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On Water-Level Error Propagation in Controlled Irrigation Channels

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Abstract— **We consider the propagation of water-level errors in a controlled string of (identical) pools comprising an open-water irrigation channel. It is shown that water-level errors are amplified as they propagate upstream, whenever the feedback control scheme is *decentralised* and load-disturbance rejection is required in steady-state. Moreover, a design trade-off is identified between local performance, in terms of set-point regulation and load-disturbance rejection, and the error-propagation characteristics. The use of feed-forward/decoupling paths is considered in terms of managing this trade-off. However, the corresponding analysis suggests it is difficult to exploit the extra degree of freedom. Finally, we investigate a so-called *distributed* generalisation of the decentralised schemes. This leads to an optimal control based framework for dealing with the design trade-off.**

Index Terms— **Decentralised and distributed control, Disturbance propagation, Irrigation networks, Control design**

I. Introduction

On a global scale, irrigation accounts for approximately 70% of all fresh water usage [1]. The distribution of fresh water for this purpose is typically achieved via an extensive civil infrastructure of reservoirs and open water channels. In large-scale networks (e.g. 1000's of kilometers of channels), water is transported under the power of gravity (i.e. no pumping) and the flow of water through the network is regulated by gates located along the channels, as illustrated in Fig. 1. The stretch of water between two gates is called a pool. Indeed, the open water channels in an irrigation network can each be thought of in terms of a string of pools linked by the gates.

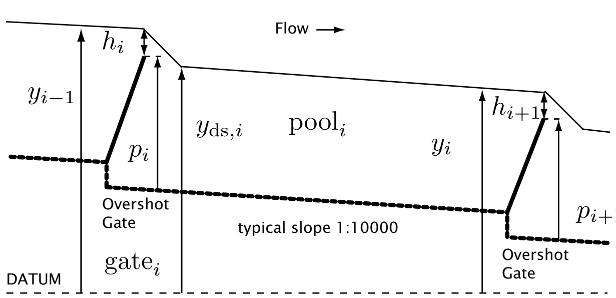

Fig. 1. Stretch of an open water channel with overshot gates

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Water off-take points to farms and secondary channels occur along the network channels. Within a single pool, these points are typically located towards the downstream end. The supply of water at the off-take points is also commonly powered by gravity, with flow demand satisfied by ensuring water levels (i.e. potential energy) remain above reference levels, while managing the loss associated with over-supply. To this end, one can employ automatic controllers which impose gate positions on the basis of measured water levels [2], [3], [4], [5], [6], [7], [8], [9]. This can lead to significant benefits in terms of reduced water losses [10].

In this paper, we investigate how the water-level error resulting from an off-take load disturbance in one pool propagates along an irrigation channel under different feedback control information structures. In particular, with reference to Fig. 1, the following three control schemes are considered:

- *Decentralised feedback*, in which the head h_i over gate_i is controlled using the measured water level y_i in pool_i;
- *Decentralised feedback with feed-forward*, in which both y_i and h_{i+1} are available for controlling the head h_i over gate_i;
- A so-called *distributed* generalisation of the decentralised schemes, in which neighbouring decentralised feedback compensators can exchange information.

Understanding the water-level error propagation characteristics is important from the perspective of overall system performance and the fact that error amplification can result in actuator saturation if not appropriately managed.[1]

Note that under each of the control schemes just described the downstream water-level in a pool (where most of the off-takes are located) is effectively regulated via the corresponding upstream gate. As such, control actions are always delayed, because it takes time for water to travel from the upstream end to the downstream end of a pool. This ultimately limits achievable performance [12]. But these control schemes yield better overall system performance in terms of water wastage, compared to systems in which the downstream water level is effectively regulated via the downstream gate [2], because the water-level is being controlled via the flow into the pool from the source, rather than via the flow out. Moreover, although one could expect better performance with a centralised control scheme (see [3] and [4] for example), such schemes are, by and large, impractical from the perspective of the communications infrastructure required, particularly for large-scale systems in remote areas.

Briefly, the paper is organised as follows. In Section

[1] An anti-windup bumpless-transfer augmentation of controllers for irrigation channels is described in [11].

II, we present an irrigation channel model for feedback control. This model is used in the subsequent analysis of system behaviour under each of the three controller structures identified above. The corresponding analysis is presented in Sections III, IV and V, respectively. This analysis is similar in spirit to that presented in [13], where the disturbance propagation characteristics of controlled vehicle strings are considered. Concluding remarks are given in Section VI.

II. An irrigation channel model for control

A side-view of a stretch of channel is illustrated in Fig. 1, where in pool_i the symbols p_i and h_i denote the position and the head over gate_i, respectively, and y_i denotes the water level at gate_{i+1}. The following pool model, which is based on conservation of mass, was recently proposed in [14], [15]:

$$\pi_i(\frac{d}{dt})y_i(t) = \gamma_i h_i^{3/2}(t-\tau_i) - \gamma_{i+1}h_{i+1}^{3/2}(t) - d_i(t), \quad (1)$$

where the $h_i^{3/2}$ and $h_{i+1}^{3/2}$ terms are proportional to the flow over gate_i and gate_{i+1}, respectively, d_i models water off-take disturbances and τ_i is the time delay associated with the time it takes for water to travel the length of the pool. The polynomial $\pi_i(\cdot)$ characterises the dynamics, and for pools of up to several kilometers in length, it can be taken to be of third order. This corresponds to an integrator, for the mass balance, and a lightly damped oscillatory mode, to capture the characteristics of the dominant standing wave. While the pool model (1) is much simpler than the traditional non-linear Saint-Venant equations [15], [16], [17], [18], its parameters are readily obtained via linear identification techniques and it is able to explain experimental data very well [14], [19], [20], [21], [22]. Moreover, it is more tractable from the perspective of control design. In fact, provided local control-loop bandwidths are constrained to lie at frequencies below the corresponding dominant wave frequency, the first-order model

$$\alpha_i \frac{d}{dt}y_i(t) = \gamma_i h_i^{3/2}(t-\tau_i) - \gamma_{i+1}h_{i+1}^{3/2}(t) - d_i(t), \quad (2)$$

where α_i is a measure of pool surface area, is adequate for control design [15], [23].

Now linearising via the change of variable $u_i := \gamma_i h_i^{3/2}$, which is a measure of the flow over gate, and applying the Laplace transform, yields the frequency domain model

$$P_i \;:\; y_i(s) = \frac{1}{s\,\alpha_i}\Big(\exp(-s\tau_i)u_i(s) - v_i(s) - d_i(s)\Big), \quad (3)$$

where

$$v_i(s) = u_{i+1}(s)$$

with the boundary condition $v_N \equiv 0$ (i.e. no flow over the last gate),[2] and for ease of notation no distinction is made between the time-domain and frequency-domain representations of a signal. Indeed, as a whole, the irrigation channel model can be thought of as a string of pool models (3), as illustrated in Fig. 2. This is the model employed in the subsequent sections of the paper.

[2]Provided the water level y_N remains sufficiently close to set-point the flow over the last gate can always be independently controlled to be 0. This is important since water which passes the last gate is usually wasted.

III. Decentralised feedback control

As mentioned in the introduction, a key control objective is to maintain the water level in each pool at a set point. In particular, set-point regulation is required in the face of off-take disturbances. In this section, we consider the decentralised control scheme shown Fig. 3. Note that

$$u_i(s) = C_i(s)e_i(s) := C_i(s)(r_i(s) - y_i(s)).$$

As such, the control action at gate_i is determined on the basis of the local water-level set-point r_i and the measured water level y_i communicated from gate_{i+1}. As detailed in [6], [24], [25], the design of each feedback compensator C_i can be carried out from the perspective of achieving good local set-point regulation and disturbance rejection, using the ideas of classical loop-shaping. This corresponds to treating v_i in (3) as part of an overall disturbance, and focusing on the local closed-loop transfer functions

$$T_{r_i\to e_i}(s) := \frac{1}{1+L_i(s)\exp(-s\tau_i)},$$

$$T_{d_i\to e_i}(s) := \frac{1}{1+L_i(s)\exp(-s\tau_i)}\left(\frac{1}{s\,\alpha_i}\right),$$

and

$$T_{d_i\to u_i}(s) := \frac{L_i(s)}{1+L_i(s)\exp(-s\tau_i)},$$

via the local loop-gain shape $|L_i(j\omega) := C_i(j\omega)/j\omega\,\alpha_i|$. Note that by the final value theorem, $C_i(s)$ must have at least one pole at $s=0$ to achieve zero steady-state error for step load disturbances.

For the decentralised control structure just described, an off-take disturbance in a pool results in a water-level error relative to the set point, producing a control action which in turn acts as a disturbance in the upstream pool. To understand this error-propagation phenomenon, consider for the sake of argument a string of *identical* pools, each with delay τ and surface area α. Furthermore, suppose the same decentralised feedback compensator $C(s)$ for each pool. In this case, the transfer functions from the set-point reference and disturbance to the water-level error are given by

$$T_{r_i\to e_i}(s) = \frac{1}{1+L(s)\exp(-s\tau)} = s\,\alpha\,T_{d_i\to e_i}(s) \quad (4)$$

and the water-level error propagates according to the transfer function

$$T_{e_{i+1}\to e_i}(s) := \frac{L(s)}{1+L(s)\exp(-s\tau)},$$

where $L(s) := C(s)/s\,\alpha$. This is intuitively a worst-case scenario because the local loop-gain bandwidths in neighbouring pools are identical in this case and hence, there can be significant coupling of control action upstream. Observe, in particular, that

$$T_{r_i\to e_i}(s) + T_{e_{i+1}\to e_i}(s)\exp(-s\tau) = 1.$$

Hence, with (4), note the trade-off between local performance, in terms of set-point regulation and load disturbance

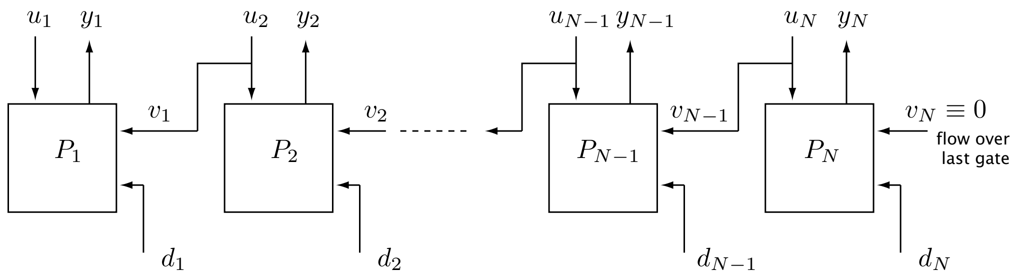

Fig. 2. Irrigation channel modelled as a string of N pools with dynamics (3)

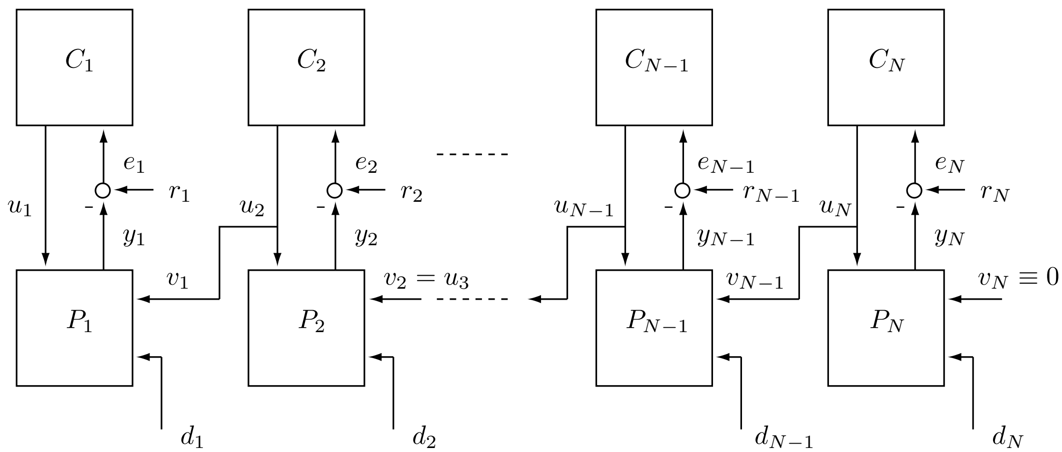

Fig. 3. Decentralised feedback control

rejection, and performance in terms of the propagation of the water-level error.

Fig. 4 shows a simulation of the deviation from set-point of the closed-loop water-levels in the three identical pools pool_1, pool_2 and pool_3, where there is an off-take disturbance in pool_3 and the flow over the downstream gate is regulated to zero. The simulation uses the third-order model (1) for each pool, with $\tau = 16$ mins, $\alpha = 43806\text{m}^2$, $\pi(\xi) = \alpha\xi(\xi^2 + 2\zeta\omega_n\xi + \omega_n^2)/\omega_n^2$, and ζ and ω_n chosen to satisfy $\varphi = \omega_n\sqrt{1-\zeta^2} = 0.2$ rad/min. The controller employed is a simple integrator with lead compensation:

$$C(s) = \kappa(1 + s\phi)/s(1 + s\rho), \tag{5}$$

where $\kappa = 7.72$, $\phi = 128$ and $\rho = 15.2$. The local disturbance rejection performance is good. See, in particular, the water-level deviation in pool_3. However, it can be seen that a component of the error is being amplified as it propagates upstream. In fact, the following analytical result implies water-level errors are amplified with any linear decentralised compensator $C(s)$ that achieves zero steady-state error in the face of step load disturbances.

Proposition 1: Let $C(s)$ be any proper rational transfer function such that $C(s)$ has a pole at $s = 0$ and the local closed-loop transfer function

$$T_{r_i \to e_i}(s) := \frac{1}{1 + L(s)\exp(-s\tau)}$$

is stable, where $L(s) := C(s)/s\,\alpha$. Then there exists an

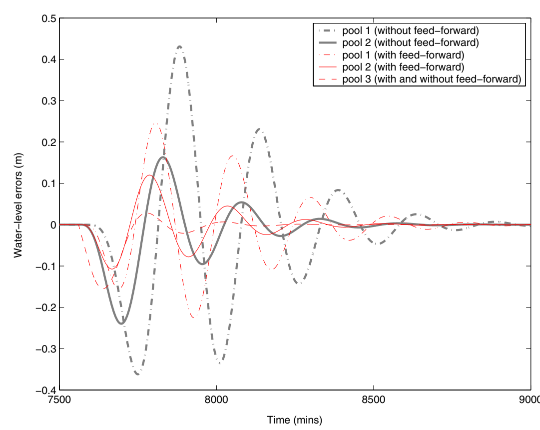

Fig. 4. Water-level error amplification in identical pools under decentralised feedback control with and without feedforward compensators $F_i(s) = F(s) = \frac{0.75 \times 0.0136}{s^2 + 0.165s + 0.0136}$ – see Sec. IV

$\hat{\omega} \in [0, \infty)$ such that $|T_{e_{i+1} \to e_i}(j\hat{\omega})| > 1$, where

$$T_{e_{i+1} \to e_i}(s) := \frac{L(s)}{1 + L(s)\exp(-s\tau)}.$$

Proof: As described in [12, Chap. 9], applying Cauchy's Theorem to

$$\int_{\mathcal{D}} \frac{1}{s^2} T_{e_{i+1} \to e_i}(s)\, ds,$$

where $\mathcal{D}$ is the standard Nyquist contour with an indentation around the origin in the complex plane, yields

$$\int_0^\infty \ln |T_{e_{i+1}\to e_i}(j\omega)| \frac{d\omega}{\omega^2} \geq 0.$$

Since $T_{e_{i+1}\to e_i}(s)$ is strictly proper, this implies the existence of a frequency $\hat{\omega}$ such that $\ln |T_{e_{i+1}\to e_i}(\hat{\omega})| > 0$. ■

We observe that that amplification of the water-level error arising from a load disturbance, is similar in nature to the propagation of a disturbance in vehicle strings, as discussed in [13].

IV. Decentralised feedback control with additional feedforward

The amplification of water-level errors can lead to actuator saturation and water losses through spillage. This problem can be viewed in terms of disturbances to the flows out of the pools. In particular, control action taken at gate_{i+1} to compensate for an off-take in pool_{i+1}, for example, disturbs the flow $v_i = u_{i+1}$ out of pool_i. This, in turn, results in a water-level error in pool_i and hence, control action at gate_i, and so on. In the purely decentralised feedback scheme considered above, these out-flow disturbances are treated as unknown. On the other hand, one would expect improved performance if knowledge of the disturbances were utilised. This is in fact possible, as a measure of the control action at gate_{i+1} can be made available at gate_i, without additional communication infrastructure. This yields the decentralised feedback with feed-forward scheme described in Sec. I and shown in Fig. 5. Note in particular, that the head over gate_i is now controlled according to

$$u_i(s) = C_i(s)e_i(s) + F_i(s)u_{i+1}(s),$$

where each feed-forward compensator $F_i(s)$ is a stable transfer function designed to manage the error propagation characteristics of the closed-loop, given decentralised feedback compensators $C_i(s)$ designed as described above, to achieve good local set-point regulation and load disturbance rejection.

Again, for the sake of argument consider a string of identical pools each with delay τ and surface area α. Furthermore, suppose that the same feedback compensator $C(s)$, of the form (5), and feed-forward compensator $F(s)$ are used for each pool. In this case the water-level error propagation characteristics are governed by the transfer function

$$T_{v_i\to e_i} := \frac{1}{s\,\alpha}\left(\frac{1 - F(s)\exp(-s\tau)}{1 + L(s)\exp(-s\tau)}\right)$$

from v_i to e_i in each pool and the relationship

$$v_i(s) = C(s)e_{i+1}(s) + F(s)v_{i+1}(s),$$

where $L(s) := C(s)/s\,\alpha$. Combining these yields the following relationship between the water-level error in neighbouring pools:

$$e_i(s) = T_{e_{i+1}\to e_i}(s)e_{i+1}(s),$$

where

$$T_{e_{i+1}\to e_i}(s) := \frac{L(s) + F(s)}{1 + L(s)\exp(-s\tau)}.$$

Observe that by augmenting the decentralised feedback compensators with the decentralised feed-forward compensators $F(s)$, an extra degree of freedom has been gained in terms of managing the error propagation characteristics. Indeed, as can be seen in Fig. 4, the inclusion of the feed-forward (or decoupling) paths can improve the error-propagation characteristics of the controlled system. Fully exploiting the additional freedom offered by the feed-forward paths, however, appears to be difficult. In particular, for a decentralised feedback compensator of the form (5) and under the constraint that the open-loop transfer function $F(s)$ be proper and stable, it follows that $|T_{e_{i+1}\to e_i}(0)| = 1$. Moreover, by observing that at sufficiently low frequencies

$$L(j\omega) \approx \frac{-\mu}{\omega^2}$$

for some $\mu > 0$, it can be shown that

$$\frac{d}{d\omega}|T_{e_{i+1}\to e_i}(\omega)| > 0$$

for $\omega << 1$. Hence, as before without the feed-forward paths, there always exists a frequency $\hat{\omega}$ such that $|T_{e_{i+1}\to e_i}(j\hat{\omega})| > 1$. Furthermore, in order to achieve a reduction in $|T_{e_{i+1}\to e_i}(j\omega)|$ where $|L(j\omega)|$ is large (e.g. within the loop-gain bandwidth), $F(j\omega)$ must be of comparably large magnitude. In this case, the gain from the flow disturbance v_i, resulting from control action taken in pool_{i+1}, to the water-level error e_i is large, since $|T_{v_i\to e_i}(j\omega)|$ behaves like $\frac{1}{\omega\alpha}$. Indeed, experience suggests that the best one can do is ensure that $|T_{v_i\to e_i}(j\omega)|$ is reasonably small within the bandwidth of the loop-gain $|L(j\omega)|$, while ensuring that $|T_{e_{i+1}\to e_i}(j\omega)|$ is not much greater than 1 at any frequency.

V. Optimal distributed control

In this section, an optimal control approach is proposed for systematically managing the performance trade-off identified above. The approach is based on the H_∞ loop-shaping paradigm of McFarlane and Glover [26] and recently developed tools for solving structured optimal control problems that are parametrised in terms of state-space realisations [27].

Fig. 6 illustrates a so-called distributed generalisation of the decentralised feedback with feed-forward control information structure of Fig. 5. Here, the water-level reference r_i and off-take disturbance d_i have been lumped into the signal $n_i := \left(\begin{smallmatrix} n_{y,i} \\ n_{u,i} \end{smallmatrix}\right)$, where $n_{y,i} := \left(\begin{smallmatrix} r_i \\ d_i \end{smallmatrix}\right)$ and $n_{u,i}$ models an additional disturbance on the flow at gate_i. For the case of identical pools, each $G_i = \left(\begin{smallmatrix} v_i \\ n_i \\ u_i \end{smallmatrix}\right) \mapsto \left(\begin{smallmatrix} w_i \\ z_i \\ e_i \end{smallmatrix}\right)$ has the generalised pool transfer function

$$G(s) = \begin{pmatrix} 0 & \begin{pmatrix} 0 & 0 & 1 \end{pmatrix} & 1 \\ \begin{pmatrix} \frac{1}{s\alpha} \\ 0 \end{pmatrix} & \begin{pmatrix} 1 & \frac{1}{s\alpha} & \frac{-e^{-s\tau}}{s\alpha} \\ 0 & 0 & 0 \end{pmatrix} & \begin{pmatrix} \frac{-e^{-s\tau}}{s\alpha} \\ 1 \end{pmatrix} \\ \frac{1}{s\alpha} & \begin{pmatrix} 1 & \frac{1}{s\alpha} & \frac{-e^{-s\tau}}{s\alpha} \end{pmatrix} & \frac{-e^{-s\tau}}{s\alpha} \end{pmatrix},$$

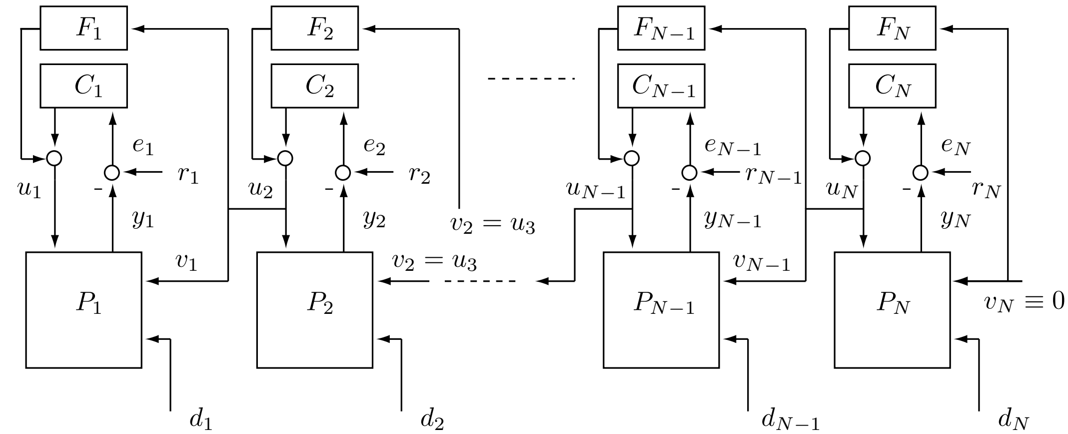

Fig. 5. Decentralised feedback control with additional feed-forward of downstream flow

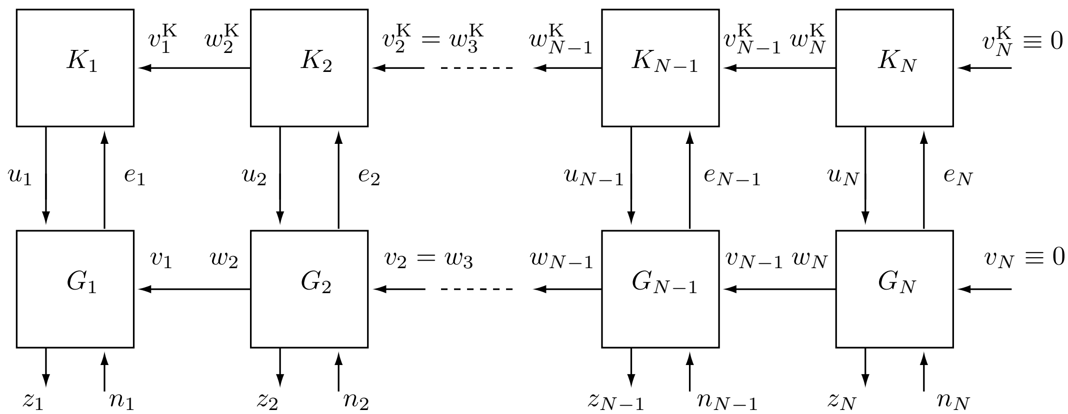

Fig. 6. Distributed control

and the interconnection is characterised by the constraint $v_i = w_{i+1}$ for $i = 1, \ldots, N-1$. In line with the first-order pool model (3) and the decentralised control schemes considered above, the signal $z_i = \left(\begin{smallmatrix} e_i \\ u_i \end{smallmatrix}\right) = \left(\begin{smallmatrix} r_i - y_i \\ u_i \end{smallmatrix}\right)$ and $w_i = u_i + n_{u,i}$. Accordingly, the control objectives discussed above can be posed in terms of minimising the collective effect of the exogenous signals n_i on the signals z_i. This is achieved with the distributed controllers $K_i = \left(\begin{smallmatrix} v_i^K \\ e_i \end{smallmatrix}\right) \mapsto \left(\begin{smallmatrix} w_i^K \\ u_i \end{smallmatrix}\right)$, under the interconnection constraint $v_i^K = w_{i+1}^K$ for $i = 1, \ldots, N-1$.

In [28], it is shown that optimally synthesised controllers for spatially-invariant distributed systems tend to exhibit localised behaviour. As such, it is often reasonable to use an infinite-extent representation of the system for the purposes of synthesis. Importantly, this can result in scalability of the associated optimisation problem and its solution – see [27]. In light of this, we now consider an optimal controller synthesis problem for an infinite interconnection of the generalised plants described above, from which the distributed controllers K_i are subsequently obtained.

Use of the 2-norm, over both the temporal and spatial domains, to characterise the control objectives in terms of the signals n_i and z_i, leads to an optimisation problem cost similar to that employed in the H_∞ loop-shaping design framework [26]. In line with this paradigm, consider the infinite-extent interconnection of the *weighted* generalised plants

$$\begin{aligned} \hat{G}_i(s) \; &:= \; \begin{pmatrix} \hat{v}_i(s) \\ \hat{n}_i(s) \\ \hat{u}_i(s) \end{pmatrix} \mapsto \begin{pmatrix} \hat{w}_i(s) \\ \hat{z}_i(s) \\ \hat{e}_i(s) \end{pmatrix} \\ &= \; \hat{G}(s) := G(s) \begin{pmatrix} I_{3\times 3} & 0 \\ 0 & C(s) I_{2\times 2} \end{pmatrix}, \end{aligned} \qquad (6)$$

where $\hat{v}_i = \hat{w}_{i+1}$ for $i \in \mathbb{Z}$ and $C(s)$ is a compensator achieving a desired local loop-gain shape $|L(j\omega)| = |C(j\omega)/j\omega\alpha|$. This spatially-invariant interconnection corresponds to the weighted open-loop mapping $\hat{\mathbf{G}} = (\ldots, (\hat{n}_{-1}, \hat{u}_{-1})^T, (\hat{n}_0, \hat{u}_0)^T, (\hat{n}_1, \hat{u}_1)^T, \ldots) \mapsto (\ldots, (\hat{z}_{-1}, \hat{e}_{-1})^T, (\hat{z}_0, \hat{e}_0)^T, (\hat{z}_1, \hat{e}_1)^T, \ldots)$. The proposed synthesis problem is now to find a 2×2 transfer function $\hat{K}^\star(s)$ to minimise the induced 2-norm of the closed-loop mapping $\mathbf{H}(\hat{G}, \hat{K}^\star) = (\ldots, \hat{n}_{-1}, \hat{n}_0, \hat{n}_1, \ldots) \mapsto (\ldots, \hat{z}_{-1}, \hat{z}_0, \hat{z}_1, \ldots)$, achieved with the spatially-invariant controller $\hat{\mathbf{K}} = (\ldots, \hat{e}_{-1}, \hat{e}_0, \hat{e}_1, \ldots) \mapsto (\ldots, \hat{u}_{-1}, \hat{u}_0, \hat{u}_1, \ldots)$ obtained by the infinite-extent interconnection of the compensators

$$\hat{K}_i(s) := \begin{pmatrix} \hat{v}_i^K(s) \\ \hat{e}_i(s) \end{pmatrix} \mapsto \begin{pmatrix} \hat{w}_i^K(s) \\ \hat{u}_i(s) \end{pmatrix} = \hat{K}^\star(s),$$

under the constraint $\hat{v}_i^K = \hat{w}_{i+1}^K$ for $i \in \mathbb{Z}$. As in the H_∞ loop-shaping framework for design, the weight C in (6) is then absorbed into $\hat{K}^\star$ to yield the transfer function for the required compensators

$$K_i(s) = \begin{pmatrix} v_i^K(s) \\ e_i(s) \end{pmatrix} \mapsto \begin{pmatrix} w_i^K(s) \\ u_i(s) \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & C(s) \end{pmatrix} \hat{K}^\star(s),$$

$i = 1, \ldots, N$. Importantly, the optimisation problem by which $\hat{K}^\star(s)$ is obtained above can be characterised in terms of a convex programme of size proportional to the order of the generalised pool transfer function $G(s)$ and the weight $C(s)$, using the tools developed in [27]. For further details see [29].

A simulation of the resulting closed-loop behaviour under a distributed controller synthesised according to the procedure just described, for the pool model and weight $C(s)$ described in the preceding sections, is shown in Fig. 7. Observe the improvement in error-propagation performance. This appears to be a result of less aggressive control action and correspondingly, degraded local disturbance rejection performance as expected.

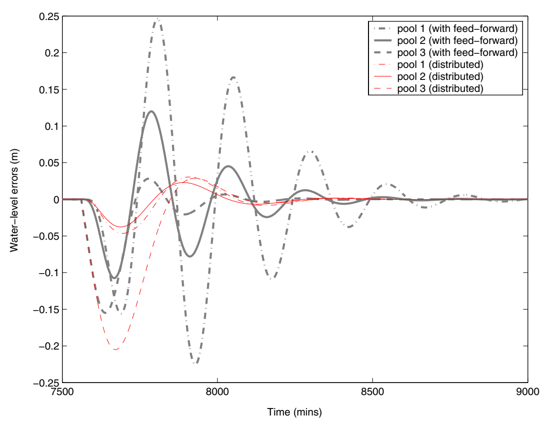

Fig. 7. Water-level error propagation under distributed control

VI. Conclusion

In this paper, we considered the error propagation characteristics of controlled irrigation channels. It is shown that, under decentralised control structures, a component of the water-level error arising from an off-take disturbance is always amplified as it propagates upstream, even with additional local feed-forward/decoupling paths for downstream flow information. Furthermore, a trade-off is identified between local set-point regulation and disturbance rejection performance and the error-propagation performance. An optimal control approach to managing this trade-off is investigated in terms of a so-called distributed generalisation of the decentralised schemes.

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