REAL-TIME IMPLEMENTATION OF A DECENTRALIZED CONTROL FOR AN OPEN IRRIGATION CANAL PROTOTYPE

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ABSTRACT

This paper presents a real-time implementation of a decentralized LQG controller to regulate the downstream levels at the end of the pools in a four-pool open irrigation canal prototype with an upstream control concept. The objective of the controller is to keep the downstream level at a constant target value in spite of flow disturbances. Controller synthesis uses a “black box” input-output identified linear model. A previous interaction analysis, via Relative Gain Array “RGA”, carried on the process model was made to verify the feasibility to design a decentralized control. The real-time close-loop results show satisfactory performance and they are compared with those obtained with a centralized LQG controller.

KeyWords: Hydraulic canal control, distributed systems, decentralized control, control applications, LQG control.

I. INTRODUCTION

The efficiency of water used in agriculture reaches a 30 percent average in a lot of countries around the world. Many researchers currently work to give adequate solution to this problem. In particular, automation of water distribution systems, as open irrigation canals, has been studied. Nowadays, the best alternative to improve the distribution efficiency and the operation of irrigation canals is by using automatic control structures.

The main goal in canal operation is to supply the crops water requirements in quantity, frequency and opportunity, it allows farmers to do a more efficient water use and to reduce spillage. For canal water distribution and conveyance, the water level at specific points in the canal must be regulated. This is done by control structures located along the canal.

The present work is being related to design and to apply in real-time, a decentralized control in an open canal prototype.

A centralized controller for multivariable systems has a full transfer matrix where the interactions among loops are taken into account in controller design. A decentralized control [1] is a controller with diagonal transfer matrix and it can be seen as a set of monovariable controllers. Therefore, this kind of controller results very attractive for many field applications, but for its nature, interactions between loops can not be considered when the controller is designed. If interactions among loops are very important it can appear degradation on the closed loop performance or stability lack.

In literature, there are many loop-interaction measures [1-3], to quantify the extent of cross-coupling effects, for linear systems. This information can orient someone, if it is feasible or not to design a decentralized control. In this work, we have chosen the Relative Gain Array (RGA) measure [2] to verify feasibility of the decentralized control. Although this measure is a static interaction measure, it was selected since the canal bandwidth is composed of very lower frequencies, then the information provided from this measure can be acceptable.

In the other way, automatization of irrigation canals is not simple, since: dynamics of water through the canals are
modeled by nonlinear partial differential equations (Saint-Venant equations); they have a lot of inputs (control gate positions) as well as outputs to be regulated (basically the levels); water flow dynamics are characterized by delays which are function of the water flow; they are subject to stochastic disturbances which are mainly due to water withdrawals or weather conditions.

A variety of control methods have been proposed for irrigation canals. Among the different proposed schemes, we have for example: PID [4], centralized LQG [5], predictive control [6], nonlinear control [7]. Respect to decentralized control we can cite the following works: In [8] a PI decentralized control to achieve constant-volume, is designed. To design this controller a minimization of a $H_2$ norm of a linear fractional transformation under the constraint that the control gain matrix must be diagonal. The water volume model used to design the controller is a very simple linear model deduced from the Saint-Venant equations. The work presented in [9] is similar to [8], but in this case an integral action is added into controller design. In [10] a decentralized predictive control is formulated to regulate the downstream level of each pool in a four-pool canal. This scheme takes into account the interactions between pools, using interconnection variables. We can also cite [11], where a local PI is designed for each pool. In that work, to enhance the PI performance, information of one or more canal pools is feed forward upstream into PI’s. All previous works show their results only in simulation and there is not loop-interaction analysis previous to design.

In [12], a decentralized control is implemented to regulate the downstream level of three pools of the Haughton Main Canal in Australia. This canal use overshot gates to level regulation, then the control variables are the head over the weirs. As local controllers, PI’s augmented with a filter are used with and without feedforward information from the downstream local controllers. The satisfactory results obtained in that work encourage to continuing the research to design more efficient decentralized control algorithms and use of composite regulators (weirs combined with orifice gates).

The main contributions in this paper are: First, design and real-time implementation, of a decentralized LQG control, to regulate the downstream level of the three first pools, of the Mexican irrigation canal prototype related to [13,14]. Second, application of a loop-interaction analysis to verify feasibility of the decentralized controller. The close-loop performances obtained in this experience are satisfactory and they are also compared with those obtained from a centralized LQG.

For the canal considered in this paper, the controlled variables are the downstream levels at the end of each pool and the control variables are the openings of the downstream slide-gates along the canal. The control concept used is upstream control [15]. We have selected these conditions since the canal build in Mexico were originally designed for this type of pool operation method (constant level at the downstream end of the pools where turnouts are located) and control concept (manual operation is actually used).

This paper is organized as follows. In section II, the characteristics of the laboratory canal are described and also the unsteady state hydraulic model. In section III preliminaries about decentralized control, the RGA interaction measure and LQG control are presented. Derivation of a “black box” linear input-output model is stated in section IV. The synthesis of decentralized control is detailed in section V. Section VI shows the real-time results obtained with the designed controller and their comparison with those obtained from a centralized controller. Finally, conclusions and future work are stated in section VII.

II. LABORATORY CANAL AND HYDRAULIC MODEL

2.1 Laboratory canal

The canal prototype used in the present study is a zero slope rectangular canal with glass walls and concrete bottom, located at the Hydraulics Laboratory of the Mexican Institute of Water Technology. The canal dimensions are 60cm wide, 50m long and 1m high. The estimated Manning coefficient is 0.01. To regulate the level, three slide gates are installed (with discharge coefficient of 0.6), see Fig. 1. The hydraulic laboratory has a pumping station that keeps the level constant on a water-tower that supplies water to the canal prototype with a constant head. The water leaving the prototype is collected by a canal network and sent it to an underground tank. From this tank the water is recirculated into the canal by a pumping station. The inflow is adjusted with a servo-valve. At the downstream end of the canal the level is regulated by a manual overshot gate. Each gate is equipped with a linear actuator, two pressure sensors to measure the levels upstream and downstream of the gates, a potentiometer to sense gate position and limit switches (maximum and minimum gate opening). The system is designed considering manual operation and RTU (Remote Terminal Unit) operation. The RTU used are two MODICOM PLC E984-245 at gates 2 and 3, and a SCADAPack from Control Microsystems at gate 1. A Pentium PC is used as a master station where the man–machine interface was installed using Lookout software from National Instruments Inc. The master station is relayed by radio to the SCADAPack (MODBUS protocol) and by wire to the PLC (MODBUS + protocol). The control algorithm was implemented on Matlab. Using the Dynamic Data Exchange option of Windows Matlab and Lookout exchange data to control the laboratory canal.

2.2 Hydraulic model: Saint-Venant equations

The flow in an open canal is described by two
III. PRELIMINARIES

3.1 Preliminaries about decentralized control and the RGA interaction measure

Basically, a decentralized control in multivariable (MIMO) systems is a controller \( G_i \) with diagonal transfer matrix \([1], i.e.\]

\[ G_i(s) = \text{diag} \{ g_{ii}(s), i = 1, \ldots, k \}; \]  

\( k \) : number of loops

The advantage of decentralized control, see Fig. 2, is that centralised controller can be substituted by local controllers (in this case one for each pool). Then, it is not necessary to transmit data to/from a central unit to determine control actions. In general, each local controller is designed as if the matrix function of the MIMO system is diagonal, i.e. as if the system was a set of monovariable systems. In this situation, if the effects of the neglected transfer functions of the transfer matrix are considerable, the designed decentralized control can be a disaster. To anticipate this situation, several loop interaction measures are reported in literature. Among the existing techniques, the Relative Gain Array (RGA) \([2]\) has been extensively used as a measure of dynamic interaction in invertible square systems as in electrical or chemical systems. In electric power system, it is possible to select the input and output (I/O) variables of the system; this problem is known as the variable-paring problem \([3]\). Using the RGA, it is possible to evaluate different variable pairing and select those with lowest RGA number \([1]\), i.e. select the I/O variables providing lowest loop-interaction.

For a system \( G(s) \), the relative gain between the input \( u_i \) and the output \( y_j \) is defined as \([2]\):

\[ \text{RGA}_{ij}(G(0)) = \left| \frac{\partial y_j}{\partial u_i} \right| \left| \frac{\partial y_j}{\partial u_j} \right|_{u_i=0, s=0}^{-1} \]

where \( \hat{g}_{ij}(0) \) is the inverse of the \((i, j)\)th element of the matrix \( G^{-1}(s) \), the inverse of \( G(s) \). Note that \( \hat{g}_{ij}(0) \):

\[ \frac{\partial y_j}{\partial u_i} \bigg|_{u_i=0, s=0} = \hat{g}_{ij}(0) \]

is the steady-state gain between \( u_i \) and \( y_j \) when only the control \( u_i \) is applied to the system, and \( \hat{g}_{ij}(0) = \frac{\partial y_j}{\partial u_i} \bigg|_{u_i=0, s=0} \) is the steady-state gain between \( u_i \) and \( y_j \) when feedback control is applied, such that in the steady-state all \( y_l \) \((l = 1, \ldots, k; l \neq i)\) are held at their nominal value \(i.e.\) there is not bias. From the previous definition, it follows that the matrix of relative gains can be calculated as

\[ \text{RGA} \{ G(0) \} = G(0) \odot [G^{-1}(0)]^T \]

where \( \odot \) denotes the element-by-element product of the

![Fig. 1. Irrigation canal prototype scheme.](image)

![Fig. 2. Decentralized control scheme.](image)
two matrices.

In fact, the RGA, coefficient provide a measure of how the stationary open-loop gain \( g_{ii} \) is changed due to the closing of others loops, which in turn is reflected in \( \hat{g}_{ii} \). In a fully decoupled system, with diagonal transfer matrix, it is easy to verify that \( \text{RGA}_{ii} = 1 \) and \( \text{RGA}_{jj} = 0 \), thus the RGA matrix is an identity matrix. If the system \( G(s) \) is triangular, the RGA is also an identity matrix, as is showed in [1].

In our irrigation canal problem, the variable-pairing is given (inputs are control gate positions and the outputs are the downstream levels). For this pairing, the RGA information is used to check the decentralized controller feasibility. The following results are useful for this aim ([1], chap. 10):

a) To avoid instability caused by interactions in the crossover region, the RGA-Matrix in this frequency range must be close to identity
b) To avoid instability caused by interactions at low frequencies the RGA-matrix must not have negative steady-state RGA elements.

In our case, it will see later that the linear model approaching the water dynamics is given by a triangular transfer matrix, thus from our previous discussion, RGA matrix is an identity one and the design of a decentralised control is feasible.

RGA measure has other interesting properties, but for sake of space, we have only cited properties required in this investigation. The interested reader can be referred to [1,2].

### 3.2 Preliminaries of LQG control

Let a minimal state representation of a linear plant

\[
\dot{x}(t) = Ax(t) + Bu(t) + v(t)
\]

\[
y(t) = Cx(t) + w(t)
\]

where \( x \) is the state, \( u \) the input, \( y \) the output, \( v \) and \( w \) are noises with spectrums \( Q \) and \( R \) respectively and \( A, B, C \) are matrices of appropriate dimension. Under habitual assumptions, the LQG signal \( u \) that minimizes [17]

\[
J = E \{ x^T(t) Q_x x(t) + u^T(t) R_u u(t) \}
\]

it is given by:

\[
u(t) = -K \hat{x} (t)
\]

where \( Q_x, R_u \) are LQ weighting matrices, \( K \) is the LQ gain [17] and \( \hat{x} \) is the Kalman estimated [17]. The Kalman estimated state is obtained from a Kalman filter [17], which is given by

\[
\dot{\hat{x}} (t) = A\hat{x} (t) + Bu(t) + L(C\hat{x}(t) - y(t))
\]

where \( L \) is the Kalman gain, and \( A, B, C \) are the matrices of the system. This filter can be seen as a copy of the system containing a correction term.

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 [17].

### IV. LINEAR MODEL

The procedure to obtain a linear model, for a given operating point, involves the identification of a transfer matrix, to approximate the input-output dynamics observed. For this experience, the opening deviations, from the operating point (see Table 1), of the gates located at the downstream end of the pools are the input variables. They are denoted by: \( u_j \) (\( j = 1, 2, 3 \)), where \( j \) denote the i-pool. The level variations at the downstream end of the pools, from the operating point, are the output variables. They are denoted by \( y_i \) (\( i = 1, 2, 3 \)), where \( i \) denote the i-pool.

For identification, the variation in the water level \( y_i (i = 1, 2, 3) \) is registered when it is applied a position step in each gate \( u_j (j = 1, 2, 3) \). The downstream level evolution obtained are presented in Fig. 3 (note that level responses are normalized with respect to its operating point value). In this figure, it is observed that downstream level responses are very similar to those of linear systems, then the input-output system dynamics can be described by a model that can be expressed in the following form:

\[
y(s) = G(s) u(s)
\]

where

\[
y(s) = \begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} \quad ; \quad G(s) = \begin{bmatrix} g_{11} \quad g_{12} \quad g_{13} \\ g_{21} \quad g_{22} \quad g_{23} \\ g_{31} \quad g_{32} \quad g_{33} \end{bmatrix}
\]

\[
u(s) = \begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix}
\]

and \( g_{ij} \) represents the transfer from \( u_i \) to \( y_j \).

Each \( g_{ij} \) is estimated using a standard graphical identification procedure [18]: First, from the level responses \( y_i \) to a step in gate opening \( u_i \) (see Fig. 3), it is observed that the canal responses can be reproduced by first order systems, with or without time delay. Second, from each graphic of the level response \( y_i \), the time constant, the steady gain, and time delay if presented are determined. In our prototype we have small delays due to the selected inputs and outputs and physical dimensions. These delays are neglected except

<table>
<thead>
<tr>
<th>Inflow</th>
<th>Gate openings</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>80l/s</td>
<td>20cm</td>
<td>0.7071cm</td>
<td>0.635cm</td>
<td>0.535cm</td>
</tr>
</tbody>
</table>
in transfer $g_{13}$, where a delay $d = 10s$ is presented. This delay is associated to the time required for a perturbation introduced on gate 3 attain the level of first pool. To hand this delay, we use the approach: $e^{-sd} \approx \frac{1}{1 + sd}$ (this is why transfer $g_{13}$ is a second order function as it will see later).

Finally, a performance index, like a mean square error criteria, is used to measure the deviation between the canal level response $y_i$ and the output response of the identified transfer $g_p$.

The resulting transfer function matrix for the canal with the selected inputs and outputs is

$$G(s) = \begin{bmatrix}
0.8475 & 0.6225 & 4.2225 \\
\frac{42s + 1}{162s + 1} & \frac{3900s^2 + 400s + 1}{366s + 1} \\
0 & 0.7 & 4.65 \\
0 & \frac{138s + 1}{366s + 1} & 5.125 \\
0 & 0 & \frac{330s + 1}{330s + 1}
\end{bmatrix} \quad (1)$$

To verify the model accuracy, the canal outputs are compared with those obtained from the linear model (1). This comparison is also shown in Fig. 3, where it can be seen that the model responses indeed follows the measured ones.

In this work, it is designed a decentralized control, i.e. a local controller is designed for each pool. To do that, from model (1), we will use only the $g_{ii}$, ($i = 1, 2, 3$) to design each local controller, i.e.

$$g_1(s) = g_{11} = \frac{0.8475}{42s + 1} ; \quad g_2(s) = g_{22} = \frac{0.7}{138s + 1} ; \quad g_3(s) = g_{33} = \frac{5.125}{330s + 1} \quad (2)$$

V. DECENTRALIZED CONTROL SYNTHESIS

The main goal of the decentralized controller used here is to keep constant the downstream levels at the end of the pools, ($y_i$ , $i = 1, 2, 3$) in spite of inflow disturbances and loop-interaction effects.

The first design steep is to verify the controller feasibility using RGA measure. As it can be seen in Eq. (1), the canal transfer matrix is a triangular one. Thus from our previous discussion in section 3, the RGA matrix is the identity matrix and then small interaction will be present. Since there are not negative entries in RGA matrix, stability of decentralized control can be expected, for operating condition close to operating point. Therefore, the design of a decentralized control is feasible.
The second step, is to design independently a controller for each pool. The small interaction among pools will be modeled as if they are the effects caused by external perturbations, as we will see later. The controller chosen for this experience is a LQG.

As the analysis techniques employed here are linear, the next step is to evaluate the performance of designed decentralized controller in simulation in many realistic conditions and if performance is acceptable, then the controller is implemented in real-time.

5.1 Disturbance model and augmented model

In order to compensate the effect of inflow variations and interaction effects (both effects, can be seen as a resultant disturbance), a disturbance model was determined. In this work disturbances are modeled as step variations affecting the outputs of the system. Then, the disturbance model for each pool (i) is proposed as:

\[ g_{pi} = \frac{1}{s}; \quad i = 1, 2, 3 \]  

(3)

To reject the disturbances, the Internal Model Principle [19] establishes that the open loop transfer function must contain the disturbance internal model. To satisfy this condition, we design each local controller \( g_i \) (i = 1, 2, 3) using the augmented linear model of each pool, i.e. the model resulting from a serial connection between the identified linear model \( g \) in (2) and the internal model of the disturbances \( g_{pi} \) in (3):

\[ g_{ai}(s) = \frac{0.8475}{s(42s + 1)} ; \quad g_{a2}(s) = \frac{0.7}{s(138s + 1)} ; \quad g_{a3}(s) = \frac{5.125}{s(330s + 1)} \]  

(4)

The state space realization used for the design of each local LQG controller is the realization of the augmented local models \( g_{ai} \) (i = 1, 2, 3) in (4). They are defined by triplet \((A_i, B_i, C_i)\), i = 1, 2, 3 where

\[
\begin{align*}
A_1 &= \begin{bmatrix} -0.0238 & 0 \\ 0.2500 & 0 \end{bmatrix} ; \quad B_1 = \begin{bmatrix} 0.2500 \\ 0 \end{bmatrix} ; \quad C_1 = [0 \ 0.3229] \\
A_2 &= \begin{bmatrix} -0.0072 & 0 \\ 0.2500 & 0 \end{bmatrix} ; \quad B_2 = \begin{bmatrix} 0.1250 \\ 0 \end{bmatrix} ; \quad C_2 = [0 \ 0.1623] \\
A_3 &= \begin{bmatrix} -0.0030 & 0 \\ 0.2500 & 0 \end{bmatrix} ; \quad B_3 = \begin{bmatrix} 0.2500 \\ 0 \end{bmatrix} ; \quad C_3 = [0 \ 0.2485]
\end{align*}
\]  

(5)

5.2 Specifications

The closed-loop canal must satisfy the following specifications:

- Level variations must be less than 10% with respect to the level of the operating point.
- The gate-opening rate should not exceed 2cm/s.
- Gate opening must respect the following canal limits: 0cm to 80cm.

5.3 LQG design

For each pool \( i \) (i = 1, 2, 3) a local LQG controller was designed by using the realization \((A_i, B_i, C_i)\) of \( g_{ai} \) given in (5). In order to satisfy the specifications the LQG synthesis matrices were proposed using the cheap control asymptotique property of the LQ and the Kalman Filter [17]. Basically, the cheap control property is obtained when relation between synthesis matrices satisfies ||R||/||Q|| → ∞, i.e. the control is more penalized that the state. This fact gives smooth control and close-loop dynamics near to the open-loop dynamics, in stable systems. Due to the smooth control, non-modeled dynamics are not excited, then it can be expected a certain robustness. In our case, we use values of the weight matrices, such that the relations ||R||/||Q|| and ||R||/||Q|| are larger enough. Furthermore, to assure good estimates, dynamics of Kalman Filter are chosen faster than the control dynamics by observing that ||R||/||Q|| > ||R||/||Q||.

LQ synthesis matrices: The state weighting matrices are \( Q_{ai} = C_i^T C_i \); \( Q_{a2} = C_2^T C_2 \); \( Q_{a3} = C_3^T C_3 \) and the control weighting matrices are \( R_{a1} = 8000 \); \( R_{a2} = 5000 \); \( R_{a3} = 3000 \).

Kalman Filter synthesis matrices: The state noise spectrum matrices are \( Q_{ai} = 40 \ I_2 \); \( Q_{a2} = 30 \ I_2 \); \( Q_{a3} = 10 \ I_2 \) and is an identity matrix of 2 × 2 and the output noise spectrum matrices are \( R_{a1} = 150 \); \( R_{a2} = 100 \); \( R_{a3} = 80 \).

Note, that the spectrums \( Q_{ai} \) and \( R_{ai} \) in this paper, as in other works, are considered synthesis matrices whose purpose is to get appropriate dynamics of the filters. Thus, these values are not statistical values of real noise.

Having the synthesis matrices, the values of \( K \) and \( L \) were calculated using \texttt{lqr} instruction of the MATLAB Control Toolbox. The values of the Kalman gain matrices \( L_i \) and the LQ controller gain \( K_i \) composing the LQG controller can be founded in [20].

Previous to real-time implementation, some studies in simulation were carried on to verify stability and performance. To this propose, we used the software Simulation of Irrigation Canal (SIC) developed by the CEMAGREF in France, which use a Preissman scheme to simulate the Saint-Venant equations. As the closed-loop simulation results were satisfactory, the real time implementation was done.

VI. REAL-TIME RESULTS

In the real-time implementation, Lookout software is used to get and deliver information from/to the process. The sampling time was fixed to 2 seconds. The operating point conditions are showed in Table 1. For this experience,
the inflow variations showed in Fig. 4 were introduced to the canal.

Figure 5 shows the close-loop performances obtained with the designed decentralized control: downstream level responses and the control gate openings. As it can be seen in this figure, the decentralized control adequately regulates the levels; the gate openings do not exceed their physical limits and the opening-rate remains below the specification. Tables 2 and 3 summarize the principal characteristics of the canal closed loop responses to the inflow variation presented in Fig. 4. From Tables 2 and 3, we can see that when the inflow changes from 80 l/s (set point) to 66 l/s (Table 2), the level 1 drops from 70.71 cm to 68.5 cm, this change represents an overshoot peak of 3% respect to set point of level 1, perturbation is rejected in 250 s; the level 2 drops from 63.5 cm to 61.56 cm, this change represents an overshoot peak of 3% respect to set point of level 2, perturbation is rejected in 180 s; the level 3 drops from 53.5 cm to 51.68 cm, this change represents an overshoot peak of 3.3% respect to set point of level 3, perturbation is rejected in 190 s; \( u_1 \) pass from 20 cm (set point) to 16.6 cm (Table 3), with a position variation \( \Delta u_1 \) of 0.01 m/s; \( u_2 \) pass from 20 cm to 15.98 cm, with a position variation \( \Delta u_2 \) of 0.01 m/s, and \( u_3 \) pass from 20 cm to 15.00 cm, with a position variation \( \Delta u_3 \) of 0.01 m/s. In the same way the lector can see that for a flow change of 24 l, the maximum level overshoot was of 9.4% and \( \Delta u_i \) satisfies that \( \Delta u_i < 2 \text{ cm/s} \) in specifications.

For the sake of comparison, following [13], a centralized LQG control was designed using the model resulting from a serial connection between the full linear model given in (1) and the following disturbance internal model:

\[
G_{pi} = \frac{1}{s} I_1. \quad \text{For this model, the state space representation has dimension 10. The LQG synthesis matrices were also selected to obtain a cheap control:}
\]

**LQ synthesis matrix:** The state weighting matrix is \( Q_c = I_{10} * 0.1 \), where \( I_{10} \) is an identity matrix of dimension 10 and the control weighting matrix is \( R_c = I_3 * 100 \).

**Kalman filter synthesis matrix:** The state noise spectrum matrix is \( Q_f = I_{10} * 0.0001 \) and the output noise spectrum matrix is \( R_f = I_3 * 10 \).

The close-loop performances obtained from this centralized LQG, are showed in Fig. 6. As it can be seen in this figure, these results are very similar to those obtained with the decentralized controller. It is obvious that the performance of centralized control is a little better than that obtained for decentralized control, but decentralized control is more attractive for field canal applications than centralized control as is explained in [12].

**VII. CONCLUSIONS**

A decentralized LQG controller has been designed to
Table 2. Level response characteristics.

<table>
<thead>
<tr>
<th>$Q$ (l/s)</th>
<th>$\Delta Q$ (l/s)</th>
<th>Level and Overshoot peak (cm)</th>
<th>Settling time (s)</th>
<th>$Q$ (l/s)</th>
<th>$\Delta Q$ (l/s)</th>
<th>Level and Overshoot peak (cm)</th>
<th>Settling time (s)</th>
<th>$Q$ (l/s)</th>
<th>$\Delta Q$ (l/s)</th>
<th>Level and Overshoot peak (cm)</th>
<th>Settling time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>0</td>
<td>70.71%</td>
<td>63.5</td>
<td>3.048</td>
<td>63.0</td>
<td>53.5</td>
<td>3.3905</td>
<td>190</td>
<td>1</td>
<td>61.6861</td>
<td>3.3905</td>
</tr>
<tr>
<td>66</td>
<td>−14</td>
<td>68.5825</td>
<td>61.5666</td>
<td>3.0447</td>
<td>180</td>
<td>56.9126</td>
<td>6.3787</td>
<td>180</td>
<td>1</td>
<td>52.2275</td>
<td>2.3785</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>75.9138</td>
<td>66.2635</td>
<td>4.3520</td>
<td>320</td>
<td>56.1357</td>
<td>4.9265</td>
<td>216</td>
<td>1</td>
<td>51.1681</td>
<td>4.3587</td>
</tr>
<tr>
<td>80</td>
<td>−20</td>
<td>67.6305</td>
<td>61.0097</td>
<td>3.9217</td>
<td>260</td>
<td>51.1681</td>
<td>4.3587</td>
<td>210</td>
<td>1</td>
<td>52.2275</td>
<td>2.3785</td>
</tr>
</tbody>
</table>

Table 3. Opening gate response characteristics.

<table>
<thead>
<tr>
<th>gate 1</th>
<th>gate 2</th>
<th>gate 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_1$ (cm)</td>
<td>$\Delta n_1$</td>
<td>$n_2$ (cm)</td>
</tr>
<tr>
<td>80 l/s</td>
<td>20.00</td>
<td>20.00</td>
</tr>
<tr>
<td>66 l/s</td>
<td>16.6080</td>
<td>0.01 m/s</td>
</tr>
<tr>
<td>90 l/s</td>
<td>23.0741</td>
<td>0.01 m/s</td>
</tr>
<tr>
<td>80 l/s</td>
<td>19.7862</td>
<td>0.01 m/s</td>
</tr>
<tr>
<td>100 l/s</td>
<td>25.1806</td>
<td>0.01 m/s</td>
</tr>
<tr>
<td>80 l/s</td>
<td>19.7285</td>
<td>0.01 m/s</td>
</tr>
</tbody>
</table>

Fig 6. Centralized close-loop performances: Levels $y_i$ and control actions $u_i$.

maintain constant the downstream levels to target values, despite flow perturbations and pool-interaction effects, in a four-pool irrigation canal prototype. An upstream control method was used. Information provided by the RGA interaction measure was used to verify the feasibility to design a decentralized control. The closed-loop real-time performances (level regulation, control actions, etc.) obtained with the present decentralized LQG control have been satisfactory and these are similar to those issue from a centralized LQG. This experience shows that it is possible to design an efficient decentralized upstream control for real irrigation.
canals, when previous interaction analysis, perturbations effects, and adequate synthesis parameters are considered in controller synthesis. Future work is devoted to design and implement a decentralized controller to a real open canal in an irrigation district in Mexico. Currently, we are working on the integrating a remote monitoring system for the Colorado River Irrigation district. All the components of the control system will be tested and a decentralized controller will be installed for the operation of the main canal of this irrigation district.

REFERENCES

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