INTERNATIONAL COMMISSION
ON IRRIGATION AND DRAINAGE

Nineteenth Congress
Beijing 2005

Q. 52
R. 6.02

APPLICATION OF MULTIVARIABLE CONTROL ON THE CANAL DE PROVENCE AIX NORD WATER SUPPLY SUBSYSTEM

APPLICATION D'UNE COMMANDE MULTIVARIABLE SUR LA BRANCHE AU SOUS SYSTEME DE DISTRIBUTION D'EAU AU TRONÇON D'AIX NORD DU CANAL DE PROVENCE

Y. Viala[1] O. Genthon[2] P. O. Malaterre[3]
J. L. Deltour[4] J. Sau[5]

ABSTRACT

"Société du Canal de Provence" has been managing its hydraulic network, thanks to the *dynamic regulation* for more than thirty years. It conducts a permanent research program in this field to keep its knowledge at the highest level. The study of integration of a multivariable automatic controller, based on optimal control, has been conducted to evaluate the possibility to improve the overall optimisation of the system. The development is made on the "Aix Nord" subsystem of the "Canal de Provence". A non-linear model is built, calibrated and validated with field measurements.

---

[1] Ingénieur, service ingénierie – Société du Canal de Provence, Le Tholonet, BP 100, 13603 AIX EN PROVENCE CEDEX 1 – France. Tél. : +33 4 42 66 70 00, Fax: +33 4 66 70 87, E-Mail : yann.viala@canal-de-provence.com

[2] Doctorant, Centre Général de TéléContrôle – Société du Canal de Provence, Le Tholonet, BP 100, 13603 AIX EN PROVENCE CEDEX 1 – France. Tél. : +33 4 42 66 70 00, Fax : +33 4 66 70 88, E-Mail : olivier.genthon@canal-de-provence.com

[3] Chercheur ingénieur, Unité de Recherche Irrigation – CEMAGREF, 361 rue J.-F. Breton, BP 5095, 34196 MONTPELLIER CEDEX 5 – France. Tél. : +33 4 67 04 63 56, Fax : +33 4 67 63 57 95, E-Mail : pierre-olivier.malaterre@cemagref.fr

[4] Ingénieur, Centre Général de TéléContrôle – Société du Canal de Provence, Le Tholonet, BP 100, 13603 AIX EN PROVENCE CEDEX 1 – France. Tél. : +33 4 42 66 70 00, Fax : +33 4 66 70 88, E-Mail : jean-luc.deltour@canal-de-provence.com

[5] Professeur – LMFA UMR 5509, Université Claude Bernard Lyon 1, 43 bd du 11 novembre 1918, 69622 VILLEURBANNE CEDEX – France. Tél. : +33 4 72 44 83 73, Fax : +33 4 72 44 80 54, E-Mail : jacques.sau@univ-lyon1.fr

The controller proposed is built with a non-asymptotic component allowing to take into account predictions on future disturbances or objectives. A state observer and a perturbation observer are also defined.

Robustness of both the controller and the observer is tested. A method for discrete control of pumping station is also defined.

The dynamic regulation program has also been rewritten in the object-oriented language JAVA. We then took advantage of the modularity of this programming approach to implement the new regulator in the program.

Finally, the new controller is compared to the current one on an example extracted from the backup files.

RESUMÉ ET CONCLUSIONS

Le Canal de Provence fonctionne à la demande. Les utilisateurs raccordés à son réseau peuvent disposer de l'eau librement, sans rotation ni tour d'eau, mais avec un débit maximum fixé contractuellement. La structure du système de distribution en charge est naturellement bien adaptée à ce mode de fonctionnement. En revanche, les canaux principaux à surface libre introduisent des retards hydrauliques qui doivent être pris en compte. Actuellement, la régulation de l'ouvrage est conçue en séparant le système en une série de sous-systèmes. L'aspect multivariable est pris en compte par une coordination de chaque réglage effectué sur les sous-systèmes, reportant ainsi les différents débits de correction de l'aval vers l'amont.

La branche d'Aix Nord présente des caractéristiques intéressantes du point de vue de la commande. On distingue en effet plusieurs systèmes hydrauliques (canal à surface libre, station de pompage, réservoirs) et un grand nombre de contraintes d'exploitations. La conception d'un contrôleur par une approche multivariable permet de gérer tous les paramètres en même temps, en ayant une optimisation globale de tout le système.

Un modèle multivariable du système est établi à partir des fonctions de transfert identifiées, dont les coefficients sont déterminés à l'aide des paramètres physiques du système. Cette approche permet, contrairement à une identification numérique type "boite noire", de rester très proche de la physique du procédé à commander.

Un modèle non linéaire est également construit, qui permet de tester et de valider les différents contrôleurs calculés. Ce modèle permet de résoudre les équations complètes de Saint-Venant sur un schéma aux différences finies. Il est calé et validé par des mesures de terrain.

Le contrôleur de type LQG, est calculé par la résolution d'une équation de Riccati. Il comprend un terme dit "non asymptotique" permettant de prendre en compte les variations de consigne et les prévisions sur les perturbations.

Le système de commande comprend des commandes discrètes (mise en route et arrêt de pompes) qui ne sont pas gérées par une commande optimale classique. Le caractère discret de cette commande est donc traité à part, et la différence entre la commande calculée et celle effectivement appliquée à la station de pompage est utilisée pour améliorer les performances du contrôleur.

Le contrôleur met en œuvre une commande par retour. L'état du système n'est pas directement accessible à la mesure. C'est pourquoi un observateur est mis en place, utilisant une approche du type "filtre de Kalman". Cet observateur nous permet également de reconstruire les perturbations qui ne sont pas mesurées.

Nous présentons ici les résultats obtenus sur le modèle non-linéaire du système. Le comportement du contrôleur est testé sur des scénarios de prélèvement extraits de la base de donnée du Centre Général de TéléContrôle.

Ce travail montre qu'il est possible d'appliquer la théorie de la commande optimale sur un système hydraulique complexe, comprenant des contraintes qui ne sont pas classiquement gérées par ce type de contrôleur. L'observateur d'état construit est satisfaisant, et l'observation des perturbations non mesurées permet d'augmenter les performances de la commande. La robustesse du contrôleur permet d'appliquer un post-traitement sur la commande gestion de la station de pompage) sans déstabiliser le système.

Ce travail de recherche a été mené en parallèle avec la réécriture complète en langage JAVA du logiciel de régulation fonctionnant actuellement sur les ouvrages du canal de Provence. L'intégration de ce nouveau contrôleur a donc été prévue dans la structure générale du programme qui est décrite ici. La mise en place de ce régulateur est donc en cours, elle confirmera la stabilité de l'ensemble observateur – contrôleur qui a été prouvée analytiquement, ainsi que la validité des marges de robustesse. En effet, seule une période de test sur les ouvrages réels permettra de valider cette nouvelle commande en la comparant à celle fonctionnant actuellement.

1. INTRODUCTION

The control of a canal system is a MIMO control. Usually, in field applications, the design starts from a Single Input Single Output (SISO) design, and the MIMO character is added after by an ad hoc procedure, like coordination between pools. Many studies of MIMO control, in particular optimal control, on canal automation have been done (Corriga 1982, Malaterre 1994 and 1998). A survey can be found in Georges and Litrico (2002). In real cases, the complete control problem must take into account the field and operational constraints that are not easily handled by the usual approaches.

The application we present here concerns the first study of a MIMO controller on an existing canal branch. We have chosen a branch with interesting characteristic for the experimentation of this kind of control. The reasons for the selection of the Canal de Provence Aix-Nord branch are the multiplicity of structures of different kinds and the existing management constraints.

The first part of this paper introduces the hydraulic system, and the way it has been modeled. Then the control theory is described, along with the manner it has been included in the regulation program. At the end, a series of tests is presented.

All tests in this paper are made with the SIC software from the CEMAGREF. This software solves the full non-linear St Venant equations on a finite difference scheme.

2. THE HYDRAULIC SYSTEM

Description of the system

The Aix-Nord branch consists of a 10 km (6.2 mile) long canal, nine reservoirs and five pumping stations. The sub-system we are interested in is shown schematically in Figure 1.

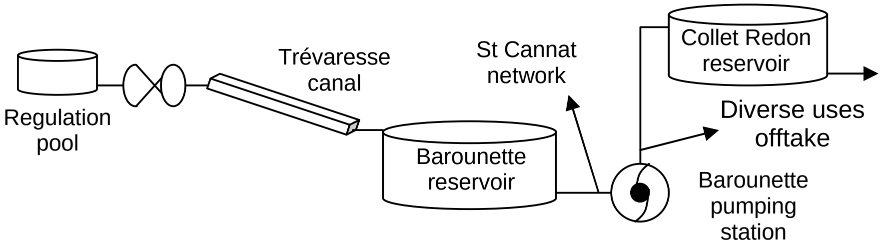

Figure 1. Outline of the hydraulic system (Schéma hydraulique du système)

A gate at the output of the regulation pool controls the discharge in the Trevaresse canal. This canal has been recently modernized by the construction of a series of duckbill weirs. This canal feeds the 13 400 m^3 Barounette reservoir, from which a pumping station feeds the 8 500 m^3 Collet-Redon reservoir.

Hydraulic variables

The hydraulic variables and their notations are the following :

- Control variables or inputs :
    - The discharge at the output gate of the regulation reservoir, u_1.
    - The discharge of the Barounette pumping station (4 pumps), u_2.

- Controlled variables :
  - Volume of the Barounette reservoir, y_1.
  - Volume of the Collet Redon reservoir, y_2.
- Measured variables :
  - Discharge downstream of the Trevaresse canal, z_1.
  - Volume of the Barounette reservoir, $z_2 = y_1$.
  - Discharge at the output of the Barounette reservoir, z_3.
  - Volume of the Collet-Redon reservoir, $z_4 = y_2$.
- Perturbations :
  - Leakage out of the canal, w_1.
  - Outlets upstream of the Barounette pumping station, w_2.
  - Customers' outlets downstream of this pumping station, w_3.
  - Output discharge of the Collet Redon reservoir, w_4, which is measured.

Constraints

The application shown here deals with many kinds of constraints :

- The Trevaresse canal capacity is 1.5 m^3/s. However, in order to avoid the emptying of the canal (important filling time), a minimum discharge of 30 l/s is needed.
- The target volume of the Barounette reservoir is 9 000 m^3.

The operation of the Barounette pumping station is more complex one. This station consists of four parallel pumps working independently on an on/off basis.

A maximum (7 700 m^3) and a minimum (4,000 m^3) volume exist for the Collet Redon reservoir. The Barounette pumping station works so as to reach the high level at the end of the night. During the day, a prediction is made and based on the result; one, two or three pumps are switch on.

An optimization of energy cost is performed. Without detailing the variation of energy prices, let us simply say that this price varies according to the period in the year and also to the time in each day. The electricity price can vary by a factor of 4 throughout the year.

3. THE SYSTEM MODELING

In order to design a MIMO controller, we need a linear model of the whole system. This model makes use of :

- The second order transfer function between upstream and downstream discharges of the canal already proposed by Deltour (1988).
- Balance relations between discharges and volumes of the reservoirs

The upstream-downstream discharges transfer function is a second order one, with double pole :

$$F(z) = \frac{N}{\left(1 - Dz^{-1}\right)^2} z^{-r}$$

with

$$D = \exp(-T_e / T)$$
$$N = (1 - D)^2$$

T_e is the control time step and T is a time constant characterizing the canal, r is the pure delay expressed in number of time steps. These two last quantities can be related to the global hydraulic delay $\Delta V / \Delta Q$ by (see Figure 2) :

$$\frac{\Delta V}{\Delta Q} = T + rT_e$$

Here, ΔV is the steady state volume variation due to a ΔQ discharge variation. This kind of parameterization is already in use at the "Société du Canal de Provence" since about 30 years and has proven its validity (Rogier 1987, Deltour 1988, Deltour 1998).

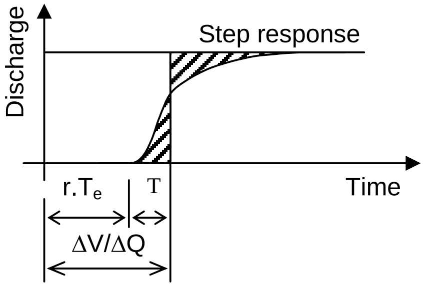

Figure 2. Characteristics times of a canal (Temps caractéristiques d'un canal à surface libre)

The pure delay itself is given by the time needed for a small perturbation to travel from upstream to downstream in the canal :

$$rT_e = \frac{L}{v+c}$$

with *L* the length of the canal, *v* the flow speed and *c* the celerity of hydraulic waves. The great advantage of this transfer function is that it is not the result of black-box identification and depends only on geometrical and physical features of the canal, with no free parameter. Figure 3 shows the downstream response to an upstream input of pseudo-random binary series (PRBS) type around a 700 l/s discharge value. This type of response is a good test for a system modeling because the rich spectral content of a PRBS (Landau 1993, Ljung 1999). In Figure 3 the result is compared with a SIC model of the canal. The agreement is very good.

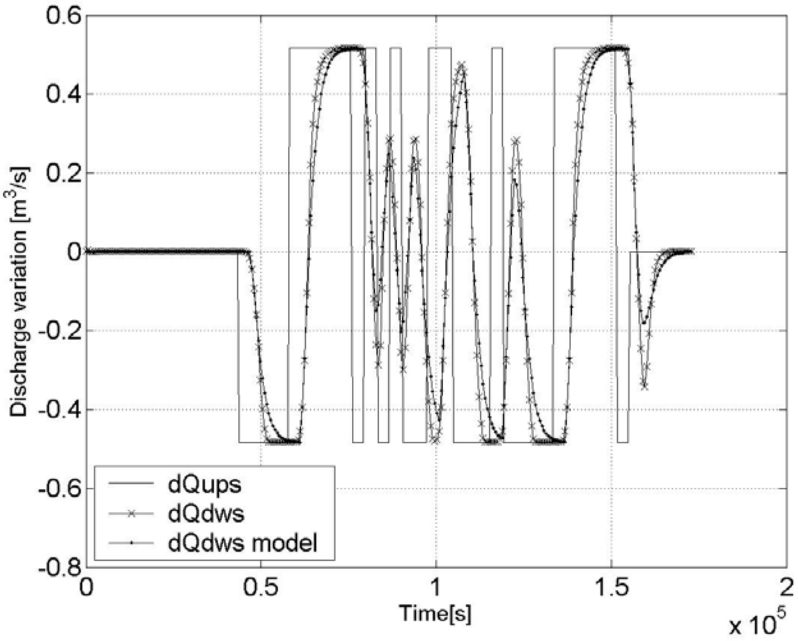

Figure 3. Comparison of downstream response discharge to an upstream PRBS. dQdws is the SIC result (Comparaison de la réponse du débit aval à un débit amont de type SBPA. dQdws est le résultat de SIC)

The modeling of the reservoirs is simpler since they are basically integrators. A discrete time approximation can lead to the following discharge-volume transfer function :

$$F(z) = \frac{T_e}{2}\frac{1+z^{-1}}{1-z^{-1}}$$

The above expressions represent a careful modeling of the hydraulic system, which is required for an efficient control design.

4. DESIGN OF THE CONTROLLER

Optimal or LQG control

In order to design a MIMO (Multi Input Multi Output) LQG controller, we shall need a state space description of the system. Starting from the above transfer function description, a minimal state space realisation can be achieved using the specialised routines of Matlab software package. However, since we need nil static error in regulation, integrator type variables must be added (Malaterre 1994,1998). The state equations then take the classical form :

$$X^{+} = A_s X + B_u u + B_w w$$
$$y = C_y X + D_{yu} u + D_{yw} w$$

X, *u*, *y* and *w* are respectively state, control action, controlled variables and perturbation vectors. $A_s, B_u, B_w, C_y, D_{yu}, D_{yw}$ are matrices of appropriate dimensions. The optimal control is obtained by the minimization of a criterion :

$$J = \frac{1}{2}\sum_{k=0}^{N-1}\left[(X(k) - X_c(k))^t Q_X (X(k) - X_c(k)) + (u(k) - u_c(k))^t R(u(k) - u_c(k))\right]$$

X_c and u_c are the wanted set point trajectories for *X* and *u*, respectively. An extensive development of the design of the control can be found in Åström and Wittenmark (1997), Malaterre (1994, 1998), Georges and Litrico (2002). The command *u* is obtained under the form :

$$u = -KX + H$$

Where, the gain matrix *K* is, in our application, solution of the asymptotic Riccati equation, and the pre-filter *H* is dependant on the open-loop or anticipatory part of the control.

Observer construction

The above control law assumes that the state vector *X* is known, which is almost all the time unrealistic. Most frequently, certain combination of states, or observed variables *z*, are effectively measured :

$$z = C_z X + D_{zu} u + D_{zw} w .$$

From variables z, the state vector X can be reconstructed, (Åström and Wittenmark 1997, Malaterre 1994, 1998). Then X is replaced by the reconstructed one, $\overline{X}$. Due to unknown perturbations, a state Kalman filter including a perturbation observer is designed :

$$\overline{X}^{+} = A_s \overline{X} + B_u u + B_w \overline{w} + L(z - \overline{z})$$

Where $\overline{w}$ is the perturbation vector estimation :

$$\overline{w}^{+} = \overline{w} + L_w (z - \overline{z})$$

L and L_w matrices can be computed through the minimization of the reconstruction error (Kalman filter, see Welch (2003)).

5. IMPLEMENTATION INTO THE DYNAMIC REGULATION PROGRAM

Context

A review of about 30 year's experience of automated canal management has been done that resulted in the decision to undertake a rewriting of the existing regulation software. In our mind, such software is the translation in the field and in concrete actions of the general strategy of canal management based on the geometrical, physical and functionalities of the whole system of regulation.

Concerning the language, it appears that an object oriented would be the most adapted, likely to represent very well hierarchised and articulated actions or components of the system. Moreover, this development allows :

- An improvement of the software documentation, with an automatic update in case of modification of the sources.
- A great potential evolving with an increased modularity, so as to accept easily modifications and adaptation to a particular canal site.
- The ability to implement easily very different control algorithms as SISO (Single Input Single Output) or MIMO control.
- a graphical specification method: UML (Booch 1999) by means of Rose software.

The chosen language was Java. This choice also allows independence on the target computer operating system.

Global software organization

An object oriented software is organized into several classes of objects, each class defining on one hand data or “members” required to describe the object and on the other hand the collection of “methods” which can be used to carry out treatments.

The renewed “Dynamic Regulation” is composed of more than 100 classes that can be spread into 3 main packages :

- Topology package related to physical elements of the system
- Regulation package related to functional elements that define the operation rules and control logic of the system
- Utilities package for data acquisition and user interface.

We are not going in detail for all classes of the application, the description can be found in Deltour (2004). The Figure 4 and 5 present the architecture the program. Hydraulic Unit and Hydraulic Adduction belong to regulation package. Reach, ramification, segment, control structure, gated structure and pumping station belong to the topology package. Sensor belongs to utilities package.

In the regulation package, the basic class is the *"Hydraulic Unit"*. It is able to control the status of its segments through action on upstream *"Control Structures"*. This class includes functions required to implement operational rules and control logic.

"Hydraulic Adductions" are composed of several synchronized *"Hydraulic Unit"*. This class gives the opportunity to share deficits or excess among several *"Hydraulic Unit"* or to implement a full MIMO controller.

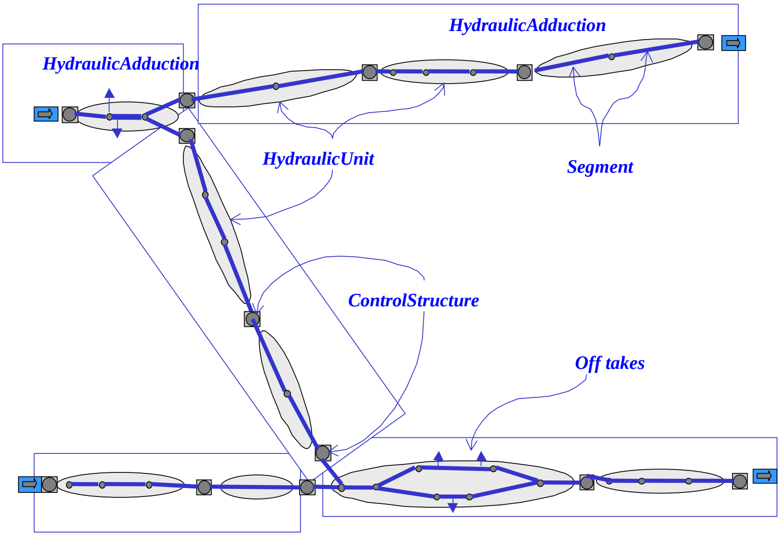

Figure 4. Topological graph of a canal system (Description Topologique d'un canal)

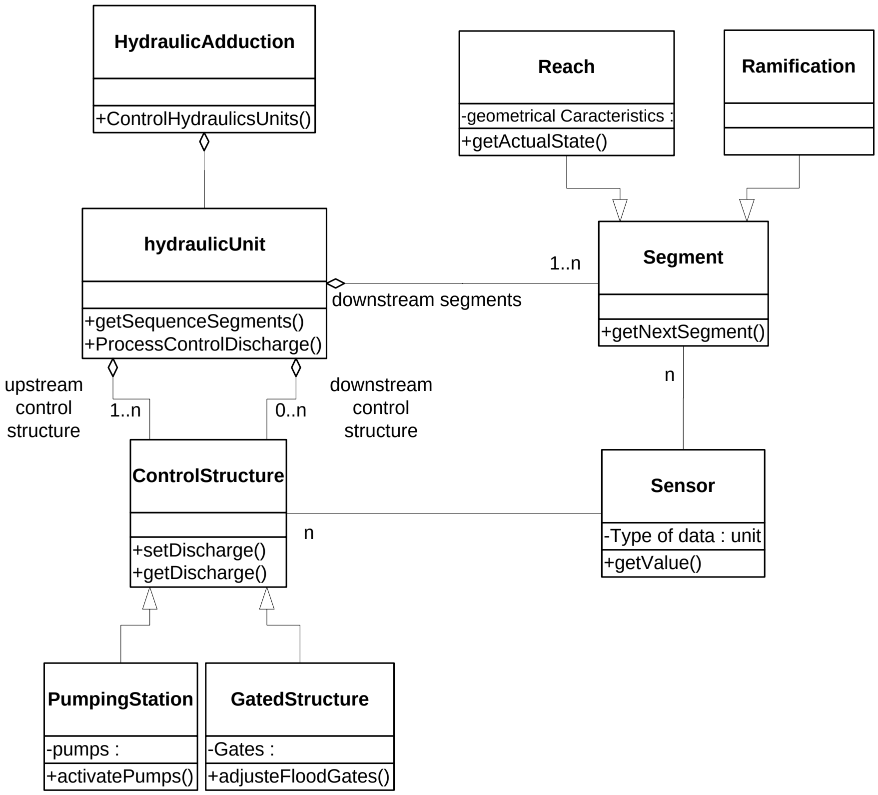

Figure 5. Classes relationship example (Exemple de relations entre classes)

6. APPLICATION TO THE "AIX NORD" BRANCH

Calibration of the parameters

The scenarios we tested are without prediction on perturbations, which represent the most difficult cases for the control. Tuning parameters are the various *Q* and *R* matrices appearing in the criterions of the control and of the Kalman filter of the observer. These matrices are chosen as diagonals, with diagonal elements according to the Bryson rule (Bryson 1975, Larminat 1993) :

$$R_{ii} = (1/\sup(u_i))^2$$

$$Q_{ii} = (1/\sup(y_i))^2$$

Where, $\sup(u_i)$ and $\sup(y_i)$ are the on-field physical magnitude of the corresponding control actions and controlled variables value. These values serve as starting points for trial and error refinement of the parameters.

Classical tests results

During the design of an automatic controller, the first step to validate the calibration is to test the command on a linear and a non-linear model on classical scenarios.

- Regulation scenario consists on testing the ability of the controller to reject unknown perturbations.
- Tracking scenario consists on testing the behaviour of the controller during a target variation on controlled variables.

All these test have been presented in Viala (2004), and are not reported here.

Tests on real case scenarios

The controller has been tested on a non-linear model, with perturbations extracted from de database of the General Control Centre. By this way, it can be compared to the current controller in use on the field. The scenario chosen takes place in the summer 2003, which has been especially hot and dry in France.

Since the second command (pumping station) is not a continuous command but a discrete one, a post-processing algorithm is implemented to deal with such discontinuities, which are not directly supported by the classical optimal command. The knowledge of the difference between the computed command and the applied one helps to improve the performances of the controller.

With the aim to optimise the Collet Redon reservoir, the target corresponding to the associate output (see Figure 7) has been defined such as to reach the low level at the end of the day (high electricity cost), and to reach the high level at the end of the night (low electricity cost).

The evolution of the first computed command (upstream discharge of the Trevaresse canal) is quite similar to the one applied this day on the field but stay smoother (see Figure 6). The second command (discharge at the pumping station) appears to be higher during low period, due to a better use of the volume available in the Collet Redon reservoir (see Figure 7).

The Figure 8 shows a good estimation on the w_2 perturbation during the simulation. There is no w_1 or w_3 water abstraction introduced in the simulation. The values that appear on the graph are rebuilt by the observer and are due to model errors.

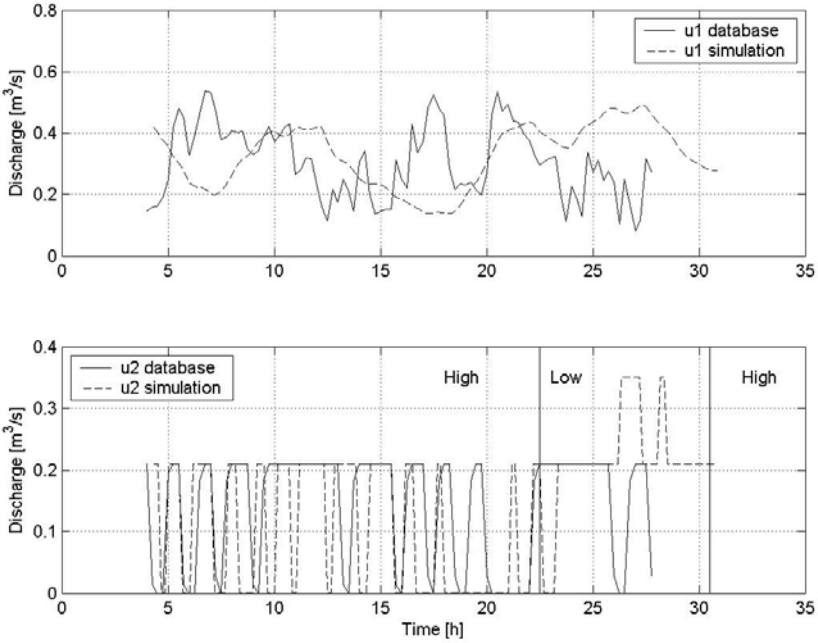

Figure 6. Commands (Commandes)

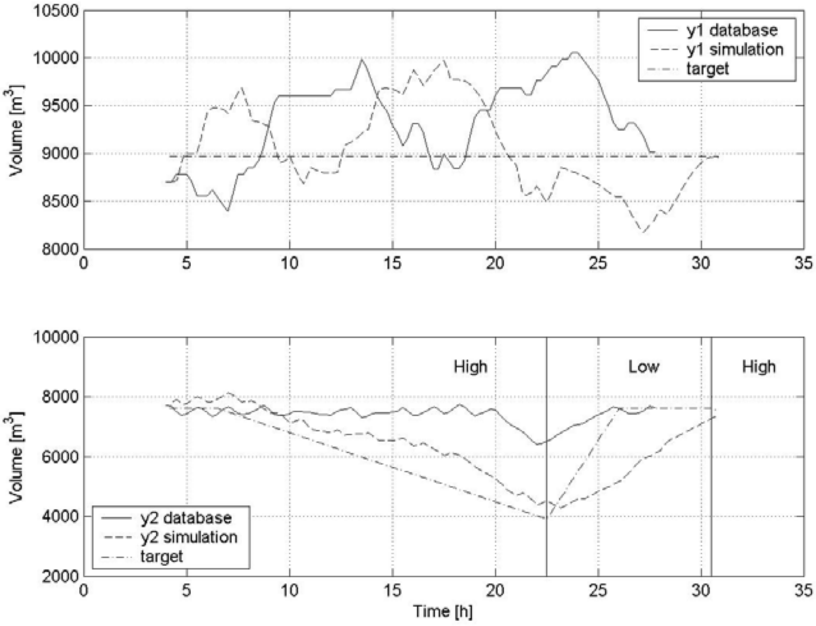

Figure 7. Controlled variables (Variables contrôlées)

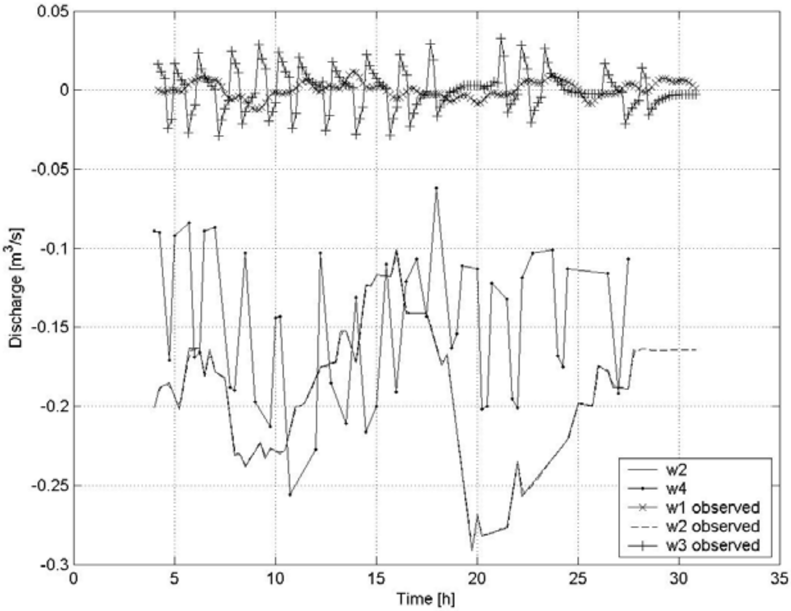

Figure 8. Perturbations (Perturbations)

7. CONCLUSION

The optimal control we have proposed aim to take into account the whole multivariable character of an irrigation canal control. This first needs a careful design of the system. However, for control purposes, the model is required to be as simple as possible. The model we proposed in section 3 fulfills these conditions. The controller appears to work well despite the discontinuous command at the pumping station. Nevertheless, testing a controller is not an easy task and realistic scenarios must be used. In the tests above, field type scenarios have been used. Now, the implementation of this controller into the dynamic regulation program running on field in Canal de Provence is in progress.

REFERENCES

Åström, K.J. and B. Wittenmark. 1997. Computer-Controlled Systems. Theory and Design. Prentice-Hall International.

Booch, G., I. Jacobson, and J. Rumbaugh. 1999. UML users guide. Addison Wesley.

Bryson, A.E., Y.C. HO. 1975. Applied Optimal Control. Hemisphere, Washington, D.C.

Corriga, G., A. Fanni, S. Sanna, and G. Usai. 1982. A Constant Volume Control Method for Open Channel Operation. International Journal of Modeling and Simulation, 2(2), 108.

Deltour, J.L. 1988. La régulation des Canaux d'Irrigation, DEA report, Société du Canal de Provence et d'aménagement de la région provençale.

Deltour, J.L. and F. Sanfilippo. 1998. Introduction of Smith Predictor into Dynamic Regulation, ASCE Journal of Irrigation and Drainage engineering. 124(1):47-55, Jan/Feb 1998.

Deltour, J.L., Y. Viala, F. Sanfilippo, and J. Sau. 2004. Dynamic regulation software migration to JAVA. Water rights and related water supply issues USCID conference. Salt Lake City. Utah, USA. October 1987.

Georges, D. and X. Litrico, 2002. Automatique pour la Gestion des Ressources en Eau. Systèmes Automatisés, Hermes. Paris.

Landau, I.D. 1993. Identification et commande des systèmes. Automatique - coll Traité des Nouvelles Technologies. Hermes, Paris.

de Larminat Ph. 1993. Commande des systèmes linéaires, Automatique - coll Traité des Nouvelles Technologies, Hermes, Paris.

Ljung, L. 1999. System Identification. Theory for the user. Prentice Hall PTR.

Malaterre, P.O. 1994. Modelisation, Analysis and LQR Optimal Control of an Irrigation Canal, Ph.D. Thesis, LAAS-CNRS-ENGREF-Cemagref. Etude EEE No. 14.

Malaterre, P.O. 1998. PILOTE:Linear Quadratic Optimal Controller for Irrigation Canals, ASCE Journal of Irrigation and Drainage engineering. 124(1):187.

Rogier, D., C. Coeuret, and J. Brémond. 1987. Dynamic Regulation on the canal de Provence . In Darell D.Zimbelman, editor, Planning, operation, rehabilitation and automation of irrigation water delivery systems – p 180-191, Portland, Oregon, July 1987.

Viala, Y. 2004. Intégration d'une commande multivariable pour la régulation des canaux d'irrigation – Application à la branche d'Aix Nord du Canal de Provence, PhD thesis. SCP – CEMAGREF – ENGREF.

Viala, Y., P.O. Malaterre, J.L. Deltour, F. Sanfilippo, and J. Sau. 2004. A mulitvariable approach for the command of Canal de Provence Aix Nord water supply subsystem, Water rights and related water supply issues USCID conference, Salt Lake City, Utah, USA, October 1987.

Welch, G. and G. Bishop. 2003. An introduction to the Kalman filter, technical report, Department of computer science – University of North Carolina.