# BEHAVIOUR OF CYCLE AVERAGING DRAIN CONTROLLERS FOR IRRIGATION IN GREENHOUSES

**G. van Straten[1], J.D. Stigter[1], Th. H. Gieling[2]**

*[1]Wageningen University, Systems and Control, Wageningen,*
*[2]Plant Research International, Wageningen UR, Wageningen*
*The Netherlands*
*corresponding author's e-mail: gerrit.vanstraten@wur.nl*

Abstract: Controllers that keep average drain flow constant, automatically compensate for crop water uptake. As irrigation is done in pulses, the issue is to what extend the water content is depleted during the episode between drain pulses. The two controllers investigated are a linear output feedback controller, and a simple heuristic controller. There is little theory to analyse controllers with time varying cycle duration. Practical experience and simulation show that both controllers are able to keep accumulated drain-flow on the desired path. The heuristic controller is easy to set up, but the output feedback controller leads in general to less depletion. 

Keywords: irrigation, greenhouses, output feedback, switched input, cycle averaging

## 1. INTRODUCTION

Keeping, on average, the drain flow constant, automatically compensates for the evapotranspiration losses of the crop. Provided that the water content in the substrate remains sufficiently high, no water stress will occur. Such a feedback system has advantages over the common feed-forward control by radiation based dosage, as it will eliminate the need to adjust the irrigation proportionality coefficient to changes in leaf area, moisture conditions within the greenhouse, and other factors, that influence the evapo-transpiration, such as EC.

Kläring (2001) reviews control strategies for water and nutrients. Feedback control of water supply is rare. Nemali and Van Iersel (2006) describe an on-off controller for pot plants, based on the measurement of the volumetric moisture content using a dielectric moisture sensor. They reported good results, although the on-off controller resulted in large off-sets at low water contents. While measurement directly in the root zone is the preferred method, there may be problems with uneven distribution of irrigation flow over many plants, as well as individual differences between plants. Moreover, due to gradients in the root zone, proper representative placement of the sensors is not easy.

Sigrimis *et al.* (2001) developed a system that adjusts the evapo-transpiration parameters used in the feed-forward controller on the basis of long term drain measurements, thus providing a form of feedback. This has the advantage that an adjusted evapo-transpiration model becomes available as a by-product. Due to the averaging procedure over number of cycles short term deviations are not immediately noticed.

In earlier work, Gieling et al. (2000, 2005) developed feedback controllers for the regulation of drain flow of a representative measurement gully of the type depicted in Figure 1. Drain flow is measured with a tipping bucket or other flow metering device. This set-up does not require advanced equipment for measuring the condition in the slab, and gives feedback on the time-scale of each irrigation event.

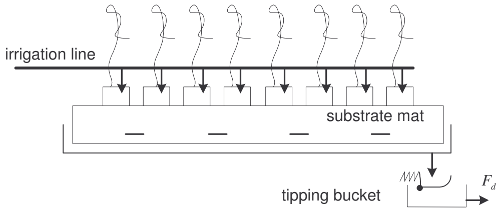


Fig. 1. Measurement Gully.

In current greenhouse practice, the supply of irrigation water is done in pulses, for reasons of economy and robustness of operation. This means that it is not possible to really keep the drain flow constant. Rather, the drain will come in pulses as well. As a consequence the water potential in the root zone will fluctuate, despite the control. This has possibly effects on the root development of the crop and it may lead to temporary water stress. It is therefore relevant to investigate what happens with the water content within the duration of each irrigation episode.

This part of the study is not unique to feedback controllers, as it occurs in all discrete event irrigation systems. Nevertheless, the depletion of the water content is an important evaluation criterion when it comes to adoption of automatic control of irrigation. Other factors are the general applicability of the controllers and the effort needed for adaptation of the design to various environments, and the robustness to system parameter variation during operation.

## 2. OBJECTIVES

The purpose of this work is to revisit two controller designs that were shown to work well in practice, and to analyse the performance in terms of these factors. The controllers differ in terms of design effort, and they also differ in number of parameters and settings needed.

The organization of this paper is as follows. First, the design of an output feedback linear state space controller is described (OFB), based on an observer model derived from identification experiments. This is the first controller. The second controller is a simple heuristic controller (SC) based on matching the cumulative measured drain with the cumulative set-point flow. Both controllers work well in practice. As the controllers were developed in different projects it was not possible to compare their behaviour in situ in extensive comparative experiments. In stead, in this paper the evaluation is performed on the basis of mathematical analysis and simulation. To this end, a model is derived that will serve as the virtual real plant. This model consists of a simple non-linear mass balance differential equation for the gully. Finally, *in silico* experiments are done to compare both controllers, and to assess factors that determine the depletion during an irrigation episode.

## 3. CONTROLLER DESIGN

### *3.1 Linear Output Feedback Controller (OFB)*

Prior to the design of the controller an identification experiment was done, using an output error estimation method of the form

$$y(k) = \frac{B(q)}{F(q)}u(k) + e(k)\ . \tag{1}$$

The result was a second order model with input delay one. This model was converted to equivalent discrete state space form

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \end{aligned} \tag{2}$$

Figure 2 shows the fit of the model. The model parameters are presented in the Appendix

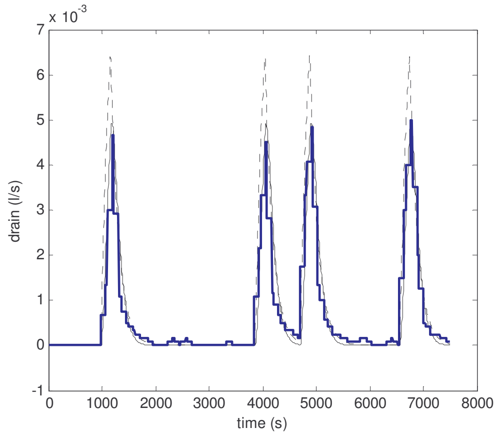


Fig. 2. Identification result. Blocked thick line: observed data, continuous line: 2-state linear model output. Dashed line: non-linear virtual system model (see below).

The linear output feedback controller (Åström and Wittenmark, 1997) has an observer based on this model of the form

$$\begin{pmatrix}\hat{x}(k+1)\\ \hat{v}(k+1)\end{pmatrix} = \begin{pmatrix}A & B\\ 0 & 1\end{pmatrix}\begin{pmatrix}\hat{x}(k)\\ \hat{v}(k)\end{pmatrix} + \begin{pmatrix}B\\ 0\end{pmatrix}u(k) + \ldots \\ \begin{pmatrix}L\\ L_v\end{pmatrix}\left(y(k) - \begin{pmatrix}C & 0\end{pmatrix}\begin{pmatrix}\hat{x}\\ \hat{v}\end{pmatrix}\right) \tag{3}$$

where *x, u, y* are the states, control input and output, respectively, and $v$ is an extra integral state to accommodate load variations (water uptake).
The controller is

$$u(k) = -F\hat{x}(k) - F_v\hat{v}(k)\ , \tag{4}$$

where the observer gains $L$, $L_v$ and the controller gain $F$ are obtained by pole placement, such that a compromise is reached between response speed and sufficient stability margin. $F_v$ is set to 1.

In the actual implementation the difference between output and reference is fed to the controller. This amounts to the so called tracking-error estimator for handling the reference input (Franklin et al., 2002). This approach may lead to overshoot, but was considered sufficient here as set-point changes are not very important in this application.

It is important to note that the control cannot be realised at each control instant, because of the pulse-wise irrigation. Therefore, the irrigation flow desired by the controller ( $u_k$ ) is translated into an equivalent time ratio between on and off, according to

$$T_{cycle}^{j} = \frac{1}{u_k} F_{i,\max} t_{on} \qquad (5)$$

where $T_{cycle}^{j}$ is the length of cycle *j*, and $F_{i,\max}$, $t_{on}$ are fixed parameters representing the irrigation pump flow rate, and the on-time, respectively, see Figure 3. The new cycle starts as soon as at any time the elapsed time since the start of the current episode surpasses $T_{cycle}^{j}$ .

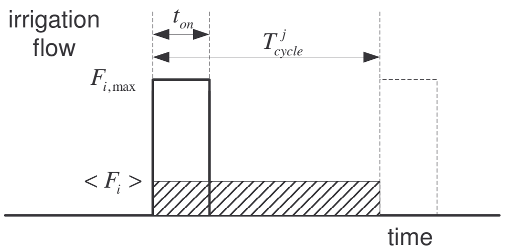


Fig. 3 Time varying irrigation flow cycle.

*3.2 Simple Heuristic Controller (SC)*

The basis of this approach is simple: as soon as the difference between the cumulative drain flow becomes less than the accumulated desired drain flow, a new irrigation pulse is given. This difference is coined 'deficit'. A negative value indicates water surplus. So, if

$$\int_{t_o^j}^{t_o^j + T_{cycle}^j} \left(F_{d,sp} - F_d\right) dt \geq 0 \ , \qquad (6)$$

or, for constant set-point, if

$$F_{d,sp} T_j^{sp} \geq \int_{t_o^j}^{t_o^j + T_{cycle}^j} F_d dt \qquad (7)$$

a new cycle begins. One could view the deficit as the state of this controller. Note that it is possible that directly after the on-time is over, a new pulse is given. In the actual implementation there is an option to wait during an additional time before another pulse is given, in order to allow cycling over various dripping sections, but this is not explored in this paper.

*3.3 Practical application*

Figure 4 shows the performance of the heuristic controller in an experiment over 18 days. During the day the average drain flow was kept at 1 L/h. The top figure shows the deficit. On days with deficits substantially higher than one there were technical problems.

## 4. MATERIALS AND METHODS

*4.1 Virtual gully system*

In the evaluation of controller performance, the simple model was used as a replacement for the true system. The mass balance equation is

$$V \frac{d\theta(t)}{dt} = F_i(t) - F_d(t) - W(t) \qquad (8)$$

where $V, \theta, F_i, F_d, W$ are the substrate volume, volumetric water content, irrigation flow rate, drain flow rate and water uptake, respectively. Darcy's law governs the drain flow $F_d(.)$. In practice, the drain shows an exponential pulse response, which suggests

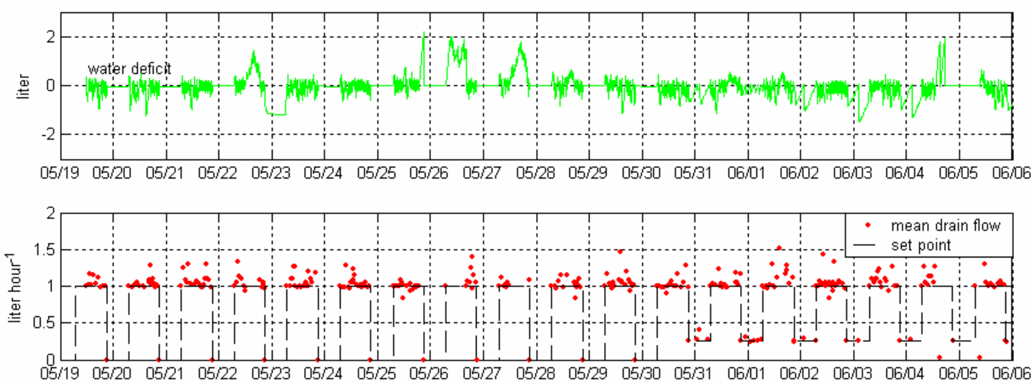


Fig. 4. Practical performance of heuristic controller (pers. comm. G.J. van Dijk, 2006). The top shows the deficit (negative values mean water surplus), the bottom the target and realised (episode averaged) drain flow.

that it can be approximated by a first order process. However, below saturation, no water leaves the mat. This leads to the constitutive equation

$$F_d(t) = \max(0, p(\theta - \theta_o)) \qquad (9)$$

where $\theta_o$ is the water retention capacity, and $p$ is a parameter that was determined by calibration.

Although a gross oversimplification of the true system - in particular in relation to spatial distribution within the substrate - the fit in Figure 2 gives sufficient confidence in the suitability for the purpose of this paper. Notice that $F_i(t) \in \{0, F_{i,\max}\}$ i.e. the input signal is quantized on two levels only.

### 4.2 Water uptake

The systems were subject to real solar radiation data. An identified first order state model relates solar radiation to water uptake. The three days differed in radiation sum, as can be seen in Fig 5.

### 4.3 Episode averaged drain

In order to evaluate the controller performance it is necessary to calculate drain averages. This is not as straightforward as it may seem, as the period between drain events is time variable. In this paper the episode averaged drain is defined as the average drain measured between the first non-zero drain pulse and the next. When a second peak overlaps with the previous one this is not counted as a separate episode, although the amount of water is, of course, accounted for. Unlike in the real system, it was assumed that the drain flow is monitored with a fixed, adjustable sampling rate (5 s).

### 4.4 Experiments in silico

Both controllers were tested *in silico* on the test gully, using Matlab/SIMULINK. The gully data are given in the Appendix. The standard run length was three days. The irrigation on-time was set equal to 3 minutes, unless otherwise stated. The performance was judged for the ability to keep the episode averaged drain constant, and to the degree of depletion. It should be noted that, obviously, average drain only will be available at the end of an episode, of which the length is not known *a priori*.

The following virtual experiments were done:
- standard controller performance
- effect of the drain flow monitoring sampling rate
- robustness test by varying system parameters
- effect of time-on.

## 5. RESULTS

### 5.1 Standard controller performance

Figure 5 shows the controller performance for both the simple controller (SC) as well as the Output Feedback Controller (OFB). It can be seen that the OFB has some problems with set-point changes, as expected, but overall both controllers can keep the episode averaged drain constant quite well. However, the depletion of the water content during an episode is less with the OFB than with the SC (see Figure 6).

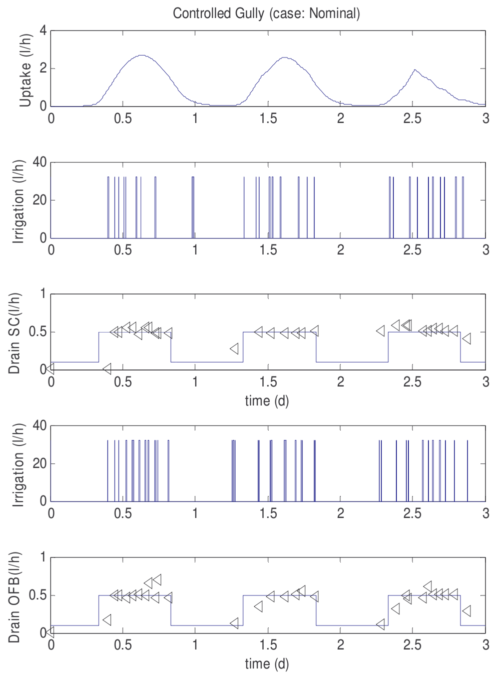


Fig. 5. Control actions (irrigation) and output variable drain (triangles) for three consecutive days. Top row shows uptake due to solar radiation. Row 2 and 3 are for SC, rows 4 and 5 for OFB.

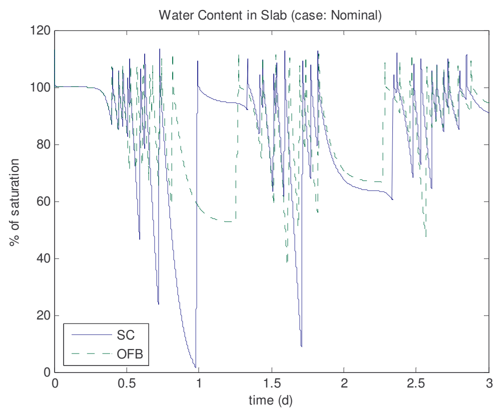


Fig. 6. Evolution of the water content over three days with the two controllers, showing the depletion, as percentage of the retention capacity of the substrate mat.

*5.2 Effect of monitoring sampling rate*

Increasing the monitoring sampling interval from 5 s to 60 s gives some deterioration of controller performance (see Table 1). In addition, there are shifts in the moments of irrigation. The OFB remains somewhat better with regard to depletion. With a monitoring sampling time of 5 minutes there are prolonged periods of dryness, in particular with the simple controller. This is due to the fact that the sampler makes the controllers believe that an observed drain lasts for at least 5 minutes. This is much more water than is realistic, and hence, less irrigation is invoked. It is therefore important that the sampling rate is faster than the duration of a drain pulse.

Table 1. Effect of monitoring interval on percentage of time with depletion below certain value

| monitoring interval (s) | % of time < 80% of saturation SC | % of time < 80% of saturation OFB | % of time < 60% of saturation SC | % of time < 60% of saturation OFB |
|---|---|---|---|---|
| 5 | 20 | 17 | 10 | 4 |
| 60 | 30 | 24 | 15 | 4 |
| 300 | 58 | 46 | 45 | 17 |

*5.3 Robustness*

A smaller water retention was invoked by increasing parameter $p$ 3-fold. Overall, the controllers can handle this situation. Because the resistance against drain is lower, somewhat less water retention is observed. The opposite is true if $p$ is reduced, which means higher water retention. The simple controller has longer pause periods, and when drain comes, it needs a series of pulses to catch up. The effect is, overall, more water depletion. The controllers still perform well when the volume is increased.

*5.4 Effect of on-time*

Figure 7 shows the effect of the on-time on the water depletion time distribution. The plot shows the percentage of total time that the water content is less than a certain percentage of the saturation value.

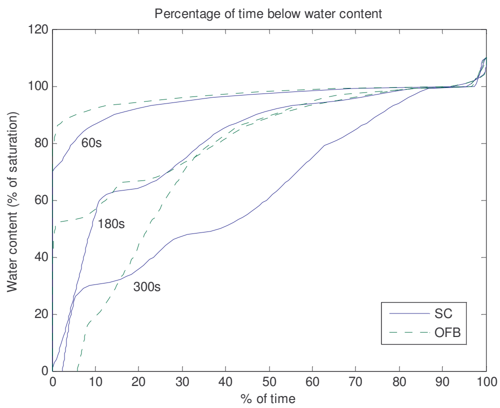


Fig. 7. Effect of on-time on depletion of water content. Graph shows percentage of time that water content is less than a certain percentage.

At first sight one might think that the appropriate response to large water depletion would be to increase the irrigation pulse time. However, this is not correct in combination with the controllers. Shorter pulses make the controller more responsive (with continuous control in the limit). The prevention of depletion requires short, more frequent pulses.

## 6. ANALYSIS

*6.1 Number of cycles*

The number of irrigation cycles during a day is dictated by the overall water balance. When the controller is successful, there is the following relation between the cumulative irrigation, drain and uptake over period $T$:

$$NF_{i,\max} t_{on} = \int_{t}^{t+T} (F_{d,sp} + W(t))dt \qquad (10)$$

where $N$ is the number of cycles. Since all other variables are set by design, $N$ is determined by the autonomous water uptake. In the depletion range where the water potential is high enough to sustain the demanded uptake, various distributions of the irrigation over time are feasible, and may still lead to more or less constant drain. This is clearly seen from plots like Figure 5. This argument applies to both controller and does not explain the difference in degree of depletion of both controllers.

*6.2 Cycle averaged analysis*

Unlike the case of standard pulse width modulation, a theory on analysing the behaviour of controllers with time varying (and state dependent) cycle duration is lacking. Cycle averaged analysis would not solve the problem of what happens in the period between pulses. It can be stated, in view of (8) that the depletion after a drain pulse stops, denoted by $t_z$, which is given by

$$\theta(t_z + T^j_{cycle}) - \theta(t_z) = -V \int_{t_z}^{t_z + T^j_{cycle}} W(t)dt \qquad (11)$$

but the practical meaning is limited as the cycle duration is not known.

*6.3 Difference between SC and OFB*

Figure 8 shows the behaviour of the states of the OFB controller between pulses. As the drain event is very fast as compared to the period between drains (time constant in the order of 100 s) the principle states of the controller quickly reach steady state. The third state is the integral state. After the drain stops, no information is available about the water uptake. The output of the controller, calculated from the states using equation (4), is therefore determined by the conditions at the end of the drain pulse. These are different from pulse to pulse, because unlike in the case of the SC, in the OFB the observer gets information about the water uptake during a drain event.

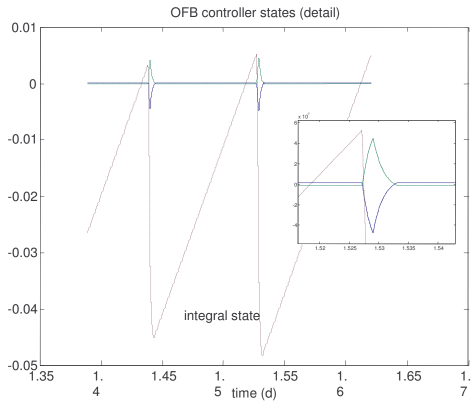


Fig. 8. OFB controller states in time (detail). The insert zooms in on the states.

## 7. DISCUSSION AND CONCLUSIONS

There is a lack of theory for the analysis of control systems with time varying, state driven, quantized control events. Nevertheless, this paper provides some insight in the mechanisms behind cycle averaged drain flow control. The simple heuristic controller is easy to set up, and does not require a large design effort. The output feedback controller requires identification experiments, but has the advantage that it leads, in general, to less depletion of the water content between cycles.

There are several ways to improve the performance further. The OFB design easily allows the incorporation of feed-forward compensation in combination with feedback. Another large improvement can be expected from moisture sensors in the mat. This sensor information makes the controller less 'blind' during periods when there is no drain. As long as properly identified models are used, the exact location of the sensor is not so important, which is a distinct advantage of the OFB design. Another option is to derived a reduced model on the basis of a detailed 2-D model for the spatial distribution within the mat, such as (Heinen, 2001).

In many practical situations, the simple heuristic controller will suffice. Acceptation of more advanced designs such as the output feedback controller depends upon the additional benefit for growers. It is likely that accurate irrigation control is going to be economical in regions with water shortage, and under strict environmental rules, and in cases where accurate supply of water is clearly related to crop yield or quality.


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## APPENDIX

*Gully Parameters*

$V$ =15 L, $p$ = 0.1 s$^{-1}$, $\theta_o = 0.475$

$F_{i,max}$ = 32/3600 L s$^{-1}$, $t_{on}$ = 180 s

*Linear discrete-time model parameters*

$$A = \begin{pmatrix} 1.9104 & 1 \\ -0.90447 & 0 \end{pmatrix},\ B = \begin{pmatrix} 0.0023216 \\ 0 \end{pmatrix},\ C = \begin{pmatrix} 1 & 0 \end{pmatrix}$$

sample time: 5 s

*Observer and Controller Gains*

$$L = \begin{pmatrix} 0.5014 & -0.4005 & 2.5844 \end{pmatrix}^T$$

$$F = \begin{pmatrix} 86.7505 & 87.8505 & 1 \end{pmatrix}$$