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Networked Control with Time Delay Compensation Scheme Based on a Smith Predictor for the Activated Sludge Process

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Abstract: In this paper, a Smith predictor compensation scheme is developed to mitigate random delays in a networked wastewater control. The focus here is the process of Dissolved Oxygen (DO) concentration as part of the Activated Sludge Process (ASP). The networked wastewater control is a new method of wastewater control in which the controller and the wastewater treatment plant are separated by a wide geographical distance and so a communication medium is required between them. The effects of network induced time delays on the DO process are investigated. Simulation results reveal that communication drawbacks adversely affect the stability of the closed loop DO process resulting in water odour, floc formation, poor sludge formation and eventual low effluent quality. This is because low DO concentration due to communication drawbacks leads to depletion of oxygen available to microorganisms that are meant to clean up the wastewater. A Smith predictor is therefore proposed to compensate for these communication drawbacks. The nonlinear DO model is linearised using the input/output feedback linearization method. PI controller is designed for the linearised DO process while a Smith predictor scheme is proposed to eliminate time delays in the control system. Analytical and simulation results confirm the effectiveness of the scheme over the PI controller to provide robustness for the control of the input-output feedback linearized DO process under the influence of random communication delays.

Keywords: Time delays, wastewater, Smith predictor, dissolved oxygen, Activated Sludge Process, Networked Control Systems

1. INTRODUCTION

The Activated Sludge Process (ASP) is one of the strategies of wastewater treatment during which oxygen is injected into wastewater in order to be used by the bacteria activities in purifying the water to meet the required effluent quality standard. ASP is the most widely applied biological wastewater treatment strategy (Vlad et al., 2011). The disadvantage of this method however is the very high electrical energy required to pump oxygen into the wastewater for the use of micro-organisms that are responsible for breaking down organic substances thereby making the water safe to be released into the environment. The concentration of DO in the ASP plays very important role in the quality of the effluent and the sludge produced during the wastewater treatment (Gaya et al., 2013; Macnab et al., 2014). It therefore becomes imperative to control the DO concentration in the ASP both for economic (reduction of electricity consumption) and process quality reasons (Vlad et al., 2011; Chotkowski et al., 2005; Sanchez and Katebi, 2003).

In the conventional wastewater treatment, the controller and the Wastewater Treatment Plant (WWTP) are usually in the same place (Vlad et al., 2011; Chotkowski et al., 2005; Sanchez and Katebi, 2003; Tzoneva, 2007). This paper considers a different approach in wastewater control in which the controller and the WWTP to be controlled are not in the same location but separated from each other by a wide geographical distance. As a result, there must be a means of communication between them. This requires a form of a Networked Control System (NCS) to be developed. The NCS advantages include flexibility, modularity and ease of maintenance to mention a few (Gupta and Chow, 2010). The Networked Wastewater Distributed Systems (NWDS) involves communication between the controller and the remote WWTPs and communication drawbacks (Nilsson, 1998) such as network induced time delays, data drop out, jitter and the likes are introduced into the control system. These drawbacks make it difficult to apply traditional control strategies in order to control the plant. For the ASP of WWTP, the inclusion of a communication network between the controller and the process results in network induced time delays and this brings about instability of the closed loop DO process.

Apart from time delays due to the communication network, another source of dead time (delay) in the ASP is the time it takes the sensors and analysers to perform their measurements or analyses. For instance, the Chemical Oxygen Demand (COD) is one of the parameters measured in order to calculate the oxygen uptake rate $r_{s_o}(t)$ in the ASP. Continuous rapid COD measurement is a procedure for quick analysis of Chemical Oxygen Demand. In the Phoenix-1010 analyser, analysis lag time between the samples that are entering the intake of the analyser and the time it takes the analysed data to be output is usually between 3 to 15 minutes for a measurement that ranges between 10 to 1500 mg/litre COD (Environmental-expert, 2014).

This paper investigates the effects of time delays (dead time) on the behaviour of the DO process and proposes a time delay compensation strategy based on the Smith predictor compensation scheme (Smith, 1957; Galvez et al., 2007; Tanaka et al., 2013; Ding and Fang, 2013). The Smith predictor is the most widely applied compensation scheme for eliminating dead time in process controls (Galvez et al., 2007; Tanaka et al., 2013). This compensation scheme is applied in this paper to eliminate dead time, provide robustness and improve controller performance of the DO process. The nonlinear DO process is first linearised by feedback linearization (Slotine and Li, 1991) using the input/output feedback linearization technique. The closed loop system of the nonlinear linearising controller and the DO process together results in an equivalent linear model of the DO process. Using the PI controller with this linear model of the DO process allows a transfer function to be used to describe the behaviour of the linearised system. The Smith predictor in this paper is used to eliminate the deadtime in the closed loop DO process when it is under the influence of network induced time delays.

The paper is arranged as follows: section 2 introduces the COST benchmark model of DO process, section 3 considers the networked wastewater distributed systems and the effects of random and constant delays on the DO process. In section 4, the compensation scheme based on the Smith predictor is proposed and applied to the delayed feedback linearised DO process. Section 5 presents simulation results while the paper concludes in section 6.

2. THE COST BENCHMARK MODEL OF THE DISSOLVED OXYGEN PROCESS AND ITS CLOSED LOOP CONTROL STRUCTURE

The WWTP under consideration in this study is the COST benchmark structure of the ASP (Olsson and Andrews, 1998; Tzoneva, 2007).

Equation 1 describes the mass balance of the dynamics of the DO concentration in the ASP as part of the COST benchmark model (Olsson and Andrews, 1998).

$$\frac{ds_{o,n}(t)}{dt} = \frac{1}{V_n} Q_n(t)\left(s_{o,n-1}(t) - s_{o,n}(t)\right) + K_{La,n}(t)\left(s_{o,sat}(t) - s_{o,n}(t)\right) + r_{s_{o,n}}(t) \qquad (1)$$

Where: $S_{o,n}$ (mg/l) is the DO concentration in the *nth* tank, $K_{La}(t)$ is the oxygen transmission coefficient, $S_{o,sat}$ (mg/l) is the DO concentration at the saturation point, r_{s_o} (d^{-1}) is the oxygen uptake rate, V_n (m^3) is the tank volume, n is the current number of the aerobic tank (n = 3,4,5). The oxygen transmission coefficient depends on the air flow rate $u(t)$ sent to the aerobic tank. This variable is used to control the concentration of the DO into wastewater (Nketoane, 2009). There are different mathematical expressions of the dependences $K_{La}(u)$, but the most used one is by an exponential function (Olsson and Andrews, 1998; Tzoneva, 2007), shown in equation 2.

$$K_{La}(t) = K_1\left[1 - e^{-K_2 u(t)}\right] \qquad (2)$$

Where the coefficients K_1 and K_2 are determined for $K_{La}(t)$ = 240 d^{-1}, $u(t)$ (m^3/d) represents the air flow rate and it is the control action. The oxygen uptake rate is represented as a nonlinear function of the dissolved oxygen concentration (Olsson and Andrews, 1998).

$$r_{S_o}(t) = -\hat{\mu}_H\left(\frac{1-Y_H}{Y_H}\right)\left(\frac{s_{S,n}(t)}{K_S + s_{S,n}(t)}\right)\left(\frac{s_{O,n}(t)}{K_{OH} + s_{O,n}(t)}\right)x_{BH}(t) - \hat{\mu}_A\left(\frac{4.57-Y_A}{Y_A}\right)\left(\frac{s_{NH,n}(t)}{K_{NH} + s_{NH,n}(t)}\right)\left(\frac{s_{O,n}(t)}{K_{OA} + s_{O,n}(t)}\right)x_{BA}(t) \qquad (3)$$

where μ_H is the maximum heterotrophic growth rate, Y_H is the heterotrophic yield, $\hat{\mu}_A$ is the maximum autotrophic growth rate, Y_A is the autotrophic yield, $s_{S,n}(t)$ is the readily biodegradable substrate concentration, $s_{NH,n}(t)$ is the $NH_4^+ + NH_3$ nitrogen concentration, $K_{NH}, K_{OA}, K_{OH}, K_S$ are the half-saturation coefficients for heterotrophic growth rate, autotrophic growth, and autotrophic decay respectively (Tzoneva, 2007). For the rest of the paper, the index n is not considered since all considerations are done for one of the tanks and can be applied for the other two tanks too.

2.1 Non-linear Linearising and Linear control closed loop structure

Investigations in the paper are done for the closed loop control system of the DO process developed in (Nketoane, 2009). Figure 1 is the open loop response of the DO concentration to a unit step response. The closed loop response of the DO process showing its dynamic behaviour according to the structure in Figure 2 is given in Figure 3.

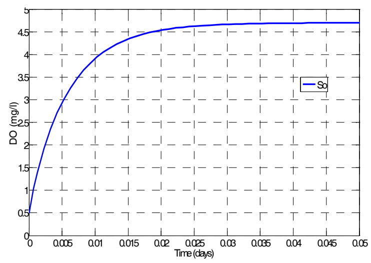

Fig. 1. Open loop response of the DO process.

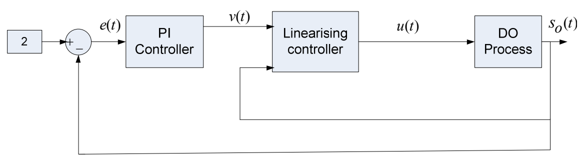

Fig. 2. Nonlinear linearising and linear closed loop control of the DO process without network time delays.

The closed loop has two components. The first is the input/output linearising nonlinear control $u(t)$ leading the nonlinear DO process closed loop behavior to be equivalent to a stable one with a desired behavior of the linear system $\dot{S}(t) = aS_O(t) + bv$, where a and b are the state and control coefficients and $v(t)$ is the linear control input to the linearized closed loop system. The second is the linear control $v(t)$ leading the linearized closed loop behavior of the DO process to follow some desired trajectory (set point).

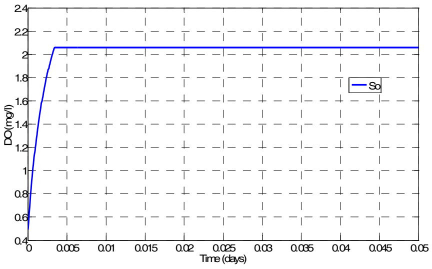

Fig. 3. Closed loop response of the DO process without network induced time delay.

The linear control is selected to be Proportional Integral (PI) described by the equation

$$V(t) = K_p\left[e(t) + \frac{1}{T_1}\int e(t)dt\right] \tag{4}$$

Where the coefficients K_p and T_I are designed for the desired linear system using the pole placement method and $e(t)$ is the error between the set point and the closed loop DO process output. On the basis of the above, the nonlinear controller can be expressed as:

$$u(t) = -\frac{1}{k_2}\ln\left\{\frac{\left(a+\frac{Q}{V}-k_1\right)s_O(t)+bK_p\left[e(t)+\frac{1}{T_i}\int e(t)dt\right]+k_1 s_{O,sat}-\frac{Q}{V}s_{O,in}(t)-r_{SO}(t)}{-k_1(s_{O,sat}-s_O(t))}\right\} \tag{5}$$

The MATLAB/Simulink model of the closed loop system given by equations (1) to (5) is developed in the paper for the parameters of the COST model (Nketoane, 2009) and is used as a basis for investigations of the impact of the network induced time delays and for the design of the Smith predictor.

3. NETWORKED DO PROCESS CONTROL UNDER RANDOM DELAYS

Introducing a communication network between the controller and the DO process (Gupta and Chow, 2010; Nilsson, 1998) would affect the dynamics of the closed loop DO process. For this purpose, time delays between the controller and actuator (τ_{ca}) and between the sensor and controller (τ_{sc}) are considered as shown in Figure 4.

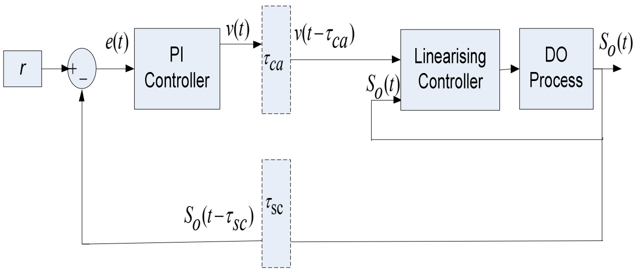

Fig. 4. Closed loop DO process under network induced time delays.

The induced time delays lead to a situation where at the moment t the control signal received by the actuator will be from the moment $t-\tau_{ca}$ and the controller will receive the sensor signal from the moment $t-\tau_{sc}$.

Simulation is carried out in order to investigate the influence of the network induced time delays on the closed loop DO process behaviour. Artificial transport delays using the MATLAB/Simulink platform are introduced in the forward path (τ_{ca}) and the feedback path (τ_{sc}) of the closed loop DO process as shown in Figure 4 to produce a combined delay ($\tau_{tot} = \tau_{ca} + \tau_{sc}$). Simulations are performed and the closed loop DO process behaviour without a time delay is compared with the behaviour of the DO process under the influence of the time delay (τ_{tot}). The Simulink block for this investigation is shown in Figure 5.

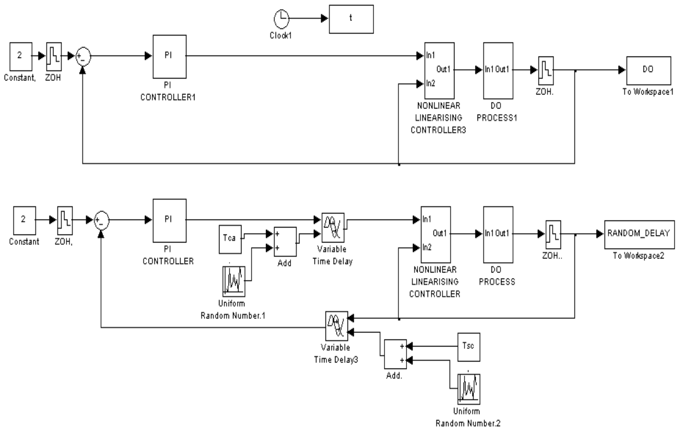

Fig. 5. Simulink block comparing the behaviour of the DO process without time delays and under the influence of random time delays.

During the simulations according to Figure 5, the transport delay values are increased from a given minimum to maximum values until a sustained oscillation is observed and even beyond the sustained oscillation when the process becomes unstable. The point of the sustained oscillation is referred to as the critical delay. The simulation is carried out under three different conditions as follows: DO process behaviour in the case of τ_{tot} less than the critical delay, DO process behaviour in the case of τ_{tot} equal to the critical delay and DO process behaviour in the case of τ_{tot} greater than the critical delay.

The communication delays (τ_{ca} and τ_{sc}) are assumed to be random variables which are uniformly distributed. The DO process is sampled at a sampling rate of T = 0.0001days (0.864secs.) using the Zero Order Hold (ZOH) method. Figure 6a shows how the uniform random delays used for simulation are generated (Velagic, 2008). Using Simulink blocks, uniform random inputs are introduced into the constant delay blocks. Preliminary simulations of the closed loop system from Figure 6a, varying the values of the random delays show that the transition behaviour of the process output starts oscillating for a delay of τ_{tot} = 0.000027 days, called the critical delay. Figure 6b shows the time distribution of the random delay at its critical value of 0.000027 days. The time distribution is selected such that the noise to signal ratio is 10% (Searchnetworking, 2014).

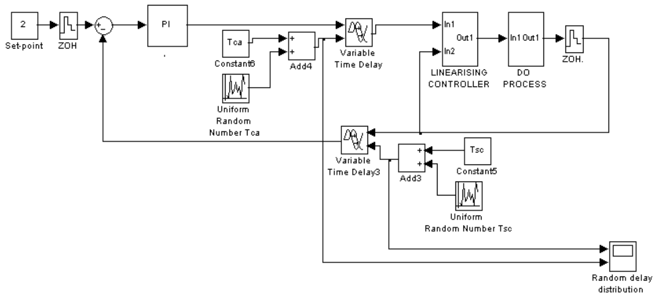

Fig. 6a. Simulink block showing generation of uniform distributed random delays.

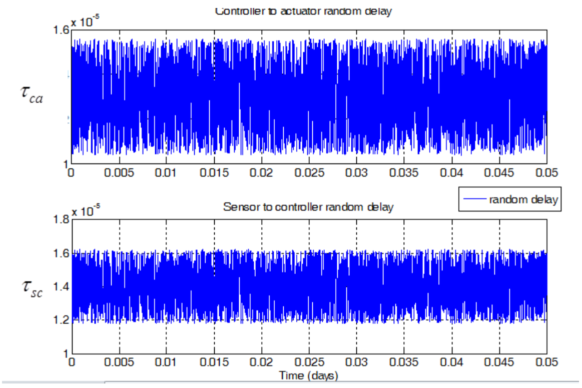

Fig. 6b. Time distribution of communication delays at their values τ_{ca} = 0.000013days, τ_{sc} = 0.000014 days for the intervals τ_{ca} ± 0.0000013 day, *and* τ_{sc} ± 0.0000014 days.

The simulation results are under the random delays are shown in Figure 7 to Figure 9.

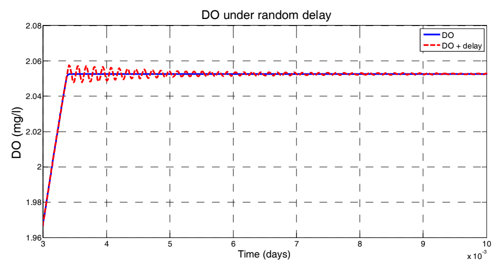

Fig. 7. Simulation of the DO process closed loop behaviour under random delays when $\tau_{tot} < \tau_c = 0.000026$days (2.25 secs) Note: Simulation time is altered for clarity purpose.

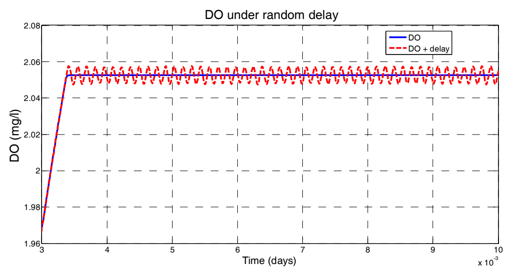

Fig. 8. Simulation of the DO process closed loop behaviour under random delays when $\tau_{tot} = \tau_c = 0.000027$days (2.33 secs).

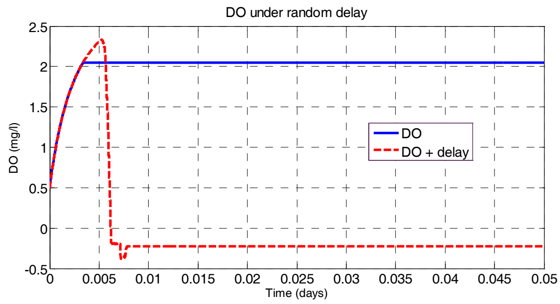

Fig. 9. Simulation of the DO process closed loop behaviour under random delays when $\tau_{tot} > \tau_c = 0.00204$ days (176.3 secs. or 2.9 minutes).

For comparison purposes, the simulation of the DO process is also carried out under the influence of constant delays and a sustained oscillation is observed when τ_{tot} is 0.000752 days (64.97 secs.). This is shown in Figure 10.

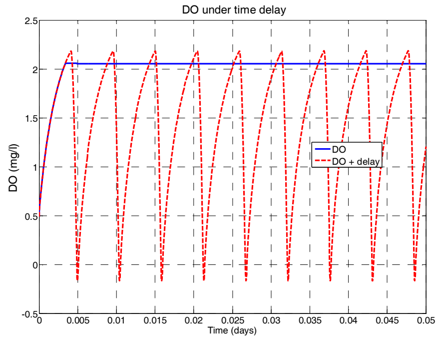

Fig. 10. Simulation of the DO process closed loop behaviour under constant delays when $\tau_{tot} = \tau_c = 0.000752$days (64.97 secs).

Table 1 shows the performance indices of the DO process behaviour at various conditions under and random time delays. Network induced time delays could be constant or random but for the purpose of this investigation, both random and constant delays are assumed.

It can be seen from Figure 7 to Figure 10 that the presence of network induced time delays in the closed loop DO process results in system overshoot. Increased network time delays result in corresponding system overshoot and poorer system performance until a sustained oscillation is experienced. This sustained oscillation is known as the critical delay and from this moment, the DO process becomes unstable. The critical delay is found to vary depending on the type of delay, the PI controller parameters, and the probability of distribution in the case of random delay. One would observe that from Figure 8, the DO process reached a critical delay in 0.000027days (2.33 secs.) under random delays, but when under constant delays, it reached critical delay in 0.000752 days (64.97 secs.) which is much longer than in the case of a random delay. These are shown in Figure 8 and Figure 10. For the random delay, one would observe from Figure 8 that at critical delay (τ_c) and beyond, the PI controller designed for the linearised DO process can no longer stabilise the control system.

The practical implication of an unstable DO concentration for the DO process is the unavailability of oxygen for microorganism metabolic activities, low quality of the effluent, poor sludge formation which could result in failure of the ASP (Vlad et al., 2011; Chotkowski et al., 2005; Sanchez and Katebi, 2003). There is therefore a need to develop a robust networked controller that is able to provide stability for the networked DO process by compensating for the communication drawbacks. In order to achieve this, the Smith predictor compensation scheme is proposed.

4. SMITH PREDICTOR-BASED COMPENSATION CLOSED LOOP CONTROL OF THE DO PROCESS

The purpose of the Smith predictor is to compensate for time delays (Smith, 1957; Galvez et al., 2007; Tanaka et al., 2013) in the networked DO process control system. The Smith predictor can be implemented under different conditions as seen in Figure 11.

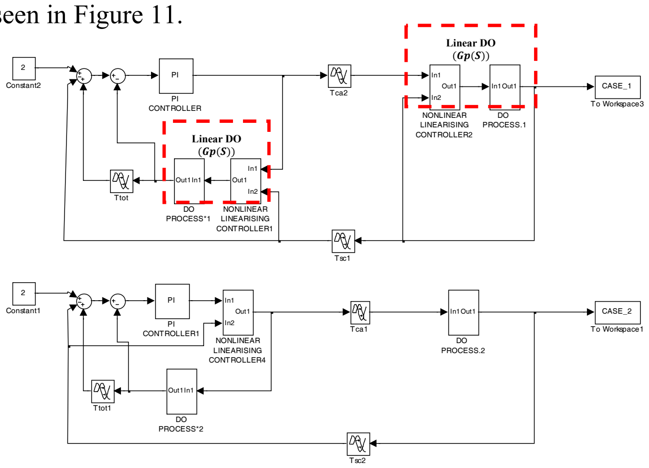

Fig. 11. Simulink block showing different implementations of the Smith predictor, a) Case1, b) Case 2.

Case 1: The closed loop system of the nonlinear controller and the DO process together results in a linearised model. This results in a transfer function to that describes the behaviour of the linearised system. The Smith predictor compensation scheme is performed on the side of the PI controller, only for the PI controller.

Case 2: In this case, the PI and the nonlinear controller are far from the DO process. This implies that a transfer function can not be applied to the model of the DO process. The Smith predictor in case 2 is performed on the side of the controllers (PI and nonlinear linearising controller).

This paper makes use of the approach in case 1. Figure 12a shows the block diagram of the networked DO process without Smith predictor while in Figure 12b, the Smith predictor compensation scheme is introduced to compensate for the time delays.

$G_p(s)$ is the transfer function of the closed loop system consisting of the DO process and the nonlinear linearising controller. As such, it is now regarded as a linearised DO process because its dynamics have been transformed from nonlinear to that of an equivalent linear DO process. $G_p^m(s)$ is the model of this linearised DO process that is used in the design of the Smith predictor. $C(s)$ is the transfer function of the PI controller designed to control the linearised DO process to ensure that its desired set point value is maintained. $R(s)$ is the desired set point to be followed. The derivation of the transfer function for the closed loop DO process under the influence of the network time delays and the Smith predictor is as follows:

$$S_o(s) = G_p(s)e^{-\tau_{ca}s}C(s)E(s) \tag{6}$$

$$E(s) = R(s) - S_o(s)e^{-\tau_{sc}s} - G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)E(s) \tag{7}$$

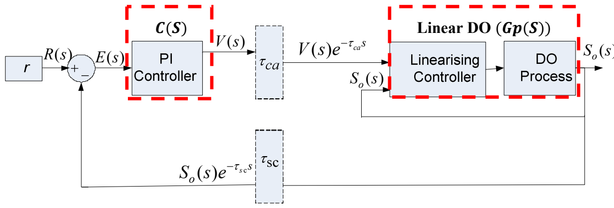

Fig. 12a. PI controller with linear closed loop DO process under the influence of network induced time delays.

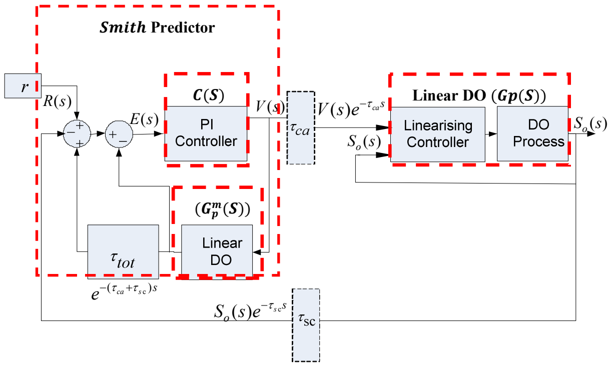

Fig. 12b. Smith predictor with linear closed loop DO process under the influence of network induced time delays.

From equation 7

$$E(s)\left[1+G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right] = R(s) - S_o(s)e^{-\tau_{sc}s} \tag{8}$$

From equation 8

$$E(s) = \frac{R(s) - e^{-\tau_{sc}s}S_o(s)}{\left[1+G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right]} \tag{9}$$

Substitute equation (9) into equation (6)

$$S_o(s) = G_p(s)e^{-\tau_{ca}s}C(s)\frac{R(s) - e^{-\tau_{sc}s}S_o(s)}{\left[1+G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right]} \tag{10}$$

$$S_o(s) = \frac{G_p(s)e^{-\tau_{ca}s}C(s)R(s)}{\left[1+G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right]} - \frac{G_p(s)e^{-\tau_{ca}s}C(s)e^{-\tau_{sc}s}S_o(s)}{\left[1+G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right]} \tag{11}$$

From equation (11), $S_o(s)$ is expressed as

$$S_o(s)\left[1+\frac{G_p(s)e^{-(\tau_{ca}+\tau_{sc})s}C(s)}{1+G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)}\right] = \frac{G_p(s)e^{-(\tau_{ca})s}C(s)R(s)}{1+G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)} \tag{12}$$

The transfer function of the closed loop system is

$$\frac{S_o(s)}{R(s)} = \frac{G_p(s)e^{-(\tau_{ca})s}C(s)\Big/\left\{1+G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)\right\}}{1+\dfrac{G_p(s)e^{-(\tau_{ca}+\tau_{sc})s}C(s)}{1+G_p^m(s)\left[1-e^{-(\tau_{ca}+\tau_{sc})s}\right]C(s)}} \tag{13}$$

Assuming that $G_p(s) = G_p^m(s)$, the transfer function for the closed loop linearised DO process is

$$\frac{S_o(s)}{R(s)} = \frac{G_p(s)e^{-\tau_{ca}s}C(s)}{1+G_p(s)C(s)}$$

This could be re-arranged as

$$\frac{S_o(s)}{R(s)} = \frac{G_p(s)C(s)e^{-\tau_{ca}s}}{1+G_p(s)C(s)} \tag{14}$$

It is observed that in equation (14), the delay $e^{-\tau_{ca}s}$ is only present in the numerator while network induced time delays in the denominator are completely eliminated. As a result, the time delays in the system are compensated for because the stability of the system is determined mostly by the denominator of the transfer function. The output of the system will delay with the delay between the controller and the actuator but the dynamics of the closed loop system will not be sensitive to the presence of the time delays.

The Smith predictor is a compensator (corrector) that attempts to virtually hide the time delays in the closed loop system in order to make available a virtual signal without time delays at the input of the PI controller (Raju, 2009). As shown in Figure 12b, the closed loop system with the Smith predictor has two feedback loops namely the outer and the inner feedback loops. The outer feedback loop is not good enough for process control due to the presence of a combined effect of network induced time delays (τ_{ca} and τ_{sc}). As a result, the outer feedback loop will only produce outdated information. In order to sustain the performance of the control system when no fresh information is available to the PI controller, the inner feedback loop which contains a Smith predictor takes over. This inner feedback loop consists of a modified model of the linearised DO process $G_p^m(s)$, the PI controller $C(s)$ and the communication delay (τ_{tot}). τ_{tot} is the sum of τ_{ca} and τ_{sc} where τ_{ca} is the controller to actuator delay and τ_{sc} is the sensor to controller delay, τ_{ca} and τ_{sc} are random delays that are uniformly distributed. The Smith predictor functions in a way such that the presence of τ_{tot} in the control system assists in eliminating (cancels out) the negative effects of communication drawbacks (τ_{ca} and τ_{sc}) in the outer feedback loop of the closed loop DO process. The aim is to ensure that the feedback signal made available to the PI controller is without network induced time delays.

In (Velagic, 2008), the author assumed that $\tau_{ca} = \tau_{sc}$ and developed a network predictive Smith controller from the mean of previous and past values of τ_{ca} and τ_{sc}. In this study, total delay τ_{tot} to be compensated is assumed to be the sum of τ_{ca} and τ_{sc}. A similar approach was used in Ding and Fang (2013) where it was applied to a radioactive material spraying equipment (Ding and Fang, 2013).

5. SIMULATION OF THE CLOSED LOOP DO PROCESS UNDER THE CONTROL OF THE SMITH PREDICTOR COMPENSATION SCHEME

The networked DO process is simulated under the influence of the random time delays and the performance of the PI controller is compared with the developed Smith predictor compensation scheme in controlling the linearised DO process. The Simulink block for this arrangement is shown in Figure 13. In this case, τ_{ca} and τ_{sc} are summed as ($\tau_{tot} = \tau_{ca} + \tau_{sc}$). The investigations of the transient behaviour of the two schemes from Figure 13 are done for the three cases of random delays:

$$\tau_{ca} + \tau_{sc} = \tau_{tot} < \tau_c$$

$$\tau_{ca} + \tau_{sc} = \tau_{tot} = \tau_c$$

$$\tau_{ca} + \tau_{sc} = \tau_{tot} > \tau_c$$

The last value is not realistic but is used to check the performance of the system with the Smith predictor in extreme conditions. The simulation results are in Figure 14 to 17.

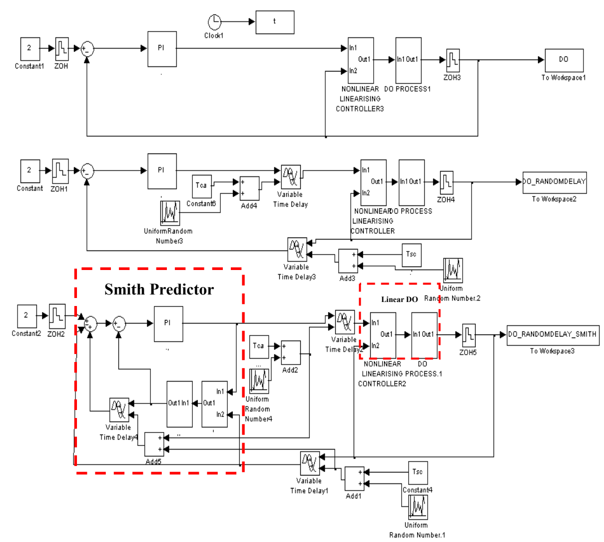

Fig. 13. Simulink diagram of the Smith predictor compensation scheme for the DO process under random delays a.) DO process without time delays, b.) DO process under random delays, c.) DO process under random delays and Smith compensator.

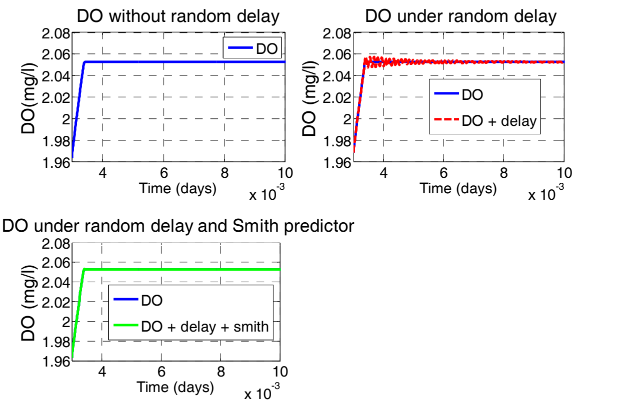

Fig. 14. a.) Simulation of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} < \tau_c = 0.000026$ days (2.85 secs.).

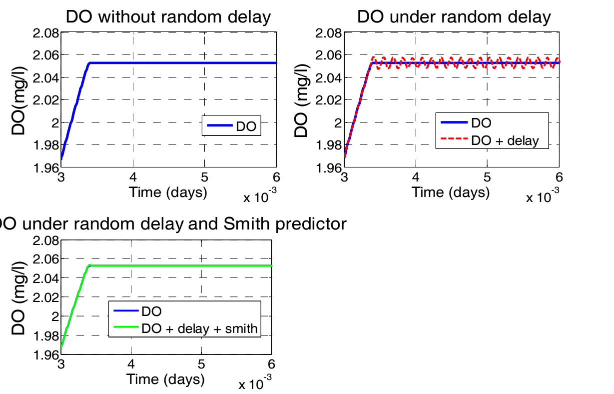

Fig. 15. a.) Simulation of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} = \tau_c = 0.000027$ days (2.33 secs.).

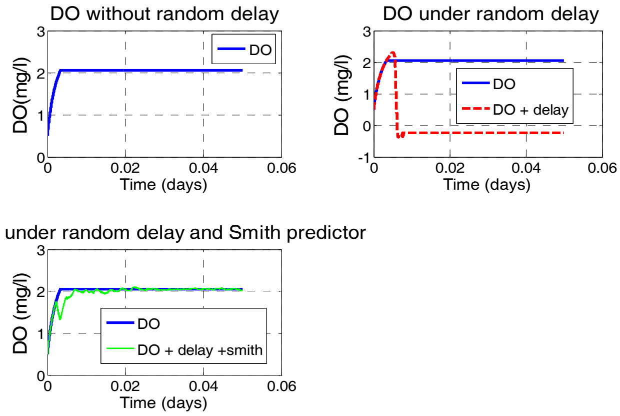

Fig. 16. a.) Simulation of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith redictor. $\tau_{tot} > \tau_c = 0.00204$ days (176.2 secs. or 2.9 mins.).

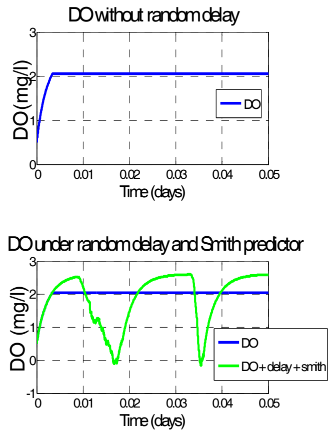

Fig. 17. a.) Simulation of the DO process closed loop behaviour without time delays b.) DO process under random delays c.) DO process under random delay and Smith predictor. $\tau_{tot} >> \tau_c = 0.01604$ days (1385.8 secs. or 23 mins.)

The performance indices of the transition behaviour of the two closed loop systems of this investigation are shown in Table 1.

6. DISUSSION OF RESULTS

Simulations were carried out for the cases of $\tau_{tot} < \tau_c$ as shown in Figure 14, $\tau_{tot} = \tau_c$ in Figure 15, $\tau_{tot} > \tau_c$ in Figure 16, and $\tau_{tot} >> \tau_c$ in Figure 17. It can be observed from the simulation results in Figures 14 to 17 and Table 1 that as the value of the network induced time delays increase; there was an increase in the percentage overshoot, oscillation amplitude and steady state error for all the cases investigated. However, the rise time and settling time of the system remained constant. This could be that the placement of the nonlinear controller close to the DO process to form a linearised DO process as described in sections 4, case 1, might have compensated for the delays that could have been experienced in the system response.

Table 1. Performance indices of the closed loop DO process under different random delay conditions.

Measurement Conditions	Time delay Values (days)	Rise Time (days)	Settling Time (days)	Percentage Overshoot (%)	Steady State Error (mg/l)	Oscillation Amplitude (mg/l)	Delay in Response (days)
$DO +$ $Random$ Delays + PI							
$\tau_{tot} = 0$	0	0.0020	0.0036	3.0	0.052600	2.05260	0
$\tau_{tot} < \tau_c$	0.000026	0.0020	0.0036	2.87	-0.0530	2.048, 2.058	0
$\tau_{tot} = \tau_c$	0.000027	0.0020	0.0036	2.88	-0.0470	2.048, 2.0475	0
$\tau_{tot} > \tau_c$	0.020400	0.0020	0.0036	30.0	27.7000	-54.000,2.600	0
	$DO +$ $Random$ Delays +PI + Smith						
$\tau_{tot} = 0$	0	0.0020	0.0036	3.0	0.0526	2.0526	0
$\tau_{tot} < \tau_c$	0.000026	0.0020	0.0036	2.65	-0.0490	2.032, 2.066	0
$\tau_{tot} = \tau_c$	0.000027	0.0020	0.0036	2.66	-0.0700	2.020, 2.070	0
$\tau_{tot} > \tau_c$	0.020400	0.0020	0.0036	30.0	0.8900	-0.380, 2.613	0

At a critical delay (τ_c) equal to 0.000027 days (2.33 secs.), the system experienced a sustained oscillation as shown in Figure 15. The above description is peculiar to the case of the DO process + random delays + PI as shown in Table 1. In the case of the DO process + random delays + PI + Smith, an improvement in the system response could be observed by a reduction in the percentage overshoot, oscillation amplitude and steady state error. For example, at the critical delay and beyond the critical delay, the PI controller was no longer able to stabilise the closed loop DO process but the Smith predictor was able to provide robust stability for the system with a steady state error of 0.89 mg/l as shown in Figure 16. It could be seen from Figure 17 that at a delay value equal to 0.01604 days (1385 secs. or 23 mins.), the Smith predictor became unstable and no longer adequate to provide the necessary stability for the system. This could be referred to as the critical delay for the developed Smith predictor. This delay is not a realistic one and it cannot exist during the normal work of the system.

7. CONCLUSIONS

In this paper, the networked control of the DO process in wastewater treatment is considered. It is realised that the communication drawbacks cause instability in the closed loop system with the PI + nonlinear linearising controllers without the Smith predictor. This situation could result in the reduction and total depletion of oxygen available to microorganisms, poor sludge formation, low quality effluent and eventual failure of the ASP. A Smith predictor-based compensation scheme is proposed to mitigate these communication drawbacks. Simulation results reveal the effectiveness of the Smith predictor-based compensation scheme over the PI + nonlinear linearising controllers designed for the DO process without time delays, to eliminate the input of the random time delays in the DO process closed loop control and to achieve the desired stability. Future studies could involve the development of strategies to improve the robustness of the developed Smith predictor compensation scheme for better performance.

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