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Data assimilation for real-time estimation of hydraulic states and unmeasured perturbations in a 1D hydrodynamic model. Application to water management problems and comparison of Kalman filter and sequential Monte Carlo approaches

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Abstract. *Scarcity of water resource and increasing competition for its use promoted recently the development of advanced control algorithms and SCADA technologies for the automatic management of open-surface hydraulic systems. In order to control hydraulic devices on irrigation canals or rivers, detailed information on the hydraulic state of the system must be available. This is particularly true when the control algorithms are based on Linear Quadratic Gaussian (LQG) or Predictive Control (PC) approaches using full state space models. Usually, the only known quantities are water levels, measured in limited locations. In this case, the design of an observer is a very useful tool for reconstructing unmeasured data, such as discharges or water levels at other locations, unknown perturbations, such as inflows or outflows, and model parameters. Several approaches are able to provide such observers. The paper illustrate the use of Kalman Filter or sequential Monte Carlo State Observer on these water management problems.*

1 Introduction

Irrigated lands contribute for more that 40% of the world food production with less than 20% of the cultivated area. Irrigation is also well-known for being responsible of more than 70% of

the fresh water withdrawal. Recent FAO figures indicate that for 2030 the food production will have to be increased by more than 80%, but with no more than 12% more water. Therefore, high levels of efficiencies of water uses are increasingly expected from the managers of irrigation canals. Hydropower production is also getting more attention in the present context of energy shortage and global warming. Automation of these systems is the best solution for allowing to reach these objectives, with many different possible approaches [5]. In order to fulfill this task, detailed information on the hydraulic state of such systems must be available. Usually, the only known quantities are the measurements performed on the hydraulic system, in limited locations. At present, no implementation of real time estimation of the complete hydraulic state of a canal or river has been realized. Only data reconciliation for daily volumes where dynamic effects can be neglected has been carried out [8]. The main causes are the noisy character of the measurements and the non-linearity of the open-channel dynamics and cross structure equations. The aim of this paper is to propose, in the open-channel hydraulic context, two approaches targeting this goal. The first one is based on Kalman filtering. Its main advantage is the computational speed compatible with real time control constraints. The second one is a new approach based on a numerical treatment of the open-channel equations associated with a Bayesian filtering using Monte Carlo method [1, 2]. This last method has the great advantage of not being subject to any linearity assumption on the model and it deals properly with the stochastic feature of the problem.

2 The hydraulic system considered

A portion of the Rhône River, between two hydropower plants managed by the Compagnie Nationale du Rhône, is selected for this study (Figure 1). This system is controlled in real time using a predictive controller based on a full Saint-Venant embedded model.

3 The open channel hydraulic model

In order to be well founded, a state estimation must be based on a proper modeling of the physical system. Cemagref is developing methodologies and software tools dedicated to consultant companies and canal or river managers allowing accurate hydrodynamic modeling [3]. The numerical tests carried out hereafter are run on the SIC hydrodynamic software developed by Cemagref [4]. This model is based on the 1D Saint-Venant equations discretized using the Preissmann implicit scheme. The equations are completed by external and internal boundary conditions such as inflows and gate equations. In order to match the typical field operating conditions, the SIC software will perform successive time steps transitions (5 min in our example), which will be called observation time steps. The numerical time step used in these successive calculations can be a smaller one (1 min in our example), so as to obtain an accurate enough description of the open channel flow.

4 Linear Kalman filter

Since the original work of Luenberger, state observers proved to be useful and are widely used in estimation and other engineering applications. In this line, the Kalman Filter, which provides a minimum variance recursive algorithm to optimally estimate the unknown states of a dynamic linear system with Gaussian uncertainties, has dominated the applications in signal processing and control areas. When the basic linear assumption is not fulfilled, Extended Kalman Filtering (EKF) has been proposed to overcome its limitations. The first step is to

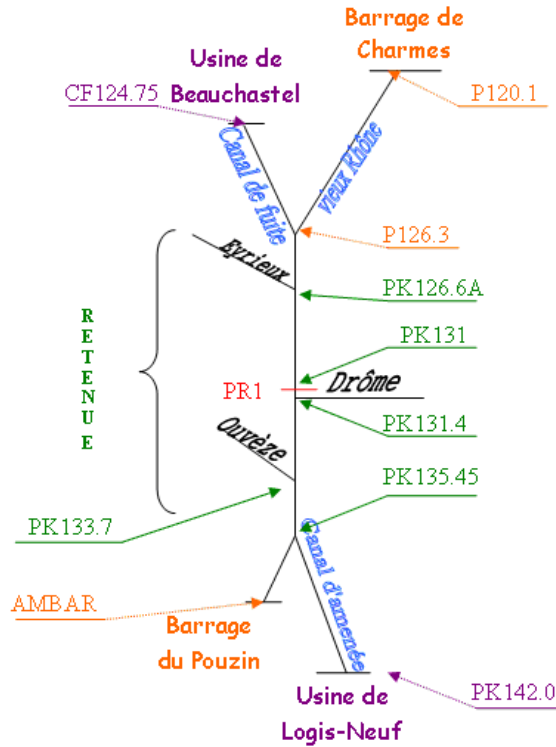


Figure 1: Portion of the Rhône river between 2 hydropower plants.

design an approximate linear model in state space form:

$$\begin{cases} x^+ = Ax + Bu + B_w w \\ y = Cx \end{cases} \quad (1)$$

where A , B , B_w and C are real constant matrices of appropriate dimensions.

This linear model is validated and compared to the full non-linear model SIC (Figure 2) for discharge change at the upstream hydropower plant from $+100$ to $+2000 m^3/s$. We can observe that for small perturbations ($+100 m^3/s$) the fitting is very good.

A Kalman Filter is first used to reconstruct unmeasured data [6]. Real-time data are used to compare and validate the methodology. But the non-linear behaviors can also be assessed for high discharge changes, when the linear approximation is no more valid. In this latter case, extended Kalman Filter or Monte Carlo approach is a good alternative.

5 Sequential Monte Carlo state estimation

We can observe that for large discharge changes that can occur when a turbine is started or stopped the non-linear effects are strong enough (Figure 2) to reduce the performance of the Kalman Filter. In this case Bayesian filtering based on Monte Carlo (MC) methods also appears to be an interesting alternative. A sequential Monte Carlo State Observer is then used to reconstruct unmeasured data.

The great increase of computational power allows resorting to MC methods which have the great advantage of not being subject to any linearity hypothesis of the model.

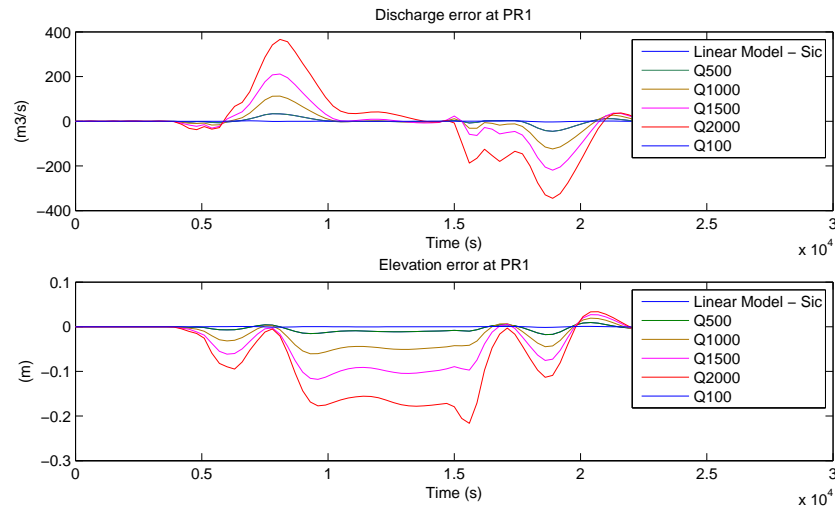


Figure 2: Comparison of state-space linear and SIC non-linear models

6 Conclusion

In this paper, we have proposed a way to estimate, in real time, the hydraulic state of a river reach from measurements. One can easily understand that this knowledge of the hydraulic state is of first importance in the current context of water resources management. Moreover, the method can be extended to the estimation of physical parameters related to the current state of the river or canal such as friction parameters.

Finally, since the application is based on Monte Carlo simulations, particular attention should be focused on the choice of the random number generator. We used Ranlux, the high quality generator based on the work of M. Luscher [9] and written by F. James [10]. This generator is asserted to have a period of 10171. It is available at the scientific library Cernlib of the CERN (European Center of Nuclear Research).

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