OPTIMAL FUZZY CONTROL FOR CANAL CONTROL STRUCTURES

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ABSTRACT

This paper presents an application of a SCADAPack Remote Terminal Unit to regulate the level in an irrigation canal prototype. The designed upstream level regulator consists of two Linear Quadratic Gaussian (LQG) controllers switched with fuzzy logic. The control scheme developed was implemented on "C" at a SCADAPack installed in a Mexican laboratory canal. The adequated closed-loop performance obtained suggests the evaluation of the developed scheme on field applications.

INTRODUCTION

Adequate water administration and distribution in agricultural requires particular attention, since agricultural is the biggest water consumer activity. Distribution of water usually requires an extensive canal network to transport water from storage reservoirs to farmers. These canals must satisfy the water demand in spite of weather variations and the physical and hydraulic canals' limitations. Currently, canals are operated manually, with a large staff, to obtain reliable irrigation service. To improve canal operation and irrigation service, automatic control offers an attractive solution.

The CINVESTAV and the Mexican Institute of Water Technology (IMTA) are working in the design of an upstream level regulator to download it to Remote Terminal Units used for monitoring and remote operation of canal control structures in Mexico. To do that, several experiments have been performed to control level in a Mexican irrigation canal prototype. In the reference 2, a LQG controller was implemented in real-time to regulate levels in a three-pool canal prototype of 50m length. Also, for the same prototype in reference 3, a predictive control was tested. In these experiments a simple Input/Output (I/O) model obtained by identification was used to design the controller and in spite of simplicity of the used model, in all experiments the closed-loop performance has

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been very satisfactory. A non linear controller also was tested in Ref 4, to only one pool of the above prototype.

This paper will present the design and test of an upstream level regulator consisting of two LQG controllers switched with fuzzy logic and presenting robustness to flow changes through the control structure. Normally, the performance of a simple level upstream regulator degrades when the flow through a control structure changes from the original flow condition considered. To avoid this problem the global controller proposed here uses fuzzy logic to combine control actions of two optimal LQG regulators designed for two different flow conditions present on a control structure. To determine how the local control laws will be combined, this regulator uses fuzzy rules based on the measured downstream level from the control gate. This information helps to indicate if the flow condition is free or submerged.

The control scheme developed is implemented through a "C" language program, stored and executed on a Control Microsystems SCADAPack PL**C** [Ref 7] installed in the "Short Canal" available at IMTA Laboratory, see Fig. 1. As will be explained later, the satisfactory closed-loop performance obtained, suggest the evaluation of the developed scheme in open canals of Irrigation Districts (I.D.) in Mexico, such as the canal of Carrizo I.D. or Mexicali I.D, where actually a SCADAPack is installed to regulate the position of a control structure.

For the canal considered in this paper: the model to design the controller is a Input-Output (I/O) model obtained by identification; the canal operation is *constant level downstream* [Ref 5] at the end of the first pool and the control method used is *upstream control.* The control variable is the gate opening. To evaluate the regulation performance, flow variations introduced by the first pool lateral outlets act as disturbances.

This paper is organized as follows. First the characteristics of the laboratory canal are presented. Next, we describe the methodology to obtain the linear I/O model used to design the proposed controller. After, the preliminaries needed and details about the control design are explained. Then the ScadaPack implementation and real-time results are presented. Finally, conclusions and future work are stated.

LABORATORY CANAL

The prototype (Fig. 1) used in this application is a concrete trapezoidal canal of 25m long and 70cm height. The Manning coefficient is 0.1 and the slop 0.0005. The control structure is a slide gate that divides the canal in two pools. In the first and second pools there are outlets. At the downstream end of the canal the level is regulated by a manual overshot gate. The slide gate is equipped with two potentiometer float level sensors (upstream and downstream), a potentiometer for gate position and limit switches (maximum and minimum gate opening). The system is designed considering manual operation and RTU (Remote Terminal Unit) operation. For this aim a SCADAPack from Control Microsystems [Ref 7] is used to control the downstream level of the first pool. A portable PC is used to download programs in "C" to the SCADAPack.

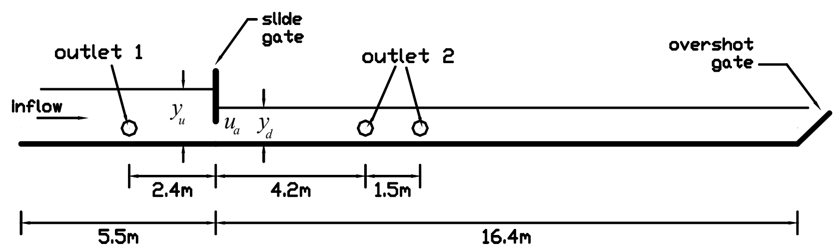

Figure 1: Canal prototype.

MODEL

The flow in an open canal is described by two nonlinear partial differential equations called the Saint-Venant equations [Ref 6]. This model is used to study the flow behavior in open irrigation canals, but in general, it is not used for control design due to its complexity. To design our controller two linear models are obtained by identification, one for each flow condition through the gate, i.e. one for free flow condition (defining the first set point): $q_c = C_d \; B \; u_a \; \sqrt{y_u - (u_a/2)}$ and one for submerged flow condition (defining the second set point): $q_c = C_d \; B \; u_a \; \sqrt{y_u - y_d}$ where q_c is the flow through the gate, C_d is the discharge coefficient, B is the gate width, u_a is the gate open height, y_u is the water depth upstream of the gate and y_d is the water depth downstream of the gate.

The transfer functions of linear models are estimated using a standard identification procedure [Ref 10]: 1) The first step is to determine the input and output variables. For each linear model, the gate opening deviation from its set point is the input variable. They are denoted as u_i (i = 1, 2), where *i* denote the model *i*. The level deviation upstream of the gate from its set point is the output variable (controlled variable). They are denoted as y_i (i = 1, 2). The set points used to obtain models 1 and 2 are presented in Table 1. Note that the level set point is always the same.

2) During the second phase, the variation in the water level y_i (i= 1, 2) is registered, when it is applied a pseudo-random binary signal (PRBS) on the respective opening gate set point. The downstream level's evolutions obtained are presented in Figure 2. In this figure the levels are normalized with respect to its set point. The data were obtained directly from the prototype each 10 s, the selected sampling time.

Table 1: Set points.

	set point 1	**set point 2**
Inflow	110 l/s	110 l/s
Upstream level y_u	36cm	36cm
Downstream level y_d	19cm	33cm
Gate opening u_a	16cm	23cm

3) Proposed model. From Fig. 2, it is observed, that level responses are similar to those of linear systems, and that is why we propose the next structure for our model:

$$y(t) = \frac{B(q^{-1})}{F(q^{-1})}u(t) + e(t) \qquad \text{(eq 1)}$$

4) Parameter identification: The estimation of coefficients of polynomials F and B (parameters) is easily achieved using the instruction **oe** of the *Matlab System Identification Toolbox*, which use least square method to adjust parameters. The inputs for this instruction are: proposed orders for polynomials B and F and the data (u_i, y_i) previously registered. To measure quality of the identified model, we use the instruction **compare,** which compares the registered canal level with the response of the identified model using a performance index. Figure 2 shows the response of the identified models, and it can be seen, the model responses follow the real level responses.

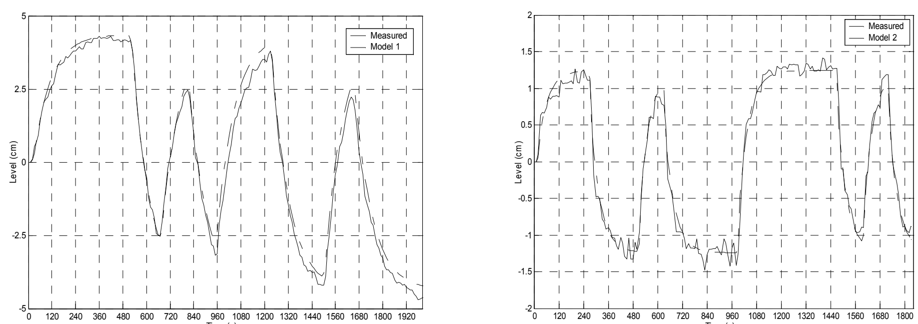

Figure 2: a) Measured level evolution at the set point 1 and Model 1 response
b) Measured level evolution at the set point 2 and Model 2 response.

4) At this stage, a model (equation 1) is obtained for each set point and they are noted as Model 1 for the response obtained using the set point 1 (free flow condition), and Model 2 for that obtained using the set point 2 (submerged flow condition). Next, these models are transformed into the following transfer functions:

$$G_1(z) = \frac{y_1(z)}{u_1(z)} = \frac{-0.05533(z^2 \ +1.565z - 3.069)}{z^2(z-0.893)}$$
$$G_2(z) = \frac{y_2(z)}{u_2(z)} = \frac{-0.03654(z \ +5.5665)(z-0.3417)}{z^2(z-0.8063)} \quad \text{(eq 2)}$$

CONTROLLER SYNTHESIS

The principal goal of the controller designed is regulate the downstream level at the end of the first pool in face of disturbances and changes in flow through the gate.

Preliminaries of LQG control

Let a minimal state representation of a linear plant

$$x(k+1) = Ax(k) + Bu(k) + v(k); \qquad y(k) = Cx(k) + w(k) \quad \text{(eq 3)}$$

where x is the state, u the input, y the output, v and w are noises and *A, B, C* are matrices of appropriate dimension and k is the discrete time. Under habitual assumptions, the LQG signal u [Ref 1] that minimizes,

$$\mathrm{J} = E\{x^{\mathrm{T}}(\mathrm{k})Q_c\, x(\mathrm{k}) + u^{\mathrm{T}}(\mathrm{k})R_c\, u(\mathrm{k})\} \quad \text{(eq 4)}$$

it is given by: $u(t) = -K_c\hat{x}(t)$, where K_c is the LQ gain and $\hat{x}$ is the Kalman estimated. The Kalman estimated state [Ref 1] is obtained from a Kalman filter which is given by

$$\hat{x}(k+1) = A\hat{x}(k) + Bu(k) + L(C\hat{x}(k) - y(k))$$

where L is the Kalman gain, and *A, B, C* are the matrices of the system (eq 3). This filter can be seen as a copy of the system containing a correction term. It is useful when the plant state is not accessible. The values of K and L are the core of LQG, and can be calculated easily using **dlqr** instruction of the *MATLAB Control Toolbox*. The LQG control is a simple and modern technique, well known in control theory, that in many control problems offers very attractive solutions. The interested lector can be referred to [Ref 1].

Preliminaries about Functional Fuzzy Systems

In a functional fuzzy system, the i-th Rule has the form [Ref 12]

If z_1 is $M_{i1},\ldots,z_j$ is $M_{ij},\ldots,z_g$ is M_{ig} Then $b_i=f_i(\cdot)$

where z_j $(j=1,...,g)$ are the premise variables; $i=1,...,r$ are the fuzzy rules; M_{ij} are the fuzzy sets and $f_i(\cdot)$ is a function in the argument $(\cdot)$. The premise of this rule is defined as in a standard fuzzy system. The consequent, instead of a linguistic term with an associated membership function, is a function. The argument of each f_i can be the premise variables but other variables may also be used. The choice of these functions depends on the application being considered. Defuzzification may be obtained by

$$b = \sum_{i=1}^{r} b_i \varphi_i(z) \Big/ \sum_{i=1}^{r} \varphi_i(z)$$

where $\sum_{i=1}^{r} \varphi_i(z) \neq 0$; $\varphi_i(z) = \prod_{j=1}^{g} \mu_{ij}(z_j)$; and $\mu_{ij}(z_j)$ is the membership function of z_j and $z^T \doteq \begin{bmatrix} z_1 & \cdots & z_g \end{bmatrix}$

Disturbance reject

In order to reject disturbances due to lateral outlets, the following integral action is added to canal model

$$\frac{z}{(z-1)} \qquad \text{(eq 5)}$$

Design of each LQG controller is then effectuated using the model resulting from a serial connection between the linear model *i* from (eq 2) and the integral action model (eq 5). This model is referred to as the i-th augmented plant, and noted G_{ai}, $i=1,2$:

$$\begin{aligned} Ga_1(z) &= \frac{z}{z-1} \cdot \frac{-0.05533(z^2 + 1.565z - 3.069)}{z^2(z-0.893)} \\ Ga_2(z) &= \frac{z}{z-1} \cdot \frac{-0.03654(z + 5.5665)(z-0.3417)}{z^2(z-0.8063)} \end{aligned} \qquad \text{(eq 6)}$$

State space realization

A LQG controller is designed using a state space realization of a system, in our case, it is necessary then to obtain the realization of the transfer function of the augmented plant *i* (eq 6). The realizations A_i, B_i and C_i (i =1, 2) obtained can be found in [Ref 9].

Specifications

The closed-loop canal must satisfy the following specifications:

- The gate-opening rate should not exceed 0.11 cm/s.
- The largest gate opening is given by the canal limits.
- Level must be within the limits given by the canal dimensions.
- Sample rate must be larger than 3 s.

Controller design

The first step to derive the proposed controller is to design a LQG for each augmented model. To do that, matrices *A, B, C* of the augmented plant are needed and also the synthesis parameters Q_c and R_c of (eq 4) and the noise spectrums of $v(k)$ and $w(k)$, which are noted as Q_f and R_f. In this work spectrums Q_f and R_f are in reality synthesis parameters to get good performances in the state estimation. The synthesis parameters giving satisfactory close-loop performance and the gains obtained are shown in Table 2.

Table 2: Synthesis parameters and gains.

Model 1		Model 2	
$Q_c = I_3(0.15)$	$Q_f = I_3(0.008)$	$Q_c = I_3(0.15)$	$Q_f = I_3(0.0015)$
$R_c = 3500$	$R_f = 0.0394$	$R_c = 700$	$R_f = 0.0442$
$K_1 = \begin{bmatrix} 0.0785 & -0.0676 & 0 \end{bmatrix}$		$K_2 = \begin{bmatrix} 0.1047 & -0.0807 & 0 \end{bmatrix}$	
$L_1^T = \begin{bmatrix} -2.0445 & -1.7736 & -1.4703 \end{bmatrix}$		$L_2^T = \begin{bmatrix} -2.2191 & -1.9842 & -1.6228 \end{bmatrix}$	

The second step is to propose intelligent fuzzy rules to switch smoothly between the two designed controllers. Because we are interested in passing the control from one controller to the other when a change in the gate flow condition regime occurs, we propose the fuzzy rules given in Figure 3. These membership functions were stated based on the next condition:

$$y_d > (2/3)\, y_u \qquad \text{(eq 7)}$$

where y_d is the water depth downstream of the gate and y_u is the water depth upstream of the gate. When (7) is satisfied the flow regime is submerged otherwise the flow regime is free.

The switching rules are:

If y_d is M_1 **then** $b_1 = -K_1\hat{x}_1$

If y_d is M_2 **then** $b_2 = -K_2\hat{x}_2$

The global control law is given by:

$$u_m(k) = \frac{M_1(y_d)\cdot\left(-K_1\hat{x}_1\right) + M_2(y_d)\cdot\left(-K_2\hat{x}_2\right)}{M_1(y_d) + M_2(y_d)}$$

where K_i (i=1,2) are the LQ gains (Table 2) and $\hat{x}_i$ (i=1,2) are the Kalman estimated states. This signal u_m is integrated before to be applied to the canal. This action can be represented by: $u_a(k) = u_a(k-1) + u_m(k)$. The scheme used to implement the global controller is shown in Fig. 4.

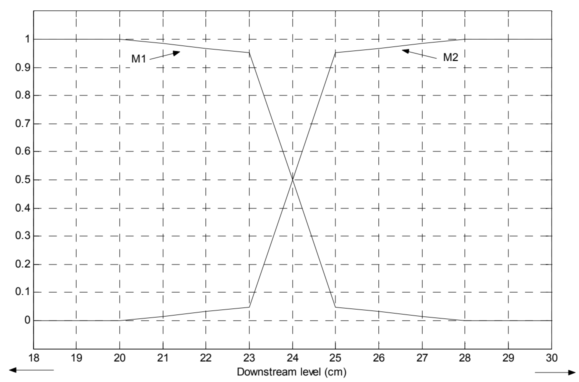

Figure 3: Fuzzy sets.

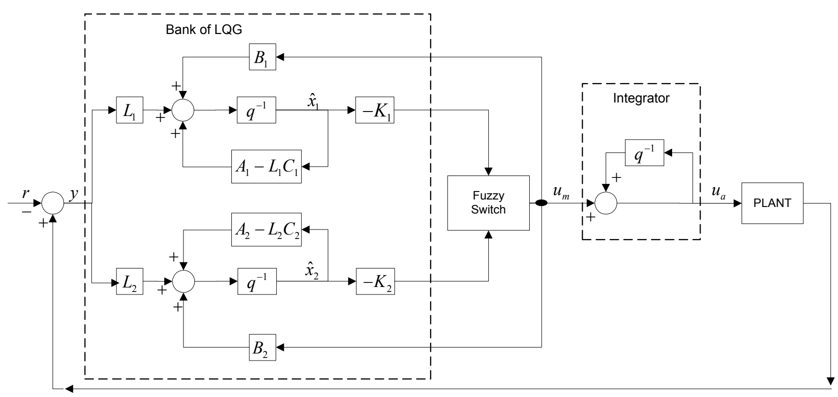

Figure 4: Controller scheme.

SCADAPACK IMPLEMENTATION

The control algorithm in Fig. 4 was implemented through a SCADAPack C program [Ref 8], [Ref 11]. This program uses the sensors measured values at each sampling time (10s) to calculate the gate opening required to maintain level at its set point. Program uses 29 registers from SCADAPack I/O register data base, three of them are user assigned and are related to level sensors, the rest of them are general purpose registers. The A_i, B_i and C_i (i=1,2) model matrices and K_i and L_i (i=1,2) gains are set in the C program; therefore they only can be changed by rewriting the program and downloading it again. Controller parameters such as set point reference, dead zone, gate opening limits and calibration parameters are registers in the I/O data base and they can be read and changed by any MODBUS device. Implementation in SCADAPack is simple, since the algorithm is programmed using only addition and multiplication of matrices [Ref 9].

REAL-TIME RESULTS

Figure 5 shows the experimental results of the proposed controller. This experiment is started at the following point: $y_u = 36,\ y_d = 27,\ u_a = 16$ (submerged regime). At time t = 240 s outlet 1 is opened allowing a withdrawal of 40 l/s. After the controller rejects this perturbation, the outlet is closed at t = 1200 s. Note that there is an adequate regulation of the downstream levels in spite of changes in flow regime through the gate taking place between t = 480 s to 1300 s. Furthermore, gate opening does not exceed its physical limits and the opening-rate is below the specification. In general, adequate performance is obtained in the closed-loop system.

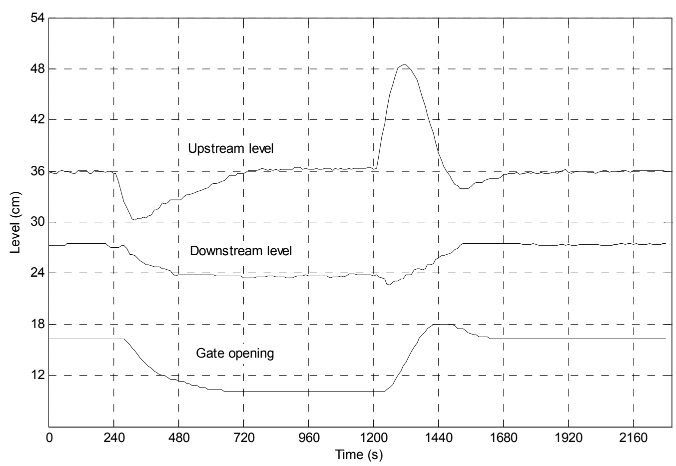

Figure 5: Responses of levels and control gate opening.

CONCLUSIONS

A controller based on a bank of two LQG controllers using functional fuzzy logic to switch them was designed and implemented in real-time in a SCADAPack to regulate the downstream level of the first pool in an irrigation canal prototype. The closed-loop real-time performance of both the level and the gate openings obtained with this control was very satisfactory in spite of the changes in the flow through the control gate. Implementation in SCADAPack was simple, since the algorithm was programmed using only addition and multiplication of matrices.

The adequate closed-loop performance and the simplicity in the real–time implementation suggest the evaluation of the developed scheme on field applications.

REFERENCES

1. Anderson B.D.O. and Moore J.B., *Optimal Control: Linear Quadratic Methods*, Prentice Hall, Englewood Cliffs, NJ, USA, 1990.

2. Begovich O., Ruíz V.M. y Zapién J.C., "Implementación en tiempo real de un control LQG en un prototipo de canal abierto de riego de varios tramos", *Ingeniería Hidráulica en México*, vol. XIX, n. 2, pp. 5-15, 2004.

3. Begovich O., Aldana C.I, Ruiz V.M., Georges D., Besançon G., "Real-time predictive control with constrains of a multi-pool open irrigation canal ", *XI Latin-American Automatic Control Congress "CLCA2004"*, La Habana, Cuba, 2004.

4. Besançon G., D. Georges, V. Ruiz-Carmona, O. Begovich, C. I. Aldana López, "First experimental results of nonlinear control in irrigation canals", *2nd IFAC Symposium on System, Structure and Control* "SSSC2004" Oaxaca, México, December 2004.

5. Buyalski C. P., Ehler D.G., Falvey H.T., *Canal Systems Automation Manual*, A water Resources Technical Publication. Bureau of Reclamation. Denver, Colorado, 1991.

6. Chow V. T., *Hidráulica de canales abiertos*, McGraw Hill Interamericana S.A., Colombia, 1994.

7. Control Microsystems, *SCADAPack Product Data Sheet*, Canada, November 2004.

8. Control Microsystems, *TelePACE C Tools User and Reference Manual*, Canada, 2003.

9. Iñiguez J. *Diseño de un control robusto ante cambios en el régimen de flujo en la estructura de control de un prototipo de canal de riego.* M. in S Thesis, Cinvestav-Gdl, Mexico, September 2005.

10. Ljung L. *System Identification: Theory for the user*, Prentice Hall Ptr, New Jersey, 1987.

11. Microtec Research Inc., *MCCM77 User´s guide*, Santa Clara, CA, 1993.

12. Passino K.M. and Yurkovich S., *Fuzzy Control*, Adison-Wesley, USA, 1998.