OPTIMUM CHOICE OF CONTROL ACTION VARIABLES

AND LINKED ALGORITHMS:

COMPARISON OF DIFFERENT ALTERNATIVES.

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ABSTRACT

This paper deals with the automatic control of open channel hydraulic systems, such as irrigation canals. A control algorithm is defined by several criteria among which some most important ones are the design method and the considered variables (measured, controlled and control action variables). Different design methods have been and are still developed and compared, by different authors.

Among the considered variables, the control action variable plays an important role. Different options have been selected by different authors, but have never been discussed, justified or compared in details by the controller designers. These different options can be gate opening or discharge. In this latter case, another algorithm must transform this discharge into a gate opening, since this is the only variable that can be manipulated on the real system. Again different options are available: model inversion using the gate equation or dynamic controller (e.g.: PID) at the same or at a different regulation time step. Also coupling effects may or may not have been taken into account, by anticipating upstream and downstream water level or discharge changes.

The proposed paper will present different techniques, and will test and compare some of them on representative benchmarks, on a full non-linear hydrodynamic model. The criteria for comparison will be hydraulic performance, robustness (to gate equation errors and change of operating conditions), and reduction of coupling effects with upstream and downstream pools.

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INTRODUCTION

An irrigation canal is an open channel hydraulic system, composed of interconnected pools, separated by cross structures (Fig. 1). Such system may have many control action variables (U_i) and many controlled (Y_i) and measured (Z_i) variables. This is called a MIMO system (Multiple Inputs, Multiple Outputs).

Control action variables (U_i) are located at cross structures (gates), controlled variables are often water levels (easy to measure) close to turnouts (outflow discharges can then be expected to be controlled correctly). It can also be volumes or discharges, but these options will not be addressed in this paper.

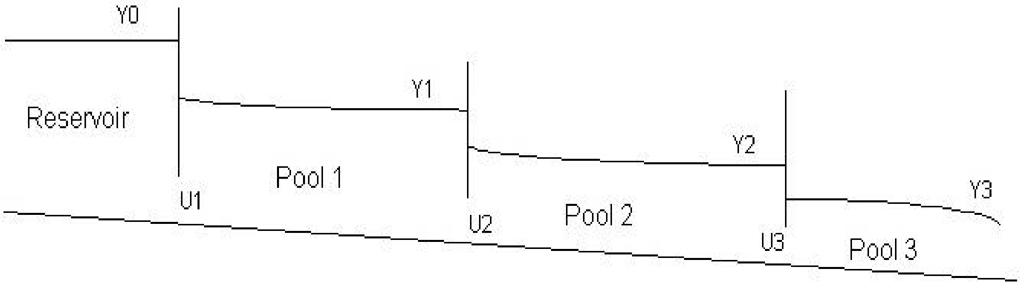

Fig. 1. Canal system

CONTROL ACTION VARIABLES

Control action variables (U_i) are issued from the control algorithm (called "master controller" in opposition to a possible "slave controller" defined below) and supplied to the cross structures' actuators in order to move the controlled variables (Y_i) towards their established target values (Yt_i). Control action variables are either gate positions (W) or flow rates (Q).

Considering gate position (W) has the advantage of allowing one taking into account the complex dynamics linking this variable with the local discharge and upstream and downstream water levels. These dynamics are important and it can be hazardous not to take them into account (e.g.: Bival, ELFLO, Littleman, Avis, and Pilote consider W as the control action variable; Cf. Malaterre et al. 1998).

Considering discharge (Q) as the control action variable allows for decoupling of the different subsystems, as this will be illustrated in the following sections. This is interesting when monovariable controllers are used in series (e.g. Dynamic Regulation, PIR). But, in this case, another algorithm must transform the flow rate into a gate position. This algorithm (called "slave controller") is important from hydraulic and control points of view. This transformation can be done through the inversion of the device static equation Q (Z_1, Z_2, W), where Z_1 and Z_2 are water levels upstream and downstream of the device, or by a local dynamic controller (e.g. PID controller). Several options exist for both approaches.

However, the dynamics of the local slave controller linking the discharge (control action variable Q) to the gate position (control action variable W) have never been taken into account explicitly in the design of the master controller. If the slave controller is very fast and precise, the global controller (master + slave) can be as efficient as expected. Otherwise, the quality of the behavior of the global controller cannot be assessed, since important dynamics are neglected in the design phase. The neglected slave controller dynamics are often taken into account implicitly by adjusting the gain of the master controller through trial and error procedure.

MULTIVARIABLE VS MONOVARIABLE SYSTEMS

The considered system is multivariable (Fig. 1). Therefore, multivariable controllers should normally be used to control such systems, controlling all (Y_i) through all (U_i) at the same time. But these algorithms are somewhat complex (Sabet et al. 1985, Tomicic 1989, Garcia et al. 1992, Khaladi 1992, Lin et al. 1992, Liu et al. 1992, Reddy 1992, Kosuth 1994, Malaterre 1994). They are sometimes difficult to design and tune, and difficult to implement (communication network, calculation requirements, etc.), at least more than a simple SISO PID controller.

A classical approach used by control engineers and also observed on our hydraulic systems, is to split the system into several simple SISO subsystems, and to design a SISO controller (single loop) for each of them. The only advantage of this approach is the structure simplicity. The controller techniques that can be used are simpler, but due to coupling effects between subsystems, the tuning can still be difficult, and there are cases where it is difficult to obtain a good overall controller by this loop-by-loop approach. Also performances are expected to be lower than with an efficient MIMO approach (Vandoren 1997).

The first problem faced in this decomposition approach, called “pairing problem”, is to decide how to define the SISO systems. For example, in the case of a system with 2 control action variables U_1 and U_2 and 2 controlled variables Y_1 and Y_2, one has to decide if Y_1 should be controlled by U_1 or by U_2 (we exclude the option of using both here since we look for SISO loops), and similarly for Y_2. This problem is straightforward if there is little interaction among the systems. And in this case we can expect that this single loop approach will give good results and that the tuning will be easy (Åström et al. 1995). But there may be difficulties when there is coupling between the loops.

In the above example (Fig. 1) we can imagine several pairing options. The most interesting and usual ones are:

- downstream control logic: control Y_1 by U_1, Y_2 by U_2 and Y_3 by U_3.
- upstream control logic: control Y_0 by U_1, Y_1 by U_2 and Y_2 by U_3.

The advantages and drawbacks of both options are well known and described in the literature (Goussard 1993, Malaterre et al. 1998). The first option (downstream control logic) is the most interesting and commonly studied by engineers, and will be further studied in the following sections.

COUPLING EVALUATION

First, consider control action variables in term of gate opening W.

If gate n°1 (control action variable U_1) is opened, then water level Y_1 will increase after a certain time due to the hydraulic delay in pool n°1, and since this increase affects the discharge going through gate n°2, water level Y_2 will, in turn, increase.

If gate n°2 (control action variable U_2) is opened, then nearby upstream water level Y_1 will decrease rapidly, and water level Y_2 will increase after a certain time due to hydraulic delay in pool n°2.

The corresponding transfer functions (g_{11}, g_{12}, g_{21} and g_{22}) can be calculated from open loop simulation and identification. They can also be calculated analytically (Baume et al. 1997, Schuurmans 1997). If we consider only these 2 subsystems, the obtained transfer function is:

$$\begin{pmatrix} Y_1 \\ Y_2 \end{pmatrix} = \begin{pmatrix} g_{11} & g_{12} \\ g_{21} & g_{22} \end{pmatrix} \begin{pmatrix} U_1 \\ U_2 \end{pmatrix} \tag{1}$$

Since none of these 4 transfer functions is nil, we can conclude that coupling does exist. There is no simple universal method to evaluate the coupling effects. An indication can be obtained from the Relative Gain Array, RGA (Åström et al. 1995, Bristol 1966) defined as (for a 2*2 dimension):

$$\lambda = \frac{g_{11}(0)\ g_{22}(0)}{g_{11}(0)\ g_{22}(0) - g_{12}(0)\ g_{21}(0)} \tag{2}$$

If $\lambda = 1$ there is no interaction. If $\lambda = 0$ there is no interaction, but the loops must be interchanged. If $\lambda = 0.5$ the interaction is very strong. Bristol's recommendation for controller pairing is that the controlled variables and control action variables should be paired so that the corresponding RGA are positive, and as close to 1 as possible (Åström et al. 1995). If the RGA are outside the interval $0.67 < \lambda < 1.5$, decoupling can improve the control significantly.

In the case of the first two pools of the example canal Type_1 described in Baume et al. 1999, with control action variables U = W, we obtain an interaction measure λ = 0.69. This means that, from this fast verification, pairing is well done, coupling is important, and we are close to the limit indicating that decoupling could improve the global controller.

Since the RGA used here is based on the static properties of the system, it does not capture all aspects of the interactions. In particular it does not take into account the effect of time lag. But a more general definition of the RGA can be used (Skogestad et al. 1998), valid for any frequency and any size of system.

DECOUPLING

To reduce coupling effects between SISO subsystems, explicit decoupling techniques based on transfer functions can be used. This method was developed and tested with an ELFLO controller (Schuurmans 1992). When a multivariable process is decoupled, each process variable effectively responds to only one actuator.

Two decouplers were proposed by Schuurmans: Decoupler I (called hereafter $Dc1_{sch}$) to compensate for the interaction effect of U_2 on Y_1 (g_{12}), and Decoupler II (called hereafter $Dc2_{sch}$) for to compensate for the interaction effect of U_1 on Y_2 (g_{21}). These two decouplers proved to improve the global controller, compared to the classical ELFLO controller (Buyalski et al. 1979, Shand 1971).

It is interesting to note that the Société du Canal de Provence uses, in its “Dynamic Regulation” controller (Coeuret 1977) and in its “PIR” controller (Deltour 1992, Deltour et al. 1998), two features that were indicated to be equivalent to Decoupler I and II quoted above (Malaterre 1994).

The first one is the fact that the control action variables (U_i) are discharges Q instead of gate openings W (technique called hereafter $Dc2_{scp}$). This is equivalent (on the philosophy but maybe not on the performance point of view) to $Dc2_{sch}$ since when a given target discharge is maintained through a gate (we assume here that this can be done technically, we will discuss this point latter on), then the downstream pool is no longer subject to perturbations occurring on the upstream pool (g_{21} = 0).

Deltour indicates that this approach also simplifies the identification procedure and limits the number of domains to be covered in case of gain scheduling (Deltour 1992).

The second one is the fact that each calculated control action variable U_i, or a portion α of it, is added to the next upstream one U_{i-1} (technique called hereafter $Dc1_{scp}$). This is equivalent (same remark as above) to $Dc1_{sch}$. Hydraulically, this means that if U_i is operated to compensate for a perturbation in its downstream pool i, then we know that this operation will have an interaction effect on Y_{i-1} (g_{12} transfer function in the above example). Of course U_{i-1} will in turn correct the effect of this perturbation (after some delay inherent to the system's characteristics) when its effect is felt on Y_{i-1}. But we can anticipate this action by adding directly the correction to U_{i-1}:

$$U_{i-1} = F_{i-1}\ Y_{i-1} + \alpha\ U_i \qquad (3)$$

Where F_{i-1} is the transfer function of the SISO (master) controller linking Y_{i-1} to U_{i-1}, and $\alpha \in [0\ 1]$. Theoretically α must be equal to 1, but for stability and robustness reasons, it is sometimes reduced close to lower values such as 0.8 for example (Clemmens et al. 1998). We can also test values $\alpha > 1$ to accelerate the controller, but with the risk of getting amplified oscillations of control actions U. In any case it can be tuned by a trial and error procedure, or optimized, using some mathematical or numerical techniques. In the tests presented bellow, we will not integrate the α coefficient in the optimization algorithm, but we will test values 0, 0.8, 1.0 and 1.2.

This correction will cancel or at least reduce the effect of U_i on Y_{i-1}, which means, in the above example, that $g_{12} \cong 0$. In fact this Decoupler I ($Dc1_{sch}$ and $Dc1_{scp}$) cannot be as good as Decoupler II ($Dc2_{sch}$ and $Dc2_{scp}$) since the delay time on pool i-1 implies that the additional correction $\alpha\ U_i$ at gate i-1 will not be felt instantaneously on the controlled variable Y_{i-1}.

This intuitive decoupler $Dc1_{scp}$ is easy to understand and to design when the control action variable U_i is a discharge Q. In case of a control action variable U_i in terms of gate opening W, a similar approach can be followed (Kaoutar et al. 1998). In this case we must estimate the effect ΔY_{i-1} of U_i on Y_{i-1} and, when calculating U_{i-1}, anticipate this perturbation by considering $Y_{i-1} + \beta\ \Delta Y_{i-1}$ instead of Y_{i-1} as the value of the controlled variable for the master controller i-1 (technique called hereafter $Dc1_{cem}$):

$$U_{i-1} = F_{i-1}\ (\ Y_{i-1} + \beta\ \Delta Y_{i-1}\ ) \qquad (4)$$

It can be remarked that both approaches are equivalent (if F_{i-1} is linear, which is the case for PI controllers) when $\alpha\ U_i = \beta\ F_{i-1}\ \Delta Y_{i-1}$. If would be interesting to check if the optimized tuning as described bellow are close to this condition.

Recently, Schuurmans finally adopted the two same features ($Dc1_{scp}$ and $Dc2_{scp}$) as in “Dynamic Regulation” and “PIR” from SCP, considering that it was simpler and more efficient than the classical decouplers (Schuurmans 1997). Garcia also used discharge (in fact rates of discharge change) in his work (Garcia 1992, p. 44), but without explanation. Among the almost 50 applications of automatic control to irrigation canals or rivers listed in the literature (Malaterre et al. 1998), 25 are using the gate opening W and 20 are using the discharge Q as control action variables. On those using the gate opening W, only one has been tested with decouplers, whereas they are the one that would most require such techniques.

SLAVE CONTROLLER

When using the discharge as the control action variable (decoupler $Dc2_{scp}$), an algorithm called "slave controller" must compute, at each time step, the required gate opening W_i able to provide the target discharge $U_i = Q_i$.

<u>Remark:</u> in some rare situations on-line pumping stations can be used to achieve this task. We will not test this option. It could be interesting to evaluate the performance obtained with this "perfect" decoupler $Dc2_{scp}$ compared to other more realistic implementations.

The gate discharge equation is non-linear and the relationship between the gate opening and the discharge depends on the upstream and downstream water levels:

$$Q = f(Z_1, Z_2, W)$$

Most authors (Deltour 1992, p. 140, Schuurmans 1997, p. 187) just inverse this gate equation at each slave regulation time step ΔT_Q, using the water levels measured at present time t:

$$W(t + \Delta T_Q) = f^{-1}(Z_1(t), Z_2(t), Q_t) \qquad (5)$$

Where Q_t is the target discharge computed by the master controller at the master regulation time step ΔT_U.

Same authors also use the same regulation time steps for both master and slave controllers: $\Delta T_Q = \Delta T_U$. Deltour (1992) describes performance loss in case of large time steps (he compares 10 and 30 minutes). In case of large regulation time steps he suggests a study of the dynamics between gate opening and controlled variable, or an improvement of the inversion procedure.

In the following sections we will evaluate the effect of using different regulation time steps for the master and the slave controllers (e.g.: $\Delta T_Q = 0.2\ \Delta T_U$).

Another possibility to improve the slave controller is to take into account the hydraulic effect of the gate movement, and, by doing this, to anticipate the modification of upstream and downstream water levels due to the gate movement. It is known from the theory of characteristics, after some simplification (no friction and uniform flow) that:

$$\Delta Z_1 = \frac{\Delta Q}{L\,(V - c)} \text{ and } \Delta Z_2 = \frac{\Delta Q}{L\,(V + c)} \qquad (6)$$

Where L (surface width), V (flow velocity) and c (celerity) are calculated for future conditions (De Leon, 1986). For simplicity reasons we will compute them for present conditions. In this case we can compute:

$$W(t + \Delta T_Q) = f^{-1}(Z_1(t) + \Delta Z_1, Z_2(t) + \Delta Z_2, Q_t) \tag{7}$$

It seems difficult to prove that both algorithms (5) and (7) are stable and will converge, since they interact with upstream and downstream pools. But we can prove that if they converge, and if there is no uncertainty on the parameters of the function f, then the obtained discharge Q will converge toward the target Q_t. The performance of both algorithms is evaluated hereafter (noted respectively U = Q and U = Qdz).

BENCHMARK AND SCENARIOS

The different control options above presented are tested on the 4 benchmark canals defined by Baume (Baume et al. 1997, 1998, 1999). These canals (called hereafter "Cemagref benchmarks") are all 5-pool canals obtained through an adimensional study. They represent all possible hydraulic behaviors, as characterized by 2 dimensionless coefficients.

$\chi = \dfrac{S_b \, . \, X}{Y_n}$ characterizes discharge propagation and $\eta = \dfrac{\chi}{F(1-F)}$ characterizes downstream water level perturbations (where S_b is the bed slope, X the length of the pool, Y_n the uniform depth, and F the Froude number).

Type_1 has short pools (first order) with wave propagation, Type_3 has short pools (first order) with damped wave motion, Type_4 has short pools (second order) with damped wave motion and Type_5 has long pools (second order with delay) with damped wave motion. Type_2 (second order without delay and with wave propagation) is not representative and not studied in this paper. Type_6 does not exist due to the relationship between χ and η.

The discharge scenarios at offtakes and optimization procedure are the same as described in Baume et al. 1999. The scenarios were elaborated from discharge measurements at pumping stations on a real on-demand system. The scenarios are composed of three phases of seven-day periods, with two peaks of discharge every day at 10 am and 8 pm. The values of the peaks are generated randomly around the mean observed value. The mean peak of discharge at each offtake is taken at 5% of the corresponding initial flow at the head of the system. The total disturbance on the 5 offtakes is therefore 25% of the initial flow. The first phase corresponds to low discharges, the second one to medium discharges and the third one to large discharges. The objective to this three-phase scenario is to provide controllers valid for a large range of canal flows.

OPTIMIZATION ALGORITHM

The optimized SISO controllers are PI controllers. These controllers are the most used in industry. But the approach can be tested with any type of control algorithm (PIR, Predictive control, etc.). Optimization and simulations are made on a full non-linear hydrodynamic model (SIC, Cemagref).

The optimization algorithm is a modified version of the Nelder - Mead simplex method. It is used to find the optimum set of the coefficients of the 5 PI controllers, providing the minimum value of a selected cost function. A relaxation technique has been used to cope with this non-convex problem.

The cost function used for the optimization procedure in this paper is:

$$\xi = \sum_{i=1}^{5} \int_0^T (Y_i(t) - Y_{ti})^2 \, dt \qquad (8)$$

where T is the length of the scenario, Y_i the water level and Y_{ti} the corresponding target at the downstream end of pool i. An additional term weighting the control action U_i could have been used in the cost function (8). It would have probably reduced expected overshoot or oscillations in control actions U_i. But the objective of the comparison here was to find the controllers providing the best hydraulic performance in terms of controlled variables, with total freedom on U. The same approach can be carried out with any cost function, and relative results presented bellow are expected to be similar.

The advantage of such optimization approach is to provide a good basis for objective comparison, since the tuning is not linked to some arbitrary choice (the only choice is the definition of ξ) and is exactly the same for all tested options.

RESULTS AND DISCUSSION

For the different options tested, we present the optimum PI coefficients minimizing the cost function ξ, and the value of the optimum ξ index obtained with these coefficients. For indication we give the control action cost:

$$\xi_w = \sum_{i=1}^{5} \int_0^T (\Delta w_i(t))^2 \, dt \qquad (9)$$

where $\Delta w_i(t)$ is the change of gate opening during the master controller regulation time step ΔT_U, at time t, for gate number i.

Results of the cost function obtained for the different approaches on the 4 canals are presented below. Absolute values ξ ($m^2 s$) and ξ_w ($m^2 s$) are displayed in Table 1 to Table 4. Relative values ξ_ρ and $\xi_{w\rho}$, compared to the values obtained for U = W are displayed in Fig. 2 to Fig. 5.

Table 1. Results on canal Type_1

	ξ	ξ_w	K_p					$K_i\ 10^4$				
W	31.3	9.44	2.97	2.31	2.02	2.28	0.62	26.44	17.4	7.73	3.93	1.16
Q; ΔT_U; α=0	38.6	13.3	50.52	50.29	23.15	23.58	9.387	89.31	88.62	59.79	66.23	10.94
Q; ΔT_U; α=1	8.97	10.2	41.9	39.5	15.1	11.4	29.1	52.1	51.3	65.9	82.65	42.5
Qdz; ΔT_U; α=0	14.6	14.2	48.6	35.1	14.9	46.5	26.9	204.6	178.5	115.4	51.9	12.1
Qdz; ΔT_U; α=1	3.99	10.9	44.1	23.1	13.8	14.7	12.1	133.6	137.1	113.6	83.6	127.1
Q; 0.2ΔT_U; α=0	12.5	8.3	29.3	29.4	18.1	18.5	23.4	236.1	236.2	134.7	103.3	14.2

Table 2. Results on canal Type_3

	ξ	ξ_w	K_p					$K_i\ 10^4$				
W	115	8.58	2.39	1.96	2.03	1.44	0.42	10.07	4.92	0.54	0.176	0.038
Q; ΔT_U; α=0	104	15.3	62.0	33.5	22.0	17.1	8.36	5.66	3.15	5.4	1.85	1.29
Q; ΔT_U; α=1	51.8	15.9	57.0	23.5	15.7	14.2	10.1	0.69	1.11	0.89	0.73	6.6
Qdz; ΔT_U; α=0	118	13.4	35.5	35.5	15.3	21.8	6.38	4.18	3.44	25.8	0.64	0.95
Qdz; ΔT_U; α=1	34.8	22.8	56.1	23.5	20.7	10.95	10.9	6.06	6.99	8.4	35.4	6.8
Q; 0.2ΔT_U; α=0	48.5	39	61.5	30.9	21.34	16.34	14.5	16.5	76.8	62.04	36.9	4.37

Table 3. Results on canal Type_4

	ξ	ξ_w	K_p					$K_i\ 10^4$				
W	248	2.87	1.41	1.167	0.962	0.42	0.068	1.45	0.112	0.064	0.073	0.0068
Q; ΔT_U; α=0	252	7.78	12.16	6.177	3.293	1.79	0.0003	0.375	0.26	0.196	0.205	0.12
Q; ΔT_U; α=1	167	9.86	10.54	4.25	2.28	2.02	0.63	0.13	0.18	0.15	0.048	0.38
Qdz; ΔT_U; α=0	211	12.4	11.75	6.12	3.98	2.34	0.045	0.42	0.056	0.127	0.08	0.051
Qdz; ΔT_U; α=1	118	12.8	10.63	4.077	3.13	2.29	1.1	0.286	0.092	0.187	0.075	0.356
Q; 0.2ΔT_U; α=0	120	20.1	11.43	6.28	4.176	3.62	1.06	2.1	5.47	1.92	0.78	0.295

Table 4. Results on canal Type_5

	ξ	ξ_w	K_p					$K_i\ 10^4$				
W	14343	12.9	0.53	0.41	0.385	0.226	0.015	1.19	0.063	0.05	0.016	0.0052
Q; ΔT_U; α=0	31651	176	29.08	16.24	8.14	5.165	0.003	1.52	0.82	0.41	0.041	0.0025
Q; ΔT_U; α=1	18385	115	23.57	11.32	4.6	5.35	0.0002	0.103	0.012	0.182	1.235	0.252
Qdz; ΔT_U; α=0	23978	291	28.3	15.77	9.23	6.095	0.0067	1.04	1.035	0.27	0.19	0.0002
Qdz; ΔT_U; α=1	13144	174	23.95	10.89	6.05	5.64	2.37	0.242	0.019	0.347	4.59	0.397
Q; 0.2ΔT_U; α=0	18069	325	27.45	15.16	10.22	6.956	0.0025	4.02	3.498	1.248	0.482	0.0005

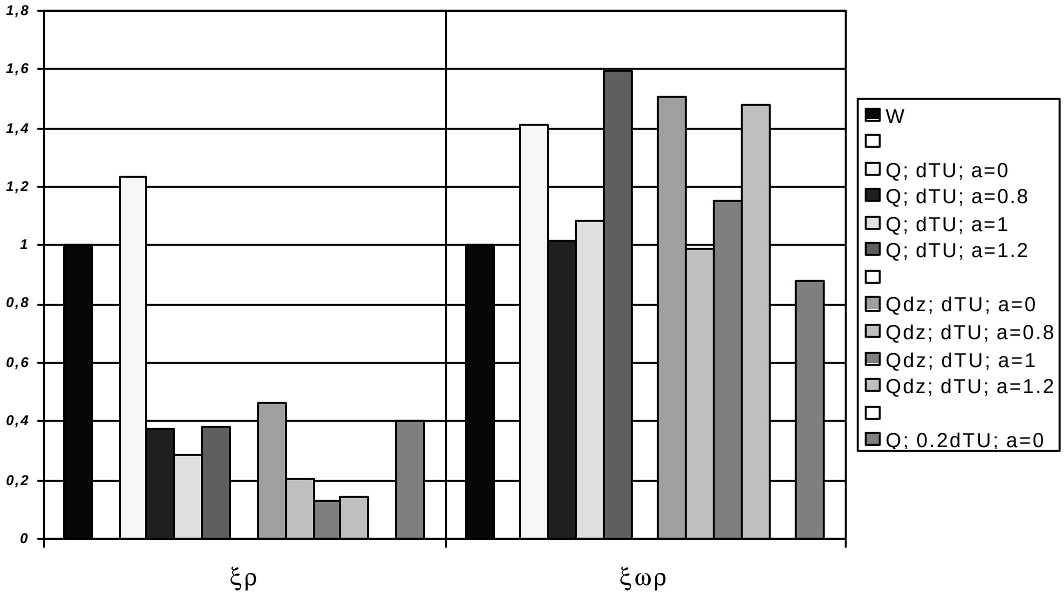

Fig. 2. Cost functions on canal Type_1

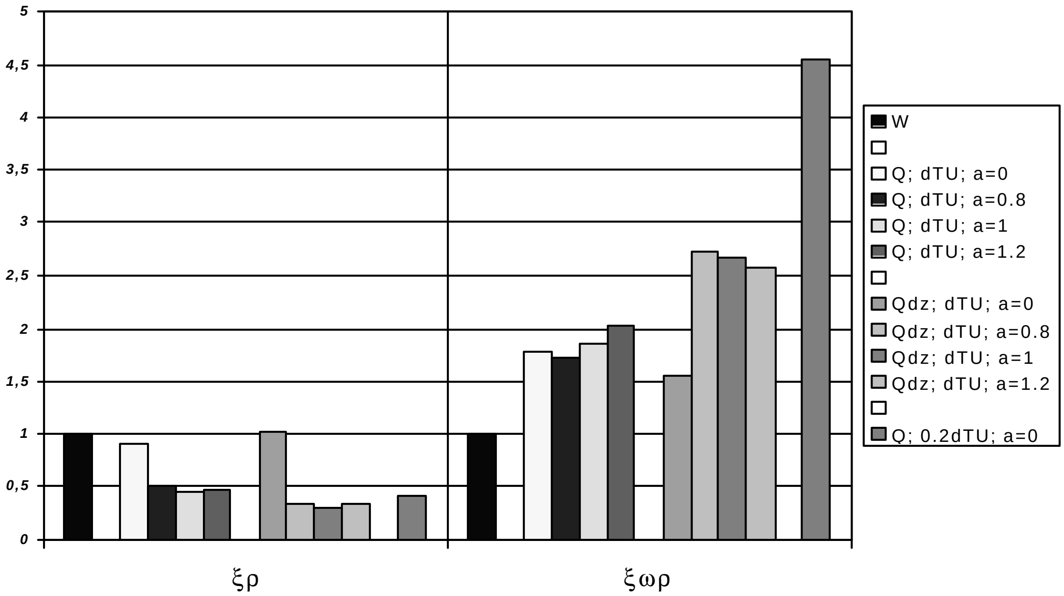

Fig. 3. Cost functions on canal Type_3

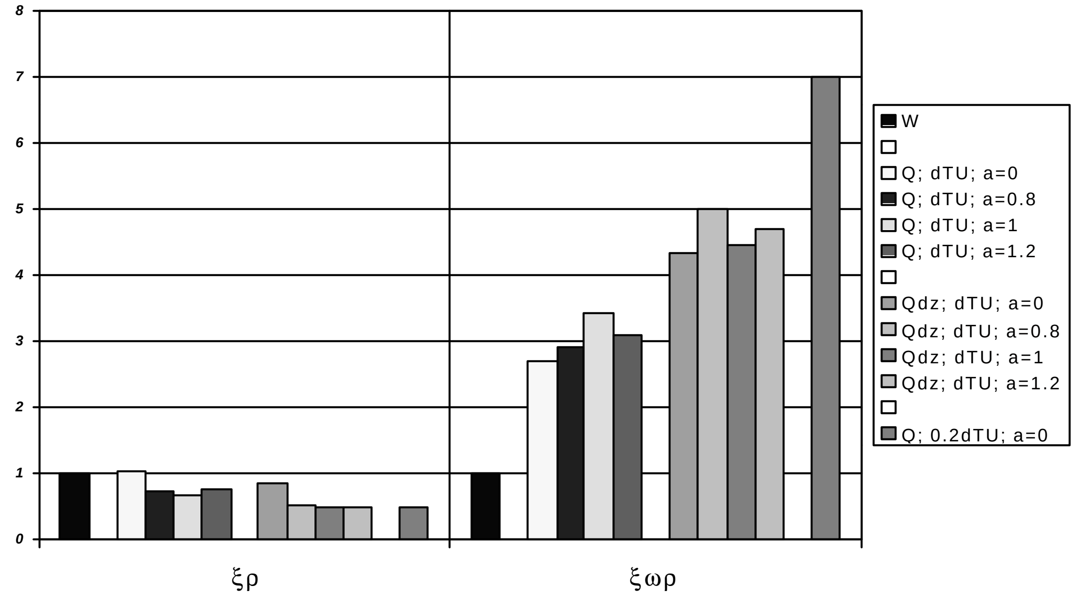

Fig. 4. Cost functions on canal Type_4

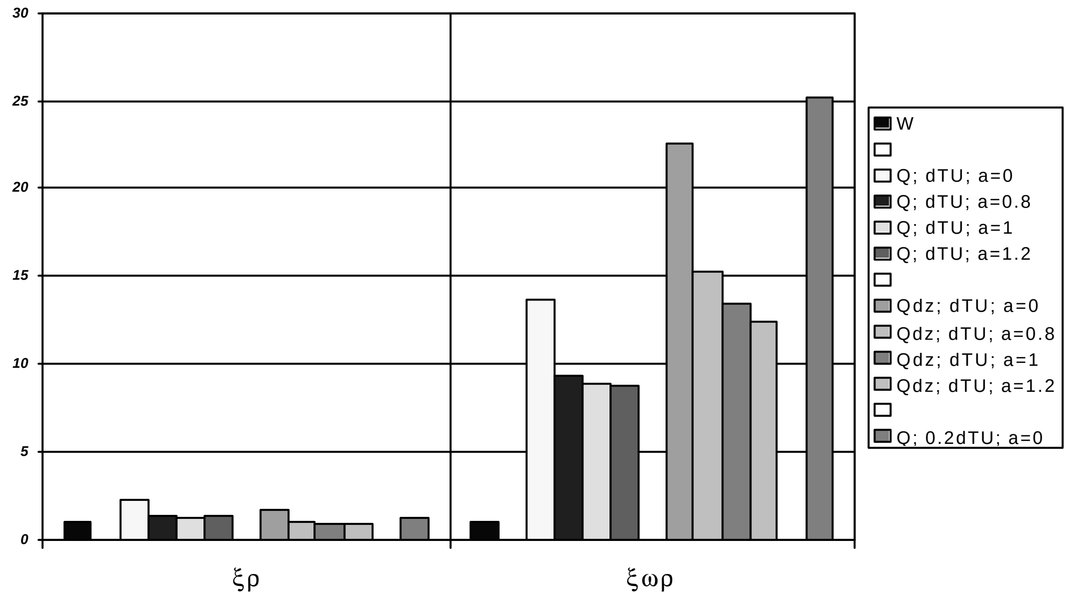

Fig. 5. Cost functions on canal Type_5

We observe that among all approaches tested, the best performance index ξ is always obtained by the one noted Qdz; dTu; $\alpha = 1$ in tables and figures. It corresponds to the one using gate discharge Q as the control action variable for the master controller ($Dc2_{scp}$), with a slave controller taking into account the anticipated variations of water levels dz_1 and dz_2 (noted Qdz). It uses the same regulation time step for both master and slave controllers (noted dTu). It incorporates the $DC1_{scp}$ decoupler, with $\alpha = 1$.

The interest of $Dc2_{scp}$ can be explained to a certain extent since this includes part of the non-linear characteristics of the subsystem into the controller, which improves the linear characteristics of the system to be controlled, and generates in fact a non-linear controller. But we observe that $Dc2_{scp}$ must be combined with $DC1_{scp}$ to give good results. Otherwise U = W gives better results.

For $DC1_{scp}$, the best performance is always obtained with $\alpha = 1$. For each option the values 0.8 and 1.2 have also been tested. They are not presented in tables for readability. For $\alpha = 0.8$ the ξ index is slightly bigger than for $\alpha = 1$, but the control action index ξ_w is slightly smaller. In some cases this former option can be preferred.

For canal Type_5, using gate opening as the control action variable (U = W) leads to a performance index ξ slightly bigger than the best option (Qdz; dTu; $\alpha = 1$), but the control action index ξ_w is much smaller. In this case this first option can be preferred.

Using a smaller regulation time step for the slave controller (1/5 of the master controller time step, noted 0.2 dTu) improves the performance index ξ significantly. But, of course, this also increases the number of operations at the check gates. This does not appear in the figures and tables above, since only gate movements at master controller time steps are taken into account in the calculation of ξ_w . This improvement is due to the fact that the quality of the translation of the discharge control action U = Q into gate opening action W is improved and improves in turn the decoupling between pool i and pool i+1 (decoupler $Dc2_{scp}$).

ROBUSTNESS TO GATE DISCHARGE EQUATION UNCERTAINTIES

In order to assess the robustness of the different controllers presented above, they are tested on degraded canals, after being tuned on the original ones. To obtain these canals, the Manning coefficients are increased by 25% and the gate discharge coefficients (Cd) are reduced by 20%, from their original values. This corresponds to realistic but strong degradation of or uncertainty on an irrigation canal.

For all controllers using the discharge as control action variable, two tests are carried out. For the first one (noted $T_{rob\ 1}$), the original (assumed but wrong) Cd coefficients are used in the slave controllers. For the second one (noted $T_{rob\ 2}$), the degraded Cd coefficients are used in the slave controllers (assuming they have been obtained from re-calibration), but without re-tuning the master controllers.

For test $T_{rob\ 1}$ we observe that the performance index is increased by a ratio from 1.3 to 7.8 for U = W, from 29 to 2100 for U = Q, from 136 to 800 for U = Qdz and from 105 to 3200 for U = Q, 0.2 dTu. In all cases the controllers remain stable but with much more oscillations. We observe that the loss of performance is obtained mainly for high discharges (phase 3 of the scenarios).

For test $T_{rob\ 2}$ we observe that the performance index is increased by a ratio from 71 to 2200 for U = Q, from 79 to 3100 for U = Qdz and from 74 to 2400 for U = Q, 0.2 dTu. In 2 cases the controller in even unstable (on canal Type_5). This means that in case of degradation of the gate discharge coefficients, re-calibration of them for the slave controllers is not sufficient, but a complete re-tuning of the master controllers must be done.

This quick a posteriori assessment of the controllers robustness shows that even though the controllers using gate opening as control action variables (U = W) have smaller performance indexes than those using discharge (U = Q), they seem more robust. It is nevertheless difficult to draw definitive conclusions from these tests since the controllers have been optimized for hydraulic performance and not for robustness. A more detailed robustness approach must be done to clarify this point.

CONCLUSION AND PERSPECTIVE

From the different tests carried out and presented in the previous sections, we can observe that the best results obtained on all 4 Cemagref benchmark canals are those with a control action U = Q (technique $Dc1_{scp}$), with transfer of discharge control action from downstream to upstream gates (technique $Dc2_{scp}$), with a transfer ratio close to one (α = 1), with a slave controller taking into account the anticipated water level changes dz_1 and dz_2. Best results can still be obtained with a slave regulation time step smaller than the master regulation time step (e.g. 0.2 dTu), but with a significant increase of the control efforts.

The robustness assessment showed that re-tuning of both master and slave controllers must be done in case of canal degradation, for best performance. This holds at least for controllers tuned with the optimization technique used in this paper. This is particularly true for controllers using discharge as the control action variable. However a detailed robust approach must be done to clarify this point and indicate if another tuning technique cannot guarantee a good robustness without reducing too much the performance of the controllers. The robustness of those using directly the gate opening as the control action variable seems satisfactory.

Only a limited number of options have been tested. More should be evaluated on the same benchmark canals, such as dynamic slave controllers (e.g. PI), explicit decouplers ($Dc1_{sch}$ and $Dc2_{sch}$), decoupling technique in the case of gate opening control action ($Dc2_{cem}$).

Maximum efforts have been put on the optimization algorithm. But the problem to be solved is a non-convex problem, and as such is difficult to handle. The risk of getting a non-global optimum remains. To reduce this risk the solution was checked from other initial conditions. Also the patterns of the obtained K_p and K_i coefficients were verified (since the pools are identical we can anticipate to get monotonous coefficients).

Maximum efforts were also put on the selected benchmark canals to draw conclusions as general as possible. But the selected canals, although covering all hydraulic behaviors determined by 2 dimensionless coefficients, remain particular 5-pool canals. Maybe the conclusions can be modified with composite selections of pools, or with different types of cross structures.

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