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PID CONTROL STRATEGY IN NETWORKED CONTROL SYSTEM

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ABSTRACT

The networked control systems (NCS) and sensor networks, where the process, actuator and the controller are separated by a network, are discussed in this paper and new problems in control are pointed out. To overcome new controller tuning techniques are needed. In this paper Discrete-time PID controller tuning for varying time-delay systems, including NCS are discussed. Optimal PID tuning results are presented for a general process model in different cases of constant, state- and time-dependent or random delays. The results are displayed as functions of process time constant and controller sampling time. PID controller design methods such as internal model control and gain scheduling are discussed in this thesis and also we develop and compare the data fusion methods in NCS.

KEYWORDS: Networked Control Systems, Discrete-Time PID Controller, Tuning, Varying Time-Delay

1. INTRODUCTION

Networked control systems (NCS) are feedback control systems wherein the control loops are closed through a real-time network. The main motivations for using networks for data transmissions in control systems are reduced system wiring, ease of system diagnosis. The problem is that the network induces a varying time-delay into the control loop, which has to be taken into account in control design. Conventional control design can't take the varying time-delay into account, new methods are called upon. Networked control systems (NCS) are researched and some results have been achieved. Dynamic programming has been proposed for controlling varying time-delay systems. But still simple tuning rules for varying time-delay systems are needed. The thesis investigates optimization in tuning controllers for varying time-delay systems using simulation.

A PID controller structure is selected to control the system as it is easy and intuitive to tune. It is used in industrial controller and also has on a particular fixed structure controller family, so it is called PID controller family. PID controllers are commonly used in industry and a large factory may have thousands of them, in instruments and laboratory equipment. In engineering applications the controllers appear in many different forms: as a standalone controller, as part of hierarchical, distributed control systems, or built into embedded components. The simplicity of these controllers is also their weakness - it limits the range of plants that they can control satisfactory.

In modern industry where discrete time PID controllers are used the controllers are tuned as if they where continuous controllers. The sampling frequency is set sufficiently high, so that the discrete-time controller approximates a continuous controller. This is possible if there is enough computing power and signaling capacity. In some new applications these are not always available. In networked control systems the network can't offer high bandwidth to transmit the measurement and control packets. The energy source and the computing power are often limited on mobile devices, such as robots and autonomous devices. In these applications one has to enter the true discrete-time domain by lowering the sample frequency.

The main contributions of this thesis are:

- Modification of the optimization and simulation based tuning method for discrete-time PID controllers in NCS.
- Tuning rules for a first order system with several varying delays.
- Internal model control and gain scheduling
- Development and comparison of data fusion methods in NCS.

The results, methods and the theory they are based on, are presented in the paper as follows: First varying time-delay systems are generally introduced and the time-delays in these systems are identified and analyzed, including the delay distribution of the Internet. Then networked control systems are explained in section 2. The discrete time PID controller and the optimization tuning are presented in section 3 among with other PID controller design methods such as internal model control and gain scheduling. The optimization tuning method is applied in a general case for a first order system and for a certain example process in section 4.

2. DISTRIBUTED SYSTEMS (STRUCTURE OF NCS)

In distributed systems the controller and process are physically separated and connected with a network.

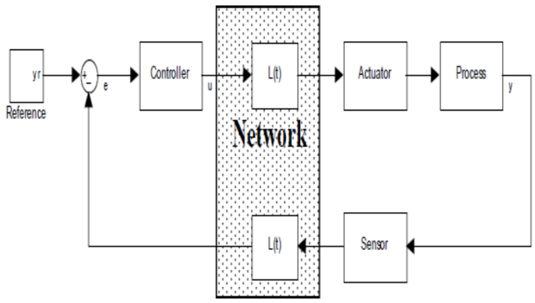

Figure 1: Fully-Distributed NCS where Controller, Actuator and Sensor are Distributed and Connected with a Network

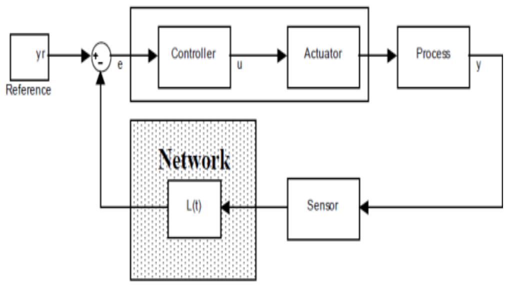

Figure 2: Semi-Distributed System Where Measurements from a Sensor are Sent Over a Network to the Controller and Actuator Node

3. DISCRETE-TIME PID CONTROLLER

The controllers used to control processes can have several structures. The choice of the structure determines how well the plant can be controlled. The textbook version of the PID controller in continuous time is,

$$u(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau + T_d\frac{de(t)}{dt}\right) = u_p(t) + u_i(t) + u_d(t),$$

Where e (t) is,

$$e(t) = y_r(t) - y(t)$$

The reference signal (the set-point) is yr(t) and the output is y(t) of the controlled process, with L(t) = 0. In transfer function above Equation becomes $G_{PID}(s) = \frac{U(s)}{E(s)} = K_p\left(1 + \frac{1}{sT_i} + sT_d\right)E(s) = P + \frac{I}{s} + Ds$

The coefficients Kp, Ti, Td and P, I, D are related by:

$$P = K_p$$
$$I = K_p / T_i$$
$$D = K_p T_d$$

The proportional part of the controller at time-step *k* is then

$$u_p[k] = u_p(t_k) = K_p e(kh)\ .$$

The integral part is

$$u_i(t) = \frac{K_p}{T_i}\int_0^t e(\tau)\,d\tau$$

Discretised by approximating the integral with a sum

$$u_i[k] = \frac{K_p}{T_i}\sum_{n=0}^{k} h\,e[n]\ .$$

This can further be simplified by computing the difference

$$u_i[k] - u_i[k-1] = \frac{K_p}{T_i}\sum_{n=0}^{k} he[n] - \frac{K_p}{T_i}\sum_{n=0}^{k-1} he[n]$$

$$\Rightarrow u_i[k] = u_i[k-1] + \frac{K_p h}{T_i} e[k].$$

The derivative part, ud[k] is,

$$u_d[k] = K_p T_d \frac{e[k+1] - e[k]}{h},$$

Which is usually not used since it amplifies random errors.

4. OPTIMIZATION FOR DIFFERENT DELAYS

The total ITAE cost is thus,

$$J(P,I,D)=\frac{1}{n}\int_{0}^{nM}\{(t \bmod M)|e(P,I,D)|\}\,dt,$$

The process is a simple first order system with time constant T and transfer function

$$G(s)=\frac{1}{Ts+1}.$$

The process is augmented with a varying time delay, *L* (*t*),

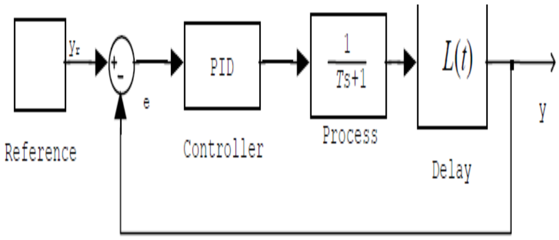

Figure 3: Model of a System with Varying Time-Delay

The delay can be a) constant, b) random, c) time-dependent, d) state- dependent. The respective delays used in these cases are described by,

- τ (t) = L
- τ (t) = rand[0.8...1.2] (6.3)
- τ (t) = sin(t)
- τ (t) = x(t)

4.1.1 Case 1a-Constant Delay- First, the PID controller is optimized for a constant delay in the process.

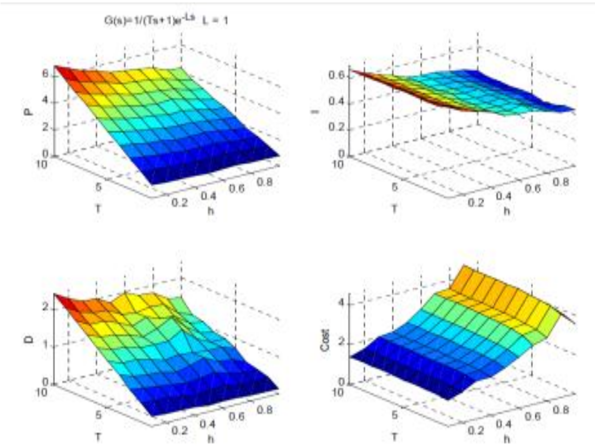

Figure 4: Optimal PID Controller Parameters for the First Order System with Constant Delay. P, I, D and Cost as Functions of Process Time Constant, *T* and Controller Sampling Time, *h*

4.1.2 Case 1b - Random Delay

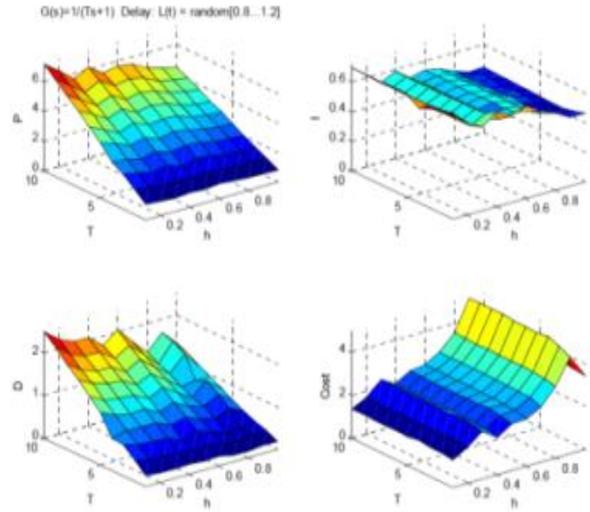

Figure 5: Optimal PID Controller Parameters for the First Order System with Random Delay P, I, D and Cost as Functions of Process Time Constant, T and Controller Sampling Time, h

Comparing the result shown in Figure 5 and the previous result there are only slight differences. The P and I terms are practically identical. There is some arbitrariness in the controller parameters, especially in the D term. This is caused by the randomness in the delay. As the results are similar to the constant case, one can assume a constant delay (the mean of the random) when tuning a PID controller for this kind of uniformly distributed random delay.

4.1.3 Case 1c - Sinusoidal Delay

In this case the time-delay varies like a sinusoid. The results are shown in Figure 6.

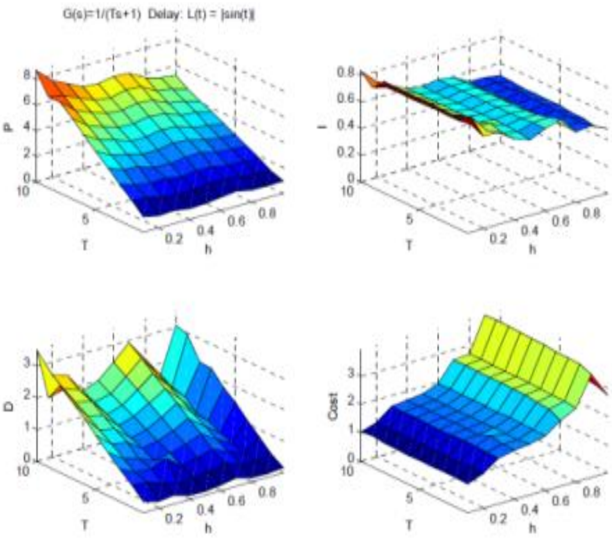

Figure 6: Optimal PID Controller Parameters for the First Order System with Sinusoidal Delay P, I, D and Cost as Functions of Process Time Constant, T and Controller Sampling Time, h

4.1.4 Case 1d - State Delay

The same system is now optimized with a state-dependent delay.

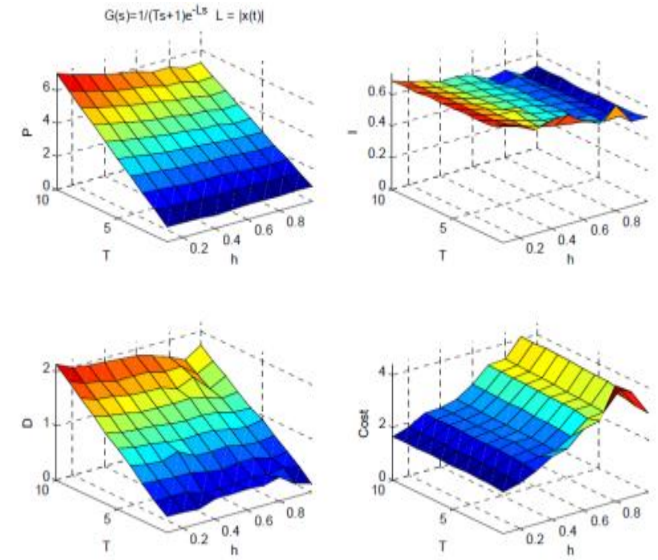

Figure 7: Optimal PID Controller Parameters for the First Order System with State Dependent Delay P, I, D and Cost as Functions of Process Time Constant, T and Controller Sampling Time, h

4.1.5 Case 2a - Constant Delay

In the previous cases the impact of the delay type on optimal PID parameters at various sampling times was investigated. Now the length of delay is studied at a constant sampling time of 0.1. Optimal parameters are found for a constant delay in the range [0.3…1.2]. In the next case the constant delay is replaced with a random delay.

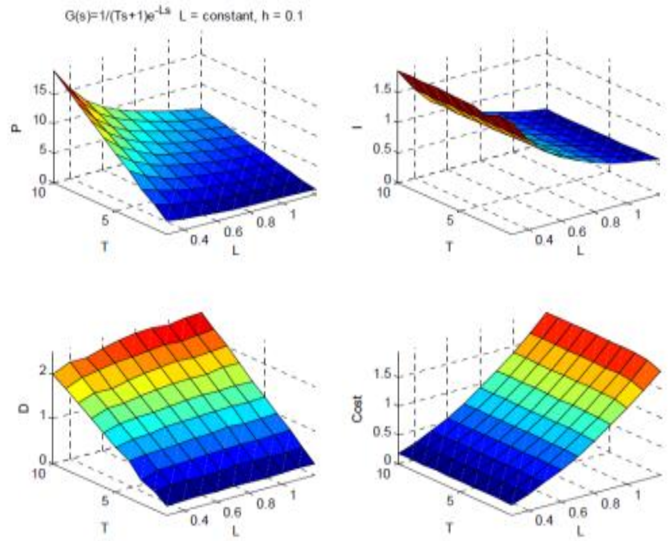

Figure 8: Optimal PID Controller Parameters for the First Order System with Constant Delay P, I, D and Cost as Functions of Process Time Constant, T and Feedback Delay, L. Sampling Time h = 0.1

4.1.6 Case 2b - Random Delay

The constant delay is swapped to a random delay with the same mean as in Case 2a.The random delay is $L(t) = L + rand[-0.2...0.2]$. The optimization is done as a function of the mean of the delay, L, ranging from 0.3 to 1.2. The delay has a mean of 0.3 in the lower end and varies in the range of 0.1 to 0.5. In the upper end the mean is 1.2 ranging from 1.0 to 1.4.

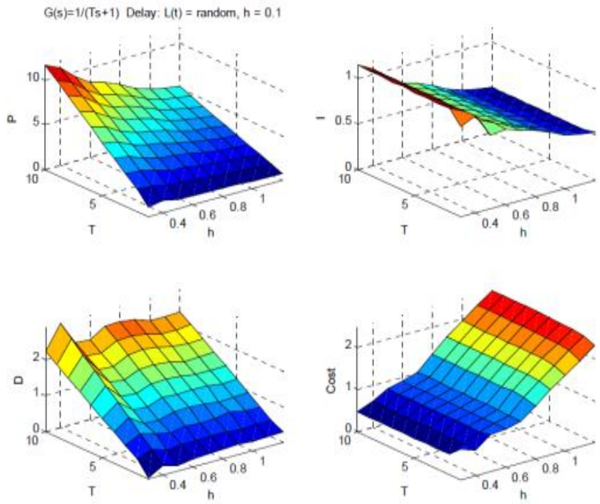

Figure 9: Optimal PID Controller Parameters for the First Order System with Random Delay P, I, D and Cost as Functions of Process Time Constant, T and Feedback Mean Delay, L. Sampling Time h = 0.1

The results are to some extent similar to Case 2a with a constant delay, but the tuning is more conservative and thus the cost is higher for all tunings. The conclusion is that random delay is more difficult to handle, and the optimal tuning can't be as tight as with constant delay. Especially the P and I terms are smaller than in the previous case and they are not as nonlinear as functions of mean delay. With a long delay, where the randomness is proportionally smaller, the results are similar to the constant delay case.

4.2 Optimization for Network Delays

In this section networked control examples are studied. The network properties are n = 3, Tstatic = 0.6 and Tstochastic = 0.4. Old packets are filtered, i.e. if a packet with higher timestamp has already been received the packet is considered outdated and dropped. A sample of the simulated network delay is shown in Figure 10.

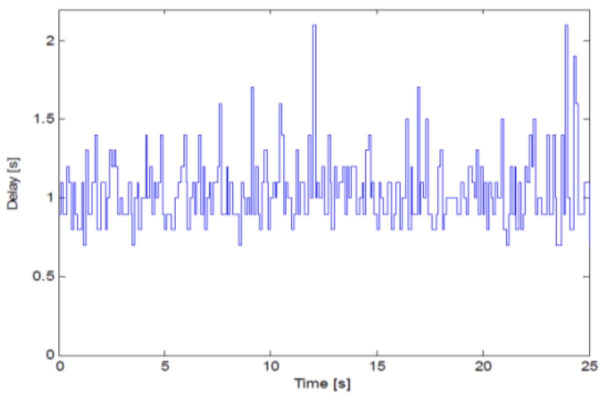

Figure 10: Sample of Simulated Network Delay

4.2.1Case3a - Semi-Distributed System

The semi-distributed system is optimized as a function of sampling time and time constant.

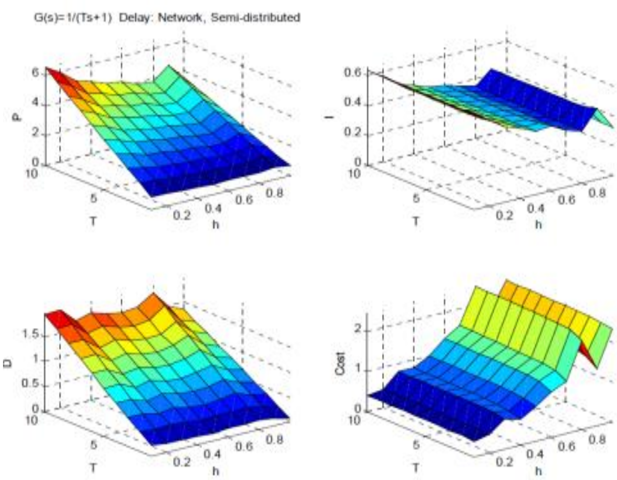

Figure 11: Optimal PID Controller Parameters for the First Order, Semi-Distributed System with Network Delay P, I, D and Cost as Functions of Process Time Constant, T, and Controller Sampling Time, h

Comparing this and Case 1b (random delay) the results are to some degree similar.

The P, I and D terms are almost the same. The cost is smaller because the error signal is not taken after the delay, but right from the process output. The cost is, though in another manner, increasing with sampling time, with dips as the delay turns into constant at the larger sample times.

4.2.2Case3b- Fully-Distributed System

The system in the previous case is extended to a fully-distributed system. Now there is an additional delay between the controller and the process. This leads not only to a larger delay in the control loop, but also to a higher cost, as the delay is between the reference signal and the process output signal.

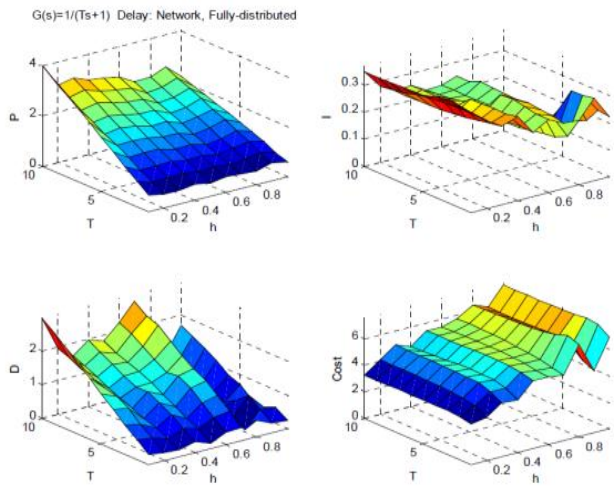

Figure 12: Optimal PID Controller Parameters for the First Order, Fully-Distributed System with Network Delay P, I, D and Cost as Functions of Process Time Constant, *T* and Controller Sampling Time, *h*

4.3 Gain Scheduling by Delay

In this case the gain scheduling is based on the current average delay of the system, in practice on a low-pass filtered measured delay. The gain scheduling strategy investigated here is depicted in Figure 13.

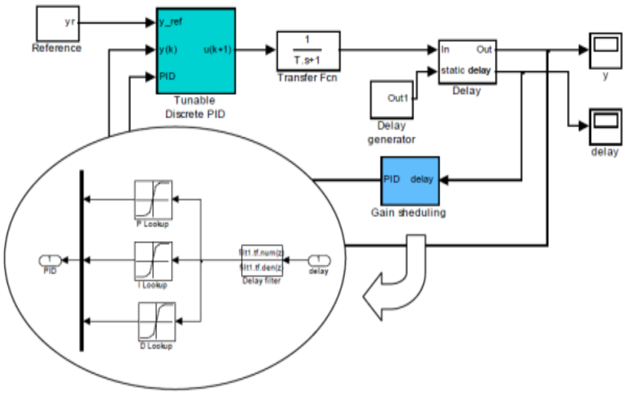

Figure 13: Gain Scheduling with PID Controller. The Gain Scheduler has a Low-Pass Filter for the Delay and Look-up Tables for P, I and D Parameters

First the delay is random with the same properties as in Case 2b, but there is a step in the mean delay from 0.5 to 1.0 at time 40 s. In the second example the delay has a slow sinusoidal variation with a frequency of 0.1 rad/s and amplitude 0.4.

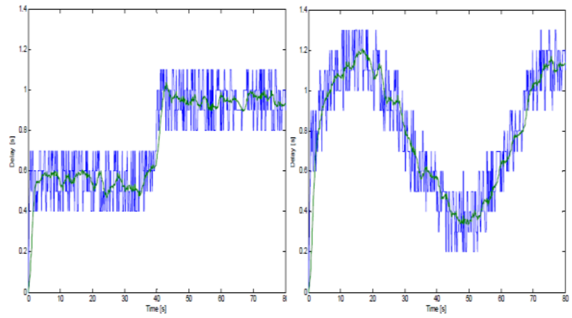

Figure 14: Delay for Simulations with Gain Scheduling. Thin Line: Measured Delay, Bold Line: Low-Pass Filtered Delay on the Left: Random Delay with Step Change. On the Right: Slow Sinusoidal Variation

4.3.1 Case 4a – Step Delay Change

The nominal delay of the system is assumed to be 0.5. The constant controller is tuned for this delay. At some stage the state of the system changes and the delay rises to 1.0. Examination of the step responses on the right in Figure 15 leads to the conclusion that the gain scheduled controller is better than the non-scheduled controller The PID parameters plotted in on the left show that, indeed, the controller is scheduled with appropriate gains for the current delay.

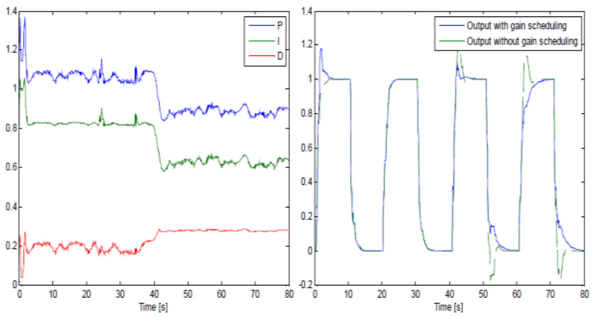

Figure 15: Gain Scheduling with Step Delay Change. On the Left: PID Parameters for Current Identified Delay as Function of Time. On the Right: Step Responses for System with and without Gain Scheduling

4.3.2 Case 4b – Sinusoidal Delay Change

In this case the random delay is assumed to have slow sinusoidal variations with amplitude 0.4 around a mean delay of 0.75. For the sinusoidal delay the controller tuned for an average variation does perform well sometimes, but as the delay changes the control loop has overshoots and there is risk of instability. These two cases show that a gain scheduled PID controller performs better than a constant controller, when the delay changes significantly.

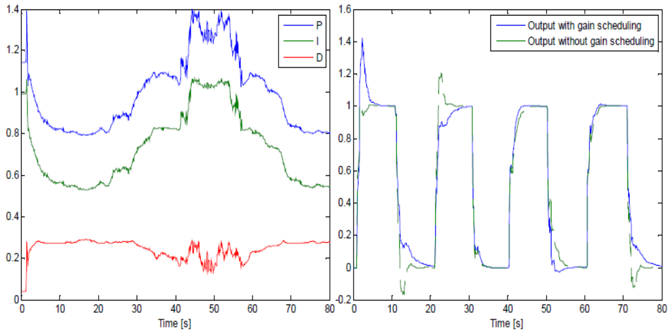

Figure 16: Gain Scheduling with Sinusoidal Delay Change. On the Left: PID Parameters as Functions of Time on the Right: Step Responses of the System with and without Gain Scheduling

4.4 Sensor Network

A sensor network is considered here with the sensor cluster having four sensors with known noise variances. The controller is hand tuned (P = 1, I = 0.7 and D = 0.2, this is near the optimal tuning for the system) to get a satisfactory step response. The simulation is run for four step responses, and the error integrals are averaged to get a better estimation of them, because of the randomness (noise, delay, packet loss) in the network that causes varying performance on the step responses at different times. The strategies are evaluated based on their step response ITAE and the fusion error IAE over the whole simulation. The results are shown in the following figures and collected in Table 1.

Table1: Fusion Strategies Results

case	Name	Step Response ITAE	Fusion Error IAE
1	Fusion_no	1.56	3.7
2	Fusion	1.36	1.33
3	Fusion_by_timestamp	1.16	1.12
4	Fusion_by_timestamp2	1.85	3.05
5	Fusion_with_delay	1.21	1.61

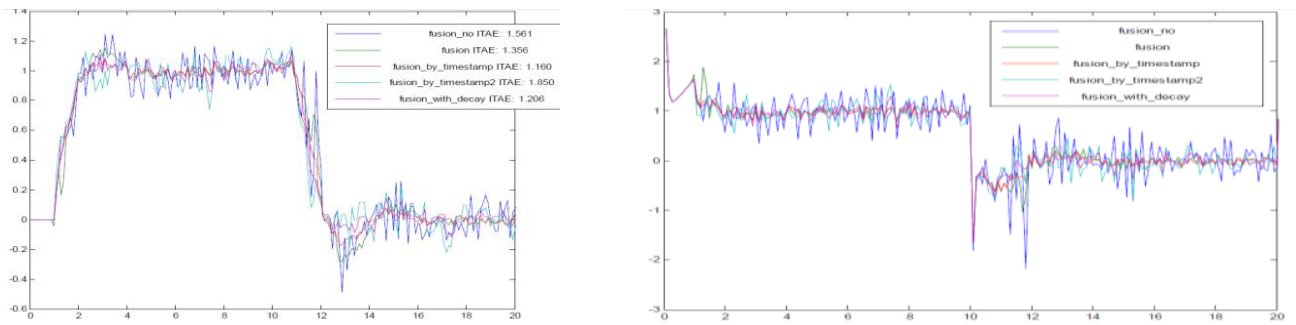

Figure 17: Simulated Step Responses (Top) and Control Signals (Bottom) with Various Fusion Strategies

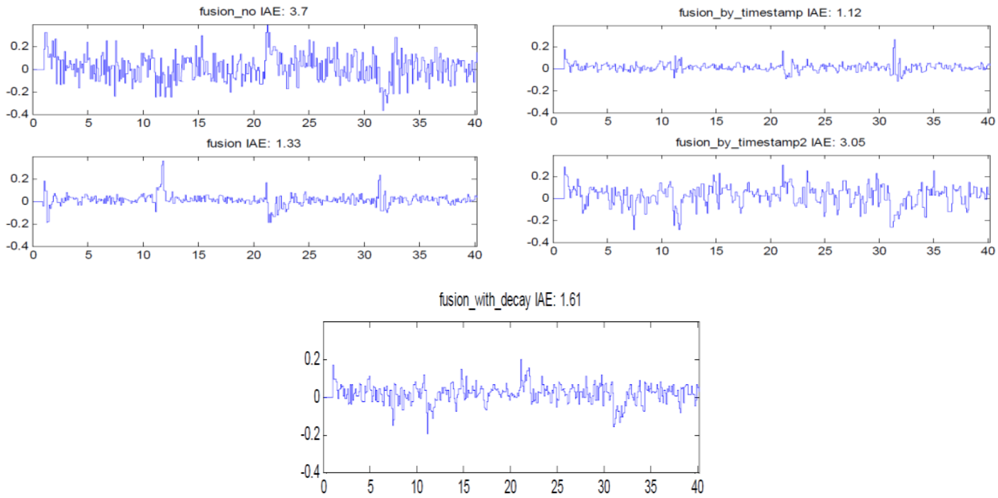

Figure 18: Fusion Errors for Various Fusion Strategies during a Simulation

6.5 Tuning for Example Process

The parameters for the network are presented in Table 2. The variance of the stochastic part of the delay is 3.33 ms. the parameter values approximate typical short distance Internet properties

Table 2: Network Properties, Typical Internet Parameters

Hops, n	Static delay, τ_{static}	Stochastic delay, $\tau_{stochastic}$	Packet loss
3	35 ms	100 ms	1 %

The optimization technique with the average ITAE cost on five unit step responses is used to tune the PID controller for the process.

4.5.1 Optimization Tuning

The optimal tuning is done for sampling times ranging from 0.01 to 0.25 seconds. The tuning is not as smooth as for the previous first order systems, though the results follow the general trend with decreasing PID parameters as sampling time increases. The D term is constant and nearly zero. The cost plotted in Figure 20 rises with sampling time, but it is far from smooth, with a deep valley at h = 0.16 s. At this point the effective delay varies between two values: h and 2h. With this particular sampling time 85 % of the stochastic time-delay is smaller than the sampling time. The PID tunings are listed in Table 4. With the sampling time at the local minimum of Figure 20 the overshoot is fixed with no significant impact on the speed of the response.

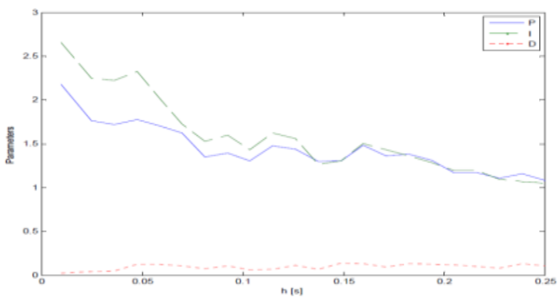

Figure 19: Optimal PID Controller Parameters for Example Process P, I and D as Functions of Sampling Time, *h*

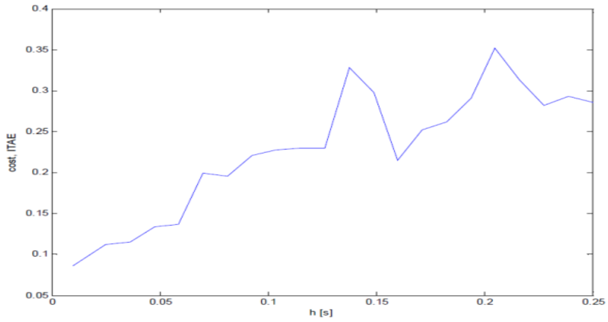

Figure 20: Optimal ITAE Cost as a Function of Sampling Time, *h*, for Example Process

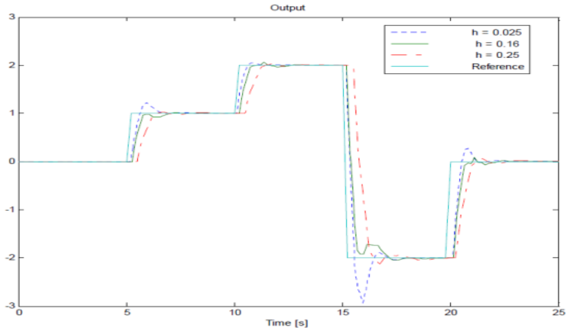

Figure 21: Step Responses with Optimization Tuning. Sampling Times: 0.025, 0.16 and 0.25 Seconds

4.5.2 Ziegler-Nichols Tuning

To compare the results of the optimization based tuning, other tuning methods are also tested. With the simulation model both Ziegler-Nichols step- and frequency response tuning is made. The step response and the critical gain tests are shown in Figure 22.

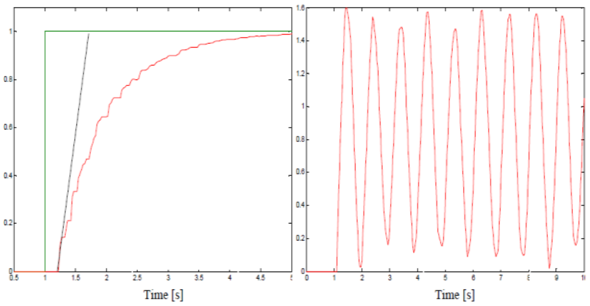

Figure 22: Step Response (left) and Frequency Response Tests for Ziegler-Nichols Tuning

From these graphs the required properties are measured and the parameters are calculated according to Table 1 and translated to P, I and D parameters using Equation I=Kp/Ti. The relevant measurements are collected in Table 3.

Table 3

	Ku	Tu	T1	T2
Simulation	4.5	0.97	0.25	0.7
Test Run	4.5	1.1	0.22	0.8

The Z-N tuning does not take into account the sampling time. A low sampling time is used h = 0.025 s, where the controller approximates a continuous-time controller to some degree. For higher sampling times the control loop becomes unstable.

4.5.3 IMC Tuning

The IMC 63 concept ensures that the controller will work and compensate for the (artificial) modeling error. The controller is tested with and without the pre-filter. The parameters in Equation Td=a2/a1 are derived in the continuous-time case because an IMC controller derived in discrete-time can't be brought to a PID controller form. Therefore only a short sampling time of h = 0.025 s is used for the discrete-time PID so that it approximates the continuous-time controller. The tuning parameter, λ, for the IMC tuning is selected to be 0.65.This results in a response with little overshoot, and with minimum ITAE cost are shown in figure 23.

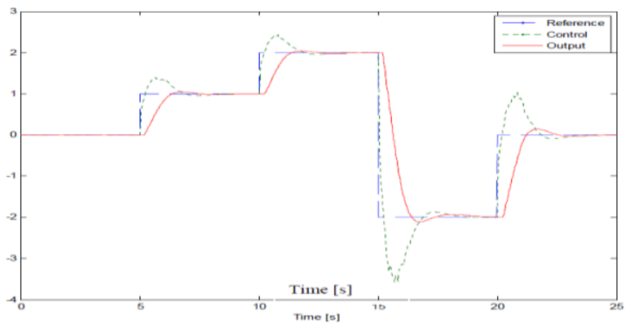

Figure 23: IMC Tuning with Pre-Filter. Simulated Step Responses for the Example Process

4.5.4 RESULTS

The process responses and the control signals for a series of reference step changes are displayed in the following figures. The PID parameters obtained with the different tuning methods and the respective average ITAE and IAE costs of the step responses. The ITAE costs of the responses are used to compare the tuning methods. This measure is chosen because it takes the whole response into account, which is not the case for measures such as the rise time or overshoot. The Z-N step response method is almost unstable and oscillates heavily: the cost is 6 times larger compared to the optimal tuning. This is due to the large gains of the tuning. The Z-N tuning methods are designed for load disturbance rejection so the poor performances originate partially from the reference step changes in the simulations. The IMC tuning with a pre-filter has a quite different step response compared to the others and does not belong here because of the filtering in addition to the pure PID controller. The optimization method has the lowest ITAE and IAE cost, followed by IMC. There is a correlation between the ITAE and IAE costs. The square integral costs (ISE and ITSE, not shown) give similar results.

Table 4: PID Parameters for Example Process and Cost from Simulations

Method	P	I	D	Cost ITAE	Cost IAE
Z-N step response	3.36	6.72	0.42	0.072	0.302
Z-N frequency response	2.7	5.57	0.33	0.027	0.034
Optimization,h=0.025	1.77	2.66	0.02	0.014	0.021
Optimization, h=0.16	1.48	1.50	0.13	0.015	0.024
Optimization, h=0.025	1.08	1.05	0.11	0.025	0.051
IMC(without pre-filter)	1.56	1.23	0.25	0.025	0.022
IMC(with pre-filter)	1.56	1.23	0.25	0.026	0.046

The tuning by optimization is the best, it has the smoothest response and settles down in a short time with little overshoot, even the larger step is not a problem. The tuning for a sampling time of h = 0.25 s works almost as well, there is only a larger delay and a slower response because of the large sampling time. It is notable that the IMC tuning (with and without a pre-filter) comes near the same performance as the optimal tuning, if one considers the error integrals. The control signals shows that the Z-N and the IMC tuning are aggressive with large control signals. The Z-N tuning oscillates strongly. The optimal tunings have a reliable and precise control signal in comparison to the other methods.

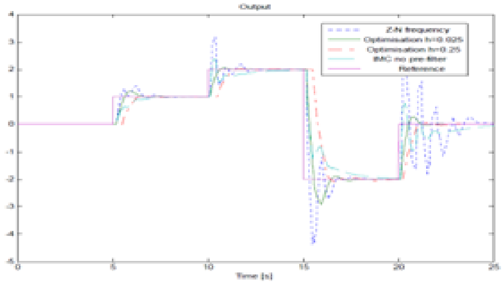

Figure 24: Simulated Step Responses for Example Process

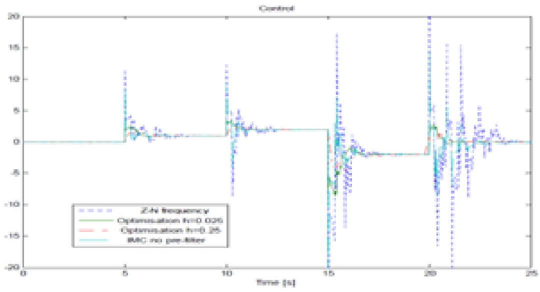

Figure 25: Control Signals for Example Process

8 CONCLUSIONS

This paper studied that the discrete-time PID controller designs and tuning for varying time-delay systems and furthermore networked control systems (NCS), including sensor networks. The discrete-time PID controller was introduced and some practical aspects, such as derivative filtering were formulated. As NCS includes a network, which transmits measurements as packets, there is an inherit discreteness to the system and therefore only discrete-time PID controllers were studied. The controller tuning was focused on an optimization by simulation technique. The tuning method was modified to work with discrete-time controllers in the context of NCSs. Other PID design methods such as Ziegler-Nichols and Internal Model Control were compared to the optimization method. It was further shown to perform better than traditional tuning methods, because it can take the varying time-delay better into account. A general study of optimal tuning for varying time-delay systems was conducted. The optimization was done for first-order systems with time-delay, as a function of process time constant and controller sampling time. The time-delay was a varying time-delay, namely time- or state-dependent and random. The results gave rules of thumbs to tune the PID controller for different types of time-delays. One general result was that with increasing sampling time the P and I terms decrease. With increasing process time constant the P and D terms increase. The tuning results of different time-varying delays were compared to the constant delay case. Differences in the optimal tuning with different types of time-delays were 74 found. However, the optimal tuning for a random delay with a small variance is virtually the same as in the constant delay case.

In the case of a small random variance in the time-delay and a larger sampling time, constant delay tuning can be used, as the sampling time rounds the delay up to nearly constant. The PID controller was found to work best when most of the stochastic time-delay was smaller than or equal to the sampling time of the controller. It performs equally well with a short enough sampling time, with the expense of a more active control signal and less robust performance. The optimized tuning results were based on the ITAE cost of the error signal. As the optimization focused on the time-response only, robustness is not guaranteed. Robustness, load disturbance rejection and noise rejection can easily be incorporated into the optimization criteria.

The down-side of the optimization technique is that a process model is needed. The model can, however, be any input-output description and it is not limited to linear and time-invariant systems. This allows one to tune for any type of processes, such as processes with time-varying delay which is done in this paper. Networked control systems and their various layouts, including sensor networks were described. The occurrence of a time-delay in the control loop of these systems was analyzed. Especially the delay distribution in the Internet was described in detail. Sensor fusion methods for sensor network systems were developed and tested in the simulations. Gain scheduling based on delay was also demonstrated with typical delay changes corresponding to fall off of a node and daily network utilization changes. The optimization method was applied on networked control systems, where the varying time-delay was modeled with the Internet delay distribution. Several tuning methods were tested on an example process in simulations. The optimization tuning cost as a function of sampling time showed that there is a local minimum at a relatively long sampling time where the performance of the controller good. The favorable sampling time is such that the resulting effective delay varies between two values. It is showed that a PID controller can be used to control a process with varying time-delay, as long as the variation in the delay is small, in the order of the sampling time. Traditional tuning methods, such as Ziegler-Nichols, do not perform well in the new setting of networked control systems. The tuning can instead be done with the optimization tuning method using simulation described in it.

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