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Process Control via Network

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Abstract: The explosive growth in the area of computing and networking has occurred. This has caused an increased reliance on distributed computing and process operations across the networks. The main aspect in the process control across network is the network delay, which depends on the network type and protocol. This paper gives the literature review about the network-based control systems and the methods developed for handling and compensating the network delay in a control loop. In the experimental part the research environment for examining the control performance of a laboratory-scaled process across three different wired networks and wireless ad-hoc network is described and the control results are compared. The wired networks are Ethernet, Internet and FUNET, which is the network operating between the universities in Finland. This means that the distances between the operator and the process to be controlled vary remarkably from twenty meters to several hundred kilometers. Also the transmission speed of the network is different. The network delays are measured and compared with each other. Also the loss of data packages in different networks is examined.

1. INTRODUCTION

The most important aspects of process control across the network are time delay, safety and concurrent user access i.e. the network load. The network delay, which can be constant, time varying or random, occurs, when sensors, actuators, controllers and humans exchange data over the network. It depends on the network structure, media and protocol. If the process has slow dynamics there is no great need to consider the influence of delays on control system performance. However, for fast-acting control loops, the delays degrade the performance and can even destabilize the system. Also the demand on the control system increases all the time and therefore it will be more and more important to take the delays into account in the analysis and design of control systems.

This paper aims to examine the control of a laboratory-scaled process over three different wired networks: Ethernet, Internet and FUNET, which is the network between the Finnish universities. The control performance and especially the delay in different networks are compared. The network-based control is compared with the control without the network and the loss of data packages is examined in different wired networks. Also the control performance over wireless ad-hoc network is studied and the control results are compared with the wired Ethernet network.

2. EXPERIMENTAL ENVIRONMENT

The experimental environment presented in Figure 1 includes a laboratory-scaled flow process. It consists of a transparent water tank, from which is fed water via a diaphragm pump. The flow of water into the tank is controlled by a control valve which in turn is controlled by a computer via a data acquisition board. The computer acts as a local access point through which data is sent to and from the system via wired or wireless network

The experiment set consists of control experiments run on the system using a remote computer via wired or wireless network. The computer local to the process collects data on the tank level from the level sensor and transmits it to the remote computer via network The remote computer collects data on the tank level, computes the control value and sends it back to the local computer which transmits the control signal to the actuator which affects the control of the tank level. The control application was developed using LabVIEW®. In Figure 2 it is a screen shot of one of the LabVIEW control application environments used in the experiments.

The system is controlled using PI control, although the program used is capable of executing PID control. However, the physical configuration of the process system makes the use of derivative control unnecessary and hence it is discarded.

The wired networks which connect the process and the operator PC are Ethernet, Internet and FUNET. The distance between the process and the operator varies from 20 meters to 650 kilometers. The maximum speed for data transmission in Ethernet is 10 Mbit/s, in Internet 2 Mbit/s and in FUNET 2.5 Gbit/s. The protocol used in all networks is UDP (User Datagram Protocol). It is a network protocol in which a host can send a message without establishing a connection with the recipient. The data communication is followed by the Commview 4.1 program. The control performance and the ability of the network to transmit packages are examined using different sample frequencies. The same control experiments are carried out both via network and without network for comparing the control performance achieved over a network and with a local control. Also the control results are compared using the wireless ad-hoc network and wired Ethernet network.

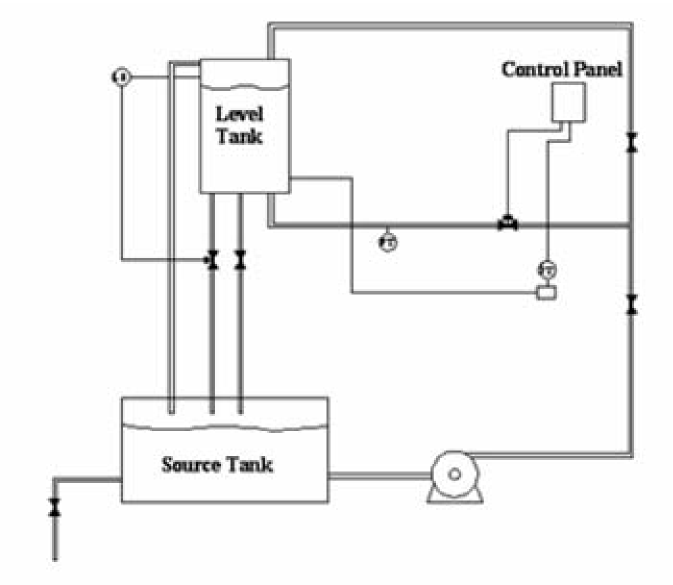

Fig.1. Laboratory-scaled flow process for examining the control across network.

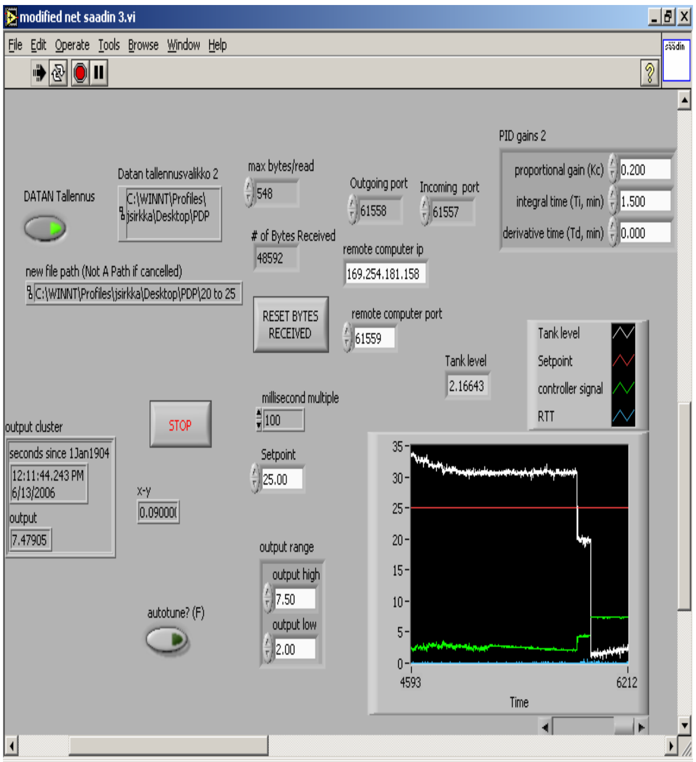

Fig. 2. LabVIEW control application environment used in the experiments.

3. NETWORK-BASED CONTROL SYSTEM

When the network belongs as one element to the control system, the conventional control design methods are not applicable. Therefore different methods for the delay compensation have been developed based on software or hardware during last few years (Tipsuwan *et al*., 2003 and Nilsson *et al*., 1998). The design methods are different depending on the network type. The methods include usually such assumptions, which can cause problems in applying the method to the reality. The most common assumptions are the following (Chow *et al*., 2001 and Wang *et al*., 2003):

- network transmissions are error-free.
- length of every data message is constant.
- computational delay of the controller τ_k^c is constant and is much less than the sampling period , i.e. it is embedded in the delays between the sensor and the controller, τ_k^{sc} and between the controller and actuator τ_k^{ca} .
- network is not overloaded.
- every dimension of output measurements or control inputs is packed into one single data message.

The control design methods can be based on the development of communication protocols, which minimize the network delay, or on the methods, which take into account the delay. The latter methods can be divided to the methods for random access networks and cyclic networks. Flammini *et al*., (2002) have compared the efficiency of the networks in the control purposes.

The network delay consists of the following transmission delays

- communication delay between the sensor and the controller, τ_k^{sc}
- communication delay between the controller and the actuator, τ_k^{ca}

The distributed control system with different delays is presented in Figure 3.

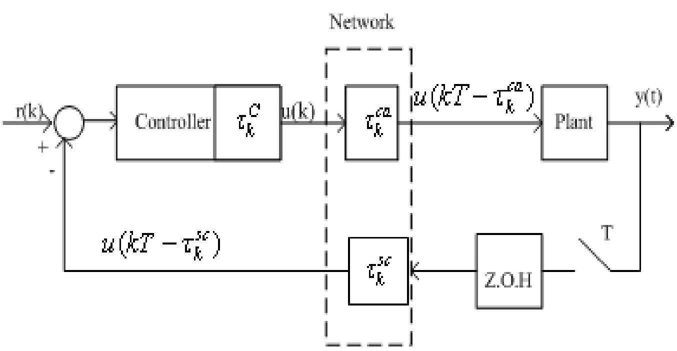

Fig.3 Block diagram of the network-based control system with different delays.

The control delay is determined as the time when a measurement signal is sampled to when it is used in the actuator. It equals the sum of these delays according to the equation (1)

$$\boldsymbol{\tau_k = \tau_k^{sc} + \tau_k^{ca}}. \quad (1)$$

Usually the total network delay includes also computational delays as computational delay in the controller $\boldsymbol{\tau_k^c}$, but they can be embedded in the delays $\boldsymbol{\tau_k}^{sc}$and $\boldsymbol{\tau_k}^{ca}$.

Besides that the total network delay includes transmission delays and computational delays it includes also delays due to the network load and failures. The length of the delay is varying, and it depends on the network used. The network can be cyclic or random access (RAN). The cyclic networks are based on token passing and TDMA (Time Division Multiple Access) as Token Ring, Token Bus and Profibus. In these networks the delay is caused primarily from the waiting time i.e. the time the node has to wait until the network is idle for sending the message. The delays in cyclic networks can be periodic or deterministic. Ethernet, CAN (Controller Area Network) and Internet belong to RAN networks. In these networks the delay behaves randomly due to the CSMA (Carrier Sense Multiple Access) technology. If the transmission occurs over several networks as in Internet, the waiting times in switches and routers cause also additional delays.

For a sample-data control system it is natural to sample the process output equidistantly with a sample period. It is also clear to keep the control delay as short as possible. The reason is that the delays give rise to phase lag, which often degenerates system stability and performance. This motivates to use a system setup with event-driven controller node and event-driven actuator node. The calculation of the new control signal takes place as soon as possible the new signal arrives from the sensor node to the controller node. The timing diagram is presented in Figure 4.

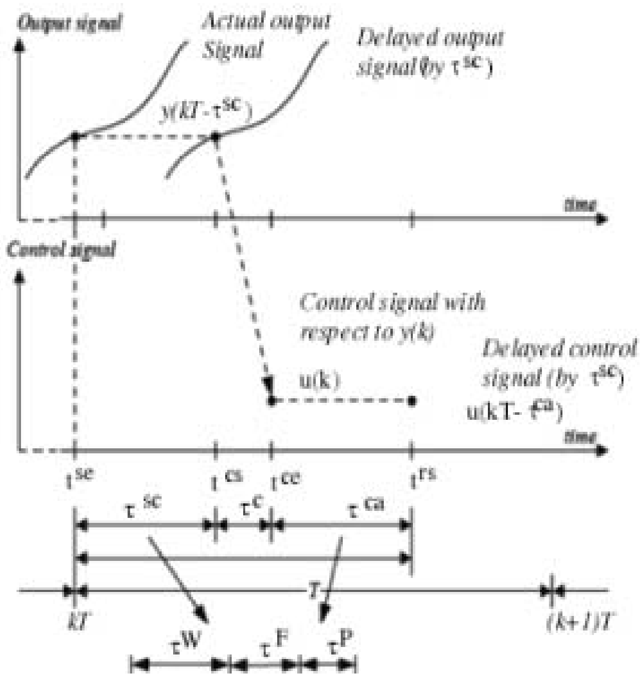

Fig.4 Timing diagram of the network-based control system.

3.1 Delay in Ethernet and in switched Ethernet

Ethernet is one of the most used local area network (LAN) technologies. It transmits data with the speeds 10, 100 or even 1000 Mbit/s. Ethernet is not intended for real-time communications. However, the large number of installed Ethernets will make it attractive for use in real-time control systems. Ethernet uses a bus access method called CSMA/CD (Carrier Sense Multiple Access with Collision Detection) which means that before sending to the network the station listens to the channel, and when the channel is idle, transmission starts. If several stations start sending to the bus the collision is detected, and the colliding stations back off, and try a retransmission after a random time. An almost unlimited number of stations can be connected to Ethernet.

The switched Ethernet differs from the conventional Ethernet in two ways. Firstly, the operation of the hub, where the stations are connected, is different. In Ethernet the hub is a passive device, but in the switched Ethernet the hub, called a switch is an active device. It identifies the destination ports and relays the frame only to those. Figure 5 presents the transmission methods of Ethernet and switched Ethernet.

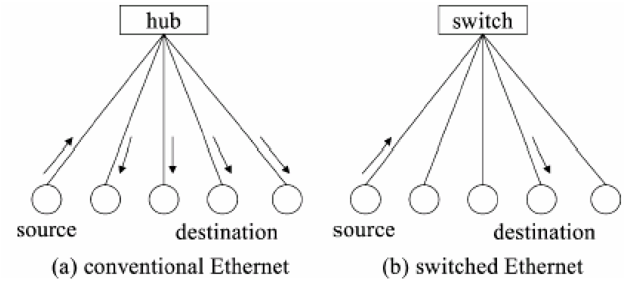

Fig.5. Operation of the conventional Ethernet and switched Ethernet.

The conventional Ethernet uses a half-duplex link, while the switched Ethernet uses a full-duplex link. This means that the switched Ethernet is free of frame collisions and the delay can be minimized. Typical method of switching technology is a "store and forward" method as shown in Figure 6.

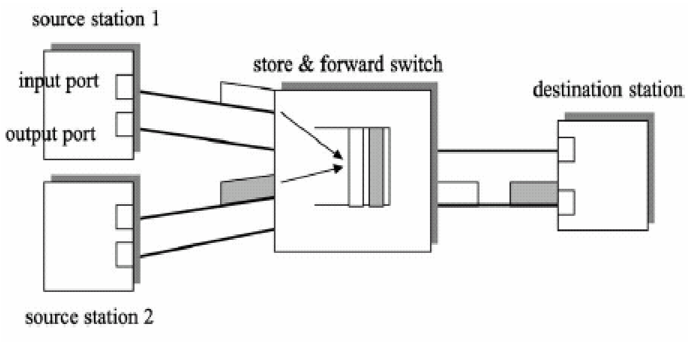

Fig.6. " Store & forward" method

In the store and forward method the switch receives the frame from a source station and checks if the reception line of a destination station is idle. If it is idle, it forwards the frame. If not, it stores the frame into its buffer and waits until the line is idle. If several frames with the same destination address are received simultaneously, the switch stores the frames into the buffer and sends them to the destination one by one.

According to the research by K.C.Lee and S.Lee, (2002) the length of the network delay in the conventional Ethernet and in the switched Ethernet differs remarkably. The length relation of delays between Ethernet and the switched Ethernet is 103. It means that the switched Ethernet applies better for control purposes.

3.2 Compensating methods for the network delay

Network delays are usually varying in a random fashion, and they can have different sources as

- waiting for the network to become free for transmission.
- data transmission errors can occur. This causes retransmission and increases delay.
- collision risks exist, if two nodes try to send messages at the same time.

To take randomness of the network into account in the algorithm, the time delays can be determined from a probabilistic distribution. The delays can have a constant probability function or the probability distribution functions are given by a Markov chain. Nilsson *et.al.* (1998) and Nilsson (1998) have developed the models for the delay based both on the constant probability distribution function and an underlying Markov chain. The LQG-optimal controllers derived use knowledge of old time delays. This is possible by using "time stamping" i.e. all transferred signals are marked with the time they were generated. By comparing the "timestamp" with the internal clock of the controller the time delay can be calculated. The optimal controller is the combination of a state feedback controller and a Kalman filter.

Luck *et al*. (1990) have introduced clocked buffers on the input in the controller node and in the actuator node. This makes possible to get rid of the time variations. If these buffers are large enough, larger than the worst case delay, the delay for a transfer between two nodes is deterministic. This means that sometimes it is used older information than it is needed, and this can lead to a degradation of performance in comparison with an event-driven setup.

Srinivasagupta *et al.* (2004) has examined the applicability of MPC (Model Predictive Control) to compensate the delay due to the network. They propose that previous values of the delays are taken into account in the control algorithm. The round-trip time (RTT) is measured i.e. the total delay is formed from the delay τ_k^{sc} and from the delay τ_k^{ca}. The measurements are based on time-stamping. Time-stamped model predictive control (TSMPC) makes possible to get better stability by decreasing the modelling error of the algorithm.

Tipsuwan *et al*. (2003) have proposed the gain scheduling method for networked PI controller over IP network. In this method the new gain β is used for changing the original gains of the PI controller. This depends on the delays concerning the transmission of measurement and control signals. The aim is that the system is stable and the specifications of the system i.e. the percentage overshoot, settling time and rise time are achieved. The method is developed both for the constant and random delays. The minimization of the cost function together with the mean squared error index determines the performance of the control with the parameter β. The simulation results show that the proposed gain scheduling method for a networked PI controller on IP network environment with reasonably long RTT delays and relatively low variations is applicable.

Almutairi *et al.* (2001), has examined, how the fuzzy compensation can be used in the networked control systems. The compensation method is developed for a PI controller over the network with randomly varying delay. The method has been applied as an example on a network-based controlled DC motor by determining the parameter β by fuzzy logic. Figure 7 illustrates the block diagram of the modified network-based PI control with fuzzy modulation.

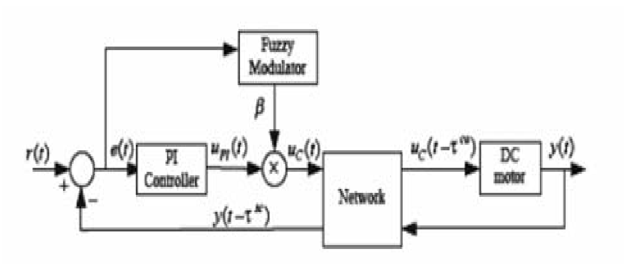

Fig.7. Block diagram of fuzzy modulation.

In this method the output of the PI-controller is modified according to the equation (2)

$$u_C(t)=\beta*u_{PI}(t)=\beta*K_P e(t)+\beta*K_I\int_{t_0}^{t} e(t)dt \quad (2)$$

The parameter β is determined based on the following rules

If e is **S**mall then $\beta = \beta_1$
If e is **L**arge then $\beta = \beta_2$

such that $0 < \beta_1 < \beta_2 < 1$, where $\beta i,j = 1,2$, are the consequent parameters corresponding to the modulation parameter β, and e is the error. The membership functions for the error are according to Figure 8.

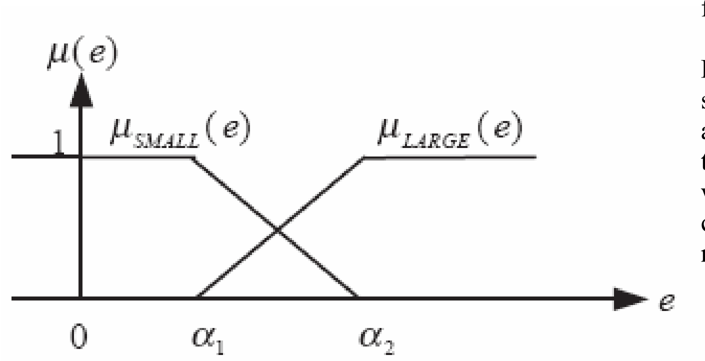

Fig.8. Membership functions for the error.

In Figure 8 α_1 and α_2 are parameters, which make possible to change the shapes of the membership functions. The tuning of the membership functions is based on three different cost functions. Two of them are on-line and one off-line. Almutairi and Chow (2002a, 2002b) have presented two methods for the tuning. In the first method the on-line/off-line tuning includes only the adaptation of the consequent parameters β_1 and β_2 in the fuzzy rules. In the other method also the antecedent parts in the fuzzy rules will be adapted.

4. EXPERIMENTAL RESULTS

The experimental control results presented below can be divided as follows:

-control results over three different wired networks (Ethernet, Internet, FUNET) and without network i.e. local control

- control results over the wired Ethernet and wireless ad-hoc network

- sampling frequencies used in the experiments are 1,2 and 3 MHz: the reason for this is to see how the network copes with different data loads.

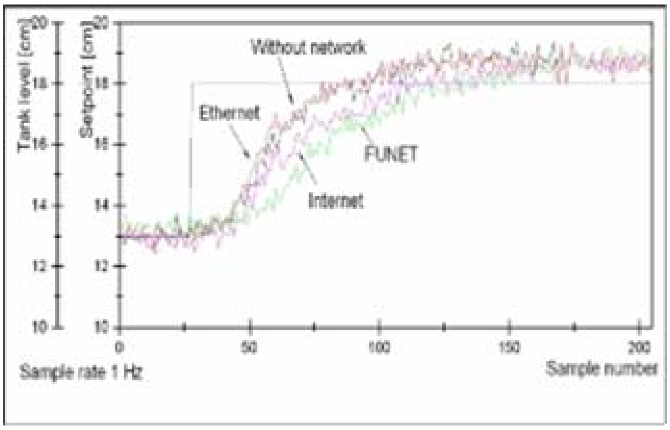

Fig. 9. Experimental process responses via Ethernet, Internet, FUNET and without network

As Figure 9 shows the control across Ethernet is similar to the control without network. The control performance via Internet and FUNET is slower than via Ethernet as the responses show. The experiments with the sample frequencies 2 and 3 MHz gave similar results.

Figure 10 shows the control of the laboratory-scaled tank system using the wired Ethernet and wireless ad-hoc network at a sampling rate of 1 MHz. As you can see from the Figure the Ethernet network response is nearly identical to the wireless network response in terms of process delay and the curve definition. Figure 10 also shows that the ability of the networks to control the process is virtually identical.

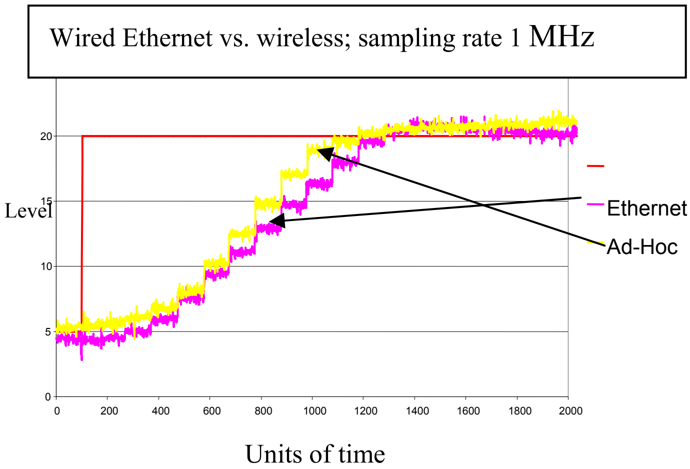

Fig.10. Experimental process responses via the wired Ethernet network and wireless network at a sampling rate of 1 MHz.

Figure 11 shows the same experiments carried out with the sample rate of 3 MHz. The responses show that at this frequency the ability to control the process is beginning to wane. This is most likely due to the use of UDP as the transport protocol as there are limitations on the amount of data that can be sent at one time via UDP when using the LabVIEW control environment.

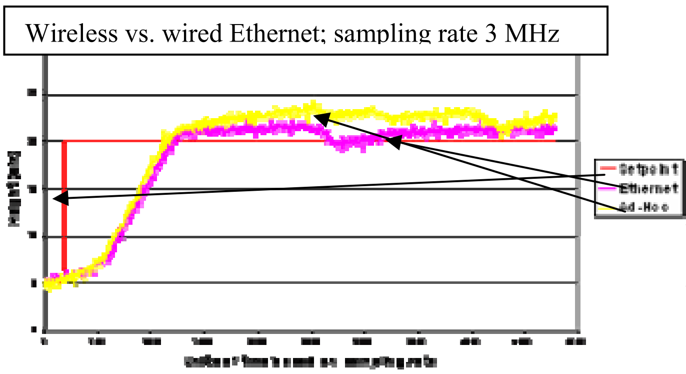

Fig.11. Experimental process responses across wired Ethernet and wireless network at the sampling rate of 3 MHz.

The ability of different wired networks to the process control was also examined by measuring the time which goes when a measurement signal is sampled to when it is used in the actuator. The sample frequency in all experiments was 1 MHz. The experiments show that this time in Ethernet is very small i.e. in average 1 ms. The corresponding time in Internet and in FUNET is about 30 ms. Besides that the time is bigger in Internet and FUNET than in Ethernet it also varies quite much. In Ethernet the time is constant.

The loss of data packages in wired networks was examined using Commview program. The results showed that no remarkable loss of data packages could be detected. The loss for measurement packages was 0.096 % and for control packages 0,023 %.

The control experiments carried out by the laboratory-scaled flow process show that the difference of the control performance between different networks is negligible. The next step would be to examine the control ability of different networks to more complicated experimental environments for detecting the stability, safety and efficiency of networks to process control.

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