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DECENTRALISED PI CONTROL OF AN OPEN WATER CHANNEL *

Erik Weyer

CSSIP, Department of Electrical and Electronic Engineering
University of Melbourne, Parkville VIC 3010, Australia
Email: `e.weyer@ee.mu.oz.au`

Abstract: In this paper we consider decentralised PI control of the water levels in an irrigation channel. The water levels are controlled using overshot gates located along the channel, and the output of the controllers is the head over gate. This choice of manipulated variable is advantageous since the head over gate is directly related to the flow over the gate. The PI controllers are augmented with a first order low pass filter in order to ensure a low gain at the resonant wave frequency. A distant downstream controller configuration with feedforward is used. In this configuration a gate controls the water level immediately upstream of the next downstream gate. The controllers are tuned based on simple linear system identification models using frequency response methods, and the designed controllers have shown very good performance in field tests. The water levels recovered smoothly from disturbances without excessive oscillations, and the deviations from setpoints were small.

Keywords: PI control, irrigation channel, environmental systems, system identification models

1. INTRODUCTION

Water is becoming an increasingly scarce resource throughout many parts of the world today, and it is therefore important to manage water resources well and minimise the losses. This is particularly important in networks of irrigation channels where the losses can be large. One reason for the losses is the conflicting demands on the water delivery system. Not only should the losses be minimised, but the channels must also be able to deliver water to the farmers on demand. As it can have dramatic consequences for the rural sector if water is not delivered on time, irrigation channels tend to be operated conservatively with relatively large volumes of water in the channels. As there are few opportunities for recapturing water that is not used, having large water volumes in the channels leads to increased losses.

As the level of instrumentation and automation in channel networks increase, there is a large potential for reducing the losses via better prediction and control of the irrigation channels. In most irrigation channels the water levels are the controlled variables, and the gate positions are the manipulated variables. The two most common control strategies in the literature are to use either decentralised PI controllers or a centralised LQ or predictive controller, see Malaterre and Baume (1998) for an overview.

In this paper we consider decentralised PI control of an irrigation channel controlled by overshot gates. Although we expect a centralised LQ or predictive controller to give better performance, decentralised PI control has advantages when it comes to ease of design and implementation. As irrigation channels are in rural areas and the gates are considerable distances apart, the measurements and control signals are sent over a radio network. Since decentralised PI control only requires local information, the communication requirements are much less than for a centralised con-

* A patent has been applied for to cover the developments that are described in this paper.

troller. Moreover, in many systems existing controller configurations are able to realise decentralised PI controllers, so the control strategy can be implemented relatively easily. Decentralised PI control also serves as a useful benchmark for assessing the performance of more advanced controllers.

The models we use for control design were obtained from system identification experiments on the channel (Weyer (2001)). The controller configurations we consider in this paper are similar to those in Malaterre and Baume (1999) and Schuurmanns et. al. (1999). However, since the irrigation channel is equipped with overshot gates there is no need for the "slave controller" used in those papers. Both control of a single and multiple reaches are studied, and comparisons of controllers with and without feedforward are made. The controllers were tested at the Haughton Main Channel (HMC) in Queensland, Australia.

This work is part of an ongoing research project between the University of Melbourne and Rubicon Systems, Australia on system identification and control of networks of irrigation channels.

The paper is organised as follows. In the next section, a description of the HMC and the models used for control design are given. Section 3 is devoted to a discussion of the control problem. Control design and results from the field tests are presented in Section 4, before conclusions are given in Section 5.

2. MODELS OF THE HAUGHTON MAIN CHANNEL

The water levels in the HMC are controlled by overshot gates located along the channel as sketched in Figure 1. The measurements we have available are the water level upstream of each gate and the gate position. All water levels are given in mAHD (meters Australian Height Datum) which are relative to a reference level. The height of water above the gate is called the head over the gate. The stretch of a channel between two gates is referred to as a reach or a pool.

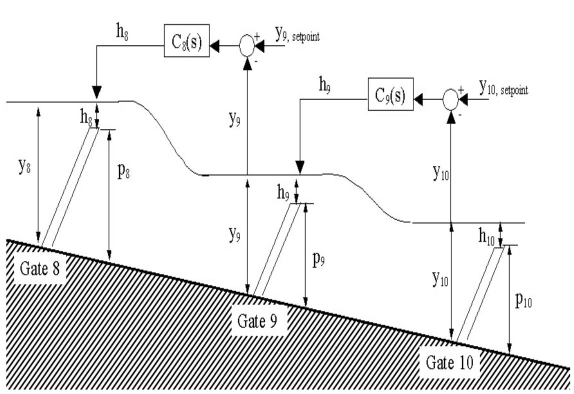

Fig. 1. Sideview of irrigation channel with distant downstream controller configuration.

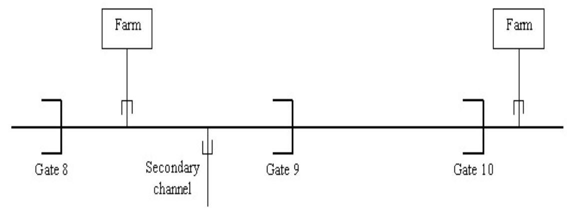

Fig. 2. Topview of irrigation channel with farms and secondary channel.

Along the channel there are offtakes to farms and secondary channels feeding off the main channel, see Figure 2. The flow out of the channel at these offtakes varies with demand. Usually one would not have measurements at these offtakes, and they are treated as disturbances, although in many cases the water authorities do have information about the anticipated offtakes since the farmers have to order their water in advance.

The controller task is to keep the water level on setpoint (see Section 3), and hence we seek models for the water levels. A basic mass balance gives

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

where V is the volume of the pool Q_{in} and Q_{out} the in- and outflows. Bos (1978) suggests that the flow over an overshot gate can be approximated as

$$Q(t) = ch^{3/2}(t) \tag{1}$$

where Q is the flow, h the head over the gate and c an unknown parameter. This approximation assumes that the gate is in free flow, meaning that the top of the gate is above the downstream water level. This is always the case for the reaches of the HMC we consider since there is a drop in bed elevation just after the gates.

Assuming that the volume in a pool is proportional to the water level and ignoring offtakes, we arrive at

$$\begin{aligned}\dot{y}_9(t) &= \tilde{c}_{in} h_8^{3/2}(t-\tau) + \tilde{c}_{out} h_9^{3/2}(t) \\ &= \tilde{c}_{in} h_8^{3/2}(t-\tau) + \tilde{c}_{out}(y_9(t) - p_9(t))^{3/2}\end{aligned} \tag{2}$$

where referring to Figure 1, y_9 is the water level upstream of gate 9, h_i the head over gate i, $i = 8, 9$, and p_9 the position of gate 9. A time delay τ has also been included to account for the travel time from the upstream to the downstream gate. This model structure is the same as the integrator-delay model used by Schuurmanns et. al. (1999) with flow equation given by (1). For control design, the linear model

$$\begin{aligned}\dot{y}_9(t) &= c_{in} h_8(t-\tau) + c_{out} h_9(t) \\ &= c_{in} h_8(t-\tau) + c_{out}(y_9(t) - p_9(t))\end{aligned} \tag{3}$$

was used. A discussion of the two model structures from a control design point of view is given in Section 4.3.1.

Pool	Length (m)	c_{in}	c_{out}	τ (min)
8	1600	0.014	-0.017	6
9	900	0.046	-0.042	3
10	3200	0.009	-0.010	16

Table 1. Pool lengths and model parameters

The unknown parameters of the models were found from system identification experiments using discrete time models (Weyer (2001), Ooi and Weyer (2001)), and it was shown that the models tracks the main trends in the water levels very well.

The controller tests were carried out on pool number 8 to 10 at the HMC, where the pool number is given by the upstream gate, i.e. Figure 1 shows pool 8 and 9. The parameters of the linear models are given in Table 1 together with the length of the pools. More accurate higher order models were also obtained from the system identification experiments, and these models have been used in the simulations.

3. CONTROL OBJECTIVES AND CONTROLLER CONFIGURATION

3.1 *Objectives*

The overall goal is that the irrigation channel should be able to deliver water to the farmers on demand, and at the same time minimise the wastage of water. Traditionally, since the offtakes to the farms are gravity fed, i.e. no pumping, this requirement has been translated into setpoint regulation of the water levels, and this is the problem we consider here. It is, however, an open question if this is the best way to achieve the overall goal; this issue will not be addressed in this paper.

The main "disturbances" acting on the system are the scheduled and unscheduled offtakes to farms and secondary channels. The water level setpoints do change with operational conditions, but these changes are relatively rare, so disturbance rejection is more important than tracking set point changes.

3.2 *Controller configuration*

The most suitable decentralised controller configuration for demand driven irrigation channels is distant downstream control, where a gate controls the water level immediately upstream of the next downstream gate. See Figure 1. The input to the controller is the deviation between measured water level and setpoint, and the output of the controller is the head over the gate. This a more natural choice of manipulated variable than gate position since the head over gate is directly related to the flow over the gate; see (1).

3.3 *Controller specifications*

Just from observing the irrigation channel or looking at water level data (Weyer (2001)), it is clear that there are waves present in the channel. The wave frequencies are multiple of each other and the lowest frequency is usually the dominant one. We refer to this frequency as the wave frequency. In order not to amplify these waves, it is important to have a low controller gain at the wave frequency, and the PI-controllers are therefore augmented with a first order filter. Their transfer functions are given by

$$C(s) = \frac{K(1+T_i s)}{T_i s(1+T_f s)} \tag{4}$$

This observation and augmentation has also been made by Schuurmanns et. al. (1999). Initially we specified somewhat arbitrary a gain margin of at least 6dB, a phase margin of at least $45°$, and a maximum controller gain at the wave frequency of -14 dB. The specified gain margin is usually achieved once the gain at the wave frequency satisfies the specifications. As we gained more experience and confidence the requirements were relaxed, and the controllers presented here have different robustness margins, reflecting our experience and confidence at the time of design.

3.4 *Controller tuning*

The controllers used in this paper were all tuned using frequency response techniques which can be found in any standard text book (e.g. Franklin et al. (1994), or Ogata (1997)). Subject to the robustness margins, we tried to achieve as high bandwidth as possible. After the initial design, the response to setpoint changes and disturbances was simulated, and the controller parameters were fine tuned a bit. After an initial field test the integral action was adjusted in some of the controllers. However, no elaborate optimisation of the controller parameters took place.

4. CONTROL DESIGN AND PERFORMANCE

4.1 *Control of a single pool*

Here control of a single pool where the downstream gate is in a fixed position is considered. With reference to Figure 1, we control the water level y_{10} when p_{10} is constant using gate 9. This situation does occur in channels which are only partly automated. The positions of the gates that are not automated are changed manually usually once a day, and its position is calculated based on the demand for water further downstream using the assumption that the water level immediately upstream of the gate is on set point.

As the downstream gate is in a fixed position, it is natural to base the control design on a first order plus time delay model (see (3)):

$$y_{10}(s) = \frac{c_{in} e^{-\tau s}}{s + c_{out}} h_9(s) \tag{5}$$

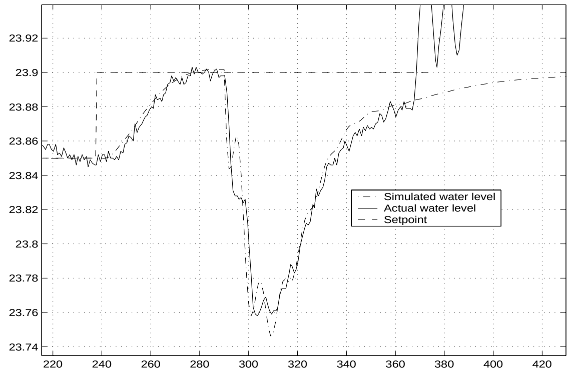

Fig. 3. Field test of controller for pool 9. Water level in meters (mAHD). The time unit is minutes.

A controller was designed for pool 9 with $T_i = 25$, $T_f = 8.3$ and $K = 1.25$. This controller had a gain of -14 dB at the wave frequency and a phase margin of $60°$.

The controller was tested the HMC under the following conditions. First the setpoint was increased by 0.05m, and when the new set point had been reached, the downstream gate (gate 10) was dropped by 0.3m. The effect of dropping the gate is similar to a disturbance in the form of a sudden increase in the outflow to a farm or a secondary channel feeding off the pool.

The response is shown in Figure 3. The oscillations at time 370 minutes are due to the test being stopped at that time. The water level tracks the setpoint change well and recovers smoothly from the disturbance. Moreover, there is excellent agreement between the simulation model and the real irrigation channel.

4.2 *Control of several consecutive pools*

4.2.1. *Models and controllers* In steady state the inflow and outflow of a pool are equal, and under normal operating conditions they are also constant. This means that the controllers keep the head over the gates constant. Suppose a disturbance occurs in pool 8 on Figure 1, e.g. an increase or decrease in an offtake. The controller which actuates gate 9 will not see this disturbance since it controls the next downstream water level, y_{10}, and provided no disturbances occur there it will maintain a constant head over gate 9. Equation (3) can be written as (ignoring the effect of the offtakes)

$$\dot{y}_9(t) = c_{in} h_8(t - \tau) + d$$

where d is a constant, which means that the model

$$y_9(s) = \frac{c_{in} e^{-\tau s}}{s} h_8(s) \tag{6}$$

i.e. an integrator with time delay, should be used for control design.

We can take advantage of the availability of downstream measurements, and introduce feedforward action. From equation (3) we have

$$y_9(s) = \frac{c_{in} e^{-\tau s}}{s} u_8(s) \tag{7}$$

where $u_8(t) = h_8(t) + \frac{c_{out}}{c_{in}} h_9(t + \tau)$.

Again, this is an integrator with time delay model. The head over gate is now given by $h_8(t) = u_8(t) - \frac{c_{out}}{c_{in}} h_9(t+\tau)$ where $u(t)$ is the output of the controller. This equality does depend on future signals, so in practice we will use $h_8(t) = u_8(t) - \frac{c_{out}}{c_{in}} h_9(t)$, i.e. we use feedforward from the downstream head. Physically this makes sense since information about a disturbance downstream is transmitted upstream faster. There is a possibility that the feedforward term will excite the wave frequency so the downstream head is lowpass filtered, and the gain in the feedforward path is reduced. The total controller with feedforward for pool 8 is

$$\begin{aligned} u(s) &= C_8(s)(y_{9,\text{setpoint}}(s) - y_9(s)) \\ h_8(s) &= u_8(s) - K_{ff} F(s) \frac{c_{out}}{c_{in}} h_9(s) \end{aligned}$$

where K_{ff} is the feedforward gain, and $F(s)$ is a low pass filter. The same controller configuration is also used for pool 9 and 10. In Malaterre and Baume (1999) and Schuurmanns et. al. (1999) the feedforward term is called a decoupler since it reduces the dynamic influence of the downstream pool on the upstream pool.

The filters used are second order Butterworth filters with cut off frequency around half the wave frequency and $K_{ff} = 0.75$. The controllers were tuned using frequency response methods. The gains at the wave frequencies were now around -10 dB, and the phase margins around $30°$.

4.2.2. *Field tests* During the test gate 11 maintained a given head over gate 11, and gate 8, 9 and 10 were controlled by the augmented PI controller with feedforward from the downstream head.

The controllers were implemented in discrete time using an Euler approximation for the augmented PI controller. The sampling interval was 1 minute for pool 9 and 2 minutes for pool 8 and 10. At time 0 minutes all water levels were in steady state at setpoint. At time 270 the head over gate 11 was increased from 0.12 m to 0.30 m. Then at time 520 the setpoint in pool 9 was reduced from 23.80 to 23.75 mAHD, and at time 600 the head over gate 11 was reduced back to 0.12 m. The changes in head over gate 11 have the same effect on the water levels as if an offtake took place in pool 10.

In order to reduce the wear and tear there was a 0.015m deadband on gate position movements, i.e.

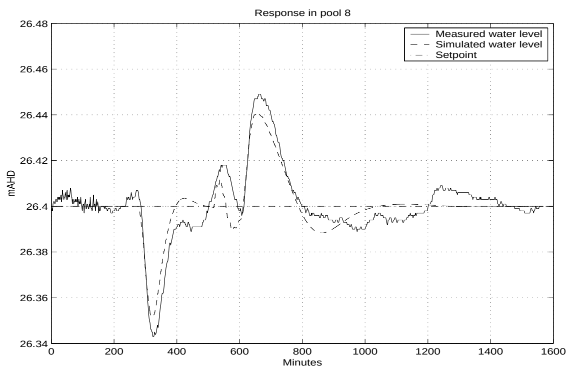

Fig. 4. Field test pool 8.

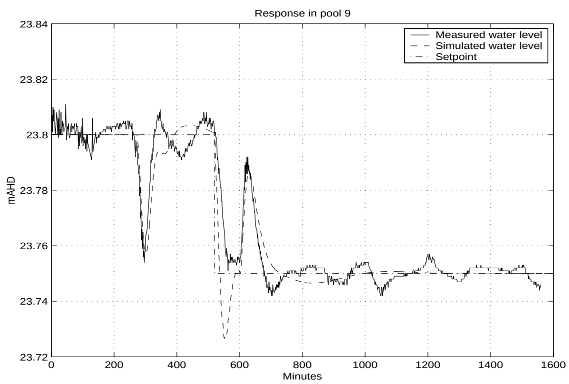

Fig. 5. Field test pool 9.

if the calculated gate position was less than 0.015m away from the current one, the gate did not move. For this reason the water levels do not stabilise exactly on setpoints, and the deadband is also the reason behind the slow oscillations around setpoints which can be observed, particularly in pool 9.

The water level responses are shown in Figure 4 to 6, where we have also included the simulated responses. From the figures it can be seen how the effect of a change in the head over gate 11 travels upstream. The controllers show excellent performance. The water levels recovers smoothly with no excessive wave motion to their setpoints. The maximum deviation from setpoint is only about 0.05m which is very good. The response times are about twice as fast as the open loop response times.

There is also very good agreement between the actual water levels and the simulated ones, although the initial maximum deviation from setpoint after a disturbance or a setpoint change is sometimes a bit larger in the simulations, but the difference rarely exceeds 0.02m. Also note that the only external data used in the simulations were the water level setpoints, the head over gate 11 and the initial water levels.

4.2.3. *Controllers with and without feedforward*
Figures 7 and 8 show the response in pool 9 and 10 for augmented PI controllers with and without feedforward from the downstream head. The initial

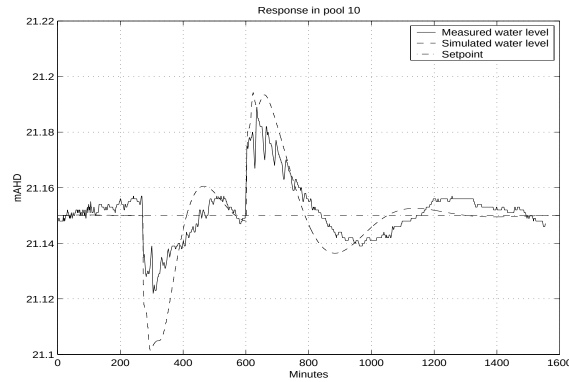

Fig. 6. Field test pool 10.

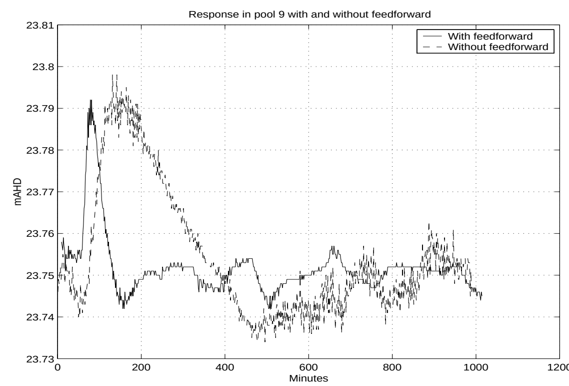

Fig. 7. Water level in pool 9. Augmented PI controllers with and without feedforward

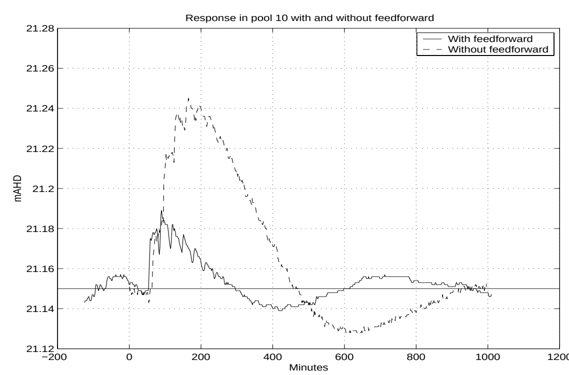

Fig. 8. Water level in pool 10. Augmented PI controllers with and without feedforward

disturbance is due to that the head over gate 11 was reduced from 0.30m to to 0.12m. The responses are much better with feedforward. It should however be said that the comparison is not 100 % fair since the controller for pool 10 was retuned between the tests, and there is more integral action in the controller used together with feedforward. Another issue which complicates the comparison is that gate 9 saturated in a fully closed position when there was no feedforward (antiwindup was implemented). Despite this, it is clear that the performance is much better with feedforward, and simulation studies have also shown this. The maximum deviation from setpoint is smaller, and the water levels are back on setpoint much quicker.

4.3 *Discussion*

4.3.1. *Nonlinear models for control design* A natural extension of the design in Section 4.2.1 is to use the nonlinear models

$$\dot{y}_9(t) = \tilde{c}_{in} h_8^{3/2}(t-\tau) + \tilde{c}_{out} h_9^{3/2}(t) \qquad (8)$$

which are accurate over the whole flow regime. Introducing $u(t) = h_8^{3/2}(t) + \frac{\tilde{c}_{out}}{\tilde{c}_{in}} h_9^{3/2}(t+\tau)$ equation (8) can be written as $\dot{y}(t) = \tilde{c}_{in} u(t-\tau)$ which is the same as model (7) with different parameters $\tilde{c}_{in}$ and $\tilde{c}_{out}$. The head over gate is calculated as $h_8(t) = \left(u(t) - \frac{\tilde{c}_{out}}{\tilde{c}_{in}} h_9^{3/2}(t)\right)^{\frac{2}{3}}$. Intuitively, one would think that faster responses could be achieved over the whole flow regime by basing the control designs on these models. However, the design specification which imposes the biggest limitation on the speed of response is that the gain at the wave frequency should be low, and since $(A + B\sin\omega t)^{\frac{2}{3}} \approx A^{\frac{2}{3}} + 2/3A^{-\frac{1}{3}}B\sin\omega t$ assuming B/A small, the gain is increased when the "average head" A is less than 0.3 m. Simulation studies have also shown that there is relatively little to be gained by using the model (8) for control design due to the requirement of a low gain at the wave frequency.

4.3.2. *Feedforward from scheduled offtakes* The water authorities do have information about the scheduled offtakes in advanced, and this information could be incorporated into the control strategy using feedforward action. However, simulation studies have shown, that unless the offtake occurs on time, and is not say put forward or pushed back an hour by the farmer in a last minute decision, which does happen, there is not much to be gained by using feedforward from scheduled offtakes.

5. CONCLUSIONS

In this paper we have considered decentralised PI control of an irrigation channel with overshot gates. The PI controllers have been augmented with a first order lowpass filter in order to ensure a low gain at the resonant wave frequency. The output of the controllers is the head over gate which is advantageous since it is directly related to the flow over the gate. The designed controllers have shown excellent performance in field tests at the HMC, and the water levels recover smoothly from disturbances without excessive oscillations and only small deviations from setpoint. Using feedforward from the downstream head over gate gives much improved responses in terms of response times and deviations from setpoints.

The results presented also demonstrate that there is a large potential for improving the performance of networks of irrigation channels by using modern system identification and control techniques. The commercial implementation of this technology by Rubicon Systems throughout the Australian irrigation industry is resulting in improved water use and water distribution efficiencies. This work is expected to have impact at a national water resource management level leading to significant environmental benefits.

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Patent. A patent has been applied for to cover the developments that are described in this paper.

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