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Tuning of Discrete-Time PID Controllers in Sensor Network based Control Systems

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Abstract - **This paper studies the tuning of discrete-time PID controllers for processes that are observed with sensor networks. It is assumed that a wireless sensor network gathers information from the process. The characteristics of sensor networks cause varying delays to the measurements, and the tuning of a discrete-time PID controller is studied in this framework. Controller tuning rules are developed by optimizing the performance of the closed-loop system with respect to certain cost criteria. Constrained optimization is used for finding optimal controller parameters and to guarantee the desired gain and phase margins and stability of the system even if the delay varies.**

Index Terms - **PID controller, varying delay, networked control, optimization, sensor networks.**

I. INTRODUCTION

Wireless sensor networks seem to spread out to many fields. Many current research projects in the area concentrate on communication protocols and problems in setting up energy-aware, high-band networks. There are yet many upper level problems that should be solved before the full power of sensor networks can be utilized. When control issues are considered, there are two main problems caused by the networks in general: 1) varying delays in transmission of packets, and 2) packet loss (see e.g. [1], [2], and [3]). This paper concentrates on the former.

The PID (Proportional – Integral – Derivative) controller is the most common controller algorithm used in control systems. For example, in the mid 1990's the PID controller was used in over 95 % of the control loops in process control [4]. The reason for the wide usage is the good properties of the controller: it provides feedback, it eliminates steady-state offsets and it can anticipate the future. These properties can only be achieved if the controller is well tuned. The tuning of PID controllers has been considered in numerous papers and books, but varying delays have not been addressed very often. A recent paper by Koivo and Reijonen [5] discusses the tuning of a continuous-time PID controller, and mainly a state-dependent delay. Here the interest is on discrete-time PID controllers, because nowadays controllers are often run by computers and calculations are done at discrete times.

Sensor networks are well suited for monitoring process variables, but so far the networks have not been used in feedback loops. Before this can be done, the impact of sensor networks on the total performance of the controlled process has to be considered. The main problem is how the stability and robustness in the closed-loop control system could be guaranteed. This paper suggests a new method for solving this problem.

The problem of control over networks has been studied e.g. by Lincoln [1], who has formulated optimal control for networks with long random delays. The stability analysis of networked control systems has been carried out e.g. by Zhang [3]. In their work the theoretical side of the control problem is well analyzed. Still there remains a need to consider more practical issues like the tuning of a PID controller. This paper takes a practical approach to the problem by developing a new tuning method for discrete-time PID controllers.

The paper is divided into the following sections: the control system and controller properties are discussed in Section II. In Section III the optimization methods that are used for solving the problem presented in Section IV are discussed. The tuning results are given in Section V, and conclusions are offered in Section VI.

II. THE CONTROL SYSTEM

In this study, a new tuning method is developed for discrete-time PID controllers in networked control systems where time-varying delays are present. The problem is motivated by the increasing interest of using wireless sensor networks in feedback loops. The control system consists of a process, a discrete-time PID controller, an actuator and a wireless sensor network. The use of sensor networks in process control can be justified by the fact that there is no need for expensive cabling of sensors, since the sensors operate wirelessly. Wireless sensors have free mobility so that they can be connected to the places where the monitored system is moving (rotating axes etc.). There is also more freedom if the monitored process is far away from the controller or if the process is very wide, and it is difficult (and sometimes impossible) to use wired coupling. On the other hand, multiple sensors are required for redundancy and for guaranteeing reliable operation of the whole measurement system. Fig. 1 presents the control system with a wireless feedback loop.

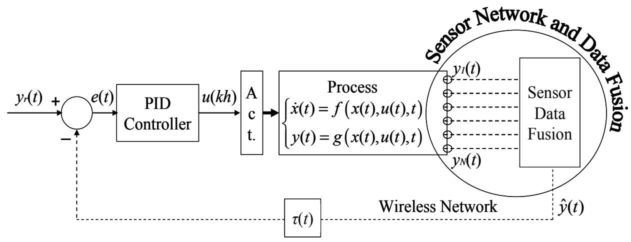

Fig. 1. Wireless networked control system.

Although many processes have multiple inputs and multiple outputs (MIMO), they are generally controlled with several SISO (single input – single output) controllers. If a sensor network is used for observing the process variables, data fusion methods are needed in order to fuse the rich information (measurements $y_1 \ldots y_N$) provided by the sensor network. The SISO controllers can only use a one-dimensional measurement of the process variables. Thus the measurements obtained from the sensor network have to be combined into one estimate of the real value of the controlled variable (denoted $\hat{y}(t)$).

After fusing the information, the estimate of the controlled variable is transmitted to the controller node that calculates the new control signal value $u(kh)$. There is a delay in the feedback loop caused by the sensor network, data fusion and estimate transmission, and it is obvious that the delay is time-varying. The total delay is described by a single variable $\tau(t)$ in Fig. 1. It is the varying delay that makes controller tuning a challenge.

PID controller tuning has been widely studied for processes with constant delays. E.g. the Smith-predictor or the IMC tuning method could be used if the delay was constant. Generalization of these methods for systems with varying delays is not a straight-forward task.

A. Process model

The presented tuning method is applicable to linear and nonlinear, time invariant and time variant as well as continuous- and discrete-time processes. The process can be modeled from first principles or the model can be derived using identification. A very general process model is

$$\begin{cases} \delta x(t) = f\left(x(t), u(t), t\right) \\ y(t) = g\left(x(t), u(t), t\right) \end{cases} . \tag{1}$$

Here $\delta x(t)$ denotes the derivative of process state variable x at time t in the case of continuous-time process, and $x(t+1)$ in the case of discrete-time process.

B. PID controller

Generally [6], the continuous-time PID controller algorithm is given in time domain as

$$u(t) = K\left(e(t) + \frac{1}{T_i}\int_0^t e(\alpha)d\alpha + T_d \frac{de(t)}{dt}\right), \tag{2}$$

where u is the control signal and e is the error between reference y_r and process output y. The controller tuning parameters are K (gain), T_i (integration time) and T_d (derivative time). The controller is often presented in the form

$$u(t) = K_p e(t) + K_i \int_0^t e(\alpha)d\alpha + K_d \frac{de(t)}{dt}, \tag{3}$$

where the tuning parameters are related to those in (2) by

$$K_p = K,\ \ K_i = \frac{K}{T_i},\ \ K_d = KT_d . \tag{4}$$

The Laplace transform of the PID controller algorithm is given in (5) - (8). The gain of the derivative term at high frequencies is limited using a proper approximation [6].

$$U(s) = P(s) + I(s) + D(s), \tag{5}$$

$$P(s) = KE(s) = K_p E(s), \tag{6}$$

$$I(s) = \frac{K}{T_i s}E(s) = \frac{K_i}{s}E(s), \tag{7}$$

$$\begin{aligned} D(s) &= KT_d sE(s) \approx K\frac{T_d s}{1 + T_d s/N}E(s) = \\ &= \frac{K_d s}{1 + K_d s/\left(K_p N\right)}E(s). \end{aligned} \tag{8}$$

Here N is a filtering time constant. At low frequencies the approximation is quite accurate, but at higher frequencies, where measurement noise occurs, the gain is limited. [6]

In practice, controllers are discrete-, not continuous-time. The continuous-time controller can be approximated with a discrete-time one (sampling interval h). The proportional part of the controller requires only sampling, and the backward differences method can be used in the approximation of the integral and derivative parts. The discrete-time PID controller algorithm is given in (9) - (12).

$$u(kh) = p(kh) + i(kh) + d(kh), \tag{9}$$

$$p(kh) = K_p e(kh), \tag{10}$$

$$i(kh) = i(kh-h) + K_i he(kh), \tag{11}$$

$$\begin{aligned} d(kh) &= \frac{K_d}{K_d + K_p Nh}d(kh-h) \\ &\quad + \frac{K_p K_d N}{K_d + K_p Nh}\left[e(kh) - e(kh-h)\right]. \end{aligned} \tag{12}$$

C. Gain and phase margins

One way to improve the robustness of a control system is to tune the controller such that the gain and phase margins of the system are sufficient. If either gain or phase margin of a system becomes negative, the stability of the system is lost. In this study, the desired gain and phase margins are determined beforehand and then the optimization of controller parameters is performed such that these margins act as optimization constraints.

The gain margin is the number of decibels that the open-loop gain can be increased before it reaches 0 dB at the frequency where the open-loop phase shift is –180°. If the gain should be decreased, then the gain margin is negative. Formally, the gain margin (in decibels) is defined

$$m_g = 20\log\left(\frac{1}{M(\omega_{pc})}\right), \tag{13}$$

where $M(\omega_{pc})$ is the open-loop frequency function at the phase cross-over frequency ω_{pc}. The phase margin m_p is the additional phase lag that is allowable before reaching –180° at the frequency where $M(\omega)$ equals one (0 dB).

$$m_p = \varphi(\omega_{gc}) + 180^{\circ} \tag{14}$$

Here $\varphi(\omega_{gc})$ is the phase at the gain crossover frequency ω_{gc}, for which $M(\omega_{gc}) = 1$ (or 0 dB). [7]

D. Delays

Delays play an important role in the field of control in sensor (and actuator) networks. Since the measurements are transmitted from sensors to actuator(s) via a wireless network, the delays are varying. Usually the delay distribution depends on the environment and on the equipment, but also on the protocols used. In sensor networks e.g. routing affects the time it takes to transmit the measurements through the network. The effect of the delay, when control is considered, is that it decreases the phase margin of the controlled system. In the worst case, the closed-loop system may become unstable because of the delay.

This study makes a comparison between constant and random delays. A constant delay is used as a point of comparison for the random Gaussian distributed delay. The distribution is cut at zero, since negative delays are not realistic. This kind of delays are detected, e.g. in the Internet, where a path of packets consists of several nodes that can be modeled as FIFO queues with random arrivals and exponentially distributed service time. If the number of queues traversed increases, the resulting total delay approaches the Gaussian distribution [2]. Random delays are also present in sensor networks, although the delay distribution is other than Gaussian. The range of the delay is more important than the exact form of the distribution and the Gaussian distribution is used here for simplicity.

III. Optimization

The tuning method presented in this paper uses constrained optimization in solving the optimal and robust controller tuning parameters. To optimize e.g. the closed-loop performance, a cost function must be determined. In this study the ITAE (Integral of Time-weighted Absolute Error) cost function is used as the optimization criterion. The cost depends on the absolute value of error between the reference and process output signals. The error is weighted with the time of occurrence of the error. The absolute value ensures the monotonous growth of the cost function. The ITAE cost criterion is

$$J_{ITAE} = \int_0^\infty t\left|e(t)\right| dt = \int_0^\infty t\left|y_r(t) - y(t)\right| dt \,. \tag{15}$$

Other similar cost criteria could also be determined. For example, IAE (Integral of Absolute Error), ISE (Integral of Square Error) or ITSE (Integral of Time-weighted Square Error) could be used. When designing controllers for real systems, often the control signal usage has to be considered. The cost function should then be formulated such that it depends on both error and control signals as e.g. in optimal control. In this section the basic methods for minimizing a cost function are presented.

A. Constrained optimization

There are many methods for unconstrained optimization (e.g. steepest descent or quasi-Newton's methods) that can be used if the decision variables are not bounded and there are no other constraints affecting the optimization. Often in practice, there are several limitations or requirements in the control system and these can be expressed as constraints. There are different methods for solving unconstrained and constrained optimization problems. A general constrained optimization problem can be expressed as

$$\begin{aligned} &\min f(x) \\ &\text{s.t. } g(x) = 0 \\ &\quad h(x) \le 0 \\ &\quad x \in \mathbb{R}^n, \end{aligned} \tag{16}$$

where f is the objective function to be minimized. If single-objective optimization is used, f is a scalar-valued function. In a multi-objective case f is a vector. The feasible set for variables x is determined in (16) by *equality* and *inequality constraints* or $g(x)$ and $h(x)$, respectively.

B. Sequential quadratic programming

Sequential quadratic programming (SQP) is an advanced method for solving constrained nonlinear optimization problems. The SQP algorithm consists of three main phases. At each iteration the Hessian matrix of the Lagrangian function is first updated. The Lagrangian is given by

$$L(x,\lambda) = f(x) + \sum_i \lambda_i g_i(x) + \sum_j \lambda_j h_j(x) \,, \tag{17}$$

where λ_i and λ_j are the Lagrange multipliers.

Secondly, a quadratic programming subproblem is solved and the solution is used to calculate a new search direction. Finally, the step length and the next iterate are calculated using a proper line search method.

The main idea of SQP is the formulation of a quadratic programming (QP) subproblem based on a quadratic approximation of the Lagrangian function. The QP subproblem is obtained by linearizing the nonlinear constraints. The solution of the QP problem gives an optimal search direction which is used to calculate the next iterate x_{k+1}. [8] The QP subproblem is defined

$$\begin{aligned} &\min_{d_k} \ \frac{1}{2} d_k^T H_k d_k + \nabla f(x_k)^T d_k \\ &\text{s.t.} \quad \nabla g(x_k)^T d_k + g(x_k) = 0 \\ &\qquad \nabla h(x_k)^T d_k + h(x_k) \le 0. \end{aligned} \tag{18}$$

Here d_k is the search direction at iteration k and H_k is a positive definite approximation of the Hessian matrix of the Lagrangian function. The subproblem is solved in the presence of linearized constraints. The new iterate

$$x_{k+1} = x_k + \alpha_k d_k \tag{19}$$

is calculated using the step length α_k which is determined by a line search procedure so that the objective function is decreased sufficiently.

There are several variations of SQP. E.g. the vector of Lagrangian multipliers or the Hessian matrix can be estimated using different approaches. It has to be taken into account that an iterate x_{k+1} can violate the original nonlinear constraints $g(x)$ and $h(x)$, because the iterate only satisfies the local linearized approximations of the constraints. A slightly different method called *feasible* SQP guarantees that all iterates satisfy the original constraints. [9]

IV. Problem Statement

The problem is to tune a discrete-time PID controller for a known process model such that optimal performance of the controlled system is achieved despite of the disturbances and of the varying delays in the measurements. The delay varies, because e.g. the path of packets is not constant in sensor networks. The optimality measure is the ITAE cost criterion given in (15). It is assumed that the delay is not measurable and that a constant sampling interval is used. Thus it is not possible to vary the controller sampling interval for compensating the varying delay.

A unit step is used as the reference signal. The ITAE criterion is well suited for this kind of reference signal, because it is desirable that the response of the system reaches the reference signal level quickly and that the response remains on the reference signal level as time goes on. Oscillation should not occur in the output. As time passes after the step change in reference, weighting of the error increases in the ITAE criterion. In that sense, an optimal response does not oscillate, but it rather goes quickly and smoothly to the reference.

Often a controller that is optimally tuned in the performance sense is not robust. An unexpected disturbance may cause the controlled system to go unstable. Besides measurement and load disturbances, varying delays must be considered in sensor network based control systems. In order to make the controller more robust, constraints can be formulated in the optimization problem such that controller robustness is increased at the expense of maximal performance. The varying delays can be compensated by tuning the controller such that the control system has large enough gain and phase margins. The closed-loop system must also be stable, i.e. the poles of the discrete-time model of the closed-loop system must lie inside the unit circle. The ITAE criterion and the mentioned constraints lead to the formulation of an optimization problem as

$$min\, f(x) = \int_0^\infty t\left|y_r(t) - y\left(t-\tau(t),x\right)\right|dt \tag{20}$$

such that

$$g(x) = \varnothing\,, \tag{21}$$

$$h(x) = \begin{cases} x > 0 \\ m_g\left(x, p(\tau)\right) > 3\text{ dB},\ \tau \in S \\ m_p\left(x, p(\tau)\right) > \dfrac{\pi}{3}\text{ rad},\ \tau \in S \\ \left|z_{cl,k}(x, p(\tau), \tau_{wc})\right| < 1, k = 1,2,...,n,\ \tau \in S \end{cases}, \tag{22}$$

$$x = \begin{bmatrix} K_p & K_i & K_d \end{bmatrix}^T \in \mathbb{R}^n\,. \tag{23}$$

The decision variables in the optimization problem are the discrete-time PID controller gain, integration time and derivative time, and they constitute the decision vector x as shown in (23). The filtering time constant N of the derivative part of the controller has a constant value 10. The optimization criterion or the objective function is given in (20). $\tau(t)$ is the time-variant delay of the sensor network. The response of the system $y(t - \tau(t), x)$ depends on the controller tuning parameters and on the network delay. There are no equality constraints (21). The inequality constraints are formulated such that the PID controller parameters are positive, there is a 3 dB gain margin and a 60° ($\pi/3$ rad) phase margin for a known delay distribution $p(\tau)$. These values of the margins are often used in control system design. If the delay was e.g. Gaussian distributed, the gain and phase margins could be calculated using different values for the delay between max(0, μ-3σ) and μ+3σ, where μ is the expectation value and σ is the deviation of the distribution. In order to have a finite number of constraints (the set S in (22)), delay values are taken from the distribution at sampling time intervals and the gain and phase margins are calculated based on those delays (see Fig. 2). Each value of the delay produces three constraints: one for gain and another for phase margin, and the third for the closed-loop system stability requirement.

Each of the n poles of the closed-loop system must lie inside the unit circle, i.e. the absolute value of the poles must be smaller than one. To calculate the last constraint, a closed-loop transfer function is derived using a discrete-time approximation of the process, discrete-time PID controller and a given worst case value of the delay τ_{wc}, which is the worst possible delay of the measurements in the network. For Gaussian distributed delay, $\tau_{wc} = \mu + 5\sigma$ is suitable, and that is also used in Fig. 2. By using the presented constraints in the optimization, the gain and phase margins are adequate in normal operation of the control system, but additionally the closed-loop stability is guaranteed for exceptionally long delays.

To solve the optimization problem, the inequality constraints (22) need to be put into the general optimization problem form as in (16). By defining ε a small positive number, the inequality constraints can be given in the required form as

$$h(x) = \begin{cases} -x + \varepsilon \le 0 \\ -m_g\left(x, p(\tau)\right) + 3 + \varepsilon \le 0 \\ -m_p\left(x, p(\tau)\right) + \dfrac{\pi}{3} + \varepsilon \le 0 \\ \left|z_{cl,k}(x, p(\tau), \tau_{wc})\right| - 1 + \varepsilon \le 0, k = 1,2,...,n \end{cases}. \tag{24}$$

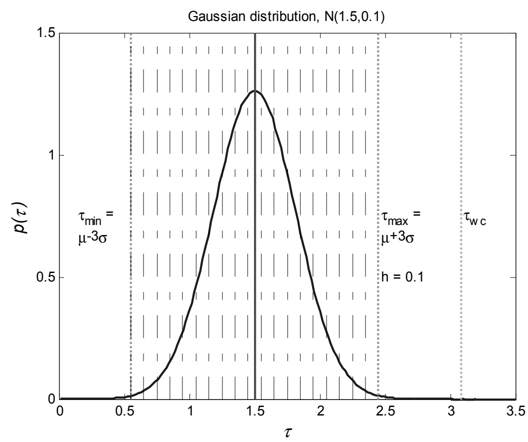

Fig. 2. Formation of the optimization constraints.

V. THE TUNING RULES

The problem presented in (20) - (24) is solved for a first order linear process that is controlled with the discrete-time PID controller given in (9) - (12). The process is modeled as a continuous-time transfer function

$$G(s) = \frac{1}{Ts+1}\,. \tag{25}$$

Besides the process time constant T, the sampling time of the controller must be chosen. To have a wider view on the behavior of optimal controller parameters, the problem is solved for different process time constants and controller sampling times. The process time constant is varied between 0.1 and 10, and the sampling time between 0.1 and 1. Two different delay types are considered here: constant and random Gaussian distributed.

The problem is solved using a PID tuning tool described in detail in [10]. The tool is implemented with the MATLAB/Simulink software and the Optimization Toolbox extension. The solution is based on the SQP constrained optimization algorithm described briefly in Section III. At each optimization iteration new PID controller parameters and optimization constraints are calculated, a closed-loop system Simulink model with process, controller and delay is simulated, and the cost function is evaluated. This iteration is repeated until the cost function value does not decrease anymore. The optimization is performed for different combinations of process time constants and controller sampling times. The reference signal that is used in the optimization is a unit step at 1 s. The length of a single simulation is 20 s.

A. Constant delay

First, a constant delay $\tau = 1$ s is considered. This case is used as a point of comparison for the other case with a random delay. The optimization constraints are calculated such that 3 dB gain margin and 60° phase margin are guaranteed for the nominal system (with constant delay 1 s). Besides these margins, stability is guaranteed for the closed-loop system with a worst case delay of 2 s.

The optimal PID controller parameters for the constant delay case are shown in Fig. 3. The parameters are presented as 3D plots. The other horizontal axis is the process time constant and the other is the controller sampling time. The vertical axis represents the controller parameter value. There are three tuning parameters in the PID controller, and they are presented separately in Fig. 3 as subfigures. The fourth subfigure is the ITAE cost criterion value.

It can be seen that the gain and the integration time form rather smooth surfaces, but the derivative time surface is more or less rough. The investigation of the cost function values reveals that certain sampling times are more suited for this constant delay than others. These better sampling times are 0.5 s and 1 s. This is natural, since the delay in these cases is either twice or exactly the length of the sampling time.

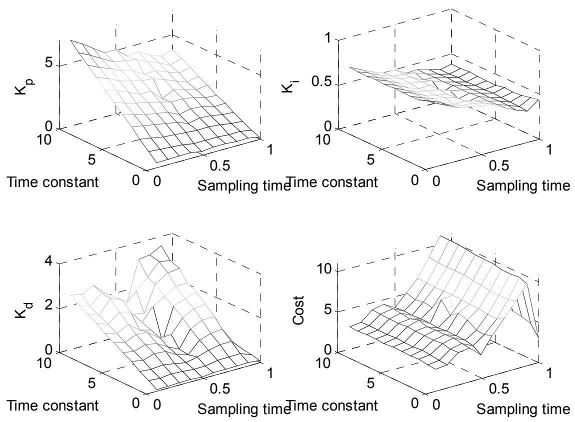

Fig. 3. Optimal PID controller parameters and ITAE cost function values for constant delay $\tau = 1$ s.

B. Gaussian distributed delay

The optimal PID controller parameters when the delay $\tau(t)$ is random Gaussian distributed with mean $\mu = 1$ and variance $\sigma^2 = 0.1$, are shown in Fig. 4. The gain and phase margins of 3 dB and 60°, respectively, are guaranteed for delays in the range $[\max(0, \mu - 3\sigma), \mu + 3\sigma]$ at sampling time intervals. In addition to that, stability of the closed-loop system is guaranteed for a worst case delay of $\mu + 5\sigma$. The optimal parameters form rather smooth surfaces. The integration time seems to be nearly independent of the process time constant whereas the derivative time is independent of the sampling time. The gain depends clearly on both variables.

Fig. 5 shows the difference in PID controller parameters and in cost functions between the constant and random delay cases. The negative values in Fig. 5 indicate that the parameter in concern is smaller in constant delay case than in random delay case. It can be seen that if the delay is random, in general smaller controller gain and integration time should be used. The difference in the gain parameter increases as the sampling time decreases and time constant increases. The difference in integration time is more dependent on the sampling time than process time constant.

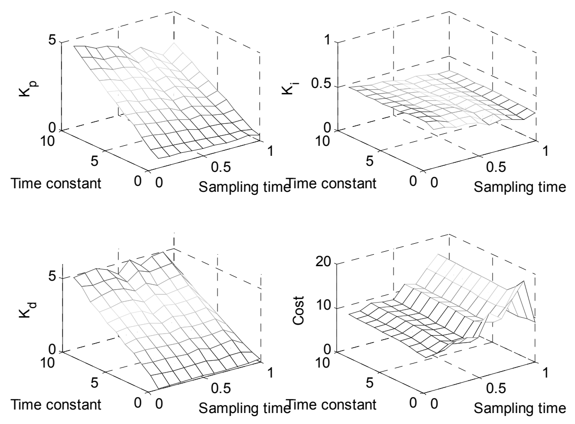

Fig. 4. Optimal PID controller parameters and ITAE cost function values for random Gaussian distributed ($\mu = 1$, $\sigma^2 = 0.1$) delay.

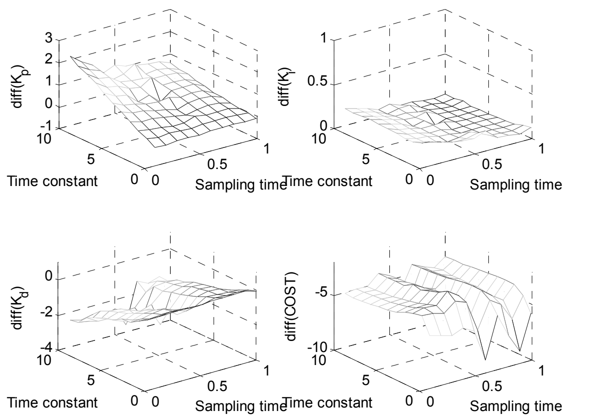

Fig. 5. Comparison of PID controller parameters in constant and random delay cases (random subtracted from constant).

For derivative time bigger values should be used, if the delay is random. Especially in the case of slow processes, i.e. large time constants, the derivative time should be increased significantly. For random delay the cost function shows an increase of approximately 5 units for all time constants and sampling times except for the two well suited sampling times of constant delay (0.5 s and 1 s). When using these sampling times the difference in cost function values is even bigger.

VI. CONCLUSIONS

The paper has presented a method for discrete-time PID controller tuning in varying time-delay systems. Varying delays are present in control systems if sensor networks are used for collecting process data. The tuning parameters produced by the presented method are designed for controllers with constant sampling interval. Thus it is not required to measure the delay of each transmitted packet when applying the method in practice. The controller is tuned rather for a known delay distribution than for exact delays. It is possible to measure the delay distributions in advance, and the tuning method can be applied for a standard PID controller without any modifications to it. The method is based on well-known optimization and simulation techniques, but here the gain and phase margins from classical control theory are formulated in the optimization problem as constraints to improve the robustness of the closed-loop system with respect to varying delays. Mainly first order processes were investigated in the paper, but the method is general in the sense that it can be used for higher order, linear or nonlinear processes as far as they can be modeled. Besides wireless sensor networks, the method is also applicable for other networked control systems.

The optimal tuning rules were presented for first order linear processes as functions of process time constants and of controller sampling time. The tuning rules were optimized with respect to the ITAE cost criterion. Comparisons between the optimal parameters in constant and random Gaussian distributed delay cases were made. It was seen that optimization creates rather smooth parameter surfaces, but in the constant delay case especially the derivative term surface becomes a little grainy. The difficulty of varying delays in a feedback loop can be seen in the cost function values. When the constant delay cost function values were compared with those of random Gaussian distributed delay, it was seen that the cost was clearly higher in the latter case. Even though the controllers were optimized with respect to the same cost criterion and the expected worst case delays were almost the same in both cases, the varying delay caused significant increases in cost.

In sensor network based control systems the PID controller has to make decisions of the control signal value at each sampling time without knowing the length of delay. Thus the controller is unaware of how old measurements it is handling. The measurements from the process output may easily arrive in disorder to the controller because of the varying delays, but still the controller should be able to maintain the stability and robustness of the controlled system. The presented method is able to produce controller tuning parameters that are optimal and robust.

The tuning method is knowledge intensive in the sense that the process model and the controller structure have to be known in advance. Anyway, this cannot be seen as a major drawback, since most of the advanced control methods are model based. The method requires some knowledge of the delays that are present in the system, but it is not necessary to carefully model e.g. the delay distribution.

The formulation of the problem with varying delays, discrete-time PID controller, and suggested constraints is new. The tuning method has been presented and its properties have been discussed. The future work consists of generating more general tuning rules for a wider range of processes. Also MIMO systems should be considered, because the interactions between the subsystems affect the controller tuning. Especially in dense actuator networks these issues arise. Development of coordination principles is also required for sensor and actuator networks, where varying delays are present.

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