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Another Novel Modification of Predictive PI Controller for Processes with Long Dead Times

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Abstract: PID controllers are indisputably the most common controller type encountered in process control applications. They are used for regulating processes with diverse dynamics in industrial applications. Especially, processes with long dead times should require special attention as they are difficult to handle with conventional PID controllers. A lof of different dead time compensating control methods have been introduced in theory. This paper presents another modification of a predicitive PI controller contributing to its inventor and, also hereby, Smith predictor. The proposed method has resemblance with a PID controller and, therefore, is rather applicable for industrial implementations for dead time dominating processes. The introduced method has an additional tuning parameter which is, however, intuitively rather appealing.

Keywords: PID control, dead time, predictive, estimation, performance.

1. INTRODUCTION

Since introduction of the Smith predictor (Smith, 1958), there has been an increasing interest on controller structures that could similarly be used for regulating systems with long dead times. Some of the PID controller tuning methods aim to include the dead time in the design phase in order to compensate its deterioring impact on control performance such as IMC control (Rivera, 1986). For other methods on dead time compensation, the reader is referred to Morari & Zafiriou (1986), Åström & Hägglund (1995) and Ingimundarson & Hägglund (2001).

Later, it was shown that a PID controller could be extended to include dead time compensationg by replacing its derivative control part by prediction (Hägglund, 1996). The resulted predictive PI control (PPI) was a truly convincing example of an elegant and an applicable realization for industrial process control. It generated new modifications to improve its robustness (Normey-Rico, 1997, 1999) and also, an extended variation for some typical industrial processes (Airikka, 2011).

This paper proposes another novel modification for the PPI controller. The proposed method was actually invented accidentally when impact of different prediction horizons of the Smith predictor were studied. The resulted modified PPI (mPPI) controller contributes to the work by Hägglund (1996) and Smith (1958) and, thefefore, has a strong resemblance especially with the PPI controller.

The proposed mPPI controller has an additional parameter to those of the PPI controller, prediction horizon. It is shown in this paper that there is a recommendable range of the prediction horizon being both lower and upper bounded. Also, the impact of the prediction horizon to controller responses are shown to give some insight.

To allow comparison between PI, PPI and mPPI controller, performance analysis is made in terms of a time-domain based performance criterion. And, finally, two simulation examples with control responses are given.

2. MODIFIED PPI CONTROLLER

2.1 *PPI controller*

Consider a predictive PI (PPI) controller for processes with long dead-times as presented by Hägglund (1996)

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)d\tau - k_{pr} \int_{t-L}^t u(\tau)d\tau \qquad (1)$$

where $u(t)$ is controller output and $e(t) = r(t) - y(t)$ is control error for setpoint $r(t)$ and controlled variable $y(t)$. The PPI tuning parameters are proportional gain k_p, integral gain k_i, predictive gain k_{pr} and process dead-time estimate L. Typically, integral and derivative gains are given by their time-based counterparts integral time $t_i = k_p / k_i$ and derivative time $t_d = k_d / k_p$.

The PPI controller (1) can be derived from a Smith predictor for FOPTD (First Order Plus Dead Time) processes and although having a different formulation it actually has an exact match to a Smith predictor for a FOPDT process. The proposed structure, as well as the Smith predictor in general, actually can have a dual representation. Considering the measurement that is taken to the predictor, it is no longer the measurement as itself but modified. The modified measurement $y_m(t)$ which is fed back to the controller can be presented as

$$y_m(t) = \hat{y}(t+L) \tag{2}$$

where process output y is predicted over process dead time L.

2.2 *Modified PPI controller*

The PPI controller can be modified in terms of different process model (Airikka, 2011). In this paper, the modification has been done by extending the prediction horizon over the dead-time. When extending the horizon over the dead-time, the controller performance, however, does not improve. Instead, the dead-time L itself is the best possible prediction horizon for succesful control. But when introducing two different process measurement predictions, the situation changes.

Consider two predicted measurements with different prediction horizons L and M $(M > L)$ combined as follows

$$y_{\mathrm{m}}(t) = \hat{y}(t+L) + \left(\hat{y}(t+L) - \hat{y}(t+M)\right) \tag{3}$$

The modified measurement y_m being summed up of two different predicted measurements provides process output information at two different predicted time instants. Prediction horizon M can be considered as a tuning parameter affecting the modified PPI controller performance. When the prediction horizon M is set to $M = L$, the resulted modified PPI controller reduces to a PPI controller as given by (1).

After applying transfer function block math on the illustrated block diagram in figure 1, the closed loop system can be given in an equivalent control-oriented block. The resulted controller is called a modified PPI (mPPI) controller and it can be expressed as follows:

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)d\tau + k_{pr}\left(\int_{t-L}^{t} u(\tau)d\tau - \int_{t}^{t+M} u(\tau)d\tau\right) \tag{4}$$

Compared to the PPI controller (1), the mPPI controller has an additional term which is the last subtraction containing the predicted control signal over the prediction horizon M.

For implementation of the mPPI controller, either (3) or (4) can be considered. When (3) is chosen for implementing mPPI, it should be simply connected to a conventional PI controller. For that, the controller implementation must include process models for allowing predictions of measurements up to time instant $t + L$ and $t + M$.

When (4) is chosen for implementing mPPI controller, it does not require inclusion of model processes for calculating predicted process outputs. However, as given in (4), prediction of control signal is needed for the time range $t \ldots t + M$. This adds considerable complexity and, therefore, to avoid that it is suggested that the future control actions are considered to remain unchanged since time instant of t. The same principle has generally been applied in model predictive controls. With this simplication, the easily implementable and applicable version of the mPPI controller can be expressed as

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)d\tau + k_{pr}\left(\int_{t-L}^{t} u(\tau)d\tau - Mu(t)\right) \tag{5}$$

The block diagram of the mPPI controller having resemblance with the Smith predictior is given in figure 1.

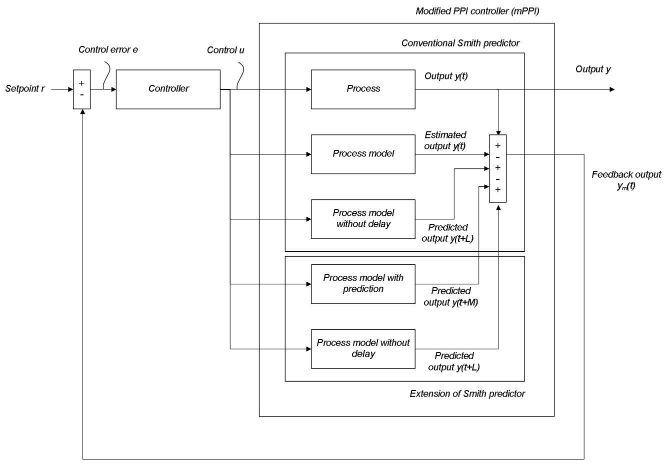

Figure 1. Modified PPI (mPPI) controller structure illustrated using a block diagram representation based on Smith predictor extension.

2.3 *Modified process output*

The modified measurement or process output (3) can be considered as an estimator where the process output is the predicted measurement $\hat{y}(t+L)$ which is corrected by an error between the predicted outputs $\hat{y}(t+L)$ and $\hat{y}(t+M)$. After setpoint or load disturbance transients, in steady states, the following holds

$$\lim_{t\to\infty}\left|\hat{y}(t+M)\right| = \left|\hat{y}(t+L)\right| \tag{6}$$

resulting in a steady-state observation of the modified process output being the same as in Smith predictor in a steady state

$$\lim_{t\to\infty}\left|y_m(t)\right| = \left|\hat{y}(t+L)\right| \tag{7}$$

During the setpoint or load disturbance transients, the predicted process output at time horizon $t + L$ is typically smaller than $t + M$ resulting in a transient observation of the modified process output

$$\left|\hat{y}(t+L)\right| < \left|\hat{y}(t+M)\right| \Rightarrow \left|y_m(t)\right| < \left|\hat{y}(t+L)\right| \tag{8}$$

Thus, the mPPI controller sees the process output worse than it is in real during setpoint or load disturbance transients.

Figure 2 illustrates what the modified process output may look like during a setpoint and a load disturbance change. The mPPI controller receives a modified output which reflects a worse control situation than what it actually is (Fig. 2, upper). Figure 2 also shows what the predicted measurements $\hat{y}(t+L)$ and $\hat{y}(t+M)$ look like during the same transient responses compared to the real process output.

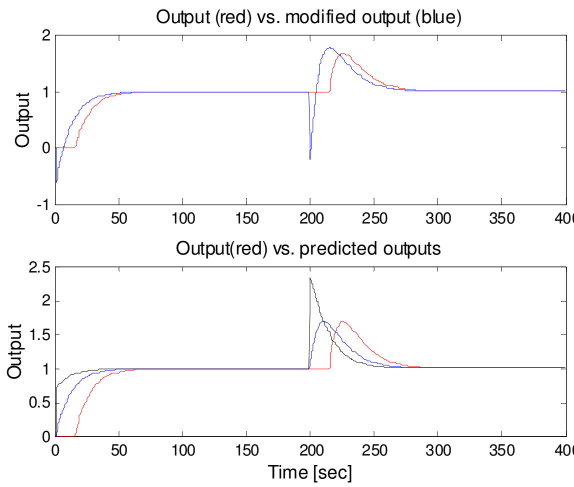

Figure 2. Modified process output. Upper: modified proces output (blue) vs. normal process output (red). Lower: predicted process outputs $\hat{y}(t+L)$ (blue) and $\hat{y}(t+M)$ (black) vs. normal process output (red).

2.3 *Impact of prediction horizon*

The prediction horizon M is an additional tuning parameters as shown in (3) or, optionally, in (4). The prediction horizon has a lower limit of L but it is not upper bounded. However, as shown in performance analysis (section 3), for a good performance, the prediction horizon M should be limited to $2L$ to overcome PPI controller, or $3L$ to outperform PI controller. Consequently, the suitable range for the prediction horizon is $L < M < 2L$.

Figure 3 shows the impact of prediction horizon on process output and control responses. The simulated process has a dead time L = 30 sec, time constant T = 10 sec and the prediction horzion has been varied for $M = L$ .... $2L$. For $M = L$ = 30 sec, the mPPI controller matches to a PPI controller (or Smith predictor).

When the prediction horizon M increases, the setpoint responses starting at t = 0 get faster. Similarly, load disturbance responses initiated at t = 200 get faster and improved for increasing M, but on the other hand, the peak values of the control signals get higher as well. Thus, the prediction horizon is a trade-off between process output and control signal performance.

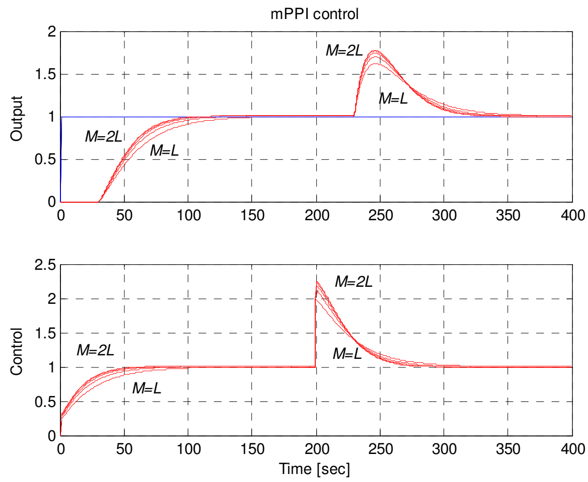

Figure 3. Impact of prediction time horizon M. Upper: outputs. Lower: control signals.

3. PERFORMANCE ANALYSIS

3.1 Performance criteria

The most typical task of a control loop is to attenuate and compensate load disturbances. Controller performance for load disturbance rejection can be evaluated using a performance criterion of Integrated Absolute Error (IAE)

$$J_{IAE} = \int_0^\infty |e(t)| dt \tag{9}$$

For sufficiently damped closed loops, IAE can be estimated by Integrated Error (IE) by $J_{IAE} \approx J_{IE}$ where the integrated error is calculated as

$$J_{IE} = \int_0^\infty e(t) dt \tag{10}$$

For a PI(D) controller, IE is a simple function of PI controller parameters

$$J_{IE} = \frac{1}{k_i} = \frac{t_i}{k_p} \tag{11}$$

PI controller parameters resulting in a well-damped closed loop for a dead-time dominant process ($L > T$) is suggested by Hägglund (1996) using $k_p = 1/(4k)$ and $t_i = L/2$ when k is static process gain. Then, IE (11) is can be represented as

$$J_{IE_{PI}} = \frac{1}{k_i}\Delta u = \frac{t_i}{k_p}\Delta u = 2\, Lk\Delta u \tag{12}$$

To obtain similar well-damped closed-loop control performance with a PPI controller, Hägglund suggests PPI controller parameters to be set as $k_p = 1/k$ and $t_i = T$ resulting in IE as follows

$$J_{IE_{PPI}} = (\frac{1}{k_i} + Lk)\,\Delta u = (\frac{t_i}{k_p} + Lk)\,\Delta u = (L+T)k\Delta u \qquad (13)$$

where Δu is a load disturbance change which is assumed to affect the process input. For mPPI controller using PPI control parameters, the same control tuning criterion results in IE

$$J_{IE_{mPPI}} = \left(\frac{1}{k_i} + (M-L)k\right)\Delta u = (T+M-L)k\Delta u \qquad (14)$$

3.2 Comparison between PI, PPI and mPPI controllers

Using (14) and (12), the comparison between mPPI and PI controller indicates that the control performance of the mPPI controller with any prediction horizon M is better than that of the PI controller

$$\frac{J_{IE_{mPPI}}}{J_{IE_{PI}}} = \frac{T+M-L}{2L} < 1, \quad \text{for } L > T \text{ and } 0 < M < 3L - T \qquad (15)$$

Similarly, using (14) and (13), the comparison between mPPI and PPI controller indicates that the control performance of the mPPI controller with a prediction horizon M can be better than that of the PPI controller if the prediction horizon remains smaller than $2L$.

$$\frac{J_{IE_{IMPI}}}{J_{IE_{PPI}}} = \frac{T+M-L}{T+L} < 1, \quad \text{for } L > \text{T and } 0 < M < 2L \qquad (16)$$

4. SIMULATION EXAMPLES

4.1 PI vs. mPPI control

Consider a FOPDT system with a static gain k =1, time constant T = 10 sec and dead time L = 15 sec being controlled by a PI controller with proportional gain k_p = 0.25 and integral time t_i = 7.5 for well-damped closed loop with no overshooting. Similarly, the mPPI controller is tuned with parameters k_p = 0.5, t_i = 10 and prediction horizon M = 32 ($\approx 2.13L$).

The step setpoint change $\Delta r = 1$ is applied at time t = 0 and the load disturbance step change of 1 at time t = 200 sec for the closed loop. The process output and control signal responses are plotted in figure 4.

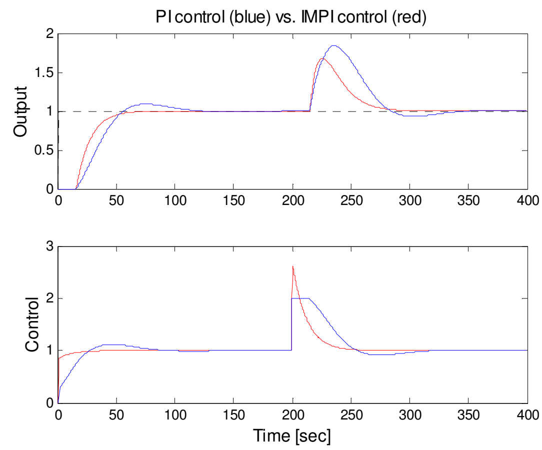

Figure 4. mPPI (red) control vs. PI control (blue). Upper: output responses. Lower: control signals.

The mPPI controller is faster than the PI controller in both setpoint following and disturbance rejection. For disturbance compensation, the mPPI has clearly a better response. The control signal of the mPPI, however, has a bigger initial peak at time of the load disturbance striking the process.

4.2 PPI vs. mPPI control

Consider the same FOPDT system with a static gain k =1, time constant T = 10 sec and dead time L = 15 sec being controlled by a PPI controller with proportional gain k_p = 0.5 and integral time t_i = 10 for well-damped closed loop with no overshooting. Similarly, the mPPI controller is tuned with the same parameters and prediction horizon M = 32 ($\approx 2.13L$).

The step setpoint change $\Delta r = 1$ is applied at time t = 0 and the load disturbance step change of 1 at time t = 200 sec for the closed loop. The process output and control signal responses are plotted in figure 5.

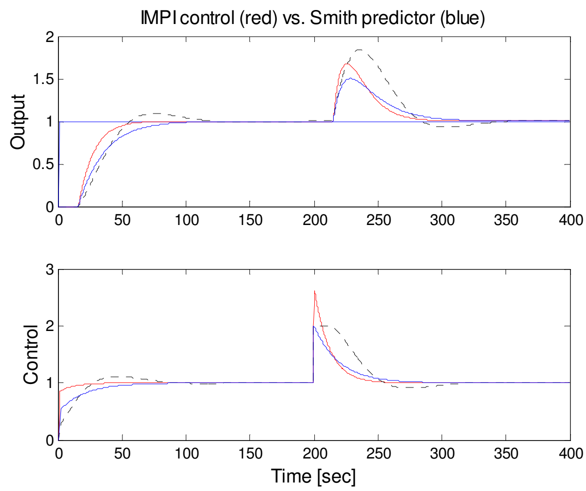

Figure 5. mPPI control (red) vs. PPI control (blue). Upper: output responses. Lower: control signals. In both upper and lower: PI control response as in previous case (dotted).

Again, the mPPI controller is faster than the PPI controller in both setpoint following and disturbance rejection. For disturbance compensation, however, the difference is now smaller than in the case of the PI control. In addition, the mPPI has both a bigger output response and control signal peak than the PPI controller at the time of load disturbance entering at $t = 200$ sec.

5. CONLUSION WITH BENEFITS AND PITFALLS

This paper presented a modified PPI controller (mPPI) for processes with long dead times. These dead time dominating systems are rather common in industrial process control applications. The proposed mPPI has a simple structure being rather similar to that of the PPI controller or, PID controller in general. The simple structure enables an easy implementation as no significant modifications to the PPI or PID are needed.

The mPPI controller has an additional tuning parameter M which is called prediction horizon. It sets the horizon up to which the process output, or measurement, is to be predicted along with the prediction horizon of dead time L. The suitable range for the prediction horizon is in the range of $L \ldots 2L$ where $M = L$ corresponds to a PPI controller or Smith predictor.

Performance analysis showed that the closed-loop PI and PPI control performance can be exceeded in terms of the performance criterion of integrated error. The improved control performance was illustrated using two process control examples for a FOPDT system.

However, robustness of the proposed method against model uncertainties and especially uncertainties in estimated dead time were not considered in this paper. Naturally, robustness can be indirectly considered using robust control design methods such as maximum sensitivity -based tuning methods guaranteing specified robustness margins against modelling uncertainties.

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