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Generalized Minimum Variance (GMV) Control in Waterborne Wastewater Treatment

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The performance of generalized minimum variance (GMV) is examined when applied to the wastewater pH control of waterborne paint production process. The control strategy is tested under batch coagulation condition on the wastewater. $Al_2(SO_4)_3$ is chosen as coagulant. $Ca(OH)_2$ is used as manipulating variable while H_2SO_4 is fed continuously at constant rate. The evaluated parameters of the GMV algorithm are employed precisely in the control law computation. The success of the control action is estimated using negative maximum error, the first set point reaching time, and offset. The constant offset problem is experienced with the GMV control. This offset is reduced by employing a reduction of coagulant amount.

1. Introduction

Generalized minimum variance control has become an active application area since many techniques have been combined with the algorithm in order to deal with problems encountered. Zayed et al. (2001) proposed a GMV algorithm using a pole-zero placement technique, and used a recursive least-squares algorithm to evaluate the model parameters. Doi and Mori (2002) studied GMV algorithm for time varying systems. Patete et al. (2008) analyzed the GMV algorithm for a discrete time system subject to noise.

Coagulation has always attracted considerable attention in wastewater treatment. Aboulhassan et al. (2006) improved the coagulation process applied to a paint wastewater by adding coagulant aids.

In our work, waterborne paint wastewater is treated by using chemical coagulation and flocculation method. $Al_2(SO_4)_3$ is chosen as a coagulant. Absorbance is used as performance criteria.

2. Experimental Setup

Experimental equipment is shown in Figure 1. A 1 L glass-jacketed reactor was utilized. The pH was measured with a pH meter and was recorded on-line every 1 second by a computerized data acquisition system. The pH meter converts the pH signal into a voltage signal for onward transmission to an A/D channel of an IBM 586-compatible

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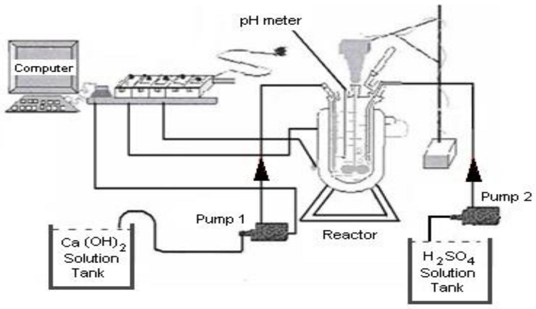


Figure 1: Experimental set-up

control computer. The control programs were written in Visual Basic. In the experiments, the GMV based strategy took data from the on-line pH monitor and adjusted the peristaltic control pump. The control pump delivered a solution of concentrated $Ca(OH)_2$ into the wastewater reactor.

As shown in Figure 1, the acidic stream is fed into the reactor by a metering pump from the top of the reactor. It is not controlled, but flows in as a step disturbance effect and the acid flow rate is set according to reactor volume. Then the pH is monitored. At the end of the reaction, polyelectrolyte is added and the reactor agitated slowly. The addition of additive chemicals enhances the coagulation through promoting the growth of flocks. The samples are then allowed to stand for 60 min, after which the color and absorbance value of the supernatant water are measured.

Generally, neutralization processes are non linear and difficult to model. Usually detailed first principle dynamic models are amenable to practical control designs. The GMV control method has been implemented to pH control of waterborne paint wastewater.

3. The Generalized Minimum Variance Controller

The GMV cost function provides additional penalties in terms of the process output error and the control signal - see

$$J(u,t)=[(y_{t+1}-r_{t+1})^2+\lambda u_t^2] \tag{1}$$

The GMV approach employs a system of pseudo output $\Phi(t)$ determined by

$$\phi(t+k)=Py(t+k)+Qu(t)-Rr(t) \tag{2}$$

where r(t) is the set point, and P, Q and R are transfer functions in the backward shift operator z^{-1}, specified as P=1 etc., Q=λ etc., R=1 etc.

It is by the choice of P, Q and R that the user can obtain the wider range of control behaviour.

$\Phi(t+k)$ consist of two independent terms. The first term can be defined as:

$$\phi(t+k\,\big|_t)=\frac{1}{c}\,[(BE+QC)\,u(t)+Gy(t)-CRr(t)+Ed] \tag{3}$$

and represents the best forecast of $\Phi(t+k)$ established on data up to time t. The second term is:

$$Ee(t+k) = \phi(t+k) - \hat{\phi}(t+k\,|_t) \tag{4}$$

which is the output prediction error originating from the noise sources e(t+1), e(t+2), ..., e(t+k). It was pointed out previously that these latter sources cannot be removed by the control signal U(t).

Clearly y is minimized by setting the predicted out-put (best forecast) equal to zero, i.e:

$$\hat{\phi}(t+k\,|_t) = 0 \tag{5}$$

This gives the control law:

$$Fu(t) + Gy(t) - Hr(t) + Ed = 0 \tag{6}$$

where

$$F = BE + QC \tag{7}$$

and

$$H = CR = 1 \tag{8}$$

Hence:

$$u(t) = \frac{Hr(t) - Gy(t) - Ed}{F} \tag{9}$$

The steps in the implementation of the GMV algorithm may be summarized as:

a. Apply a Pseudo Random Binary Sequence (PRBS) to the system as a forcing function and obtain the plant output.

b. Estimate F, G from (6) implementing the recursive least square algorithm.

c. Employ equation (9) to evaluate the control signal.

d. Apply the control signal.

e. Return to a.

4. Results

In the present work, single variable generalized minimum variance (GMV) control algorithms are applied to waterborne paint wastewater to keep pH at desired value. This known as Generalized Minimum Variance (GMV) control and employs a one-step-ahead optimal control law. The technique is generally to hold λ as small as possible in order to stay as close as required to the objective of sustaining a minimum output variance while still preserving closed loop stability. The positive weighting coefficient λ simply prevents control signal saturation. The GMV algorithm involves a feed-forward element represented by the polynomial Q. In this work, Q is chosen equal to λ, and P and R are transfer functions in the backward shift operator z^{-1}, specified as P=1, R=1.

The PRBS signal applied to the system is shown in Figure 2. The obtained wastewater process output (pH) is also shown in the same figure. To estimate F, G polynomial coefficients, recursive least square technique is utilized. Second order CARMA model is used in GMV algorithm.

In the present case, the PRBS applied is of 0.65 pump signal magnitude. The PRBS is added to the controller output which is then employed as a forcing function to disturb the process. Equation (6) which gives the control law is employed to estimate F and G polynomials parameters as following by using recursive least square technique.

$$F = f_0 + f_1 z^{-1} \tag{10}$$

$$G = g_0 + g_1 z^{-1} + g_2 z^{-2} \tag{11}$$

$f_0 = -1.07,\ f_1 = 0.0694,\ g_0 = -0.00806,\ g_1 = -0.00315,\ g_2 = 0.00794$

There are two parameters in the GMV algorithm that have to be defined by the user, viz the supposed process dead-time in terms of k (the integral number of sampling intervals) and λ (the control weighting). Of these two the control weighting is a tuning knob, whereas k is a function of the rate of sampling and the dead time. However, it is important to have a proper knowledge of k, otherwise unstable control can result without a careful choice of λ. In the present work, k applied is of unit magnitude and λ value is chosen as 0.002 (Table 1 and 2).

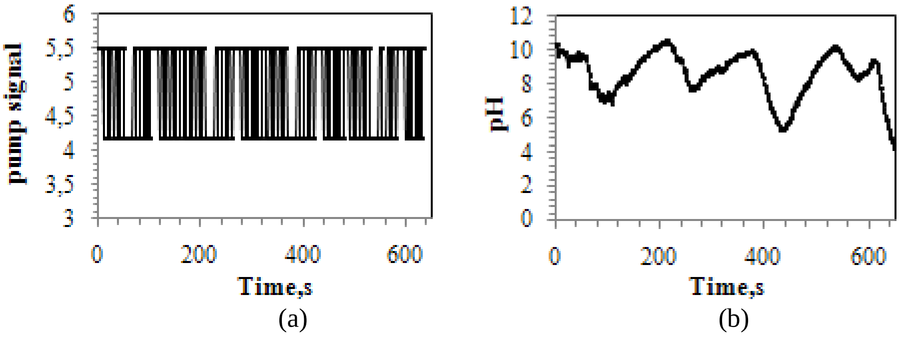


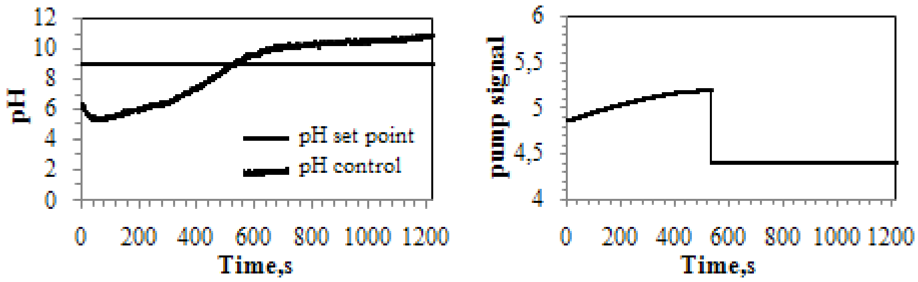
Figure 2: A pseudo-random binary sequence (PRBS) as a forcing function (a) PRBS signal used (b) pH change in the face of PRBS signal given to base flow rate

In Figures 3 and 4, the pH control results by using GMV algorithm is demonstrated experimentally. The waterborne paint wastewater treatment reactor is utilized. The pump feeding rate of $Ca(OH)_2$ solution as the manipulating variable is changed with time while GMV control algorithm is being executed.

These are also given in Figures 3 and 4. Although there is a difficult control at pH 9, the GMV adapts to the desired set point. It is shown that the absorbance value obtained by using GMV algorithm is less than one without treatment (see Table 1).

There are several approaches to the problem of constant offset experienced with the GMV algorithm (Clarke and Gawthrop (1979). One procedure is to modify the P polynomial by the addition of an integrator.

The second method is to add integrators to both the P and R polynomials in the auxiliary model. The third approach is to modify the Q polynomial (Clarke and Gawthrop (1979).



(a)

(b)

Figure 3: The GMV control result (a) pH change with time (b) Pump signal change with time (pH set point=9, weighting parameter $\lambda=0.002$, $Al_2(SO_4)_3$ amount=5 g/L, $Ca(OH)_2$ solution= %2, H_2SO_4 solution=%6 and acid pump signal=0.23)

Table 1: The GMV control performance (pH set point=9, weighting parameter $\lambda=0.002$, $Al_2(SO_4)_3$ amount=5 g/L, $Ca(OH)_2$ solution=%2, H_2SO_4 solution=%6 and acid pump signal adjustment=0.23)

λ	*Negative maximum error*	*First set point catching time, s*	*Offset*	*Treated Absorbance*		*Raw Absorbance*
				with polyelectrolyte	*without polyelectrolyte*	
0.002	0.95	521	0.5	0.073	0.068	1.697

Table 2 The GMV control performance (pH set point=9, weighting parameter $\lambda=0.002$, $Al_2(SO_4)_3$ amount=3.5 g/L, $Ca(OH)_2$ solution=%2, H_2SO_4 solution=%6 and acid pump signal adjustment= 0.23)

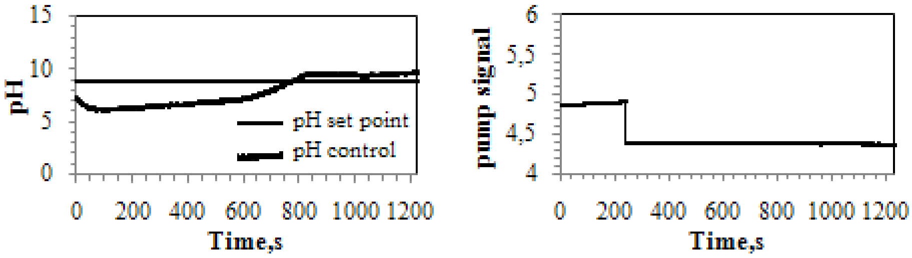
λ	*Negative maximum error*	*First set point catching time, s*	Offset	Treated Absorbance		*Raw Absorbance*
				with polyelectrolyte	without polyelectrolyte	
0.002	0.75	780	0.2	0.058	0.055	1.697

In the present case, the offset is removed considerable by reducing the coagulant ($Al_2(SO_4)_3$) amount (see Figure 4 and Table 2).

5. Conclusion

There does not appear to have been any published work concerned with the application of the GMV controller to waterborne paint wastewater treatment reactor. The current study involves the successful implementation and application of the GMV controller to such systems.

The constant offset problem experienced with the GMV control may be solved by employing a reduction of the coagulant amount. $Al_2(SO_4)_3$ is good coagulant for this suggested waterborne paint wastewater treatment system. The success of the control action has been estimated using negative maximum error, the first set point reaching time, and offset. It is noted that the absorbance value obtained by using GMV control is less than one obtained without control, and that the GMV control application to this process is very successful.



(a) (b)

Figure 4 The GMV control result (a) pH change with time (b) Pump signal change with time (pH set point=9, weighting parameter $\lambda=0.002$*,* $Al_2(SO_4)_3$ *amount=3.5 g/L,* $Ca(OH)_2$ *solution=%2,* H_2SO_4 *solution=%6 and acid pump signal adjustment= 0.23)*

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