PIDPlus Controller over WirelessHART Network for Cyber-Physical Process Automation

Shivaji G. Thube[1] and Poonam Syal[2]

[1,2]*National Institute of Technical Teachers' Training and Research, Chandigarh, India*

Abstract

The wireless cyber-physical process control applications demand high network reliability, low latency, energy savings, and secure communication as well as optimal and robust control performance with utmost safety. To address these challenges, the co-design of PIDPlus controller and Wireless HART network is proposed in this paper for closed-loop control of industrial slow processes. The real-time wireless network experiments are conducted using Dust Networks' Smart Mesh Wireless HART sensor test bed to collect the network statistics, while extensive wireless control tests are performed using modified True Time 2.0 simulator to measure the performance of proposed PID Plus controller. The results of wireless HART network experiments show that it provides 99.99 % network reliability, 95.23 % path stability, and 2139 ms average upstream latency, and 1280 ms downward latency. From simulation results, it is revealed that PID Plus controller produces improved set-point tracking and good disturbance attenuation performance over wireless PID controller for delayed process measurements and communication interruptions.

Keywords

Wireless Cyber-Physical System, Process Control, PIDPlus Controller, WirelessHART Network, and Co-design Approach.

1. Introduction

Smart process manufacturing and automation plants require interaction and collaboration among wireless field sensors, actuators, and process controllers to achieve a greater level of productivity and operational efficiency. This is possible with the proper deployment of next generation feedback control systems known aswireless cyber-physical systems (CPSs) [1, 2, 3]. The internationally approved industrial wireless communication standards mainly WirelessHART [4] and ISA100.11a [5] have boosted the wireless cyber-physical process automation in many process industries. Due to reduced installation and maintenance costs, faster deployment, and more expandability, different process industries such as oil and gas refineries, chemical, pharmaceutical, and fertilizer have started deploying industrial wireless sensor networks (IWSNs) for process monitoring, equipment maintenance, and asset management [6,7]. Despite these applications, the wireless closed-loop control applications are still non-existent in process industries. In the presence of dynamic radio frequency (RF) industrial environments, the insertion of wireless network in feedback control loop creates many network imperfections such as network delays, jitter, and communication interruptions. More specifically, the practical deployment of wireless control application requires high reliability, low latency, energy savings, and secure communication as well as stable, optimal, and robust control performance with added safety [8]. All these challenges are required to be addressed in the design phase of wireless process control applications. In communication and control areas, these challenges

International Conference on Emerging Technologies: AI, IoT, and CPS for Science & Technology Applications, September 06–07, 2021, NITTTR Chandigarh, India
EMAIL: shivag_thube@yahoo.co.in (A. 1); poonamsyal@nitttrchd.ac.in (A. 2)

are being tackled through separate design of industrial wireless networks [9] and hybrid PID control algorithms [10, 11]. However, these individual designs are not sufficient to meet all the requirements of wireless process control. There is a need of CPS based co-design approach which will integrate the designs of wireless network and control algorithm and coordinate with process dynamics. Hence, the objective of this paper has been to design jointly the WirlessHART network and PIDPlus controller in connection with slower dynamics of industrial processes. The contribution of paper has been threefold:

1. Co-design of WirelessHART network and PIDPlus controller is proposed for closed-loop control of industrial slower processes.
2. Real-time experiments are conducted using Dust Networks' SmartMesh WirelessHART sensor testbed to measure the network and mote statistics.
3. Modified TrueTime-2.0 co-simulator is utilized to validate the performance of PIDPlus controller in comparison with wireless PID controller.

The rest of paper is structured as follows: The related work is outlined in section 2. The proposed co-design of WirelessHART network and PIDPlus controller is detailed in section 3. Section 4 discusses the findings and results of real-time WirelessHART network experiments and simulated wireless control tests. Lastly, in section 5, conclusion is drawn with future direction of work.

2. Related Work

The different hybrid PID control algorithms such as internal model control (IMC), predictivePI, fixed, and adaptive set-point weighting control are proposed for WirelessHART based process control applications[9, 10]. However, these studies only address the stochastic network delays. Industry researchers have proposed PIDPlus control algorithm [11] to compensate the non-periodic process measurement updates and communication interruptions. However, this work does not cover design of industrial wireless network. In [12,13], CPS based joint design of model predictive control (MPC) and asymmetric routing methods is presented to reduce effects of communication loss on control performance. There has been limited work available in the context of wireless process control applications.

3. Co-Design of PIDPlus Controller Over Wireless HART Network

In this section, the Wireless HART network and PIDPlus controller are jointly designed for closed-loop control of industrial slower processes (temperature, pH, composition, and large volume tank level processes) having process response times in the range of minutes to hours.

3.1. Wireless HART Network Design

Wireless HART protocol (IEC 62591) enables the reliable and secure communication through time synchronized data link layer with channel hopping, self-organizing, self-healing multi-hop mesh network technology, and 128-bit AES encryption system [4]. In addition to protocol selection, the practical Wireless HART network must be deployed with some design guidelines. The update time of wireless transmitters should be 4-8 times faster than process response time for closed-loop control applications. Practically, select the update times 4, 8, 16, 32+ sec to extend battery life for 4-10 years. Minimize the number of hops between gateway and wireless field devices to reduce the communication latency. The effective device range (EDR) of wireless field devices for clear line of sight (no obstruction) is 228m, light obstruction (typically tank farms) is 152 m, moderate metallic obstruction is 76m, and heavy metallic obstruction is 30 m. Every Wireless HART node must have at least three neighbors with in its effective range. Every wireless network must have at least five wireless nodes within the range of gateway [14].

3.2. PIDPlus Controller Design

In PIDPlus controller design, the integral (I) and derivative (D) control actions of standard PID controller are modified to deal with delayed process measurement updates and communication loss. Both actions are updated only when controller receives new process measurements. During the communication loss intervals, these actions are frozen to prevent integral windup and derivative kick problems [11]. An improved version of PIDPlus control algorithm is applicable with both wireless measurements and wireless actuation unlike original PIDPlus controller.

$$\text{P- control:} \quad P(k) = K_c\big(\beta\, r(k) - y(k)\big) \tag{1}$$

$$\text{I- control:} \quad F(k) = F(k-1) + [O(k-1) - F(k-1)]\,(1 - e^{\frac{-\Delta T}{T_i}}) \tag{2}$$

$$\text{D- control:} \quad D(k) = K_d\left(\frac{e(k)-e(k-1)}{\Delta T}\right) \tag{3}$$

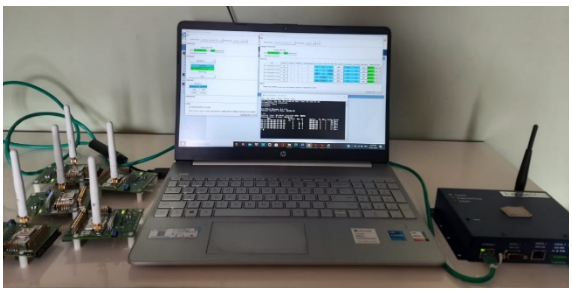
where, P(k) is proportional control output, $K_c$is proportional gain, β is set-point weighing constant, r(k) is set-point, and y(k) has been process output. F(k) has been filter (integral action) output, F(k-1) is filter output during previous execution, O(k-1) is controller output during last execution, ΔT is elapsed time since reception of last new measurement, and T_i is integral time. D(k) is derivative action output, e(k) has been current error input, e(k-1) is last error input since reception of last new measurement, and K_d is derivative gain.

4. Experimental Results and Analysis

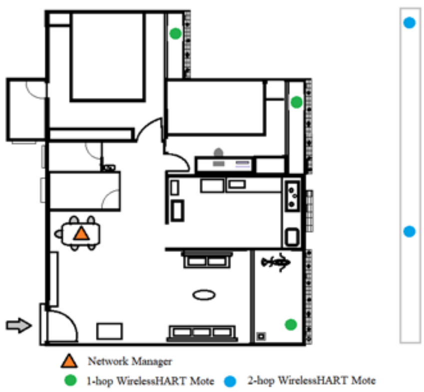
This section discusses the experimental as well as simulation results and data analysis to assess the performance of PIDPlus controller over WirelessHART network.

4.1. Real-time WirelessHART Network Experiments and Results

The Dust Networks SmartMesh WirelessHART starter kit (DC9022B-ND) [15] is utilized to measure the performance of WirelessHART network. The network is deployed for ambient temperature monitoring application. The motes with inbuilt temperature sensors are located at different places in building premises as shown in Figure 1 (b) as per design guidelines recommended by Emerson Process Management. Figure 1 (a) shows the experimental setup of WirelessHART network. The network performance is measured in terms of network reliability, path stability, and upstream latency (UL) and downstream latency (DL) for successive 15 days with 8 sec update time for wireless nodes. Table 1 displays the statistics of network and mote (00-17-0D-00-00-31-CB-D5) that were recorded while experimentation.



a) Dust Networks SmartMesh WirelessHART sensorbed



b) Location of motes in building premises

Figure 1: Experimental setup of WirelessHART network for ambient temperature monitoring

Table 1
WirelessHART network performance for ambient temperature monitoring application

Network Parameters	Network Statistics			Mote* Statistics		
	Life Time	Last Day	Last 15 min	Life Time	Last Day	Last 15 min
Reliability (%)	99.99	99.99	99.99	99.99	99.99	99.99
Path Stability (%)	95.23	98.46	99.02	--	--	--
Latency (ms)	1407	2106	1323	UL: 1427 DL: 1280	UL: 1139 DL: 1280	UL: 2139 DL: 1280

UL: Upstream latency ; DL: Downstream latency *Mote MAC: 00-17-0D-00-00-31-CB-D5

From the results of real-time experiments, it is clear that properly designed and deployed WirelessHART network provides higher reliability (99.99%), high path stability (95.23 %), and extended battery life with update time of 8 sec, and low varying upstream latency and constant downstream latency.

4.2. Wireless Process Control Simulation Tests and Results

To validate the performance of PIDPlus controller, wireless process control test setup is developed using modified TrueTime 2.0 co-simulator with WirelessHART network block [16]. Two major wireless control performance tests namely, the set point tracking and disturbance compensation tests are performed in the presence of delayed process measurements and communication interruptions. For controller testing, the following set of standard process models representing industrial slower processes (such as temperature and gravity-based large sized tank level processes) is employed.

Lag dominant self-regulating process

$$G_1(s) = \frac{1}{(40s+1)} e^{-20\,s}$$

Dead time dominant self-regulating process

$$G_2(s) = \frac{1}{(30s+1)} e^{-45\,s}$$

Figures 2 and 3 depict the set point tracking and disturbance attenuation responses of wireless PIDPlus and PID controllers for lag and delay dominant process models respectively.

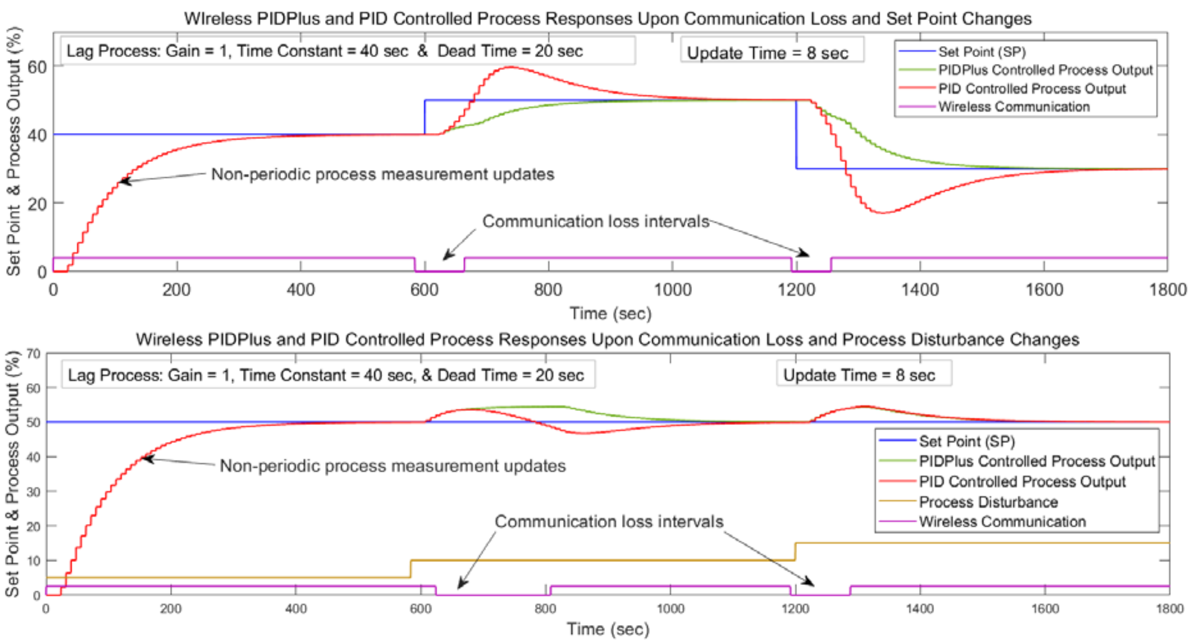
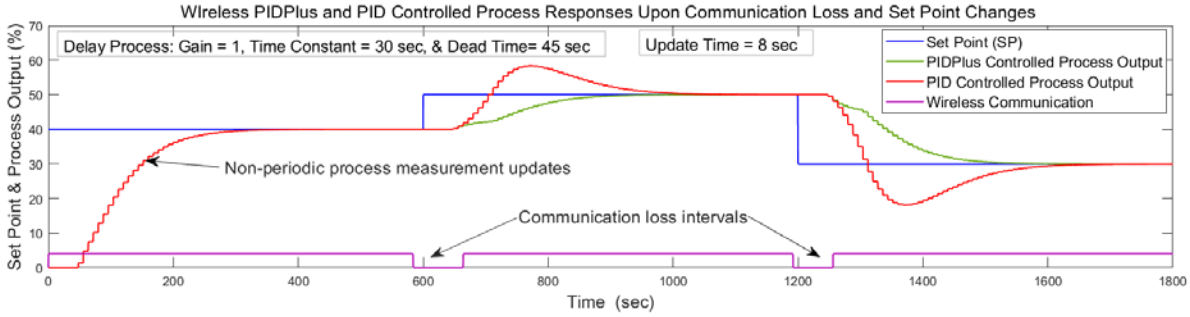


Figure 2: Set point tracking and disturbance attenuation responses of PIDPlus and PID controllers for Lag dominant self-regulating process



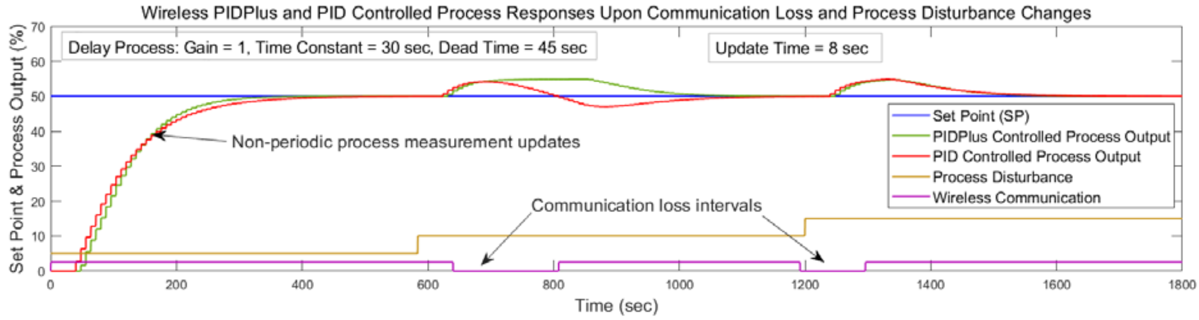


Figure 3:Set point tracking and disturbance cancellation responses of PIDPlus and PID controllers for Delay dominant self-regulating process

From figures 2 and 3, it is observed that wireless PIDPlus controller produces better set point tracking and disturbance compensation responses as compared to that of wireless PID controller for delayed measurement updates and communication loss intervals.

The performance of both controllers is also measured in terms integral absolute errors (IAEs). Table 2 displays the numerical values of IAEs for both controllers. The box plots indicating IAE statistics of both controllers for both processes upon communication loss and set point tracking are illustrated in Figure 4.

Table 2

IAEs of wireless PIDPlus and PID controllers upon communication loss

Wireless Controllers	Set Point Tracking		Disturbance Rejection	
	Lag Process	Delay Process	Lag Process	Delay Process
PIDPlus	7788.48	9376.18	7288.31	8265.18
PID	9592.72	10286.91	7068.02	7965.28

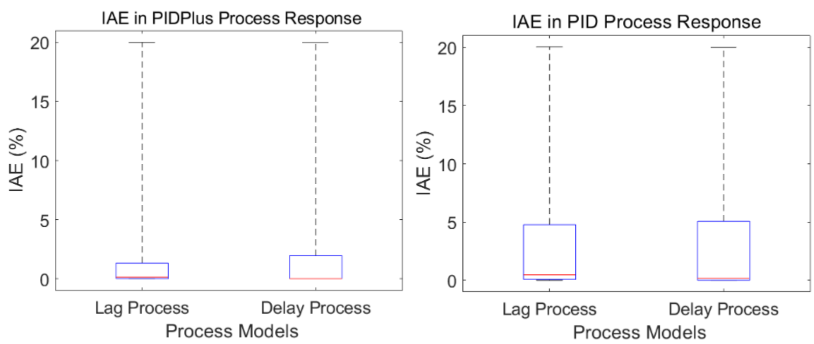


Figure 4: Box plots of IAEs in wireless PIDPlus and PID controllers process responses for Communication loss and set point tracking

The analysis of IAEs in PIDPlus and PID controlled process responses using recorded IAE data and box plots, it is revealed that PIDPlus control provides improved and robust set point tracking capabilities than that of PID controller for communication loss periods.

Conclusion

The co-design of PIDPlus controller and WirelessHART network is proposed in this paper for regulatory type control of industrial slower processes such as temperature and large volume tank level processes. From the results of experimentation and simulation tests, it is revealed that CPS based co-design approach meets the maximum requirements of wireless control applications. WirelessHART network provides 99.99 % network reliability, 95.23% path stability, and 2139 ms average upstream latency, and 1280 ms downward latency. PIDPlus controller produces optimal and robust set point following and disturbance attenuation performance as compared to standard PID controller for delayed measurements and communication interruptions. However, controller control algorithm has drawback of proportional kick during communication loss and set point changes. Future work will focus on improvement of PIDPlus control algorithm for process disturbance variations.

5. References

[1] C. Greer, M. Burns, D. Wollman, E. Griffor,Cyber-physical systems and the internet of things, NIST Special Publication, 1900, 202 (2019).

[2] G. N. Nguyen, N. H. Le Viet, M. Elhoseny, K. Shankar, B. B. Gupta, A. A. Abd El-Latif, Secure blockchain enabled Cyber–physical systems in healthcare using deep belief network with ResNet model, Journal of Parallel and Distributed Computing, 153, 150-160 (2021).

[3] M. B. Dowlatshahi, M. K. Rafsanjani, B. B. Gupta, An energy aware grouping memetic algorithm to schedule the sensing activity in WSNs-based IoT for smart cities, Applied Soft Computing, 108, 107473 (2021).

[4] I. E.C. 62591: Industrial communication networks, wireless communication network and communication profiles-WirelessHART., IEC: Geneva, Switzerland (2009).

[5] International Society of Automation, ISA-SP100 wireless systems for automation (2010). URL:http://www.isa.org/isa100.

[6] P. Zornio, B. Karschnia, Realizing the promise of wireless, American Institute of Chemical Engineers (AIChE), Chemical Engineer Progress (CEP) (2009).

[7] T.Akhtar, B. B. Gupta, Analysing smart power grid against different cyber-attacks on SCADA system, Int. J. Innovative Computing and Applications, 12(4), 195-205, (2021).

[8] E. P. Godoy, Networked control systems: Research challenges and advances for application, 1-200 (2018).

[9] T. D. Chung, R. Ibrahim, R., V. S. Asirvadam, N. Saad, S. M. Hassan, WirelessHARTTM: Filter design for industrial wireless networked control systems, CRC Press (2017).

[10] S. M. Hassan, R. Ibrahim, N. Saad, K. Bingi, V. S. Asirvadam, Hybrid PID based predictive control strategies for WirelessHART networked control systems (Vol. 293), Springer Nature, (2020).

[11] T. Blevins, M. Nixon, M. Zielinski, Using wireless measurements in control applications, International Society of Automation (ISA) (2103).

[12] B. Li, Y. Ma, T. Westenbroek, C. Wu, H. Gonzalez, C. Lu, Wireless routing and control: a cyber-physical case study, ACM/IEEE 7th International Conference on Cyber-Physical Systems (ICCPS) , pp. 1-10 (2016).

[13] Y.Ma, D. Gunatilaka, B. Li, H. Gonzalez, C. Lu, Holistic cyber-physical management for dependable wireless control systems, ACM Transactions on Cyber-Physical Systems, (2-018).

[14] Emerson Process Management, System Engineering Guidelines IEC 62591 (2016). URL:https://www.emerson.com/documents/automation/engineering-guide- system-engineering-guidelines-iec-62591-wirelesshart-en-79900.pdf

[15] Linear Technology, SmartMesh WirelessHART User's Guide (2015).

URL:http://www.analog.com/media/en/technical-documentation/user-guides/smartmesh_wirelesshart_users_guide.pdf.
[16] A. Cervin, K. E. Årz´en, TrueTime: Simulation tool for performance analysis of real-time embedded systems (pp. 93-119), CRC Press (2009).