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EXPERIMENTAL TRANSFER FUNCTION BASED MULTI-LOOP ADAPTIVE SHINSKEY PI CONTROL FOR HIGH DIMENSIONAL MIMO SYSTEMS

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Abstract

The industrial process systems with a delay dominance, an inseparable high dimension and nonlinearity always exhibit most uncertain traits, when attempted to control their process variables. This experimental study demonstrates the performance of Shinskey Tuned PI controller (STPI), which has been designed and implemented in real time on an interacting Dual Spherical Tank Liquid Level System (DSTLLS) which is a Second Order System Plus Delay (SOSPD) model. An extensive usage of PI and PID controllers has been a solution for uncertainties and there are also many instances where they have been implemented effectively for such processes. Equivalent Transfer function modelling analogy and software defined real time multi-loop STPI mechanism using novel data acquisition strategies were implemented which further enhance the effectiveness of the results obtained.

Keywords: Equivalent transfer function model, First order systems plus delay (FOSPD), MIMO systems, Multi-loop PI, Nonlinearity, Second order systems plus delay (SOSPD).

1. Introduction

An extensive and diversified usage of the multitudinous nonlinear systems is prevailing almost in all industrial elements. The key aspect that needs utmost consideration is the controller tuning for these kinds of processes which have a greater degree of non-linearity, delay dominance and unstable dynamics. The fact to be observed is that, many of these systems have one or more control and process variables, which further make the controller implementation a difficult task. The design strategy of controllers for such systems should be robust enough to reject the disturbances which affect the inputs and controlled variables, thereby making these Multiple Input Multiple Output (MIMO) systems and the controllers quite critical. With the wider spectrum of the developing science, digital technology and faster automatic control methods, many novel classical PI control mechanisms have evolved to address the complexities and uncertainties of the MIMO systems.

In the past few decades, the efficiency of the PI controllers has been substantiated by their wide usage in the industrial processes. The mathematical model dependent controllers have been estimated, designed and used for industrial systems by different simpler methods using graphical methods and transients in the process [1, 2]. The SOSPD stable systems with inherent higher order, a boundless open loop system identification method of modelling has been adapted [3]. A better realization of higher order systems can be visualized when used SOSPD models in comparison to First order systems plus delay (FOSPD) models [4].

Usage of correlation equations, the step response data and estimation of SOSPD parameters by three point and four-point method are performed [5].But critically damped SOSPD models are tough to realize using these categorical point methods. Literature demonstrates many methods of designing PID controllers for critically damped SOSPD systems like Internal model control (IMC) method, which is the most used method [6].An experimental implementation of relay tuning method for parameter estimation of critically damped and delayed SOSPD systems was preformed [7]. There are traces of implementations of very simple PID controller tuning methods for single- loop systems which are genuinely realized using FOSPD transfer function models [8].

The coefficients of poles and zeros of the closed loop transfer function are equated in this strategy and the transfer function is derived as a ratio of polynomials with nth order. The method described in [9], is no less to an optimally tuned PI controller in terms of its performance and is implemented on integrating plus delay systems. This analogy was extended to design a PI controller for stable and unstable FOSPD systems and was also implemented [10, 11] to observe an inverse response. Better controller efficiency has been witnessed than the recently reported techniques. An elaborate experimentation and validation has been done on various FOSPD models by using many controller techniques. The same experimental set up used in this article, was also employed to analyze FOSPD performance by different approaches [12, 13].

An SOSPD system was effectively controlled using an experiment by implementing an experimental model approximation method [14].Third order Cart-Inverted Pendulum System, which has many uncertainties, has been controlled using a Sliding mode control [15]. Uncertain time-delays and sensor noise are a challenge in a nonlinear system and these anomalies were effectively solved by a dynamic gain output feedback control [16]. PI controllers using various tuning methods are also implemented in MIMO systems with larger dimensions [17].

Integrating and critically damped systems which are of second order and delay based on relay feedback testing are modeled and identified using different methods and case studies under noisy effects [18]. It was inferred that, the relay with hysteresis helps in reducing the effect of noise and improves the efficacy of controller in SOSPD systems. A combined adaptive neural network and nonlinear model predictive control was designed for a multirate networked continuous stirred tank reactor system and its performance was simulated and its effectiveness was documented [19]. The further sections discuss elaborately about the real time experimental process set up, the mathematical modeling approach and the performance analysis of the STPI controller designed.

2. Experimental Process Description

The experimental set up for DSTLLS consists of dual interacting spherical tanks which have a provision of manually controlling the flow between them using a ON/OFF valve. The tanks are provided with an inflow water system which is externally pumped using a suction motor, which enables the water flow from the pre-filled reservoir. The controlled water flow in to the tank is assured by pneumatic valves, which can be controlled by application of air pressure. The air pressure building mechanism is facilitated by the compressor. A Differential Pressure Transmitter (DPT) is employed in both the tanks of the system to measure the level of water in the tanks. Besides all these, there are analog rotameters and digital ammeters to measure the flow rate and current(4-20 mA) from the motors and DPT respectively. This differential pressure transmitter is connected to the personal computer through the NI-DAQmx 6211 data acquisition module card which can support 16 analog inputs and 2 analog output channels with a voltage ranging between ±10 Volts. It has a sampling rate of 250Ks/S with 16 bit resolution. The graphical code composed in LabVIEW is then interfaced to the DSTLLS through the NI DAQmx-6211 module. All the technical details of the devices used in the experiment ate detailed in Table 1. Figure 1 shows the experimental process in real time. Figure 2 displays the interfacing pattern of NI DAQmx-6211 module and the real time process for experimental verification.

Fig. 1. Real time experimental set up of the DSTLLS process.

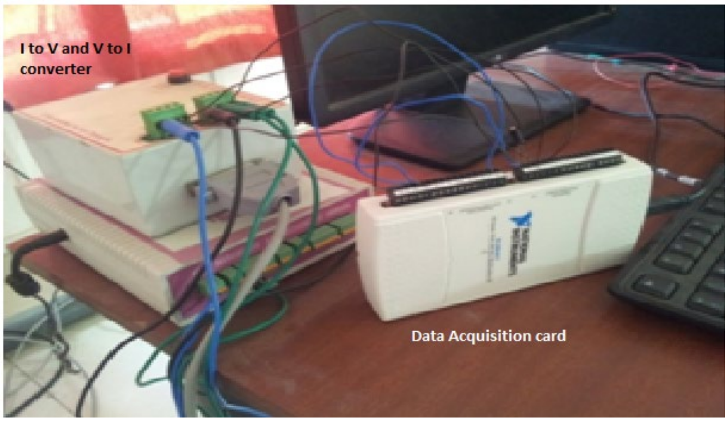

Fig. 2. Interfaced NI-DAQmx 6211 data acquisition module card.

Table 1. Technical Specifications of the experimental setup.

Part name	Details
Spherical Tank	Material: Stainless Steel Diameter:45 cm
Storage Tank	Material: Stainless Steel Volume:100 liters
Differential Pressure Transmitter	Type: Capacitance Range:(2.5 to 250)m BAR Output:(4 to 20)mA
Pump	Centrifugal 0.5 HP
Control Valve	Size:1/4",Pneumatic actuated Type: Air to close Input(3-15)PSI 0.2-1 Kg/cm2
Rotameter	Range:(0-440)LPH
Air Regulator	Size 1/4" BSP Range:(0-2.2)BAR
I/P Converter	Input:4-20 mA Output: (3-15) PSI
Pressure Gauge	Range:(0-30) PSI Range:(0-100) PSI

3.System Identification and controller design

The DSTLLS has two nonlinear interacting spherical tanks, which together favour in increasing the order and complexity of the system dynamics. The virtue of the non-linearity also invokes the instability paradigm in the level characteristic of the process. Under the assumptions that there are no external and internal disturbances and the tanks are identical, an approximate method of mathematical modelling has been demonstrated in this section. It is considered that maximum height of both the tanks is hm and area of cross section of tank1 and tank2 are A1, A2 respectively. Considering all the geometric and dynamic process parameters the individual transfer functions with their dependence on different flow rates.

Equations (1) and (2) show the relation between the height in tank 1 and flow rate through the valve in tank 1 and tank 2 respectively. Whereas equations (3) and (4) describe about the relation between the variation in height in tank 2 and the inflow rates of water from valve in tank 1 and tank 2 respectively.

$$\frac{h_1(s)}{q_1(s)} = \frac{B_{11}(s-A_{22})}{s^2-s(A_{22}+A_{11})+A_{12}.A_{21}} \quad (1)$$

$$\frac{h_1(s)}{q_3(s)} = \frac{A_{12}B_{22}}{s^2-s(A_{22}+A_{11})+A_{12}.A_{21}} \quad (2)$$

$$\frac{h_2(s)}{q_1(s)} = \frac{A_{21}B_{11}}{s^2-s(A_{22}+A_{11})+A_{12}.A_{21}} \quad (3)$$

$$\frac{h_2(s)}{q_3(s)} = \frac{B_{22}(s-A_{11})}{s^2-s(A_{22}+A_{11})+A_{12}.A_{21}} \quad (4)$$

The transfer function models of interacting DSTLLS and individual transfer functions relating heights in tank 1 and tank 2 with their varying flow rates q_1 and q_2 are given in Eq. (1) to (4).

4. Black-box modelling and design of real time multi-loop STPI controller

The system identification of DSTLLS is also derived using the black box modeling. An experimental way of identifying the mathematical model and there on designing a model based PI controller was employed. By varying a set of inflow and outflow rates of water in to the tank1 and tank2 respectively, a steady state point , where the level attains a steadfast value is observed. These level values were acquired using NI-DAQmx 6211 using the level sensor (DPT).These data were collected for different levels of the DSTLLS for varying volume and area, thus indicating different regions of non-linearity as in Fig. 3.The parameters of SOSPD transfer function model were derived, by plotting the open loop steady state data, which was recorded at different set points, in different regions of non-linearity. Using Sundaresan and Krishnaswamy method [2], the proposed times t1 and t2, are to be estimated from a step response curve obtained, which correspond to 35.3% and 85.3% response times.

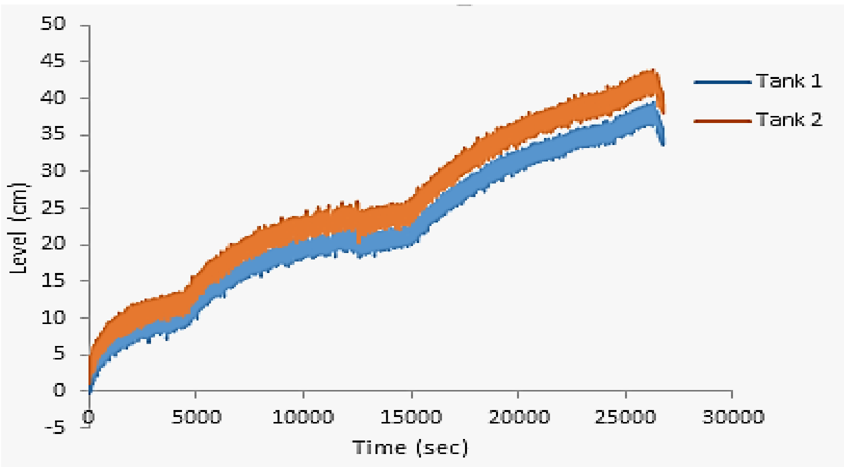

Fig. Steady state level of three regions in DSTLLS for modeling of SOSPD.

The time delay and time constant are figured out using the equations 5 and 6,

$$\tau p = 0.67(t2 - t1) \tag{5}$$

$$\theta = 1.3t1 - 0.29t2 \tag{6}$$

Table 2 demonstrates the different flow rates which were varied experimentally to obtain the open loop steady state data of DSTLLS. The pictographic representation of DSTLLS used for experimentation is illustrated in Fig. 4. After application of approximation techniques, the DSTLLS is transformed in to SOSPD model. The final transfer function models are listed in Table 3. It can be visualized that, the increasing level set point is also introducing an increasing exponential delay.

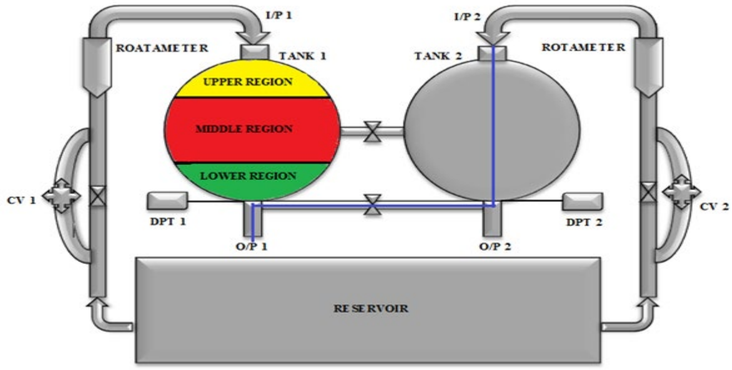

Fig. 4. Schematic model of DSTLLS illustrating the three regions of non-linearity.

Table 2. Inflow of all three non-linear models for SOSPD modeling data

Set-Point (cm)	Region	Regulated In flow (lph)
0-10	Model-1	250
10-25	Model-2	310
25-45	Model-3	360

Table 3. Second order transfer functions for DSTLLS for respective levels obtained by Black-Box Modeling.

Specified Level (Height in cm)	Transfer function G21(S)
Lower Level (0-13) cm	$\frac{19.09 \times e^{(-7703.142 * s)}}{3328198s^2 + 3650s + 1}$
Middle Level (13-25) cm	$\frac{48.56 \times e^{(-26460.844 * s)}}{13226043s^2 + 7274s + 1}$
Higher Level (25-41) cm	$\frac{101.6 \times e^{(-51967.069 * s)}}{20237614s^2 + 9005s + 1}$

Controller design is performed after the derivation of SOSPD transfer function model, which further can be used to optimize the functionality of the process level application. Proportional gain (Kp) and Integral gain (Ki) for a multi-loop STPI controller have to be properly chosen to define the optimal controller performance.

The general SOSPD model is given by,

$$G(s) = \frac{K.e^{-\theta s}}{(\tau_{m1}s+1)(\tau_{m2}s+1)} \tag{7}$$

The transfer functions of DSTLLS for different nonlinear regions of operation are given in Table 3. The proof of exponentially increasing delay and degree of non-linearity can be noticed. Three regions of non-linearity across the varying diameter of the tank are chosen to derive the transfer functions. The rules for choosing the tuning parameters for STPI controller are illustrated in Equations 8, 9 and 10 respectively. By employing the rules of Shinskey PI tuning Control method, the following parameters for the transfer functions are derived and the parameters of Kp and Ki for different regions of non-linearity are derived and given in Table 4.

Table 4. *Kc*, *Ti*, *Kp* values obtained from STPI controller.

Region	*Kc*	*Ti*	*Ki*
Lower	0.0172318	15870.6	1.08577×10^{-06}
Middle	0.004489179	41871.286	1.07444×10^{-07}
Upper	0.001505514	66157.9215	2.27564×10^{-08}

$$K_c = \frac{100\times T_{m1}}{K_m\times(\tau_{m1}+T_{m2})[50+55\{1-e^{\frac{T_{m1}}{\tau_{m1}+T_{m2}}}\}]} \tag{8}$$

$$T_i = \tau_{m1}(0.5 + 3.5[1 - e^{-\frac{3\times T_{m1}}{(\tau_{m1}+T_{m2})}}]) \tag{9}$$

$$K_i = \frac{K_c}{T_i} \tag{10}$$

5. Results and Discussion

The nonlinear DSTLLS process has been tested by STPI controller and its servo tracking response and the disturbance rejection response are documented experimentally. A changing step set point pattern of 12 cm, 22 cm and 39 cm is applied to the DSTLLS to observe the set point tracking and the load rejection performances of the STPI controller for the DSTLLS benchmark system. Figure 5 illustrates the servo tracking response of the STPI controller when applied to DSTLLS at different set point profiles 12cm, 22cm and 39cm.The same experiment has been implemented for another varied five set point profile whose characteristics are produced in Fig. 6.The regulatory tracking response of the water levels in DSTLLS is also observed and the performance is graphed in Fig. 7. In Table 5, the Performance indices for regulatory tracking of STPI on DSTLLS for varying set point profile can be observed. The ISE and IAE values are proportionally increasing in relation to increasing set point profile.

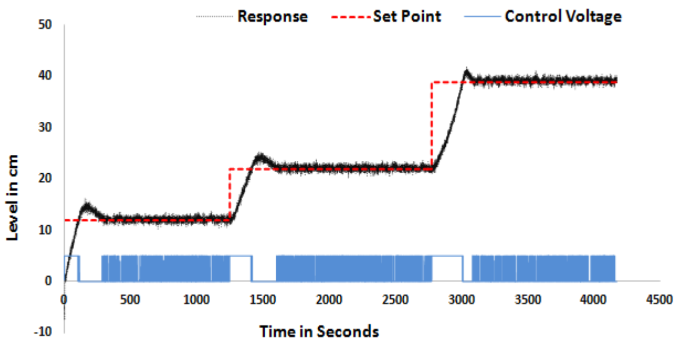

Fig. 5. Servo tracking response of DSTLLS for varying three setpoint profile.

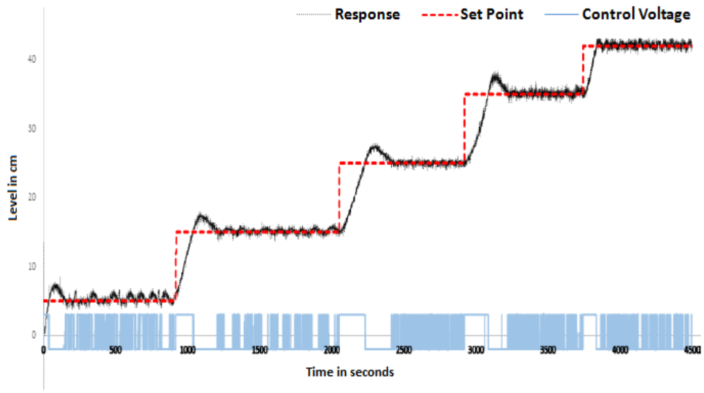

Fig. 6. Servo tracking response of the DSTLLS process for five changing set points.

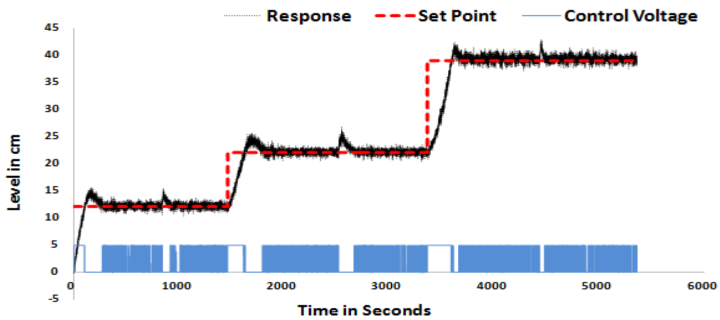

Fig. 7. Regulatory response of DSTLLS for varying setpoint profile.

Table 5. Performance indices for regulatory tracking of STPI on DSTLLS for varying set point profile.

Set Point	IAE	ISE
12 cm	1068.506	660.9797
22 cm	1062.16	655.8132
39 cm	1039.762	640.6282

That evidently says that, in the regulatory performance tracking, the error is carried forward across the nonlinear zones of DSTLLS and is proportional to the increasing volume and non-linearity. The ISE and IAE values for the servo response tracking, shown in Table 6 are the evidence of the robust disturbance rejection ability of the STPI controller. It can be noted that the Integrated Absolute Error (IAE) and Integrated Squared Error (ISE) values for the extreme curved nonlinear regions are relatively higher than that of the linear degree regions. The error seems to certain in both the nonlinear regions of the DSTLLS. All the time indices in the servo tracking are also proportional to the level and volume rise in the DSTLLS for the varying set point profile.

Table 6. Time and performance indices of the DSTLLS for set point tracking response over a changing set point profile.

Set point (cm)	ISE	IAE	Peak Time (s)	Settling Time (s)	Rise Time (s)
5	292.025	408.08	114.4218	285.25	102.98
15	155.427	346.897	182.347	189.65	164.112
25	84.2969	233.898	247.75	150.25	222.975
35	265.056	444.385	220	116.25	198
42	275.854	463.216	119.75	52.75	107.775

6. Conclusion

An experimental validation for the robust Shinskey Tuned PI controller over a non-linear higher order MIMO system has been implemented and its servo tracking and regulatory load characteristics have been observed. In all the three setpoint locations, it can be observed that the STPI gives a robust disturbance rejection for the load change under uncertain disturbances. Shinskey tuning out performs in terms of performance indices like IAE and ISE for delay dominated non-linear process systems, but for the presence of many uncertainties and chaos. There is still a scope of improvement with respect to the errors which can be certainly corrected using intelligent controllers. Usage of the optimization techniques and algorithms, the error characteristics efficiency can be further improved.

References

1. Rangaiah, G.P.; and Krishnaswamy, P.R. (1994). Estimating second-order plus dead time model parameters. *Industrial & Engineering Chemistry Research*, 33(7), 1867-1871.

2 Huang, C.T.; and Clements Jr, W.C. (1962). Parameter estimation for the second-order-plus-dead-time model. *Industrial & Engineering Chemistry Process Design and Developmen*, 21(4), 601-603.

3 Sunderasan, K.R.; Prasad, C.C.; and Krishnaswamy, P.R. (1978). Evaluating parameters from process transients. *Industrial & Engineering Chemistry Process Design and Development*, 17(3), 237-241.

4 Vivek, S.S.; and Chidambaram, M. (2012). An improved relay auto-tuning of pid controllers for critically damped SOPTD systems. *Chemical Engineering Communications*, 199(11), 1437-1462.

5 Huang, C.T. and Huang, M.F. (1993). Estimation of the second order parameters from process transients by simple calculation. *Industrial & Engineering Chemistry Research*, 32(1), 228-230.

6 Skogestad, S. (2003). Simple analytic rules for model reduction and PID controller tuning. *Journal of Process Control*, 13(4), 291-309.

7 Vivek, S.S. and Chidambaram, M. (2012). An improved relay auto-tuning of PID controllers for critically damped SOSPD systems. *Chemical Engineering Communications*, 199(11), 1437-1462.

8 Sree, R.P.; Srinivas, M.N.; and Chidambaram, M. (2004). A simple method of tuning PID controllers for stable and unstable FOSPD systems. *Computers & Chemical Engineering*, 28(11), 2201-2218.

9 Chidambaram, M.; and Sree, R.P. (2003). A simple method of tuning PID controllers for integrator/dead-time processes. *Computers & Chemical Engineering*, 27(2), 211-215.

10 Sree, R.P.; and Chidambaram, M. (2003). A simple method of tuning PI controllers for unstable systems with a zero. *Chemical and Biochemical Engineering Quarterly*, 17, 211-216.

11 Sree, R.P.; and Chidambaram, M. (2003). A simple method of tuning PI controllers for stable inverseresponse systems. *Journal of the Indian Institute of Science*, 83(3-4), 73-85.

12 Chakravarthi, K.; and Venkatesan, N. (2015). Design and implementation of adaptive model based gain scheduled controller for a real time non linear system in LabVIEW. *Research Journal of Applied Sciences*, *Engineering and Technology*, 10(2), 188-196.

13 Chakravarthi, K.; and Venkatesan, N. (2014). Design and implementation of LabVIEW based optimally tuned PI controller for a real time non linear process. *Asian Journal of Scientific Research*, 8(1), 95-106.

14 Elsayed, B.A.; Hassan, M.A.; and Mekhilef, S. (2015). Fuzzy swinging-up with sliding mode control for third order cart-inverted pendulum system. *International Journal of Control*, *Automation and Systems*, 13, 238-248.

15 Jo, H.W.; Choi, H.L.; and Lim, J.T. (2015). Dynamic gain output feedback control of a class of uncertain feedforward nonlinear systems with uncertain time-delays and sensor noise. *International Journal of Control Automation and Systems*, 13, 567-574.

16 Luan, X.; Chen, Q.; and Liu, F. (2015). Equivalent transfer function based multi-loop PI control for high dimensional multivariable systems. *International Journal of Control*, *Automation and Systems*, 13, 346-352.

17 Bajarangbali.; and Majhi, S. (2015). Identification of integrating and critically damped systems with time delay. *Control Theory and Technology*, 13, 29-36.

18 Sunderasan, K.R.; and Krishnaswamy, P.R. (1978). Estimation of time delay, time constant parameters in time, frequency and laplace domains. *The Canadian Journal of Chemical Engineering*, 56, 257-262.

19 Wang, T.; Gao, H.; and Qiu. J. (2016). A combined adaptive neural network and nonlinear model predictive control for multirate networked industrial process control. *IEEE Transactions on Neural Networks and Learning Systems*, 27(2), 416-425.