



Identification and control of integrative MIMO systems using pattern search algorithms: An application to irrigation channels

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ABSTRACT

This paper deals with the delay identification and control of irrigation channels, modelled as lumped-parameter time delay systems, focusing on the difficulties imposed by the transport delay. The adopted control scheme is based on a Modified Smith Predictor, where the delay estimation is implemented using a multi-model scheme in combination with a Pattern Search Method. Thus, the problem of delay estimation is reduced to an optimization problem whose solution is implemented by Pattern Search Techniques. Simulation examples show the effectiveness of the proposed technique in practice, being able to deal with constant and time-varying delays for which an excellent behaviour is obtained.

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1. Introduction

Water is the most valuable asset in the world and the management of this resource is a constant source of research. Taking into account that Agriculture is by far the largest consumer of freshwater (about 70% of all freshwater withdrawals go to irrigated agriculture, [Water Report, 2009](#)), and that the water distribution is made through irrigation channels, where water loss occurs, research focused on improving the management of irrigation channels is of great interest ([Schuermans, 1997](#)).

Different approaches to the modelling of irrigation channels have been used. Initially, hydraulic engineers used the Saint-Venant equations to model the water distribution ([Schuermans et al., 1999](#); [Weyer, 2001](#)). The Saint-Venant equations are nonlinear hyperbolic partial differential equations, which should be linearized near a steady flow regime to apply the linear Control Theory ([Schuermans et al., 1999](#)). It is quite clear that all the system dynamics are not modelled correctly with a linearized model and that the model parameters may experience changes through time, but this does not prevent the controllers based on these models from being effective in practice.

One issue that difficulties the control system design is the time delay, specially when it is unknown or time-varying. The delay can be due to three factors. First, the time it takes for the water to flow from the upstream to the downstream gate; generally, this is a large

delay. The other two factors are the distance and the signal transport medium between the actuator and the controller. Usually, these delays are small. Moreover, a variation in the delay value can cause a performance degradation of the closed-loop for a non-adaptive control loop and it can even make the system unstable. The variation of the time delay is a controversial issue. On the one hand, various studies have shown that the irrigation channels can present large time-varying delays when their discharge regimes change ([Diamantis et al., 2011](#); [Feliu-Batlle et al., 2009](#)). On the other hand, several works have shown that variation in the time delay does not affect the behaviour of irrigation channels ([Cantoni et al., 2007](#); [Weyer, 2008](#)). This disagreement can be due to the different structures, physical conditions, environment and sizes of the irrigation channels. Hence, the delay may not affect a particular irrigation channel but may have a large influence on another with different structure. Thus, under this situation, a general control scheme should include a strategy that takes into account the potential influence of time delay and its variations.

Several methodologies have been used for the control of irrigation channels. For instance, fuzzy control ([Begovich et al., 2007](#); [Durdu, 2006](#)), model predictive control (MPC) ([Negenborn et al., 2009](#)), optimization methods ([Garcia et al., 1992](#)), neural network ([Ömer Faruk, 2010](#)), robust control ([Feliu-Batlle et al., 2009](#); [Malaterre and Khammash, 2003](#)), and adaptive control ([Bolea et al., 2009](#); [Gomez et al., 2002](#)), among others. However, the most widely used solutions are probably the classical PID controllers ([Malaterre et al., 1998](#)) and those based on the Smith Predictor and its variations ([Feliu-Batlle et al., 2009, 2009](#); [Litrico and Georges, 1999](#)). Control strategies based on PID controllers

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have been used in a great variety of situations. Nevertheless, it has been shown that PID controllers exhibit a bad behaviour when the system has large time-varying delays (Malaterre et al., 1998), and the same thing happens to the Smith Predictor (SP), for which the nominal performance degrades under delay uncertainty. Therefore, the basic SP is not suitable when the delay is unknown, even slightly (Ibeas et al., 2008). Hence, time delay is generally a key point in the optimal and safe operation of irrigation channels.

Thus, in this paper we address the control of irrigation channels focusing on the delay identification. This is an adequate starting point since the closed-loop is indeed quite robust to uncertainties in the rational component (originated by the linearization of the Saint-Venant equations) but potentially sensitive to delay uncertainty (Liu et al., 2003; Liu and Gao, 2010). Consequently, delay identification is crucial to preserve the closed-loop stability and optimal operation. This is a scenario that can be encountered in irrigation channels control since, as commented before, changes in the discharge regime or changing friction conditions causes delay variations. Hence, a control scheme able to identify the external delay is presented in this paper and applied to irrigation channels control.

In this paper, the optimization problem is solved using a Pattern Search Method (PSM) which yields an estimation of the time delays of the system. The PSM has been used in Mathematics and Optimization Theory (Bogani et al., 2009; Liu and Zhang, 2006), but its use in Control is rather limited, existing very few works using it (Negenborn et al., 2009). Therefore, the application of PSM to irrigation channel control is one of the main contributions of the paper.

The PSM is implemented through a multi-model scheme (Herrera et al., 2011; Ibeas and de la Sen, 2006). The multi-model scheme contains a battery of models which are updated through time using a modification rule. Each model possesses the same rational component but a different value for the delay. The algorithm compares the mismatch between the actual system and each model and selects, at each time interval, the one that best describes the behaviour of the real system, providing an online delay estimation, while simultaneously ensuring closed-loop stability. Notice that the proposed approach can be a particularization of the Unfalsified method proposed by Safonov and Tsao (1997), where the Pattern Search method in combination with the multi-model scheme provides special formulations of the upgrading algorithms.

The present approach is based on the modified Smith Predictor (MoSP) (Majhi and Atherton, 1999), but it can be implemented on any other delay compensation scheme (DCS). The only requirement is that the delay is bounded and decoupled from the controller design procedure. The proposed PSM is framed in the General Pattern Search Method (GPSM) proposed by Torczon (1997). Consequently, the proposed method inherits the convergence properties of the GPSM, allowing for an analytical closed-loop stability analysis. Additionally, analytical results are presented to constant delays, while simulation results have been extended to time-varying ones showing the potential and applications of the proposed approach.

This paper is organized as follows. The model description is made in Section 2. The multi-model scheme and its stability analysis are presented in Section 3. In Section 4 simulation examples are shown. Finally, the conclusions are given in Section 5.

2. Problem formulation

As it is commented in Introduction, a linear model of the irrigation channels is necessary to apply linear control Theory. The linear model can be obtained from linearization of Saint-Venant equations near a steady flow regime. In this way and after a system reduction process, it is possible to obtain first and second order plus delay models. A complete explanation about how to linearize the Saint-Venant equations near a steady flow regime can be found in Baume et al. (1998).

In this paper, the linear model is based on the model proposed by Weyer (2001), which has been used in different works (Cantoni et al., 2007; Ooi et al., 2005; Ooi and Weyer, 2008; Weyer, 2008). Despite this linear model being a simple model (pure integrator plus delay), this presents major difficulties for controller design compared to the use of first or second-order systems with open-loop stable poles and input delays, since such models are always open-loop stable. A brief explanation of this model is given below.

2.1. Model description

The water level in the channel is controlled by overshoot gates located along the channel as shown in Fig. 1. Necessary measures for the control system are the water levels upstream of each gate y_i and the height of the gate p_i , $i = 1, 2, \dots, n$, with n being the number of total pools. The height of water above the gate is called the head over the gate w_{g_i} , and it is computed from the upstream water level and the gate position as $w_{g_i} = y_i - p_i$. The stretch of a channel between two gates is referred to as a pool. Along the channel there are offtakes to farms and secondary channels. In this work they are treated as disturbances d_i .

A basic mass balance applied to each pool gives

$$\frac{dV(t)}{dt} = Q_{in}(t) - Q_{out}(t) \quad (1)$$

where V is the volume of the pool, Q_{in} and Q_{out} are the inflows and outflows, respectively. For an overshoot gate, Q_{in} and Q_{out} can be written as (Bos, 1978):

$$Q_{in/out}(t) = c_{in/out} w_{g_{in/out}}^{3/2}(t) \quad (2)$$

where $Q_{in/out}$ is the inflow or outflow and $c_{in/out}$ is a parameter to be determined by system identification experiments. Assuming that the volume in a pool is proportional to the water level (Bos, 1978), the water level can be expressed as

$$\dot{y}_i(t) = c_{i,2} w_{g_i}^{3/2}(t - h_i) - c_{i+1,1} w_{g_{i+1}}^{3/2}(t) - d_i(t) \quad (3)$$

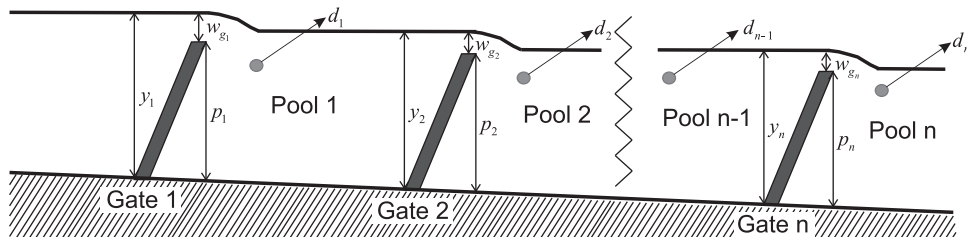


Fig. 1. Scheme of a main irrigation channel with gates.

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