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Distributed Model Predictive Control Techniques Applied to an Irrigation Canal

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Abstract— **This paper presents the application of a Distributed Model Predictive Controller (DMPC) to the control of an accurate model of an irrigation canal in Spain. The canal is modelled using the Saint-Venant equations and its model is implemented by using the well known modelling software for irrigation canals SIC. The DMPC algorithm has been implemented in Matlab and interfaced to SIC. In the distributed control algorithms, the local controllers exchange information so that their control policies are optimal in the sense that they minimize a performance index. The results show that the proposed distributed control algorithm obtains better control performance than a more conventional decentralized control scheme without information exchange. This better performance translates directly into money and resource savings.**

I. INTRODUCTION

Water is a limited resource. In addition, nowadays there are some regions in Europe and all over the world with long periods of drought. As a consequence, the development of innovative control techniques that optimize water management is a relevant issue.

The main objective of irrigation canals is to supply water to farmers according to a specific schedule. An irrigation canal is composed of several reaches, connected by gates, and usually following a tree structure. In a typical irrigation canal the length can be hundred of kilometers, there are tens of gates and hundreds of off-take points, used by farmers to take water from the canal.

Irrigation canal management involves operating gates, pumps and valves in order to satisfy user demands and minimize costs and water losses. In addition, a set of constraints imposed by the physical system and management policies has to be considered.

Automatic control techniques have widely been used in irrigation canals, most of them based on a local control of gates using classic approaches such as PI controllers (See [1] for a detailed classification of these algorithms). These decentralized approaches provide reasonable behavior in many cases, but as the coupling effect among the different local controllers (agents) is not taken into account, sometimes they produce important loss in the control performance.

The use of a single global controller for the control of the whole system (centralized control) is an alternative to deal with this problem. Model Predictive Control (MPC) (See [2]) approaches have been widely and successfully applied in water systems. However, MPC is a technique with strong computational requirements that hinder its application to large-scale systems such as water networks in a centralized way. Moreover, the communication difficulties in a system extended in a geographical area of hundreds of kilometers make the use of a centralized real-time control system based on long distance communications not an obvious choice. Another problem to use centralized approaches is the fact that sometimes different sections of the canal can be managed by different control centers and even by different organizations.

Distributed Model Predictive Control techniques to optimize the management of water in irrigation canals provide a reasonable trade-off between complexity and performance. Basically, the idea is to provide communication among local controllers, in such a way that agents can exchange information or even negotiate and reach agreements.

There are several works that address the canal control with Predictive control techniques with decentralized ([3],[4],[5]) and centralized approaches ([6],[7],[8]). A complete state-of the art of MPC applications can be found in [9] and [10]. Finally, distributed control has been also a focus of research during the last few years ([11],[12],[13],[14],[15],[16]).

In this paper we present the modelling of a section of a real canal in the South-East of Spain and its control by using predictive controllers based on the distributed MPC algorithm presented in [17] and also on feed-forward techniques. This algorithm provides a reasonable trade-off between performance and low communication requirements needed to reach a cooperative solution. The model of the canal used to test the control structure has been developed using the SIC software (Simulation of Irrigation Canals). The SIC hydraulic model solves the complete one-dimensional Saint-Venant equations using the classical implicit Preissmann scheme.

Moreover, a pair of control scenarios are illustrated in the paper, and in each of them different control structures are tested. The performance of each control structure is illustrated by means of a performance index and an estimation of the economical costs incurred by each controller.

The rest of the paper is organized as follows: The next section presents the irrigation canal benchmark and some issues regarding the control of canals. In section III, the proposed control strategy is presented. Section IV deals with the modelling and control structures chosen for this work. Experimental results for several simulations are shown in section V. Finally the conclusions are presented in section VI.

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II. CONTROL OF IRRIGATION CANALS

In the control of irrigation canals, typically, controlled variables are water levels and flows and manipulated variables are the degree of gate opening and also flows (usually only at the head of the canal).

An important issue in the control of the canal system is the location of the controlled variable relative to the control structure (i.e, gates). Mainly, two alternatives are considered. In a downstream control strategy, control structure adjustments are based upon information measured by a sensor located downstream. Downstream control transfers the downstream canal-side offtakes demands to the upstream water supply source (or canal head works). On the other hand, in upstream control, control structure adjustments are based upon information from upstream. Upstream control transfers the upstream water supply (or inflow) downstream to points of diversion or to the end of the canal. Upstream control has to be used when the flow at the head of the canal is fixed, normally by an external organization. In any other circumstances, downstream control has demonstrated to be more efficient.

Also, measurable disturbances play an important role in the control of irrigation canals. Mainly two kind of perturbations are considered: When calculating the opening/closing of any gate at any sample period, the opening/closing of the following downstream gate could be considered as a measurable disturbance. Offtakes and inflows comprise the other kind of disturbance. An offtake is a point where water is taken for a particular purpose (for example, irrigation).The flows are usually scheduled, so their value and moment of appearance can be predicted in advance. Nevertheless, the offtake gates are manipulated directly by farmers, so an uncertainty must be considered between this prediction and real values, typically not known because there is only partial information about offtake flows, for example, an aggregate value of the flows of the offtake in a determined area. Also inflows can be considered, for example, rainfall.

Finally, the aforementioned coupled nature of irrigation canals together with the usual geographical dispersion found in the actual control hardware used leads to the consideration of distributed control schemes as a practical control solution. Thus, the overall performance of the canal control system will be greatly improved if distributed control strategies are used at least in those segments of the canal in which the coupling is so strong that a measurable disturbance management only is not sufficient.

A. *The irrigation canal of La Pedrera (Murcia, Spain)*

This work is focused on the control of a section of the ”postrasvase Tajo-Segura” in the South-East of Spain. This is a set of canals which distribute water coming from the Tajo River in the basin of the Segura River. The selected section is a Y-shape canal (see Figure 1), a main canal that splits into two canals with a gate placed at the input of each one of them. The total length of the canals is approximately 24km and there are five main gates (in red in Figure 1) and 5 off-take gates in the section selected (green arrows in Figure 1).

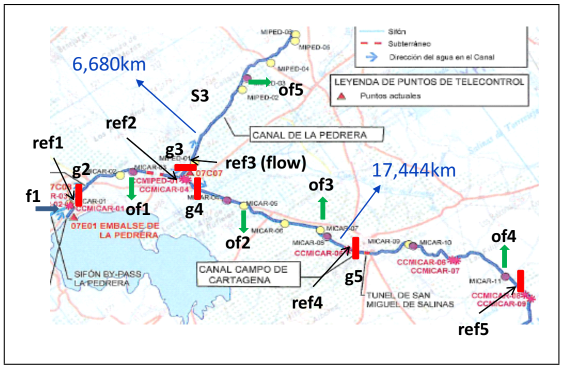

Fig. 1. Section of the Postrasvase Tajo-Segura.

The objective of this paper is to control the downstream water level at each one of the reaches in Canal de Cartagena (ref1, ref2, ref4 and ref5 in Figure 1) and the flow at the head of Canal de la Pedrera (ref3). To reach this objective, the control system will manipulate the flow at the head of the main canal (f1) and the position of the main gates (g2 to g5). The following constraints are also considered:

- Maximum and minimum levels to guarantee that offtake points are submerged.
- The flow at the head of the canal is limited.
- Maximum and minimum gates opening. Maximum gate opening is fixed by the water level.

A combination of local and distributed MPC approaches is proposed for the control of this section of the canal.

III. CONSTRAINED PREDICTIVE CONTROL OF IRRIGATION CANALS

MPC is one of the most successful techniques in the field of automatic control. The reasons of that success and the MPC basics are discussed in depth in [2], here only a brief description of the MPC structure chosen for each controller is given.

The prediction model considered here is a Controlled AutoRegressive with Integrated Moving Average (CARIMA) [2] model with an extra exogenous input used to take into account the effect of a measurable disturbance (offtake and next gate opening):

$$\begin{aligned} &A(z^{-1})y(k) = \\ &B(z^{-1})u(k-d-1) + D(z^{-1})v(k-d_v-1) + \tfrac{e(k)}{\Delta} \end{aligned} \qquad (1)$$

where $A(z^{-1})$, $B(z^{-1})$, $D(z^{-1})$ are polynomials on the backward shift operator z^{-1} obtained through identification of the dynamics of a single reach, $\Delta = 1 - z^{-1}$, $y(k) \in \Re$, $u(k) \in \Re$ and $v(k) \in \Re$ are respectively the model output, control input and measurable disturbance at sampling time k, d and d_v are dead times from the model inputs to the output, and $e(k) \in \Re$ is a random unmeasurable disturbance modelled as a white noise stochastic process.

The following constraints are considered along the prediction and control horizons:

$$\begin{array}{rclcll} \underline{u} & \leq & u(k+i|k) & \leq & \overline{u}, & i = 0, \ldots, N_u - 1 \\ \underline{\Delta u} & \leq & \Delta u(k+i|k) & \leq & \overline{\Delta u}, & i = 0, \ldots, N_u - 1 \\ \underline{y} & \leq & y(k+i|k) & \leq & \overline{y}, & i = N_1, \ldots, N_2 \end{array} \qquad (2)$$

where $u(k+i|k)$ and $\Delta u(k+i|k)$ are the control and control increments values for time $k+i$ computed at time k, and $y(k+i|k)$ is the model output for time $k+i$ predicted at time k. The performance index takes the form of a quadratic cost function of the future set point tracking errors plus a term weighting the input increments:

$$\begin{array}{rcl} J(\mathbf{u}) & = & \sum_{j=N_1}^{N_2} (y(k+j|k) - r(k+j))^2 + \\ & + & \lambda \sum_{j=0}^{N_u-1} \Delta u(k+j|k)^2 \end{array} \quad (3)$$

where $\mathbf{u} = [\Delta u(k|k), \Delta u(k+1|k), \ldots, \Delta u(k+N_u-1|k)]$, a sequence of control increment values, $r(k+j)$ is the set point for time $k+j$, $y(k+j|k)$ is the prediction of the output at $k+j$ explicitly computed using model (1) at time k and $\lambda > 0$ is the weighting factor for present and future input increments.

With all the previous elements, the optimal control sequence $\mathbf{u}^*$ produced by the MPC controller is defined as the solution of the following optimization problem:

$$\begin{array}{rll} \mathbf{u}^* = \arg & \min\limits_{\mathbf{u}} & J(\mathbf{u}) \\ & \text{s.t.} & (2) \end{array} \quad (4)$$

where $\mathbf{u}^*$ is applied using a receding horizon scheme ([2]).

The MPC strategy discussed so far involves a number of controllers that operate independently without exchanging any information. However, in an irrigation canal, control loops are heavily coupled, so a distributed control scheme seems to be appropriate. Thus, a Distributed MPC (DMPC, see [15]) is chosen here as the main control structure. The algorithm used here, which is discussed in detail in [17], involves only a pair of controllers (although it can be extended to consider any number of controllers), and it is based on cooperative game theory with only two communication cycles for each choice. Each controller has only a part of the information related to the model and the state of the overall system, although they can exchange information about their optimal control sequences. The steps of the algorithm are:

1) At sample time k Each controller $i \in [1,2]$ reads its controlled variables. Denote the optimal sequence computed in the previous sample time as $U_i^S(k)$.
2) Each controller $i \in [1,2]$ solves its local MPC problem minimizing its own cost function J_i and considering the effect of the control actions of the other controller as a measurable disturbance. It is assumed that the other controller will keep applying the optimal control sequence computed in the previous sample time (that is, $U_j^S(k)$). Denote the optimal control sequence as $U_i^*(k)$.
3) Each controller $i \in [1,2]$, assuming that it applies the optimal sequence previously obtained in step 2, computes the control sequence for neighbor j that gets the smallest value of its own cost function J_i. That is, each controller computes the neighbor input that it is more beneficial for its own performance. Denote this sequence as $U_j^w(k)$[1]. Note that each controller assumes that its neighbor behaves in an altruist way, thus it will "agree" to use $U_j^w(k)$ instead of $U_j^*(k)$.
4) Both controllers communicate the sequences computed in the previous steps. Controller 1 sends to controller 2 the sequences $U_1^*(k)$ and $U_2^w(k)$, whereas controller 2 sends to controller 1 $U_2^*(k)$ and $U_1^w(k)$. Thus, at the end of this step both controllers know all the sequences that have been computed so far.
5) Each controller i evaluates its own cost function for all the sequences it could choose. That is, controller 1 computes the set:

$$\mathbf{J_1} = \left\{ J_1(U_1^S(k)),\ J_1(U_1^*(k)),\ J_1(U_1^w(k)) \right\} \quad (5)$$

and controller 2 computes the set:

$$\mathbf{J_2} = \left\{ J_2(U_2^S(k)),\ J_2(U_2^*(k)),\ J_2(U_2^w(k)) \right\} \quad (6)$$

6) Both controllers communicate the values obtained in the previous step. That is, controller 1 sends the set $\mathbf{J_1}$ to controller 2, whereas controller 2 sends the set $\mathbf{J_2}$ to controller 1.
7) Both controllers consider the 9 possible pairs (J_1, J_2) of optimal costs in $\mathbf{J} = \mathbf{J_1} \times \mathbf{J_2}$ and pick the one that gives the minimum sum $J = J_1 + J_2$. Note that this pair has a pair of associated optimal sequences, which will be denoted as $U_1^d(k)$ and $U_2^d(k)$ respectively.
8) Each controller i apply to the controlled system the first component of $U_i^d(k)$ and the whole procedure is repeated again at the next sampling time.

IV. MODELLING AND CONTROL STRUCTURE

One of the most accepted and used model in irrigation canals simulations is the system given by the one-dimension Saint-Venant Equations. However, this system is a nonlinear partial differential equation system, which has analytical solution only in very special cases, forcing the employment of numerical methods to solve it properly. Linearizations or simplifications of the Saint-Venant equations are used for control purposes. Making use of Saint Venant equations, a reach can be modelled by two partial differential equations representing a mass balance (continuity equation) and a momentum balance (see [18] for more detail).

In order to have a realistic simulation of the irrigation canal of La Pedrera, the SIC software has been used. The SIC hydraulic model solves the complete Saint Venant equations and simulates the hydraulic behaviour of most of the irrigation canals or rivers, under steady and unsteady flow conditions.

For the task of tuning and designing a controller a simpler model than SIC is usually needed. Moreover, the control structure proposed here relies on model predictive controllers, which use a linear prediction model with the gate openings as output and gate flows or the downstream level as input. Thus a Multi Input Multi Output (MIMO) model of five inputs and five outputs has been identified using the well known Least Squares method around the operating point shown in table I. In the model, the five inputs are the flow at the head of the main canal (u1), and the position of the main gates g2 to g5 (u2 to u5 in table I). On the other hand, the five outputs that are to be controlled are water level at each one of the reaches in Canal de Cartagena (y1, y2, y4 and y5) and the flow at the head of Canal de la Pedrera (y3). The linear models for each input-output pair are first or second order models plus a transport delay caused by the distance between reaches.

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[1] Note that controller 1 computes $U_2^w(k)$ and controller 2 computes $U_1^w(k)$.

TABLE I

OPERATING POINT USED FOR PREDICTION MODEL IDENTIFICATION.

Var.	Description	Val.	Var.	Description	Val.
u1	Flow $(m^3 \cdot s^{-1})$	12	y1	Water level (m)	82.951
u2	Gate opening (m)	1	y2	Water level (m)	82.073
u3	Gate opening (m)	0.5	y3	Flow $(m^3 \cdot s^{-1})$	5.41
u4	Gate opening (m)	0.5	y4	Water level (m)	81.269
u5	Gate opening (m)	0.5	y5	Water level (m)	80.643

Once the hydraulic canal has been modelled as a MIMO plant, the following step is to design an optimal control structure. Firstly an appropriate input-output pairing must be chosen. During this research several pairings were tested, and the chosen one is detailed in table II. In this table, an input-output pair is detailed in every row and information about the involved magnitudes and the measurement points is shown. Two data are necessary to locate these points: the branch where they are situated and the kilometric distance to the end of the branch. Figure 2 gives an idea of the location of both inputs and outputs and distances between them. Some control structures will be explained below.

A totally decentralized control structure based on predictive control is proposed as a starting point. Five GPC controllers govern each aforementioned input-output pairing. GPC1 tracks a downstream water level reference by regulating the incoming water flow at the canal head gate. GPC3 monitors the downstream flow through its corresponding gate by manipulating its degree of aperture. Finally, GPC2, GPC4 and GPC5 track a water level reference using the degree of gate aperture as a manipulated variable.

An hydraulic canal is such a coupled system that every command sent to the plant in order to obtain a desirable behaviour at one of the outputs significantly affects the rest of them. This may be taken into account at every sample time when computing the following control action. Every single controller can consider control actions computed by its neighbours as a measurable disturbance. This disturbance is easily included in the control action calculation as explained in section III. Figure 3 shows how this theory is applied to this research. Each GPC will have two kinds of inputs: on the one hand the measurement of its output and the corresponding reference (red arrows), and on the other hand the measured disturbances (green arrows). Disturbances could be considered both upstream and downstream, but in this case only downstream disturbances were taken into account, in order to simplify the problem. The implementation of this feedforward compensation will be done in a sequential manner. That is, the control actions to be applied at each gate are computed sequentially, starting from the most downstream gate and proceeding upwards to the first (upstream) gate. Then, when computing the optimal aperture of a given gate, the aperture of the nearest downstream gate (which was computed in the previous step of this sequence) is considered as a measurable disturbance. This feedforward scheme is later referred in the text as a sequential feedforward. In section V results will show a significant improvement of the canal control performance by considering downstream couplings as disturbances when computing control actions.

Finally, two controllers can cooperate to obtain an optimal control sequence, by using an algorithm based on game theory. To implement this algorithm, a communication channel between the controllers (or agents) is necessary. This is a distributed control schema. Starting with the structure presented in Figure 3, the distributed control algorithm is implemented in controllers GPC1 and GPC2. A communication link is established between them and each controller takes into account the control actions performed by the other one for calculating its own control actions. The neighbour control actions will be considered as measurable disturbances.

V. RESULTS

A pair of scenarios and three control approaches have been tested in simulation. The canal benchmark has been modelled in SIC. Table I shows levels and flows at significant locations of the canal for the operation point, Three predictive approaches have been tested in the different scenarios:

- Control Schema 1: Downstream local MPC in each one of the gates
- Control Schema 2: Local MPC with sequential feedforward
- Control Schema 3: Distributed MPC in the two first gates and local MPC in the others with sequential feedforward

The sampling time has been fixed to 6 minutes. The duration of the simulation tests is four days. A comparison among

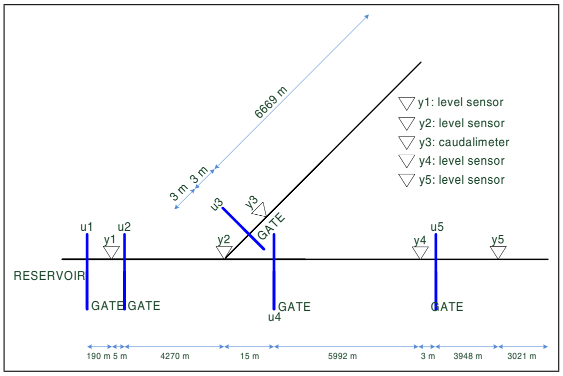

Fig. 2. Canal control: location for inputs and outputs

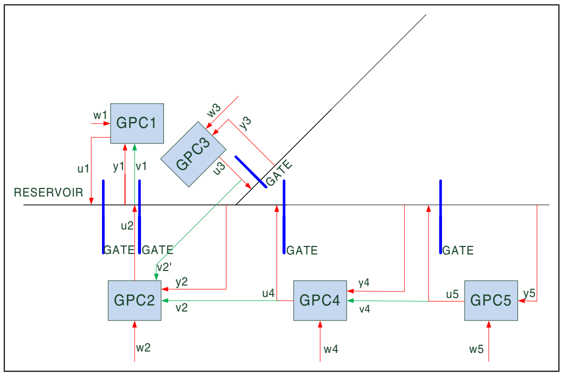

Fig. 3. Canal control structure based on decentralized GPC predictive controllers. Consideration of measurable disturbances

TABLE II

CANAL CONTROL: INPUT-OUTPUT PAIRING

Input	Description	Location	Output	Description	Location
u1	Flow $(m^3 \cdot s^{-1})$	Head Gate	y1	Water level (m)	Branch 1/ RS 4.275
u2	Gate opening (m)	Branch 1/ RS 4.27	y2	Water level (m)	Branch 1/ RS 0
u3	Gate opening (m)	Branch 1/ RS 6.672	y3	Flow $(m^3 \cdot s^{-1})$	Branch 1/ RS 6.669
u4	Gate opening (m)	Branch 2/ RS 12.964	y4	Water level (m)	Branch 2/ RS 6.972
u5	Gate opening (m)	Branch 2/ RS 6.969	y5	Water level (m)	Branch 2/ RS 3.021

the three approaches had been performed using a control performance index and also an economic index. A quadratic cost function J has been used as control performance index. Lost water and unsatisfied water demand has been considered in the economic index. In all the test cases, the demand of lateral offtakes has been satisfied properly, but also a flow demand at the end of each one of the canal branches has been considered. The flow demand has been considered constant along the simulation time, and different economic penalization for flows over the demand (0.2 euro for each cubic meter of lost water) and under demand (0.5 euro for each cubic meter of unsatisfied demand) are applied.

A. *Test 1: Offtake flow changes*

This test is devoted to analyze the behavior of the tested controllers when changes in offtake flow are produced. Offtakes are considered as perturbations since the farmers decided at any time the flow they need for their local irrigation (nevertheless, they usually follow a previous established irrigation plan). For this reason the offtake prediction is considered in the MPC control.

In the presented test, a flow of $1m^3/s$ is extracted from the canal in points of1 and of4 (See Figure 1) from the beginning of the second day to the end of the simulation period.

Figures 4 and 5 show the output and input of the second reach, that is, the level at the end of the reach (g2) and the position of gate 2. Notice that only the controller with the distributed controller (control schema 3) is able to maintain the set point level. Using local MPC (control schema 1), the gate reaches the maximum limit.

The performance of the controllers regarding the level of reach 4 can be seen in Figure 6. Again the best perturbation rejection is obtained with the third approach.

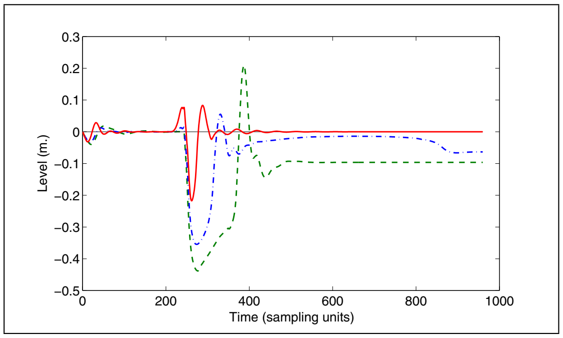

Fig. 4. Test 1: Level at the end of reach 2 (ref2)with control schema 1 (dashed green), schema 2 (dotted-dashed blue) and schema 3 (solid red)

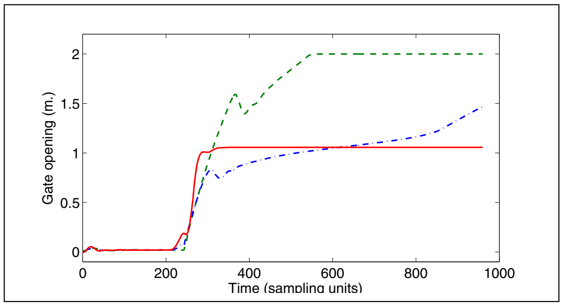

Fig. 5. Test 1: Position of gate 2 with control schema 1 (dashed green), schema 2 (dotted-dashed blue) and schema 3 (solid red)

B. *Test 2: Offtake flow and references changes*

The second test is a more complex situation with several simultaneous level and flow references and offtake flow changes. This test will show the coupling of the different subsystems and the effect of upstream perturbations at the downstream part of the canal.

The following reference changes and offtake flow modification have been considered:

- Change of $0.4m.$ in the level reference of gate 1 (Reference 1) at the beginning of the second day
- Increase $0.4m.$ in reference 2 at the beginning of the third day
- Change of $5m^3/s$ in reference 3 at the beginning of day the third day
- Change of $0.1m.$ in the level reference of gate 4 at the beginning of the forth day
- A flow of $1m^3/s$ is extracted from the canal in points off1 and off4 since the beginning of the second day

Figure 7 shows the flow through gate 3 (bifurcation to La Pedrera) and the change in the reference at the beginning of the third day. Notice that the effect of changes at the second and forth day are quite small in the flow. Also, as

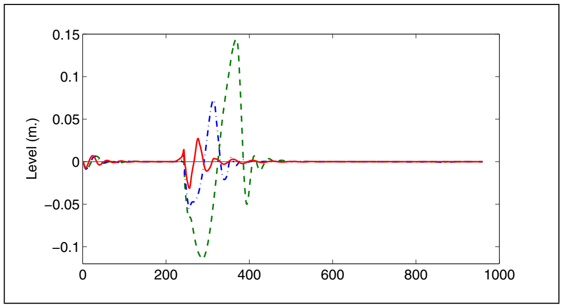

Fig. 6. Test 1: Level at ref4 position with control schema 1 (dashed green), schema 2 (dotted-dashed blue) and schema 3 (solid red)

TABLE III

PERFORMANCE INDEXES AND ECONOMIC COST OF EACH SCHEMA.

	Test 1		Test 2	
Performance	J	Euros	J	Euros
Control Schema 1	125.23	1674	157.49	12845
Control Schema 2	52.20	1101	116.43	7767
Control Schema 3	16.03	816	68.92	4660

in previous tests, the tracking of the reference change in flow is better using schema 3. Again, the worse performance is obtained with schema 1. Figure 8 shows the evolution of the level at the end of reach 4. Notice the effect of perturbations during the second and third day. Most of them are due to changes produced upstream. The behavior is quite oscillatory, but the amplitude of the oscillations is quite small (around $5cm.$). Again, the best response to perturbations and reference change is obtained when control schema 3 is used. Finally, table III presents an economic and performance indicator of the three approaches for both tests. The best results are obtained with the distributed controller (control schema 3). An important decrease of both indexes is obtained when this control schema is applied.

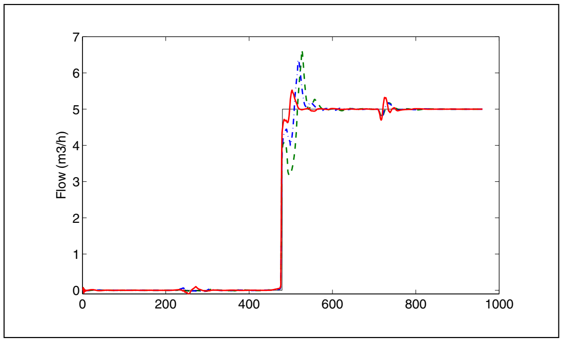

Fig. 7. Test 2: Flow at ref3 position with control schema 1 (dashed green), schema 2 (dotted-dashed blue) and schema 3 (solid red)

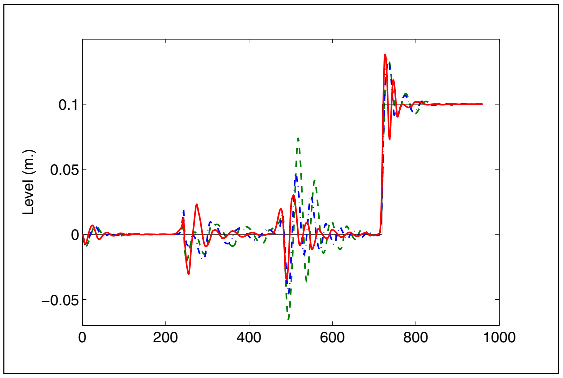

Fig. 8. Test 2: Level at the end of reach 4 (ref4) with control schema 1 (dashed green), schema 2 (dotted-dashed blue) and schema 3 (solid red)

VI. CONCLUSIONS AND FUTURE WORKS

In this paper a distributed predictive controller has been proposed to control irrigation canals. An accurate model of a real irrigation canal in Spain has been used as a test bed for the controller. The model has been developed using the SIC software. This software uses the Saint-Venant equations to model the dynamics of the canal with better accuracy than other methods. It has been interfaced to the predictive controller implemented in Matlab. The results show that the proposed distributed control algorithm achieves better control performance than a local based controller scheme without information exchange (which is the most usual control scheme in automated irrigation canals). The improvements in control performance lead to a better and more efficient management of irrigation canals that ultimately results in money and resource savings.

Future work will be focused on the development of more complex algorithms and in the validation of the controller in the actual irrigation canal. Furthermore, as the process dynamics are quite slow, the use of nonlinear prediction models and the consideration of uncertain or non measurable disturbances are possibilities that can be explored.

REFERENCES

[1] P. Malaterre, D. Rogers, and J. Schuurmans, "Classification of canal control algorithms," *ASCE Journal of Irrigation and Drainage Engineering*, vol. 124, 1998.

[2] E. F. Camacho and C. Bordons, *Model Predictive Control*, 2nd ed. Springer, 2004.

[3] J. Rodellar, M. Gómez, and L. Bonet, "Control method for on-demand operation of open-channel flow," *Journal of Irrigation and Drainage Engineering*, vol. 119, no. 2, pp. 225–241, 1993.

[4] M. Gómez, J. Rodellar, and J. A. Mantecón, "Predictive control method for decentralized operation of irrigation canals," *Applied Mathematical Modelling*, vol. 26, no. 11, pp. 1039 – 1056, 2002.

[5] S. Sawadogo, R. Faye, A. Benhammou, and K. Akouz, "Decentralized adaptive predictive control of multi-reach irrigation canal," in *Systems, Man, and Cybernetics, 2000 IEEE International Conference on*, vol. 5, 2000, pp. 3437 –3442.

[6] B. T. Wahlin, "Performance of model predictive control on asce test canal 1," *Journal of Irrigation and Drainage Engineering*, vol. 130, no. 3, pp. 227–238, 2004.

[7] P. Silva, M. A. Boto, J. Figueiredo, and M. Rijo, "Model predictive control of an experimental water canal," in *Proceedings of the European Control Conference*, Kos, Greece, 2007.

[8] O. Begovich, "Predictive control with constraints of a multi-pool irrigation canal prototype," *Latin American Applied Research*, vol. 37, 2007.

[9] P. van Overloop, "Model predictive control on open water systems," Ph.D. dissertation, TU Delft, 2006.

[10] C. Sepulveda, "Instrumentation, model identification and control of an experimental irrigation canal," Ph.D. dissertation, Universidad Politécnica de Cataluña, 2007.

[11] R. Negenborn, P. Overloop, T. Keviczky, and B. D. Shutter, "Distributed model predictive control of irrigation canals," *Networks and Heterogeneous Media*, vol. 4, no. 2, pp. 359 – 380, 2009.

[12] R. Negenborn, P. van Overloop, and B. De, "Coordinated model predictive reach control for irrigation canals," in *Proceedings of the European Control Conference*, August 2009.

[13] J. Igreja, J. Lemos, F. Cadete, L. Rato, and M. Rijo, "Control of a water delivery canal with cooperative distributed mpc," in *American Control Conference (ACC), 2012*. IEEE, 2012, pp. 3346–3351.

[14] M. Kearney, "Non-iterative distributed mpc for large-scale irrigation channels," in *Australian Control Conference (AUCC) 2011*, 2011.

[15] A. Zafra-Cabeza, J. Maestre, M. A. Ridao, E. F. Camacho, and L. Sánchez, "A hierarchical distributed model predictive control approach to irrigation canals: A risk mitigation perspective," *Journal of Process Control*, vol. 21, no. 5, pp. 787 – 799, 2011.

[16] X. Litrico, P.-O. Malaterre, J.-P. Baume, and J. Ribot-Bruno, "Conversion from discharge to gate opening for the control of irrigation canals," *ASCE Journal of Irrigation and Drainage Engineering*, vol. 134 (3), pp. 305–314, 2008.

[17] J. Maestre, D. M. de la Peña, and E. F. Camacho, "Distributed model predictive control based on a cooperative game," *Optimal Control Applications and Methods*, vol. 32, pp. 153–176, 2011.

[18] V. Chow, *Open-Channel Hydraulics*. Blackburn Press, 2009. [Online]. Available: http://books.google.es/books?id=JG9_PwAACAAJ