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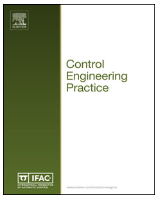

New offset-free method for model predictive control of open channels

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ABSTRACT

Irrigation or drainage canals can be controlled by model predictive control (MPC). Applying MPC with an internal model in the presence of unknown disturbances in some cases can lead to steady state offset. Therefore an additional component should be implemented along with the MPC. A new method eliminating the offset has been developed in this paper for MPC. It is based on combining two basic approaches of MPC. It has been implemented to control water levels in the three-pool UPC laboratory canal and further numerically tested using a test case benchmark proposed by the American Society of Civil Engineers (ASCE). It has been found that the developed offset-free method is able to eliminate the steady-state offset, while taking into account known and unknown disturbances.

1. Introduction

Automatic control of delivery canals has been adopted in the last years with the purpose of improving the efficiency in the management of irrigation freshwater. The idea is to automatically manipulate structures, such as gates, pumps and others, in order to achieve a control objective, which can be stated in terms of discharges or water levels. Typical control operations involve setpoint changes in these variables, according to management policies, and maintenance of such setpoints in spite of the presence of disturbances. Most common disturbances are produced due to water offtakes from the controlled canal to secondary canals or to water users. These disturbances may be known, if offtakes are scheduled in time and quantity, or unknown.

One of the control methods used to control open channels is model predictive control (MPC) (Gómez, Rodellar, & Mantecón, 2002; van Overloop, 2006; Igreja, Cadete, & Lemos, 2011; Negenborn, van Overloop, Keviczky, & de Schutter, 2009; van Overloop, Clemmens, Strand, Wagemaker, & Bautista, 2010a; Zafra-Cabeza, Maestre, Ridao, Camacho, & Sánchez, 2011; Lemos, Machado, Nogueira, Rato, & Rijo, 2009; Aguilar, Langarita, Linares, & Rodellar, 2009, 2012).

The term MPC refers to a family of control algorithms whose common property is having state and output predictions by using an internal model and carrying out an optimization using the present and future predicted data (Mosca, 1995; Martín Sánchez & Rodellar, 1996; Camacho & Bordons, 1998).

A predictive controller calculates a control action based on the difference between the existing and the predicted errors during a prediction horizon. It does not only act on the error at the first instant, but it prepares an action that would minimize the errors over the prediction horizon. If the internal predictive model was ideally correct, the controller would be able to drive the system exactly to the setpoint. However, if the model is different than the real process, or there are disturbances or noise that are not described by the model, the controller might not be able to achieve it. In particular, for constant offset-like disturbances, the controlled output could reach a steady state but with an undesired offset with respect to the setpoint. There are two main ways of eliminating the offset: (1) model the disturbances, or (2) extend the predictive controller with an integral action.

In the industry, the inclusion of disturbance models is a common prerequisite in any standard industrial MPC implementation (Venkat, Rawlings, & Wright, 2006; Camacho & Bordons, 1998) considering that the origin of the disturbances is known. Pannocchia and Rawlings (2003) and Badgwell and Muske (2002) simultaneously arrived at the same conclusions about disturbance models and deduced conditions for offset free tracking. These conditions are summarized in Borrelli and Morari (2007).

The disadvantage of disturbance models is the difficulty in tuning the observer, since very often the nature of the disturbance is unknown. Wang (2009) describes the use of a built-in integrator, but it can lead to instabilities in some cases. To solve this problem an exponential data weighting is proposed (Wang, 2001). The predictive control approach by Martín Sánchez and Rodellar (1996) proposes an

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incremental formulation, which is proved to cancel offsets for constant disturbances.

In the field of canal control, Begovich, Ruiz, Besançon, Aldana, and Georges (2007) use the internal model principle: in order to reject constant disturbances it is necessary that an integrator appears in the closed loop system, that is an internal model of the constant disturbance. Therefore they propose an augmented model, similar to that of Wang (2009), which contains a disturbance model based on integrators. The use of additional feedforward component in the control loop is described in Aguilar et al. (2009) in a predictive control scheme.

Weyer (2008) proposes a LQ regulator that can deal with known disturbances. In Cantoni et al. (2007) a feedforward term is added that also acts as a “decoupler”.

In this work a new offset-free MPC is proposed based on the predictive controller developed by Rodellar, Gómez, and Bonet (1993). This controller has zero steady state offset but cannot handle known disturbances well. The basic idea is to combine the two controllers to achieve a control that can lead to offset-free result and able to handle known and unknown disturbances. The proposed controller has been implemented and tested numerically and experimentally on the laboratory canal of the Technical University of Catalonia (UPC-PAC) and numerically on the ASCE Test Canal 2. Apart from the proposed method, other four MPC methods have been implemented numerically for comparison purposes.

This paper is structured as follows. Section 2 describes the UPC-PAC laboratory facility and the ASCE Test Canal 2. Section 3 presents the modelling issues and Section 4 presents the control developments. In order to build an offset free controller, three steps are followed: first, a basic controller is discussed (Section 4.1); second, another controller is described with integral action (Section 4.2); and finally the new offset-free predictive control is derived (Section 4.3). Additionally, in Sections 4.4 and 4.5 two methods are revised from the literature that were developed to eliminate steady state offset and are implemented in this work for comparison purposes. The test cases are presented in Section 5 and experimental and numerical results are shown and discussed in Section 6. Finally the work is concluded (Section 7).

2. Case studies

2.1. Laboratory canal

The UPC-PAC canal (Canal de Prueba de Algoritmos de Control – Universitat Politècnica de Catalunya) is specially designed to develop basic and applied research in the field of control of irrigation canals. The canal is 0.44 m wide and 220 m long and has zero slope.

In this work the canal is configured to have three pools (see Fig. 1), and each pool is separated with a motorized sluice gate. The gravity offtakes are located at the downstream end of each canal pool.

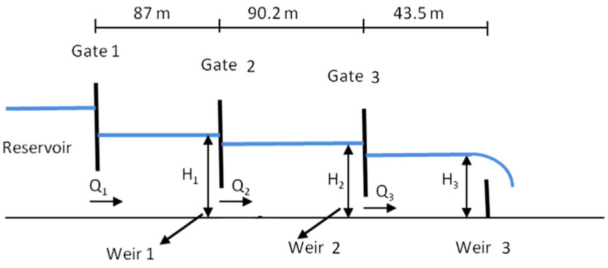

Fig. 1. Scheme of the three pool configuration of the UPC-PAC.

The SCADA system was developed in Matlab/Simulink environment, which allows the test of any control algorithm developed in Embedded Matlab language (Mathworks, 2008).

The UPC-PAC is short, completely affected by backwater. The low friction and the zero slope enhance the appearance of resonance waves. This phenomenon in the laboratory canal has been previously studied (Horváth, 2013; van Overloop, Horváth, & Aydin, 2014). it is not presented in detail herein, since this paper deals with another problem. More information about the laboratory canal can be found in Sepúlveda (2008).

2.2. The ASCE Test Canal 2

Test Canal 2 has 8 canal pools and the control objective is to keep the downstream water levels at their setpoints by controlling the gate openings in the system. Gravity offtakes are located at the downstream end of each pool. The geometry of the canal and the details of the tests can be found in Clemmens, Kacerek, Grawitz, and Schuurmans (1998).

3. Modelling

3.1. Modelling of a canal reach

A third order linear canal model is used in this work. This model was first used for simulation purposes by Weyer (2001). The model has been recently tested for control purposes (van Overloop et al., 2014). The model can be deduced from the Saint-Venant equations using the following assumptions: (1) the advection is neglected, (2) the depth, the wet cross sectional area and the hydraulic radius are considered constant. Then the Saint-Venant equations are discretized using three discretization points, then they are linearized and transformed to the Laplace domain. The result is a third order transfer function without delay, linking the upstream discharge and the downstream water level in the following form:

$$G_{IR}(s) = \overbrace{\frac{1}{A_s s}}^{\text{Integrator}} \cdot \overbrace{\frac{\omega_0^2}{s^2 + 2\zeta\omega_0 s + \omega_0^2}}^{\text{Resonance}} \tag{1}$$

Note that following this development there is no time delay in the model: the wave behaviour accounts implicitly for the time delay. Details about the model can be found in van Overloop et al. (2010b).

The integrator part has a gain that is inversely proportional to the backwater area (A_s). The second order component is a damped oscillator with natural frequency ω_0, damping ratio ζ and resonance peak M_r. A_s is the backwater area. The natural frequency ω_0 is approximated by the resonance frequency. For the ith canal reach, the downstream water level $h_i(s)$ can be expressed (van Overloop et al., 2010b) as follows:

$$h_i(s) = \frac{\omega_0^2}{A_s s^3 + \dfrac{s^2}{M_r} + A_s\omega_0^2 s} q_i(s) - \frac{2s^2 + \dfrac{2}{A_s M_r} s + \omega_0^2}{A_s s^3 + \dfrac{s^2}{M_r} + A_s\omega_0^2 s} q_{i+1}(s) \tag{2}$$

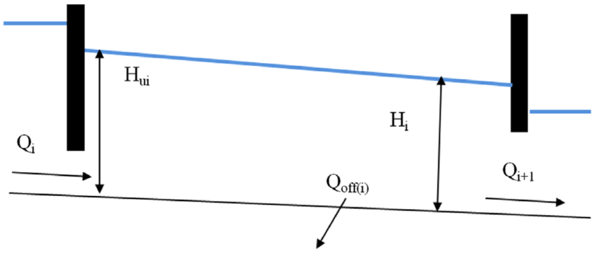

Fig. 2. Schematic view of a canal pool.