Decentralized Predictive Controller for Delivery Canals

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ABSTRACT

This paper presents the design of a predictive controller for decentralized control of delivery canal. The overall canal is decomposed into single subsystems (pools) separated by control structure (gate). The subsystems are inter-dependent because flow through the structures depends on both upstream and downstream water level. In this paper, predictive control theory is used to formulate a set of local controllers for the automatic operation of gates of each pool. The control scheme presented here takes into account explicitly the interactions among subsystems. The objective of each controller is to maintain the downstream end water level of each pool at constant target value under external perturbation. To evaluate the controller performance in realistic conditions, it is tested on an open-canal flow nonlinear model. The case study considered deals with a 4 canal reaches.

Keywords: Predictive control, Decentralized control, Canals control.

1. INTRODUCTION

The need for automatic control of irrigation canal operation is becoming increasingly obvious due to the less than desirable performance of manually controlled large-scale irrigation systems. In addition, the existing rigid schedules do not allow the farmers to tap the potential of modern irrigation technology at the farm level. Delivery schedules that are more flexible would allow the farmers the needed flexibility to achieve higher efficiencies at the farm level. In fact, timely delivery of the required quantity of water is necessary for improved agricultural production and water use efficiency. This implies flexible user-oriented water deliveries. Such deliveries are not feasible with manually-operated delivery systems.

Flow through a delivery canal can be viewed as a dynamic physical « process ». The economic need to control this process has resulted in the development of numerous automatic control methods with widely varying conceptual and practical approaches. Persistent problems encountered in most canal control methods are the result of inherent characteristics of the canal flow process which do not lend themselves easily to conventional control techniques. Delay times in transport and a highly nonlinear, multivariable process are the canal flow characteristics which pose the greatest challenge for effective control.

A variety of methods have been proposed in the literature for approaching this control problem. Recently, Predictive Control strategy was considered by several authors. [7], [8], [9], and [1] used a monovariable input/output model version of predictive controllers in order to control a single reach of canal. [6] and [5] derived a centralized multivariable controller for canal automation based on predictive control techniques. In this case, the whole canal is considered as a multivariable system, and all the measured outputs, such as water levels at selected location, are directed to a central unit which simultaneously manipulates all the control gates. This kind of approach takes into account the coupling among subsystems but, because of the number of variable involved, is usually more complicated from a design and implementation point of view.

An alternative approach consist in seeing the canal as made of a number of subsystem and to deal with the problem of controlling each one of them in a monovariable setting. Following this approach, [2] proposed a decentralized predictive controller, but did not explicitly consider interactions among subsystems.

In this paper, a decentralized predictive controller for delivery canal is presented. The overall canal is decomposed into single subsystems, each of one with an upstream control gate to be manipulated (control variable) in order to maintain the downstream water level (controlled variable) as close as possible to a target values, under external perturbations. In fact, the subsystems are inter-dependent. A gate movement affects both upstream and downstream subsystems water level. In the control structure presented in the paper, interactions among subsystems are explicitly considered in the design.
To evaluate the controller performance in realistic conditions, it is tested on an open-canal flow nonlinear model. The case study considered deals with a 4 canal reaches.

2. THE CONTROL PROBLEM

The system to be controlled is a open-canal used for water distribution and composed of the following elements (Figure 1) : an upstream reservoir, a serie of reach connected by control gates, and a sequence of pumping station located at the end of each reach.

The control system aims to match the water level at the downstream end of each reach with a target value. To reach this aim, the control system has to adjust the gate opening of each reach. In the proposed approach the overall canal is viewed as composed by subsystems. Subsystem i has u_i (gate opening) as control variable, Q_{pi} (off-take discharge) as external perturbation input variable, and yi (downstream water level) as controlled variable, and u_{i+1} (reach's *i+1* gate opening) as interconnection input variable.

The predictive control method used for the control design is able to handle step-wise perturbation rejection [2],[3], so that it is expected than each local controller will maintain the reach water level at the target values without permanent deviations.

3. PREDICTIVE LOCAL CONTROL

The objective of the predictive control is to drive the future process outputs 'close' to their reference profile over a finite time horizon, bearing in mind the control activity required to do so. To determine the future values of the controlled variable, a process control model is used. Different models can be used. Here, transfer functions are used as control model. In this section the controller for each subsystem *i* is formulated in a discrete time setting. Formulation is not derived completely, more details being found in [10].

The process model
For each subsystem the dynamic relationship between inputs and output can be described by the following discrete-time model :

$$A(q^{-1})\, y_i(k) = B(q^{-1})\, u_i(k-1) + C(q^{-1})\, Qp_i(k-1) + D(q^{-1})\, u_{i+1}(k-1) + \frac{1}{\Delta}\xi(k) \quad (1)$$

Where $y_i(k)$, $u_i(k)$, $Qp_i(k)$, and $u_{i+1}(k)$, are respectively reach's *i* downstream water level, gate opening , off-take discharge, and reach's *i+1* gate opening. $\xi(k)$ is a sequence of random variables, and Δ is the difference operator. $\Delta = 1-q^{-1}$. $A(q^{-1})$, $B(q^{-1})$, $C(q^{-1})$, and $D(q^{-1})$ are polynomials in q^{-1} of degree n_a, n_b, n_c, and n_d respectively.

$$A(q^{-1}) = 1 + a_2 q^{-1} + \ldots + a_{na+1} q^{-na}$$

$$B(q^{-1}) = b_1 + b_2 q^{-1} + \ldots + b_{nb+1} q^{-nb}$$

$$C(q^{-1}) = c_1 + c_2 q^{-1} + \ldots + c_{nc+1} q^{-nc}$$

$$D(q^{-1}) = d_1 + d_2 q^{-1} + \ldots + d_{nd+1} q^{-nd}$$

The output predictor
The prediction made at time k for the output at the future time k+j is given by :

$$\hat{y}_i(k+j) = G_j(q^{-1})\, \Delta u_i(k+j-1) + L_j(q^{-1}) \Delta Qp_i(k+j-1) + H_j(q^{-1}) \Delta u_{i+1}(k+j-1) + p_i(k+j) \quad (2)$$

with

$$p_i(k+j) = \Gamma_j(q^{-1})\, \Delta u_i(k-1) + K_j(q^{-1})\, \Delta Qp_i(k-1) + S_j(q^{-1})\, \Delta u_{i+1}(k-1) + F_j(q^{-1})\, y_i(k)$$

Where $\Gamma_j(q^{-1})$, $L_j(q^{-1})$, $H_j(q^{-1})$, $K_j(q^{-1})$, $S_j(q^{-1})$ and $F_j(q^{-1})$ are polynomials in q^{-1}, obtained from the solution of four polynomial (diophantine) equations involved in the prediction of the future values of the controlled variable.

Collecting the j-step predictor (2) for j varying from a minimum cost horizon Ni to a prediction horizon Np in a matrix notation yields :

$$\hat{Y}_i = \mathbf{G}U_i + \mathbf{L}\overline{Q}p_i + \mathbf{H}U_{i+1} + P_i \quad (3)$$

with

$$\hat{Y}_i = \left[\hat{y}_i(k+Ni) \ldots \hat{y}_i(k+Np)\right]^T$$

$$P_i = \left[p_i(k+Ni) \ldots p_i(k+Np)\right]^T$$

$$U_i = \left[\Delta u_i(k) \ldots \Delta u_i(k+Nu-1)\right]^T$$

$$U_{i+1} = \left[\Delta u_{i+1}(k) \ldots \Delta u_{i+1}(k+Np-1)\right]^T$$

$$\overline{Q}p_i = \left[\Delta Qp_i(k) \ldots \Delta Qp_i(k+Np-1)\right]^T$$

and **G**, **L**, and **H** are matrices of dimension ((Np-Ni+1),Nu) ; ((Np-Ni+1), Np) and ((Np-Ni+1), Np) respectively.

The predictive control law
The GPC controller optimizes the predicted performance of the controlled system according to the following multi-step criterion function :

$$J = \sum_{j=Ni}^{Np} \left(\hat{y}_i(k+j) - y_i^*(k+j)\right)^2 + \lambda \sum_{j=1}^{Nu} \left(\Delta u_i(k+j-1)\right)^2 \quad (4)$$

Where $y_i^*(k+j)$ = reference sequence ; Ni = minimum prediction horizon ; Np = maximum prediction horizon ;. Nu = control horizon (Nu<Np) that defines the control scenario, $\Delta u(k+j)=0$ for j>= Nu ; and λ = control weighting factor.

The optimal control law is derived by the minimization of criterion function (4) with respect to the controller output sequence over the control horizon Nu. The solution for J_{min} given the optimal control is then :

$$U_i^* = \left(\mathbf{G}^T\mathbf{G} + \lambda .\mathbf{I}\right)^{-1} \mathbf{G}^T \left[Y_i^* - \mathbf{L}\,\overline{Q}p_i - \mathbf{H}U_{i+1} - P_i\right] \quad (5)$$

According to the receding horizon strategy, only the first element of U_i^* will be used to perform the real process input $u_i(k)$. Note that the first element of U_i^* is $\Delta u_i(k)$ so that the current control $u_i(k)$ is given by :

$$u_i(k) = u_i(k\text{-}1) + k^T \left[Y_i^* \text{-} \mathbf{L}\, \overline{Q}p_i \text{-} \mathbf{H}U_{i+1} \text{-} P_i \right] \qquad (6)$$

where k^T is the first row of $\left(\mathbf{G}^T\mathbf{G} + \lambda.\mathbf{I}\right)^{-1}\mathbf{G}^T$

Notice that the control law (6) incorporate the terms $\mathbf{L}\overline{Q}p_i$ and $\mathbf{H}U_{i+1}$. This additional new feature of including $\overline{Q}p_i$ and U_{i+1} in this fashion, yields this control law, to involve feedforward properties and to takes into account the coupling among subsystems *i* and *i+1*. The control structure is depicted in figure 2.

4. SIMULATION RESULTS

Test case

The case study we have selected is composed of 4 canal reaches, as we can see in figure 3. The system is fed by a constant water level reservoir at its head. Its downstream end is closed with a passive gate. There is an orifice offtake at the downstream end of each canal reach, the bottom slope of the canal = 2.64 10^{-4} , Manning's n = 0.02, the side slope = 1.5, all the reaches are equal, with a length of 3 000 m.

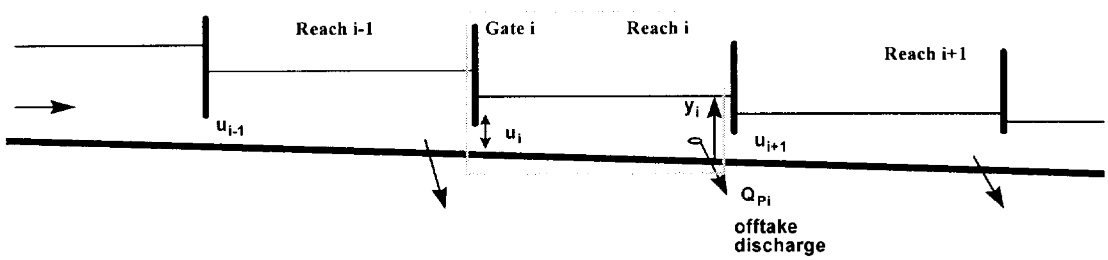

Figure 1 : Schematic of an irrigation canal

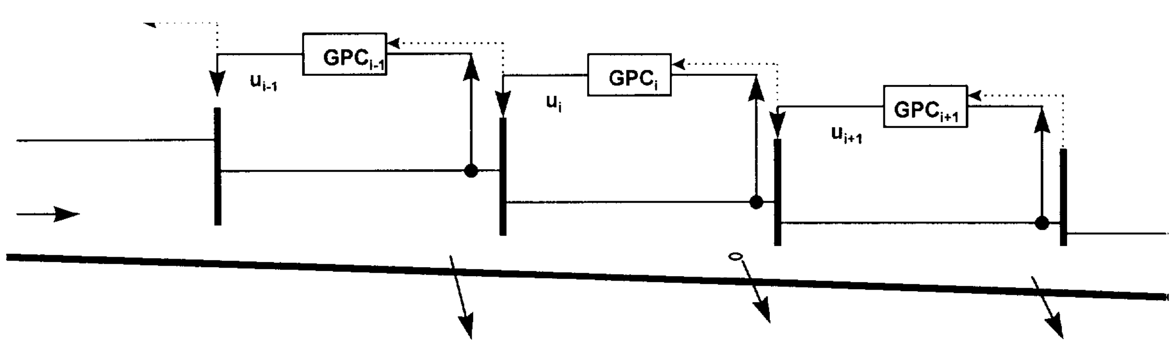

Figure 2 : Control struture

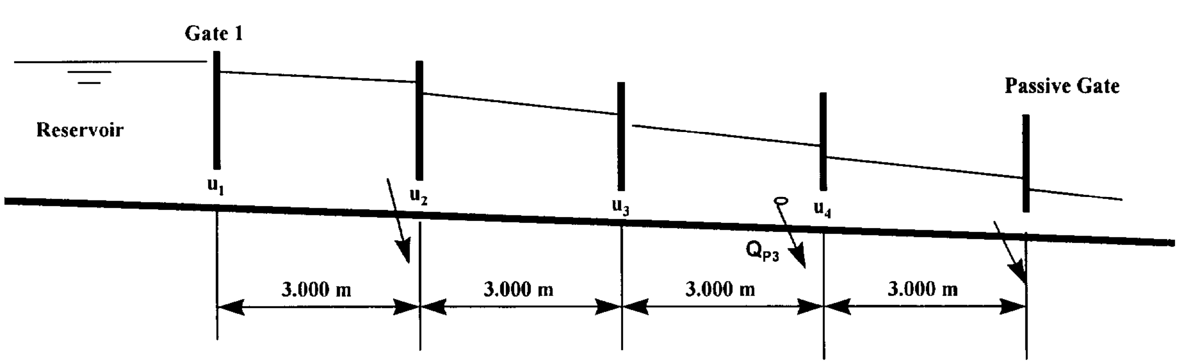

Figure 3 : Sketch of the test canal

The tests are performed using the unsteady flow simulation model SIC (Simulation of Irrigation Canals) developed by CEMAGREF, [3].
The input /output linear model of a subsystem is carried out with the commercially available package Matlab & Simulink . The following model is identified from the nonlinear simulation model , with a sampling interval of 10 minutes :

$$A(q^{-1})\, y_i(k) = B(q^{-1})\, u_i(k-1) + C(q^{-1})\, Qp_i(k-1) + D(q^{-1})\, u_{i+1}(k-1)$$

with

$$A(q^{-1}) = 1 - 1.1438q^{-1} + 0.2279q^{-2}$$

$$B(q^{-1}) = 0.0071 + 0.0330q^{-1}$$

$$C(q^{-1}) = 0.0874 - 0.0608q^{-1}$$

$$D(q^{-1}) = -0.2200 + 0.1844q^{-1}$$

Simulation results

The design parameters of the predictive control are Ni, Np, Nu, and λ. Guidelines of how to choose these design parameters have been given in [4].

Simulation results presented are performed with the following design parameters :

	Ni	Np	Nu	λ
pool 1	1	2	1	0.09
pool 2	1	2	1	0.80
pool 3	1	5	1	1000.0
pool 4	1	5	1	1000.0

At the initial steady state, flow rate through each offtake is 0.0 m^3/s, the discharge through each control gate is 2.5 m^3/s, and the opening of all control gate is 0.44 m.
There is a scheduled change in off-take discharge at 1 hour, and an unscheduled change in off-take discharge at 15 hours. During the scheduled change, flow rate through off-take 1 and 2 is increased by 0.2 m^3/s. During the unscheduled change, flow rate through off-take 2 is decreased by 0.1 m^3/s.

Figure 4 depicts the response of the system : (a) opening of each control gate ; (b) discharge through each control gate ; (c) discharge through each lateral offtake ; and (d) change of water level at the downstream end of each pool. A stable control law is obtained.

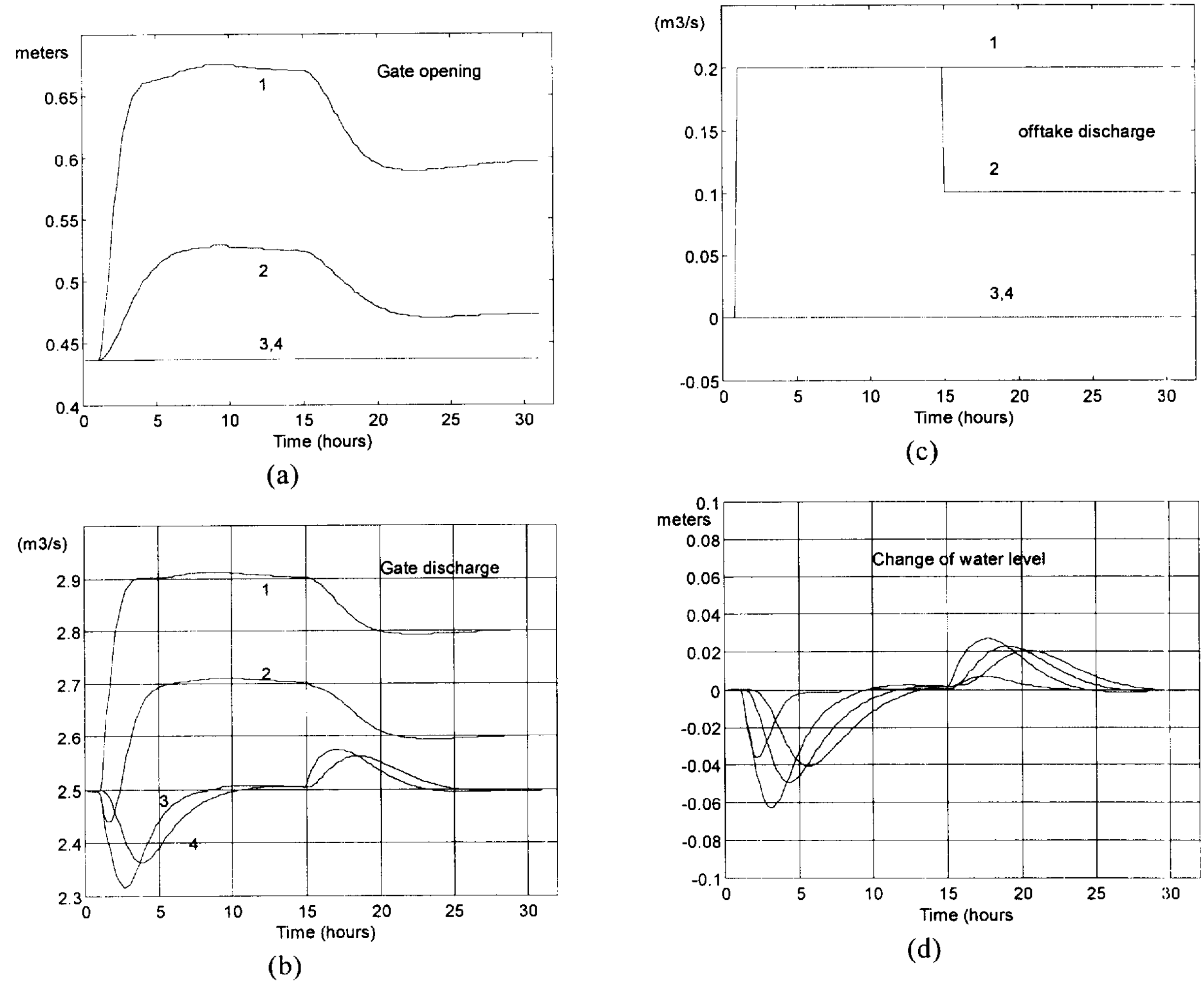

Figure 4 : Response of the system

5. CONCLUSION

A decentralized control scheme has been proposed for irrigation canals. A local controller based on predictive control theory , has been designed for manipulating each gate with the objective of ensuring the setpoint water level at the downstream end of each pool under external perturbation. Each control uses the pool's downstream end water level as feedback information. Interactions among controllers has been explicitly considered in this work. The controller has been validated, by simulation on nonlinear model and prove to be efficient.

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