some disadvantages as communication constraints, dependability of control from network faults, asynchronous elements of control, unpredictable network faults etc. All of mentioned disadvantages lead to network induced delays. The implementation of communication networks into control system loops has motivated a number of researchers (Walsh, *et al*., 2001; Barger, *et al*., 2002) to analyse negative impact of the network to control systems stability and performance. Many of them designed effective methods to compensate effect of network delays, but those systems require more complex approach then just some, event the most sophisticated, control algorithm. This paper is focused to design of NCS from implementation point of view. The problem solved is, how to change control strategy (sampling period, regulation constants, configuration of individual NCS nodes, etc.) after implementation of network interconnection between several control nodes.

2. NCS AND ANALYZED PROBLEMS

Apart from NCS problems mentioned in introduction of the paper, NCS have many problems connected to their configuration and control algorithm. This chapter shows NCS specific features, those are the a reason of the special approaches in case of the NCS.

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2.1 NCS sampling phenomenon

The performance chart shown on Fig.1 (Lian, *et al.*, 2002) depicts sampling phenomenon of NCS.
The chart is the comparison of control performance versus sampling period for continuous control, digital control, and networked control. For a fixed control law, the worst, acceptable, and best regions can be defined based on control system specifications. Since the performance of continuous control is not a function of sampling period, the performance index is constant. For the digital control case, the performance only depends on the sampling period assuming no other uncertainties. The performance degradation point A (sampling period P_A) in digital control could be estimated based on the relationship between control system bandwidth and sampling rate. For the networked control case, point B needs to be determined by further investigating the characteristics and statistics of network-induced delays and device processing time delays. As the sampling period gets smaller, the network traffic load becomes heavier, the possibility of more contention time or data loss increases, and longer time delays result. This situation causes the existence of point C in networked control.

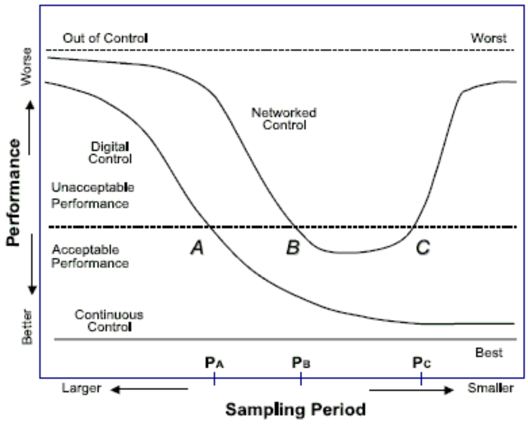

Fig. 1. Performance comparison of continuous control, digital control, and networked control cases (Lian, *et al.*, 2002)

Smaller sampling period results in high frequency communication and may degrade the network *QoS* (Quality of Service). The degradation of network *QoS* could further worsen the control *QoP* (Quality of Performance) due to longer time delays when the network is nearly saturated. Due to the interaction of the network and control requirements, the selection of the best sampling period for a NCS is a compromise.

2.2 Network delay consideration

Network time delays are a function of processing times, level of sharing of communication medium (that depends on number of connected nodes with network requests) and on MAC mechanism of concrete control network.
There are three kinds of delays in a NCS:

- network delay between the sensor and the controller τ_k^{sc}
- computation delay of all NCS elements τ_k^{all}
- network delay between the controller and the actuator τ_k^{ca}

Network induced delay can be solved like dynamically changeable deadtime. But as presented thereinafter, from analytical point of view network delay differs from the deadtime.

Deadtime is known as delay between applied control input and its first effect on the process or delay between a controlled system and a sensor. Its modelling is in direct branch of feedback control loop. But network delay is always between sensor and controller and its modelling is correct in feedback branch of feedback control loop.

Next problem is problem of sensed value. Value sensed in cases of NCS and of deadtime differs, because those values are sensed in different times. In case of the NCS, the plant output is sensed in discrete time (kT), but in case of deadtime the value of plant output is sensed in discrete time ($kT+T_d$), where T_d is deadtime value.

Until this time, we spoke just about the feedback branch of feedback control loop, in concrete about the delay between sensor and controller τ_k^{sc}. But the biggest analytical problem of NCS is problem of delay τ_k^{ca} between controller and actuator. It is not possible to compensate real value of this delay in the controller node immediately, because this delay occurs behind the controller. There is possible to compensate real value of delay τ_k^{ca} in the discrete step kT just in an actuator node. Controller might compensate just predicted value of τ_k^{ca}, like medium statistic value of delay.

2.3 Negative effect of synchronization in NCS

The term synchronous NCS used thereinafter means, that all networked nodes of the NCS loop (sensors, controllers and actuators) are sampled with the same sampling period in the same sampling times. In the synchronous NCS, shown on Fig.2, has each delay smaller then sampling period (even the smallest) between individual NCS nodes effect of one sampling period. The reason is the same sampling time of each networked node that causes processing of delayed value at the next sampling period.

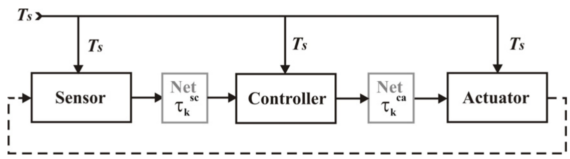

Fig. 2. Sequence of control data flow between individual elements of a NCS with synchronized sampling. This figure represents so called TTT initialisation (Ligušová, *et al.*, 2004).

On the assumption that sum of network delays between sensor and controller τ_k^{sc} and between controller and actuator τ_k^{ca} is less or equal to sampling period T_s:

$$(\tau_k^{sc} \le T_s) \wedge (\tau_k^{ca} + \tau_k^{all} \le T_s) \qquad (1)$$

the total delay τ of the NCS equals to two sampling periods: $\tau = 2.T_s$ (2)

Considered synchronous NCS has following one sample processing:

1. the sample is sampled by sensor at the discrete time k
2. because of network media delay the same sample is obtained by a controller at the discrete time $k+1$
3. and finally again because of network media delay the control value from a controller processed from a sample sampled in discrete time k is reached by an actuator at the discrete time $k+2$

So each receiving node in synchronous NCS causes delay of one sampling period.

3. NCS DESIGN

Many papers in area of NCS designed methods for improvement of control networks to prevent occurrence of delays or methods of control to compensate effect of network delays. The main point of this paper is to propose the complex methodology of NCS design and the behaviour algorithms for individual NCS nodes. The main tasks of the NCS design are setting of the controller parameters and setting of the sampling period.

The algorithm has assumptions as follows:

- the model of the controlled system is known,
- they are designed (based on the discrete control theory) controller constants and sampling period of treated system,
- used communication network and number of connected nodes is known.

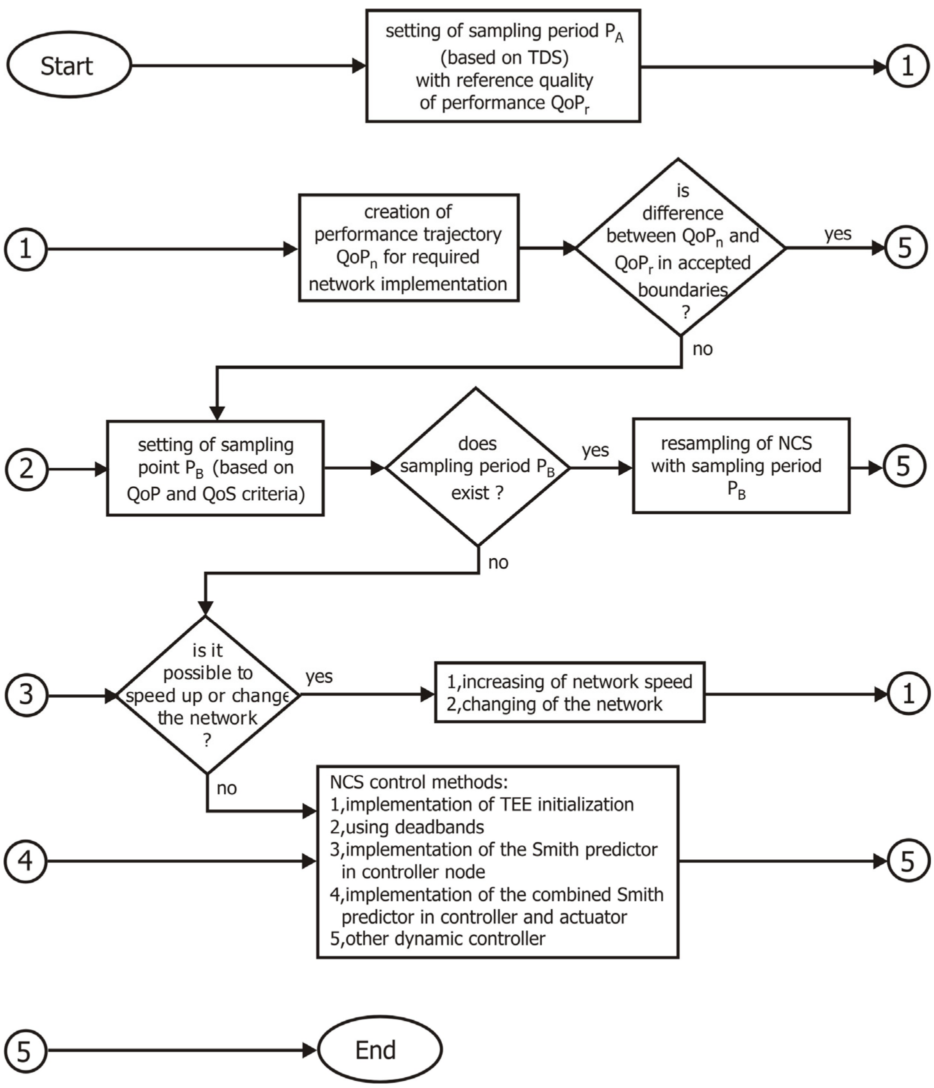

Fig. 3. *NCS flowchart for setting of the controller parameters and revaluation of the sampling period*

3.1 NCS design flowchart

The NCS design flowchart shown on Fig. 3 presents the methodology of NCS design. At first the problem of the suitable sampling period is solved and next the control algorithms are proposed. The NCS design flowchart is realized by decision system in practice. In regard to algorithm assumptions mentioned above the input of the flowchart are model of controlled system and network type with number of connected nodes.
From those input information the system achieves network parameters of *QoS* (delay statistics, network efficiency, network utilization and packet loss from the network database), the control parameters of *QoP* (phase margin, IAE/ITAE), sampling period P_A and PSD controller constants. The algorithm next designates the sampling period in the network implementation P_B from *QoP* and *QoS*. In case of NCS resampling, the PSD controller constant needs to be recalculated. If the NCS performance is not still satisfactory, the system next finds the most suitable control algorithm for the treated NCS.

Proposed NCS control methods base consists of four designed NCS methods simulated in NCS system with time delays less and bigger then sampling period. Presentation of those methods is not the main point of the paper. They are results of our previous work, mentioned just because of their occurrence in the flowchart.

The system will choose following four methods of NCS control:

1. *TEE initialisation* – this method partly eliminates negative effect of delays and is suitable for synchronous systems, where time initialisation (T-driven) causes more intensive effect of delays. When no other method for NCS control is used, it is recommended to use TEE initialisation, where E-initialised node is node, whose function depends on receiving the packet from the network, not from constant sampling (Ligušová, *et al*., 2004). Thereinafter the simulation results of modelled system (control of liquid level in tank) are presented. There were realized Monte – Carlo simulations (100 simulation cases per each initialization type) of models with initializations TTT, TTE, TET and TEE. Considered factors of regulation quality are regulation time T_{reg}, overshooting σ_{max}, deadtime T_d, relative standard deviation error *RSDE*. From the simulation results, shown in Table 1 the case of TEE initialization is the most robust, i.e. the influence of random delays is the smallest on quality.

Table 1 comparison of considered factors of regulation quality for each simulation case, including control loop without network.

Factor of control quality	without network	TTT	TTE	TET	TEE
T_{reg} [su]	175	175	119	164	129
σ_{max} [%]	0	8,69	2.59	5.43	0
T_d [su]	0	10	7	10	4
RSDE [%]	0	0	17.5	34	14

2. *Deadbands* – deadbands is well known method in area of control elements. The presented method is suitable, when the network is saturated, and it is necessary to decrease network utilisation. Deadbands are usable as well in case of synchronous as asynchronous systems (Otanez, *et al*., 2002).
3. *Smith predictor in controller node* – this method effectively uses Smith predictor in controller in case of synchronous systems. The method works on assumption that delay between controller and actuator τ_k^{ca} has to be known, or statistically evaluated, because this delay appears behind the controller, so cannot be measured (like in case of delay τ_k^{sc}). This method uses timestamps, so the sensor node has to send timestamps.
4. *Combined Smith predictor in controller and actuator node* – this method effectively uses Smith predictor in both controller and actuator nodes. In suitable for synchronous systems. The size of delays need not to be known, because actuator node can compensate delays those appear behind the controller. This method uses timestamps, so the sensor and the controller have to send timestamps (Ligušová, *et al*., 2003).

3.2 NCS design algorithm

NCS design flowchart on Fig.3 represents following algorithm:

- There is designed sampling period point P_A with reference quality of performance QoP_r and controller constants based on discrete control theory for control system without network.
- Implementation of designed control strategy in NCS implementation requires revaluation, it is necessary to specify sampling area IWA (Ideal Working Area) for NCS in regard to *QoP* and *QoS* parameters.
- Creation of performance trajectory QoP_n for required network implementation of treated control system depended on sampling period. After implementation of the communication network into the NCS designed without network consideration the quality of control will change, so it is necessary to change sampling period.

- Difference between QoP_r and QoP_n in sampling period P_A is Δ_{QoP}.
- If Δ_{QoP} is in accepted boundaries ε, $0<\Delta_{QoP}<\varepsilon$, then NCS revaluation is finished. This situation means, that control performance degradation after implementation of the network still fulfils our requirements.
- If Δ_{QoP} is out of ε boundaries, $\varepsilon<\Delta_{QoP}$, it is necessary to look for point P_B (point P_B is point whose QoP is the same then QoP_r). Videlicet, the quality of control after implementation of the network is not satisfied, so reevaluation process starts.
- If point P_B doesn't exist, it is required to
  - increase network speed or to change network
  - change the communication network with another, faster (Lian, *et al.*, 2001)
  - implementation of some NCS control method:
    1. implementation of TEE initialization
    2. using deadbands
    3. implementation of the Smith predictor in the controller
    4. implementation of the combined Smith predictor in the controller and the actuator
    5. another dynamic controller
- In the NCS design point P_C is not as important then point P_B.

4. RECOMMENDED FEATURES OF THE NCS ELEMENTS

Further are presented algorithms of NCS elements behaviour. There are listed sensors, controllers and actuators requirements in the NCS implementation.

4.1 NCS sensor requirements

Based on NCS analyse and simulations it is recommended to meet following features of NCS sensors:

- *internal clocks with ability to synchronise with other NCS nodes* - capability to send actual timestamps (t_s^s-timestamp sent from sensor) with precision to *ms*, resp. μs both to controller and to actuator node,
- *ability to choose between continual sensing and sampling* (with chosen sampling period) of the plant output - the plant output is in case of continual sensing sensed in intervals smaller than chosen sampling period T_s.
- *ability to program rules for sending of network packets (D-initialization)* - it is useful to program rules for sensor's deadband and to reduce network saturation (improve *QoS*) by this way.

4.2 Network controller requirements

Based on NCS analyse and simulations it is recommended to meet following features of network controllers:

- *internal clocks with ability to synchronise with other NCS nodes* - capability to send actual timestamps (t_c^s-timestamp sent from controller) to actuator node with precision to *ms*, resp. μs,
- *deadtime evaluation capability* - ability to evaluate deadtime between sensor and controller. It is possible to realise the evaluation by two ways. The first way is evaluation based on timestamp sent from sensor and the second is evaluation based on statistic methods
- *ability of on-line modification of the model with delay model* - controller can change model with deadtime (for example, in case of Smith predictor, where used model is system with deadtime),
- *implementation of prediction mechanism in controller node*, eliminating network delays of both types (delay of direct and feedback branch),
- *ability to realise event initialisation of controller node (E-initialization)* - considered event is a communication event. It requires activity of the controller out of sampling period, immediately after receiving of the information from sensor that has to be immediately processed by controller,
- *ability to program rules for sending of network packets (D-initialization)* - it is useful to program rules for controller's deadband and to reduce network saturation (improve *QoS*) by this way.

4.3 NCS actuator requirements

Based on NCS analyse and simulations it is recommended to meet following features of NCS actuators:

- *internal clocks* with ability to synchronise with other NCS nodes – there is no reason in the case of actuator to send actual timestamp value, because actuator node is the last node in the control loop sequence,
- *ability to evaluate total loop delay caused by communication network* (from sensor to actuator) - it is useful to give to actuator node some additive features. The actuator node is able to evaluate real size of delay τ_k^{ca} from timestamp sent from controller. The real delay size acquired by this way is continuously sent to controller, where the effect of this delay is eliminated by the Smith predictor,

- *ability to realise event initialisation of the actuator node (E-initialization)* - considered event is again a communication event. It requires activity of the actuator out of sampling period, immediately after receiving of the information from controller that has to be immediately applied to controlled system.
- *ability to program rules for applying of control input (D-initialization)* - it is good way just to retain reliability of actuator, because the actuator cannot affect network *QoS*.

5. CONCLUSION

The methodology of NCS design is the main theoretical advantage of this paper. Next results of the paper are presentations of the recommended features of the individual NCS elements and criteria for implementation of control algorithms in the NCS. There are several approaches to control the NCS and they are all based on the same idea, to solve the problem of constant or random delays (Nilsson, *et al*., 1997) caused by communication network. But none of them brings the methodology for design of these systems. One of the results of our research is, that not every NCS requires special control method. Important factor of each networked system is *QoS* (Quality of Service), whose detail description is not presented in this paper, for details see (Lian, *et al*., 2002). The main procedure of the paper is to use controller parameters and sampling period designed by theory of discrete systems. Proposed methods were verified by computer simulation of models created in Design/CPN simulation tool and some of them were applied in the practice. Design/CPN is modeling and simulation tool of coloured Petri nets.

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