Robustness and Stability Analysis of a Predictive PI Controller in WirelessHART Network Characterised by Stochastic Delay

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ABSTRACT

As control over wireless network in the industry is receives increasing attention, its application comes with challenges such as stochastic network delay. The PIDs are ill equipped to handle such challenges while the model based controllers are complex. A settlement between the two is the PPI controller. However, there is no certainty on its ability to preserve closed loop stability under such challenges. While classical robustness measures do not require extensive uncertainty modelling, they do not guarantee stability under simultaneous process and network delay variations. On the other hand, the model uncertainty measures tend to be conservative. Thus, this work uses extended complementary sensitivity function method which handles simultaneously those challenges. Simulation results shows that the PPI controller can guarantee stability even under model and delay uncertainties.

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1. INTRODUCTION

Emergence of WirelessHART and ISA100 Wireless as the only industrial wireless standards for monitoring and automation has prompted researchers to explore their control application capabilities [1, 2]. This is due to the advantages wireless has over the wired system of flexibility, scalability and improved reliability due to the mesh topology the two standards support [3, 4]. The two standards both operate on the 2.5GHz Industrial scientific and medical (ISM) radio frequency band and are based on the IEEE802.14.4 physical layer [1].

WirelessHART being based on the traditional HART standard and the first to hit the public domain, has an edge over the ISA100 wireless standard. There are close to 30 million HART enabled devices already installed globally in the industries that can easily be converted to support WirelessHART [4]. However, application of the standard for control comes with problems of stochastic network delay, non periodic update of measurement and uncertainties such as packet loss [5, 6]. To curtail this problems, especially that of the stochastic network delay, several control strategies have been proposed, among which is the use of Predictive PI controller (PPI) [7, 8]. The controller is a compromise between the expensive and complex model based controllers and the simple but poorly performing PID. The controller allows for model mismatch hence can function well in a stochastic delay setting [9].

It is worth noting that a key task of any control system is to ensure close loop system stability even in the presence of uncertainties and process parameter change. This is not an exception with the PPI controller. Thus, the PPI controller if used in the WirelessHART environment must also ensure system stability under changing conditions of the network and plant. There are many robustness measures to evaluate the extend to which controllers can effectively perform while maintaining system instability [10, 11, 12, 13]. The two most commonly used measures are the classical and model uncertainty methods [14]. The former is based on phase, gain and deadtime margins while the latter is based on sensitivity and its complimentary functions. However, the key shortcomings of these approach is that they too conservative. For example, the classical method consider variation in the process separately while the model uncertainty does not take into account variation in delays.

In this work, a robustness measure using complementary sensitivity function [14, 15] will be used to examine the robustness of the PPI controller in a WirelessHART environment. The method considers simultaneously variation in process parameters such as gain, phase, deadtime and also network stochastic delays.

The rest of the paper is organized as follows: the methodology is given in Section 2, while results are discussed and analysed in Section 3.. The last section draws conclusion.

2. METHODOLOGY

2.1. The Predictive PI controller

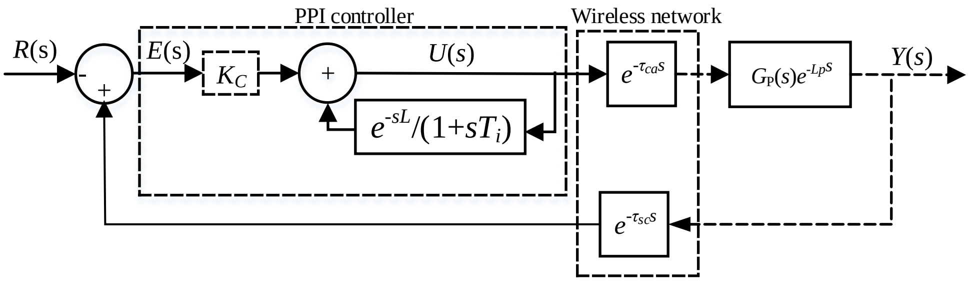

Figure 1. PPI controller in wireless network set-up

Consider the control set-up shown in Fig. 1, the network delay τ_N is the sum of the controller-to-actuator delay τ_{ca} and the sensor-to-controller delay τ_{sc} given as

$$\tau_N = \tau_{ca} + \tau_{sc} \tag{1}$$

Thus, the total loop delay is then given as

$$L = \tau_N + L_p \tag{2}$$

where L_P is the process deadtime. Consequently, the PPI controller $G_c(s)$ of Fig. 1 for the wireless systems can be expressed as (3).

$$U(s) = K_c E(s) + \frac{1}{1+Ts} e^{-sL} U(s) \tag{3}$$

Equation (3) can be expressed as a cascade of a PI controller and the predictor as follows

$$G_c(s) = K_c\Big(1 + \frac{1}{T_i s}\Big)\left(\frac{1}{1 + \frac{1}{T_i s}(1 - e^{-sL})}\right), \tag{4}$$

where, $C_{PI}(s) = K_c(1 + \frac{1}{T_i s})$, is the PI controller and $C_{pred}(s) = \frac{1}{1+\frac{1}{T_i s}(1-e^{-sL})}$ is the predictor.

2.2. Extended Complementary Sensitivity Function Based Robustness

Robust stability condition of the PPI controller given in (3) and (4) will be established based on the extended sensitivity function method proposed by [14]. The method is adopted here to include alongside model parameter variations the wireless stochastic delay. The robustness computation is established on the open loop transfer function. If the controller in (4) is used to control the process $G_p(s)e^{-L_p s}$ of Fig. 1, assuming commutativity between process deadtime L_p and total network dealy τ_N, the entire process model including network delays under nominal conditions can be expressed as

$$G(s) = G_p(s)e^{-sL}, \tag{5}$$

where, $G_p(s)$ is the delay free process. Consider some deviations from nominal condition where there is variation in both process deadtime and network induced delays, assuming that the delay error is $\Delta L \in [\Delta L_{min}, \Delta L_{max}]$.

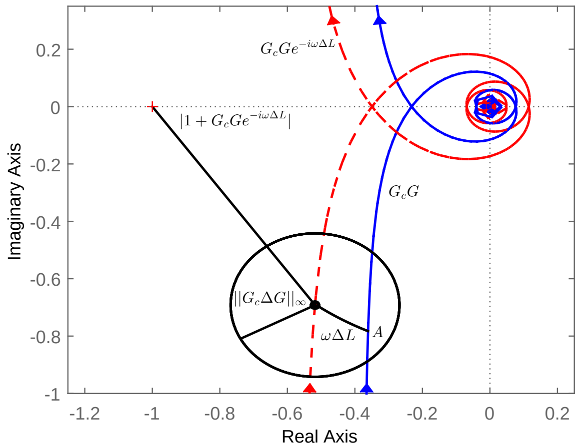

Figure 2. Open loop transfer function Nyquist plot for nominal system and its uncertainty due to respective variation in process ΔG and total network delay ΔL.

Assume also that the multiplicative uncertainty between the nominal process $G_p(s)$ and the real process $G(s)$ is $\Delta G(s)$, then the process model together with uncertainties can be written as

$$G(s) = G_p(s)\left(1 + \frac{\Delta G(s)}{G_p(s)}\right)e^{-s(L+\Delta L)}, \tag{6}$$

If the controller of the system is considered to be $G_c(s)$, the nominal open loop in the frequency domain given as $G_c(i\omega)G(i\omega)$ is thus assumed to be stable and also norm bounded. Consider the Nyquist diagram of the nominal open system (G_cG) shown in Fig. 2, with uncertainty in the delay ΔL, if point A is rotated through angle $-\omega\Delta L$ and moved slightly to any direction $|G_c\Delta G(i\omega)| = |G_c\Delta G(i\omega)e^{i\omega(L+\Delta L)}|$, it will stay within a circle defined by centre $G_cG(i\omega)e^{i\omega(\Delta L)}$ and radius $||G_c\Delta G(i\omega)||_\infty$. The distance from centre $G_cG(i\omega)e^{i\omega(\Delta L)}$ to the critical point -1 is $|1 + G_c\Delta G(i\omega)e^{i\omega(\Delta L)}|$. This indicates that the upset $G_c\Delta G(i\omega)e^{i\omega(L+\Delta L)}$ will not drive the system unstable as long as

$$|G_c\Delta G(i\omega)| < |1 + G_cG(i\omega)e^{i\omega(\Delta L)}|, \ \forall\, \omega, \Delta G, \Delta L \tag{7}$$

Dividing (7) by G_cG_p and assuming $e^{-i\omega(L+\Delta L)} = 1$, the equation can be written as

$$\left|\frac{1 + Gc(i\omega)G(i\omega)e^{-i\omega(\Delta L)}}{Gc(i\omega)G(i\omega)e^{-i\omega(\Delta L)}}\right| > \left|\frac{\Delta G(i\omega)}{G_p(i\omega)}\right|, \tag{8}$$

Defining the extended complementary sensitivity function as the inverse of LHS of (8) we have

$$T(s, \Delta L) = \frac{G_c(s)G(s)e^{-s\Delta L}}{1 + G_c(s)G(s)e^{-s\Delta L}}, \tag{9}$$

Therefore, the condition for robust stability can be given as

$$\left\|\frac{\Delta G(s)}{G_p(s)}T(s, \Delta L)\right\|_\infty < 1,\ \Delta L \in [\Delta L_{min}, \Delta L_{max}]. \tag{10}$$

where ΔL_{min} and ΔL_{max} are the lower and upper delay variation bound, ΔG is the process model change. If for ease of presentation in this work $\left\|\frac{\Delta G(s)}{G_p(s)}T(s, \Delta L)\right\|_\infty$ is represented as γ, the robust stability condition can now be written in terms of γ as follows

$$\gamma < 1,\ \Delta L \in [\Delta L_{min}, \Delta L_{max}]. \tag{11}$$

3. RESULT AND ANALYSIS

For the purpose of this analysis, we use the model of a thermal chamber given in (12) [16]. The measured network delay as obtained from the network is shown in Fig. 3, while the statistics of the delay is given in Table 1. In the result analysis, robustness of the controller to changes in both delay and process variable for the WirelessHART network based on the delay information obtained from the network will be evaluated in both time and frequency domains. The parameters of the PPI controller used for this plant throughout this work are $K_c = 0.125$ and $T_i = 9.13s$. The simulation results in this work will be reported in two phases. The first phase will report on robustness while the second will focus on stability.

$$G(s) = \frac{8}{1 + 9.13s} e^{-10s} \tag{12}$$

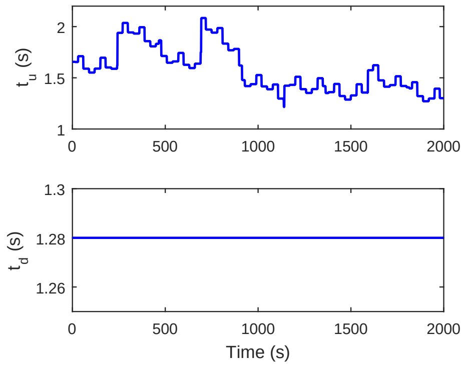

Figure 3. Network delay profile

Table 1. Network Delay Statistics

Delay type	Max	Min	Mean	Std.
Upstream (s)	2.084	1.214	1.573	0.217
Downstream (s)	1.280	1.280	1.280	0.000

3.1. Robustness Analysis

This section first analyses the robustness of the PPI controller to stochastic network delay, then further analysis is provided to its robustness to process model perturbation. The analysis here is given in the time domain.

3.1.1. Robustness to Delay Mismatch

To analyse the performance of the PPI controller to delay mismatches, the plant with the controller is simulated to three different conditions of delay as given in Table 1. These conditions are maximum, minimum and average delays. However, the controller design is based on the average value of the delay. The simulation results for this scenario are given in Fig. 4, while the regions of interest from this table are zoomed in Fig. 5. Numerical figures of the figures are given in Table 2. From both the figures and the table, PPI 1, PPI 2 and PPI 3 represents the three conditions of average, maximum and minimum delays respectively. Thus, it can be observed that for all cases of delay, the performance of the PPI is still better than that of PI controller in terms of both setpoint tracking and disturbance regulation ability. For all the three conditions, the overshoot rise time and both settling times of the PPI controller are less than those of the PI controller compared.

Table 2. Robustness performance of the PPI controller to delay change

Parameters	PPI 1	PPI 2	PPI 3	PI
Rise Time (s)	19.7659	18.4454	21.4858	26.7562
Settling Time 1 (s)	55.7688	51.4477	60.3851	99.4896
Settling Time 2 (s)	269.0980	268.0324	272.1358	301.2938
Overshoot (%)	0.0000	0.0050	0.0000	5.8924
IAE	2309.3	2290.7	2341.1	3044.7

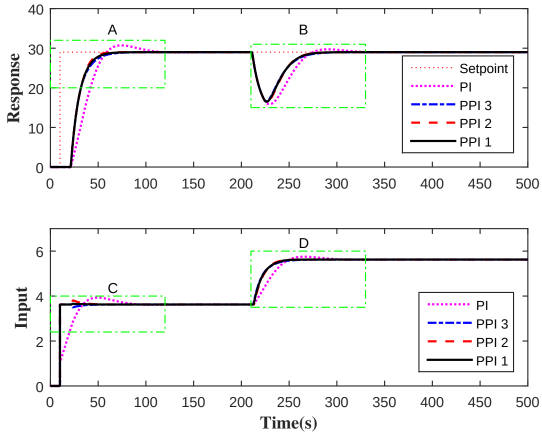

Figure 4. Robustness of the PPI controller to change in network delay.

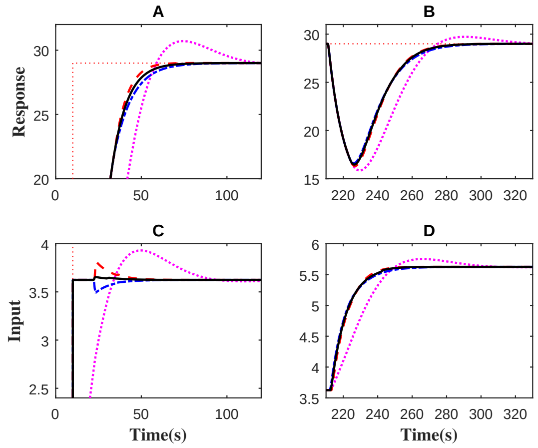

Figure 5. Zoomed-in view of regions of interest A, B, C and D of Fig. 4.

3.1.2. Robustness to Model Mismatch

To analyse the performance of the PPI controller to model mismatches, The plant with the controller is simulated to three different conditions of model parameters. These conditions are nominal and $\pm 10\%$ change in both process gain K and time constant T. However, the controller design is based on the average value of the delay. The simulation results for this scenario are given in Fig. 6 while the regions of interest from this table are zoomed in Fig. 7. Numerical figures of the figures are given in Table 3. From both the figures and the table, PPI, PPI$+10\%$ and PPI-10% represents the three conditions of nominal, 10% increase and 10% decrease in plant model parameters respectively. Therefore, it can be observed that for all the three cases of nominal, increase and decrease in parameters, the performance of the PPI outperformed than that of PI controller in terms of both setpoint tracking and disturbance regulation capability. Numerical assessment of settling time before and after disturbance, overshoot and IAE also confirmed that the performance of PPI controller is better. However, the PI controller responds faster than PPI-10% with a rise time of about 27s as against the 29s of the latter.

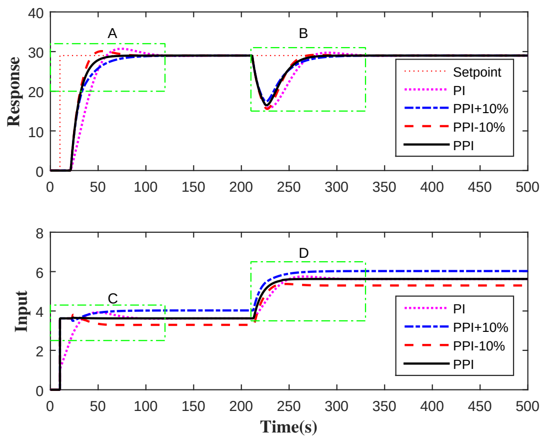

Figure 6. Robustness of the PPI controller to $\pm 10\%$ change in model parameters.

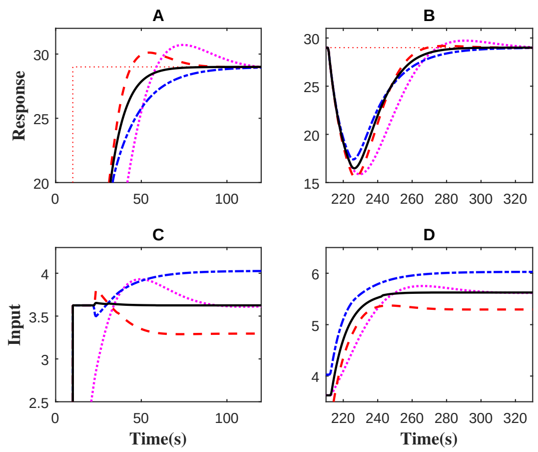

Figure 7. Zoomed-in view of regions of interest A, B, C and D of Fig. 6.

3.2. Stability Analysis

This section analyses the stability of the PPI controller in the frequency domain through Nyquist plots based on the robust stability conditions given in Section 2.2.. First, analysis will be given based on the delay statistics of

Table 3. Robustness performance of the PPI controller to model mismatch

Parameters	PPI	PPI $+10\%$	PPI -10%	PI
Rise Time (s)	19.7698	15.4891	29.4930	26.7578
Settling Time 1 (s)	55.7806	68.5160	78.6990	99.4898
Settling Time 2 (s)	269.1218	261.5824	280.7254	301.3191
Overshoot (%)	0.0000	3.8335	0.0000	5.8919
IAE	2184.9	2169.6	2358.3	2920.2

Table 1 and $\pm10\%$ change in model parameters as discussed in Section 3.1.2., then a variation of both delay and model parameters of up to $\pm20\%$ will be analysed for stability.

3.2.1. Stability of PPI Controller Under WirelessHART Network Delay and Model Mismatch

The Nyquist plot of the plant for mean, maximum and minimum WirelessHART network delays in Table 1 is given in Fig. 8 while the plot for plant with $\pm10\%$ model mismatch is given in Fig. 9. From the first figure, it can be seen that the Nyquist plots for all the three delay condition satisfy the Nyquist stability criteria. The second figure contains the Nyquist plots of the plant with both delay and model mismatches. To further confirm the stability of controller at these conditions, the robust stability condition given in Section 2.2. is tested for different frequencies as given in the results of Table 4. It is noted as given in the table that for all the frequencies considered, the robust stability condition is met.

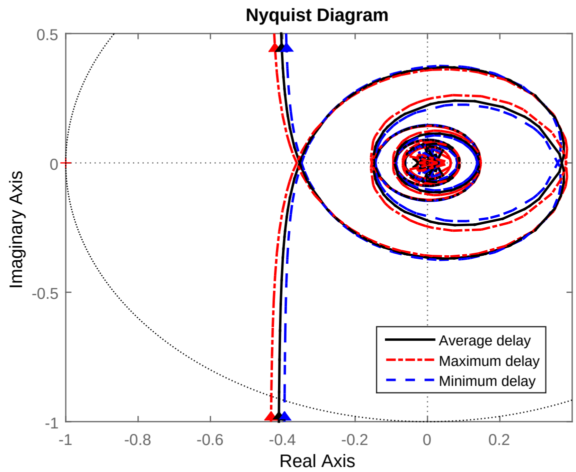

Figure 8. Nyquist plot for mean, maximum and minimum network delays.

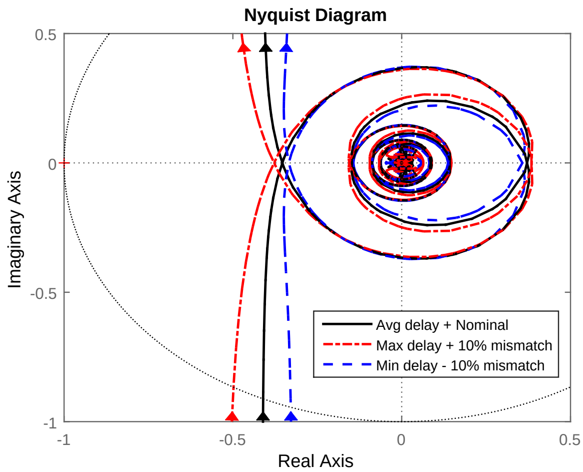

Figure 9. Nyquist plot for nominal, $\pm10\%$ in model mismatch.

Table 4. Robust stability test of PPI controller at different frequencies

$\omega(rad/s)$	γ		$\gamma < 1$?
	Δ_{max}	Δ_{min}	
0.1	0.0269	0.0357	Yes
1	6.41×10^{-4}	9.12×10^{-4}	Yes
10	6.54×10^{-6}	9.30×10^{-6}	Yes
100	6.55×10^{-8}	9.31×10^{-8}	Yes

3.2.2. Stability of PPI Controller Under $\pm20\%$ Delay and Model Mismatches

To further ensure that the PPI controller will maintain stability even with wider range of parameter variations, $\pm20\%$ mismatches in both model parameters and network delay are considered. The corresponding Nyquist plots are shown in Fig. 10. The two robust stability conditions of (7) and (11) are applied at frequency $\omega = 0.6\ rad/s$. The result of this stability test is given in Table 5. From the table, it is shown that the PPI controlled plant is stable at that frequency even with the large perturbation.

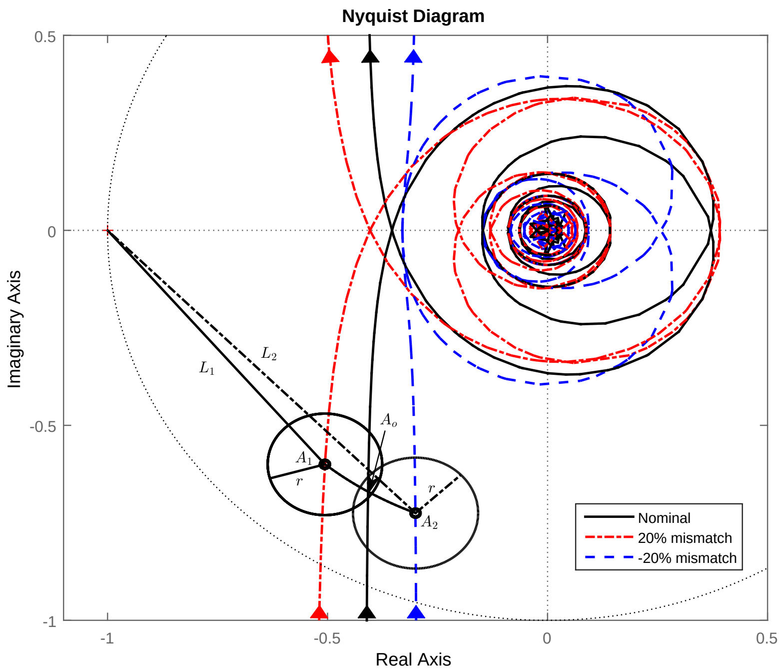

Figure 10. Nyquist plot for $\pm 20\%$ mismatches in both delay and model parameters $\omega = 0.6\ rad/s$.

Table 5. Robust stability test of PPI to model and delay variations at different frequencies

Parameter change	γ	Length (L)	Radius (r)	$\gamma < 1$?	$r < L$?
Δ_{max}	0.5716	0.6450	0.1301	Yes	Yes
Δ_{min}	0.3888	1.0080	0.1402	Yes	Yes

4. CONCLUSION

This paper has discussed the robustness and stability of a PPI controller when used in a wireless networked environment. The robust stability analysis is based on the condition derived from the extended complementary sensitivity function which handles simultaneously both process parameter changes and delay variations. It has been found from the analysis result that the plant controlled with the PPI controller still retains stability even with wide variation of model parameters and delay. This implies that the PPI control though simple in design, can handle the challenges of uncertainties associated with wireless networked control.

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REFERENCES

[1] S. Petersen and S. Carlsen, "WirelessHART versus ISA100. 11a: The format war hits the factory floor," *IEEE Industrial Electronics Magazine*, vol. 5, no. 4, pp. 23–34, 2011.

[2] S. M. Hassan, R. Ibrahim, K. Bingi, T. D. Chung, and N. Saad, “Application of Wireless Technology for Control: A WirelessHART Perspective,” *Procedia Computer Science*, vol. 105, pp. 240–247, 2017.

[3] N. Petreska, H. Al-Zubaidy, B. Staehle, R. Knorr, and J. Gross, “Statistical Delay Bound for WirelessHART Networks,” in *Proceedings of the 13th ACM Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, & Ubiquitous Networks*. ACM, 2016, pp. 33–40.

[4] A. N. Kim, F. Hekland, S. Petersen, and P. Doyle, “When HART goes wireless: Understanding and implementing the WirelessHART standard,” in *Emerging Technologies and Factory Automation, 2008. ETFA 2008. IEEE International Conference on*. IEEE, 2008, pp. 899–907.

[5] T. D. Chung, R. B. Ibrahim, V. S. Asirvadam, N. B. Saad, and S. M. Hassan, “Adopting EWMA Filter on a Fast Sampling Wired Link Contention in WirelessHART Control System,” *IEEE Transactions on Instrumentation and Measurement*, vol. 65, no. 4, pp. 836–845, 2016.

[6] S. M. Hassan, R. Ibrahim, N. Saad, V. S. Asirvadam, and T. D. Chung, “Setpoint weighted wirelesshart networked control of process plant,” in *Instrumentation and Measurement Technology Conference Proceedings (I2MTC), 2016 IEEE International*. IEEE, 2016, pp. 1–6.

[7] S. M. Hassan, R. B. Ibrahim, N. B. Saad, V. S. Asirvadam, and T. D. Chung, “Predictive PI controller for wireless control system with variable network delay and disturbance,” in *Robotics and Manufacturing Automation (ROMA), 2016 2nd IEEE International Symposium on*. IEEE, 2016, pp. 1–6.

[8] M. De Biasi, C. Snickars, K. Landernäs, and A. Isaksson, “Simulation of process control with WirelessHART networks subject to clock drift,” in *Computer Software and Applications, 2008. COMPSAC’08. 32nd Annual IEEE International*. IEEE, 2008, pp. 1355–1360.

[9] T. Hägglund, “An industrial dead-time compensating PI controller,” *Control Engineering Practice*, vol. 4, no. 6, pp. 749–756, 1996.

[10] A. Sassi and A. Abdelkrim, “New Stability Conditions for Nonlinear Systems Described by Multiple Model Approach,” *International Journal of Electrical and Computer Engineering*, vol. 6, no. 1, p. 177, 2016.

[11] J. Cvejn, “PID control of FOPDT plants with dominant dead time based on the modulus optimum criterion,” *Archives of Control Sciences*, vol. 26, no. 1, pp. 5–17, 2016.

[12] V. Vesely and D. Rosinova, “Robust output predictive sequential controller design,” *Archives of Control Sciences*, vol. 20, no. 1, pp. 31–46, 2010.

[13] N. R. Raju and P. L. Reddy, “Robustness Study of Fractional Order PID Controller Optimized by Particle Swarm Optimization in AVR System,” *International Journal of Electrical and Computer Engineering (IJECE)*, vol. 6, no. 5, pp. 2033–2040, 2016.

[14] P.-O. Larsson and T. Hägglund, “Robustness Margins Separating Process Dynamics Uncertainties,” in *Control Conference (ECC), 2009 European*. IEEE, 2009, pp. 543–548.

[15] P. Larsson and T. Hägglund, “Comparison between robust PID and predictive PI controllers with constrained control signal noise sensitivity,” *IFAC Proceedings Volumes*, vol. 45, no. 3, pp. 175–180, 2012.

[16] K.-K. Tan, K.-Z. Tang, Y. Su, T.-H. Lee, and C.-C. Hang, “Deadtime compensation via setpoint variation,” *Journal of Process Control*, vol. 20, no. 7, pp. 848–859, 2010.

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