Applicability of Internet-based Distributed Control System

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Abstract: The rapid development of distributed control systems has caused the necessity of knowledge and understanding of communication network in a process of a dynamic system modelling and controller synthesis. A lot of work has been done to determine the suitability of dedicated networks for data transmission in control systems. This paper is an approach in the problem of control of a remote system over the Internet. The work is an attempt to model and simulate a transmission network characteristics, taking into account the delay introduced by the network. Additionally, the experiment was conducted on a real network to determine the applicability of the Internet in distributed control systems.

Keywords: distributed control system, network based control system

Many modern automation systems are designed as distributed control systems. Distributed Control System (DCS) might use dedicated telecommunication network (LonWorks, CAN, ProfiBus) or commonly used network (Ethernet, Internet). There are several advantages of distributed control system, like a reduction in wires and power requirements, flexibility of operations, ease of maintenance, diagnostics and monitoring [7]. However, a communication network in the feedback loop generates two major problems: an unpredictable delay and packet losses. These problems threaten the stability of the entire automation system and have a significant impact on the dynamics and the behaviour of the system. That is why methods of the control system design need the knowledge about the properties of telecommunication networks. The aim of Internet-based distributed control system is direct network control, insensitive to the inherent Internet time delay [2].

1. Dynamic model of distributed control system

Let us consider the following continuous-time linear system with communication delay (1).

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t-\tau^{ca}) \\ u(t) = -K_p x(t-\tau^{sc}-\tau^{c}) \end{cases} \qquad x(t)\in\mathbb{R}^n \quad u(t)\in\mathbb{R}^1 \tag{1}$$

The linear state-feedback controller has a constant gain K_p. A communication network connects the sensor-controller nodes and the controller-actuator nodes. The overview of distributed control system over network is depicted in Fig. 1 The structure and utilization of the network affect the sensor-to-controller delay (τ^{sc}) and controller-to-actuator delay (τ^{ca}). The delay of the control signal computation is denoted by τ^{c} and it is not dependent on the telecommunication network (Fig. 2).

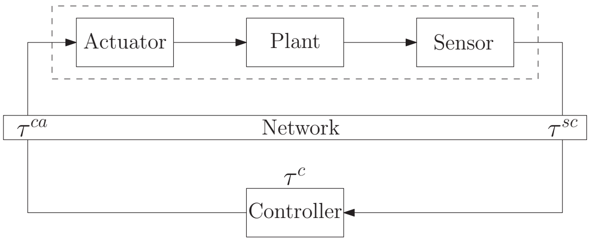

Fig. 1. The model of a distributed control system
Rys. 1. Model układu sterowania rozproszonego

The closed-loop system, obtained with proportional controller is described in (2).

$$\dot{x}(t) = Ax(t) - BK_p x(t-\tau(t)) \qquad \tau(t) = \tau^{sc}(t) - \tau^{c} - \tau^{ca}(t) \tag{2}$$

The discretization of continuous time-delay system is given in (4), where T_0 is the sampling time. The extended state space leads to transform representation (1) and (2) into finite-dimension system. An extension of state space model is shown in (8). This model can be used for simplification of the controller synthesis [4]. The closed-loop system equations are valid for the condition (3). Otherwise, the actuator operates in the open-loop mode [5].

$$0 \leqslant \tau(k) \leqslant T_0 \tag{3}$$

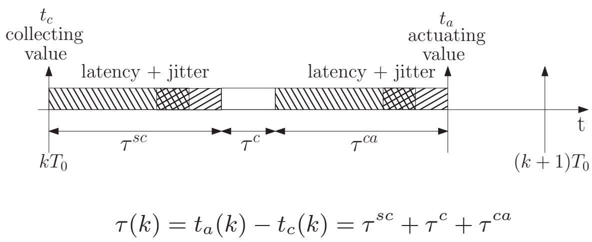

Fig. 2. Timing relationships in the model of a distributed control system [7]
Rys. 2. Zależności czasowe w modelu sterowania rozproszonego [7]

The block structure of the discrete time-delay system is shown in Fig. 3.

$$\begin{aligned} x\left[(k+1)T_0\right] &= \Phi_0 x(kT_0) + \Gamma_0(\tau)u(kT_0) \\ &+ \Gamma_1(\tau)u\left[(k-1)T_0\right] \end{aligned} \tag{4}$$

where:

$$\begin{aligned}\Phi_0 &= e^{AT_0} &(5)\\ \Gamma_0(\tau) &= \int_0^{T_0-\tau} e^{As} ds B &(6)\\ \Gamma_1(\tau) &= \int_{T_0-\tau}^{T_0} e^{As} ds B &(7)\end{aligned}$$

$$\begin{bmatrix} x(kT_0+T_0) \\ z(kT_0+T_0)\end{bmatrix} = \begin{bmatrix} \Phi_0 & \Gamma_1(\tau) \\ 0 & 0\end{bmatrix}\begin{bmatrix} x(kT_0) \\ z(kT_0)\end{bmatrix} + \begin{bmatrix} \Gamma_0(\tau) \\ I\end{bmatrix} u(kT_0) \quad (8)$$

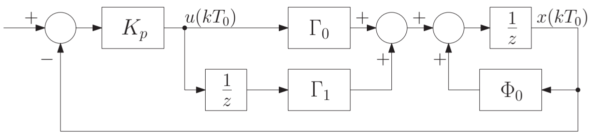

Fig. 3. The discrete system block diagram
Rys. 3. Struktura systemu dyskretnego

2. The Internet network structure

The Open System Interconnection (OSI) reference model classifies communication tasks into 7 layers. The standard has been developed for a reduction of a complexity of a network. It defines internal data flow between each layer. Each layer modifies data using encapsulation by an addition of the header control information. A time of the encapsulation in the particular OSI layer is difficult to determine and depends on many factors, like hardware architecture applied, processor utilization etc. The delay introduced by the encapsulation at each layer is negligibly small value compared to the propagation delay, therefore, will be omitted for further consideration. The Internet Protocol Suite (IPS) is the most popular protocol stack used in Ethernet standard networks. The IPS reorganizes the OSI model and defines 4 layers [10]: Application, Transport, Internet and Link (Fig. 4). Two of the most popular protocols used in the transport layer are the Transmission Control Protocol (TCP) and the User Datagram Protocol (UDP). TCP [9] is connection-oriented protocol and provides connection establishment (handshaking), acknowledgements and data flow control. UDP [8] is a connectionless simple protocol and does not provide any confirmation of the correct receipt of data.

The bottom – link layer provides i.a. distributed media access control system. The Carrier Sense Multiple Access with Collision Detection system (CSMA/CD) allows any device to attempt to transmit via a network. In case of occupancy of a shared transmission medium, the data are buffered. The CSMA/CD system introduces an additional random delay. A full understanding of the data exchange protocol in the network, allows to create an accurate and model of transmission delay.

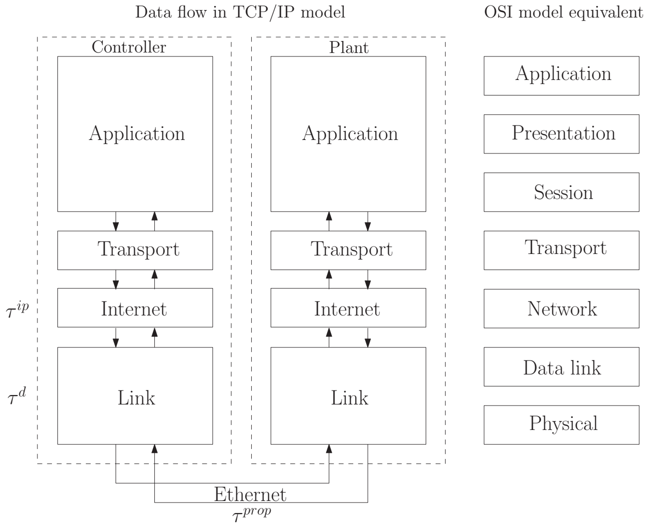

Fig. 4. Control signal and feedback loop in the IPS model
Rys. 4. Sygnał sterujący i pętla sprzężenia zwrotnego w modelu IPS

3. Case study and experiments

3.1. Package drop and delay simulation

As a case study a continuous linear time-invariant (LTI) model from [1] is chosen (9). The model represents a first order water tank system. Constant system parameters are given in Tab. 1. A discrete-time system (10) has been obtained using equations (4–8).

$$\begin{cases} \dot{x} &= -\frac{1}{\alpha}x + \frac{\alpha}{\beta}u \\ y &= x \end{cases} \quad (9)$$

$$\begin{aligned}\Phi_0 &= \exp\left(-\frac{T_0}{\alpha}\right)\\ \Gamma_0(\tau) &= \frac{\alpha^2}{\beta}\left[1-\exp\left(\frac{\tau-T_0}{\alpha}\right)\right] \\ \Gamma_1(\tau) &= \frac{\alpha^2}{\beta}\exp\left(-\frac{T_0}{\alpha}\right)\left[\exp\left(\frac{\tau}{\alpha}\right)-1\right]\end{aligned} \quad (10)$$

Tab. 1. Parameters of the dynamic system [1]
Tab. 1. Parametry systemu dynamicznego [1]

parameter	value
time constant	$\alpha = 63.2456$
control input gain	$\beta = 15.8144$

The discrete-time dynamic system (10) has been modelled in MATLAB/Simulink environment (Fig. 5). In a control signal transmission line and a process value transmission line a constant delay block has been placed. The first experiment is done to determine the impact of the delay block on the quality of control. Integral Time Square Error (ITSE) objective function has been used (11). As can be seen from Fig. 6, the quality is rapidly degraded when the delay exceeds about 12 milliseconds.

$$ITSE = \int_0^{\infty} t \cdot e^2(t)dt \quad (11)$$

For the second simulation experiment, the average delay time has been calculated based on a statistical analysis of the network connection (Fig. 8) and it equals 160 ms. The control line is disconnected from the process at a random instant. This part of the model simulates open-loop mode of system operation, as a result of buffering effect (when the assumption (3) is not fulfilled). The simulation performance results of the closed-loop control are shown in Fig. 9.

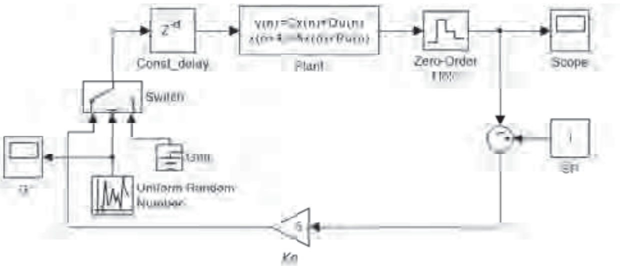

Fig. 5. The MATLAB/Simulink model [1]
Rys. 5. Model systemu w programie MATLAB/Simulink [1]

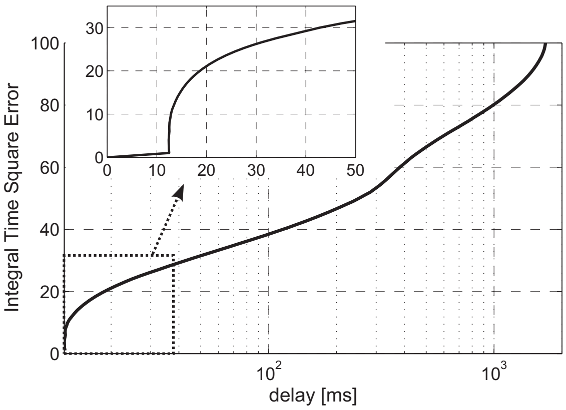

Fig. 6. Effect of propagation delay on the quality of control
Rys. 6. Wpływ opóźnienia sygnału na wartość wskaźnika jakości sterowania

3.2. Control system via Internet

The network delays in the distributed control system can be either determined or random. The delay variation between a host **A** in Kraków (Poland) and a host **B** in Raleigh (USA) is shown in Fig. 7. The Network time delay histogram is presented in Fig. 8. As can be seen, a minimal signal propagation time between locations is 138 ms.

To evaluate the feasibility of the Internet medium for distributed control purposes, a dedicated client/server Java program was written. The server side (host **B**) emulates the discrete-time dynamic system (10). The client side (host **A**) connects to the server using the 6780 TCP port, receives the process value and transmits the control signal. If the signal propagation time exceeds the sampling time limit ($\tau \geqslant T_0$), the packet is rejected and the actuator uses the last valid control value. Real time clocks on the host **A** and the host **B** have been synchronized by the Network Time Protocol (NTP). Fig. 9 shows the evolution of the process value, obtained with a MATLAB/Simulink simulation and with a real-network experiment. As can be seen, the time-delay equals around 150 ms. There is a good degree of accuracy between the simulation and real-network

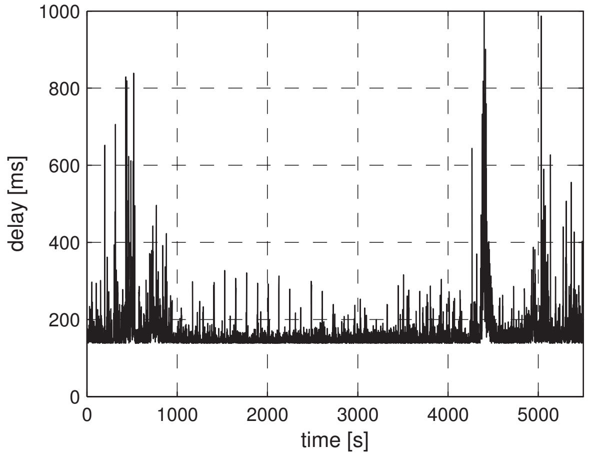

Fig. 7. The evolution of the network delay between a host A in Kraków and a host B in Raleigh
Rys. 7. Zmiana opóźnienia sieciowego połączenia pomiędzy serwerami w Krakowie i Raleigh

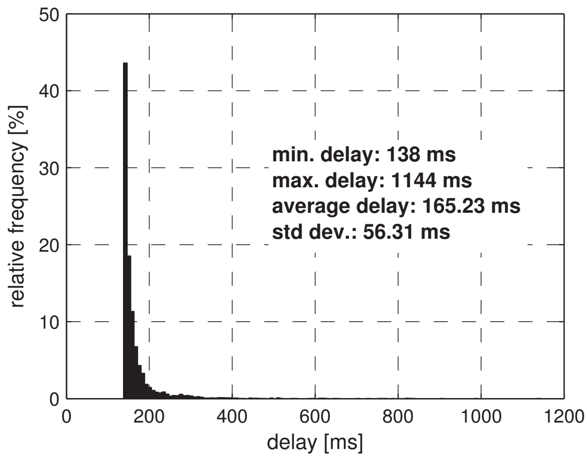

Fig. 8. The histogram of the network delay
Rys. 8. Histogram opóźnienia sieciowego

experiment results. Some of the packets have been rejected due to too long propagation time (7.3 %). However the impact of network gives weak effect, due to the relation between average delay time and model dynamics.

4. Conclusions

In the following paper it was shown that control system for a gradually changing, structurally stable process can be distributed over a very long distance. Analysis was conducted, based on simulation results and real-world experiments. The study leads to the conclusion that Internet can be used as a medium for transmission of control and process signals. The application of the TCP protocol reduces the chance of a packet loss while it increases slightly the closed-loop delay.

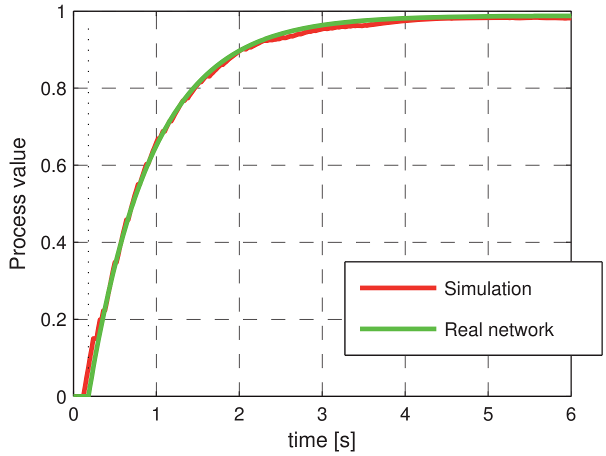

Fig. 9. The simulation and the real network results for the distributed control system

Rys. 9. Wyniki symulacyjne oraz wyniki eksperymentu sieciowego dla systemu sterowania rozproszonego

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Aspekty sterowania rozproszonego i analiza możliwości sterowania odległymi systemami poprzez Internet

Streszczenie: Gwałtowny rozwój rozproszonych systemów sterowania spowodował, że w procesie modelowania systemów dynamicznych oraz syntezy regulatorów konieczna okazuje się wiedza i zrozumienie działania sieci przesyłu danych. Wiele badań zostało poświęconych określeniu przydatności dedykowanych sieci umożliwiających przesył danych w układach sterowania. Niniejsza praca stanowi próbę przybliżenia problemu sterowania odległymi systemami poprzez Internet. Praca zawiera próbę zamodelowania właściwości sieci transmisyjnej i przeprowadzenia symulacji z uwzględnieniem opóźnienia wprowadzonego przez sieć. Ponadto został przeprowadzony eksperyment na rzeczywistej sieci, mający na celu określenie przydatności sieci Internet w systemach sterowania rozproszonego.

Słowa kluczowe: sterowanie rozproszone, sterowanie poprzez Internet, rozszerzona przestrzeń stanu

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