TOTAL CHANNEL CONTROL™ — THE VALUE OF AUTOMATION IN IRRIGATION DISTRIBUTION SYSTEMS

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ABSTRACT

Total Channel Control™ is a patented automation design for large scale open canal irrigation networks that manages water distribution within capacity constraints to achieve on-demand water delivery whilst maximizing water distribution. Here it is shown that this decentralized and distributed control implementation realizes near globally optimal performance. Furthermore, the performance enhancement above optimally scheduled open loop or manual operations is exemplified.

INTRODUCTION

When considering automation, with its requirements to invest in a considerable information infrastructure to realize this automation, inevitably there arises the question of what is the economic value of this investment/automation. In the best of circumstances, this is a difficult question to answer. It is the subject of much research in the control and systems engineering communities.

Indeed, especially in the context when automation is considered for the first time, there is simply no experience with the behavior of the system under the automation regime to be introduced. Even in the situation where manual operations are being mimicked through automation, the mere presence of automation always leads to new possibilities in operating or managing the system that more often than not were simply inconceivable before the automation was realized. Without a thorough understanding of this behavior, it is difficult if not impossible to ascertain what the economic impact will be. So typically, pilot studies are called for to quantify the impact automation can make. Pilot studies enable one to evaluate realistically the behavior realized under the automation regime, how it differs from the open-loop, manually managed system behavior and consequently one may confidently predict what impact automation has on the bottom line.

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Alternatively, simulation studies can be completed, to predict the potential changes in behavior, with the aim of deducing or predicting what the (economic) impact can be. This requires that a good simulation model is available for the system under consideration, one that allows for the consideration of the automated behavior over time scales that enable economically valid conclusions. This is not a simple task in general, requiring information from very different realms of expertise, which is not easily integrated.

In this paper a simulation study for the case of automating an open channel irrigation system is considered. The simulation study considers a number of various scenarios. The study benefits from the hindsight of a number of completed pilot and commercial implementations of Total Channel Control™ (see patents [1,2]) in Victoria, Australia. Nevertheless, the simulation study does not evaluate the economic impact, but rather emphasizes the achieved quality of service in water distribution through channel management, as measured by regulation accuracy, water on-demand and water efficiency. This study must be complemented with an economic model that considers the value of water and the affected crops, as well as a model for the infrastructure cost and depreciation costs to arrive at an economic impact statement. This is outside the scope of this paper.

The paper is organized as follows. In the next section Total Channel Control (TCC™) is briefly described. In the following section the simulation study is introduced. There TCC™ is compared with a manual regime and a globally optimal management regime. The former is an idealized representation of a near optimal manual exploitation for the channel system under consideration. The latter is an automation regime where all information is available at all regulator sites. This regime represents the ideal true globally optimal management strategy. The outcomes of the simulation study are discussed in the next-to-last section, before the concluding remarks.

TOTAL CHANNEL CONTROL

TCC™ is a model based automation design implemented in Victoria Australia by Rubicon Systems Australia, Pty Ltd, based on joint research and development completed at the University of Melbourne, Australia. TCC™ is implemented in a purely gravity fed irrigation district. The quality of service is determined by three main features:

- how well the water levels are regulated in the canal,
- how much the water demand is met in real-time,
- how small the out-flows at the bottom end of the irrigation canal are (water distribution efficiency).

TCC™ as implemented in Victoria consists of an information infrastructure where all the regulator structures and water off-take gates along the canal are on a radio network. The logical structure is represented in Figure 1. A relatively low bit rate, packet based radio network, managed in an internet like fashion forms the back bone of the communication network. The regulators and off-take gates are the lowest level nodes in the communication network. Within a limited range they can communicate in peer-to-peer mode or broadcast mode. A single router can accommodate a number of local networks, characterized by a different carrier frequency to ensure radio communication. The router communicates over a higher bit rate channel to a major router, which communicates over optical fiber to the central command node.

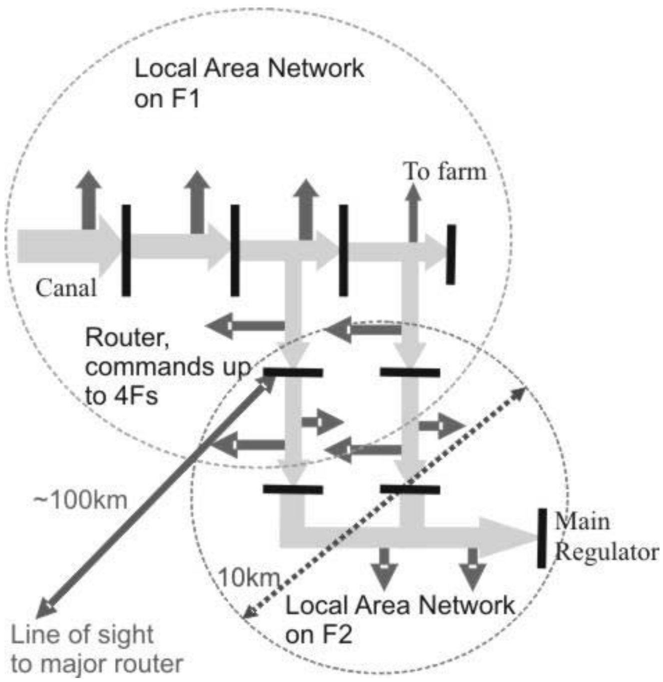

Figure 1: Logical Structure of Radio Based SCADA Network for TCC™.

A picture of the actual hardware implementation is shown in Figure 2. It represents an in canal regulator and a few off-take gates in the pilot project. The radio antennae are seen on top of the solar panels that provide the energy for the regulator actuator and communication hardware.

Figure 3 represents the typical flow of information in TCC™, from a water order to its implementation. It identifies the main nodes in the system, a central node that functions as the overseer, repeater nodes relaying messages, canal nodes where the main control action takes place and on farm nodes that provide automation of water delivery, and ensure water accounting. The farmer does not have direct command over the on-farm water delivery gate (apart from an emergency override function). All automation is requested via the central node, which arbitrates water order requests (orders and cancellations; timing, flow, volume) and implements these on behalf the requestors. Depending on the local authority's policy, water orders require some lead time, which may be as short as an hour. Although in this paper we will consider TCC™'s ability to deliver water on-demand, where the lead time is simply the time required to verify the physical system limits to respond to the requests. In case the decision is negative, i.e. the required water cannot be met, a delay time that allows the request to be met will be indicated.

Figure 4 represents the generic TCC™ distributed control law which is implemented on the canal nodes. The control action for the (overshot) gate consists of a feed forward term and a feedback term. The feed forward term compensates for the known downstream water demand (the sum of the water demand in the downstream pool and the water demand over the next regulator structure. The feedback term ensures that water level regulation is achieved for the distant downstream water level in the pool. The feedback also compensates for any leakage or other disturbances in the pool. Both feed forward and feedback control actions are low pass filtered to ensure that the actuator action does not excite any standing waves in the pool. Moreover, a simple anti-windup action is implemented to ensure that the control gates provide smooth control action without getting stuck at the control limits (fully open/fully closed). For more details about the actual control algorithms refer to [3,4].

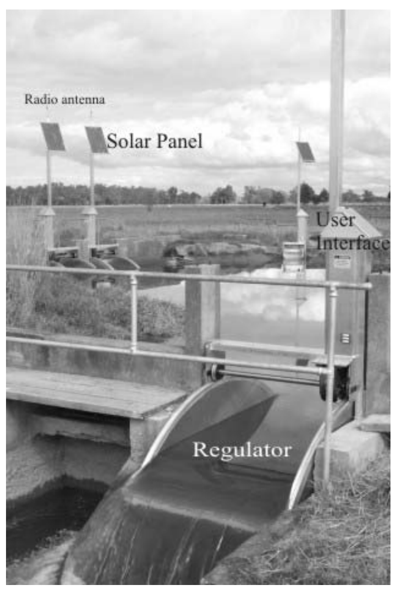

Figure 2. Automation Infrastructure for TCC™.

The controller structure in TCC™ is distributed, and requires only local information exchanges (only neighboring regulator structures must be able to communicate with each other) to realize the actuator commands. The information exchange is event driven, i.e. information is only exchanged when a significant (downstream) regulator change is implemented or a significant (downstream) water level change is detected.

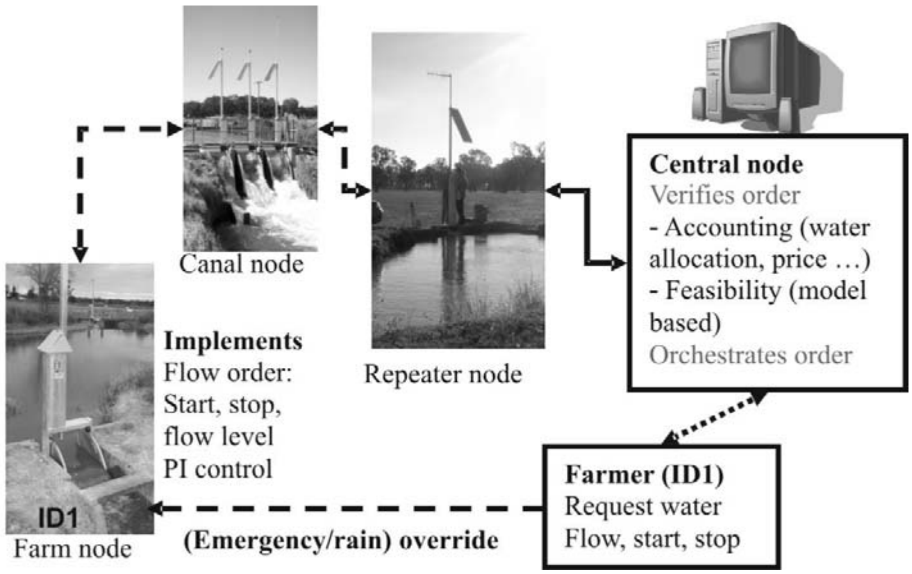

Figure 3: TCC™.

Besides the more frequent local communications, some information requires network wide communication. The set points for the water regulation form part of the system set up, and can be updated as needed. It requires peer-to-peer communication from the central command node to the particular regulators for which the set points need to be updated. Also the water demand must be managed on a canal wide basis. TCC™ enables in as much as feasible water on-demand management. Water requests are communicated to the management centre, where the scheduling software determines whether the water order can be met in real-time. If so, this water request is immediately communicated to the off-take gates, and this information is also communicated to the up-stream in-canal regulators. If not, the scheduler suggests an alternative irrigation period that can be accepted or rejected by the requestor. These water demand events are relatively infrequent[3] and can easily be managed over the radio based SCADA network.

The actual control algorithms implemented in the feedback and feed forward and filter blocks that determine the gate actuation are maintained in a data base at the central node, and can be updated through the radio network as required. This may be necessary in case of hardware failures.

The control algorithms implemented on the canal nodes are a function of the network topology and the functionality of the regulators. In case of hardware failures, sensors or actuators, or in case actuators are essentially out of the loop because of saturation (as would be the case under maximum flow conditions), the

[3] Without TCC™, farmers place water orders on a semi-regular basis with on average a single major irrigation every two weeks over the season. Under TCC™ a significant shift in behavior is observed, with more and smaller (in time and volume) irrigation requests being placed based on actual crop conditions.

control algorithm must be adjusted to reflect the new situation. The latter is taken care of by the anti-wind-up schemes, and is really considered part of the normal operation of the system, but the failure situations have to be approached in a different manner. Due to the inherent redundancy in the hardware (multiple sensors and actuators in parallel), or the system redundancy (due to the dynamic dependency between the variables being manipulated or sensed) there is significant potential to exploit this redundancy to have the performance degrade gracefully with hardware failures. This is achieved through a reconfiguration of the information loops underpinning the control loops, which will typically involve changes in the controller settings. For example, in the unlikely event a regulator would fail (say in the open position), a new situation arises in which one less water level can be regulated, and the upstream and downstream regulators must be now be retuned to reflect this situation (new information loops, new pool model, new controller settings). The performance will degrade on two pools, (down stream and upstream of the affected regulator) but the main consequences of this fault are essentially isolated to just these two pools (with only a minor degradation in overall performance). Similar scenarios can be worked through for other sensor and hardware failures.

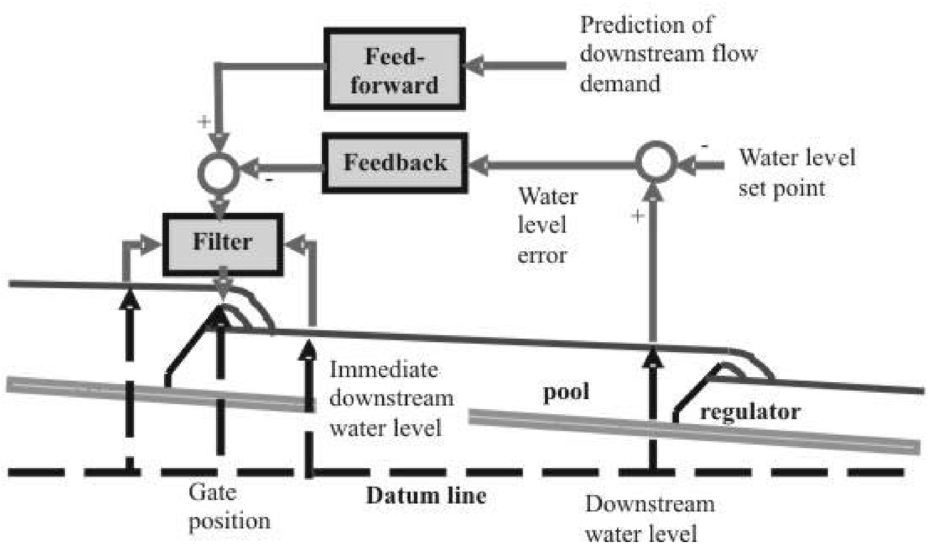

Figure 3: TCC™ distributed real-time control structure for water distribution and in-canal water level regulation.

SIMULATION SCENARIOS

Two main scenarios are considered. The first consists of the management of a canal consisting of 3 consecutive pools; the next scenario considers a canal with 8 pools in line. All regulators are overshot gates. The canal models reflect actual major canals in Australia. The data used to represent the canals/scenarios are derived from previous pilot projects. The simulation scenario runs over a period of 9 days (12960 min).

The canal considered in either scenario has a freeboard of 20cm above the set point. Acceptable quality of water level control is defined as a water level not less than 10cm below the set point, and not higher than 20cm above the set point. Three figures of merit are considered to compare the various management strategies:

- Water efficiency; defined as one minus the ratio of total water volume flowing over the downstream end of the canal to the total water volume dispatched into the canal. (This way the unavoidable losses of leakage, seepage and evaporation, which cannot be affected by automation are not considered in the efficiency calculation.)
- QST (Quality Service Time); defined as the ratio of the total duration of time where the water level is 10cm below the water level set point (on any pool where on-farm water delivery takes place) or 20cm above the water set point and the total simulation time. A QST of 100% means that all water orders are met in real time.
- Critical loss of service time (CT); defined as the ratio of flood time over the total rain time.

Scenario 1: Three Pools

The pools in the channel have the following characteristics:

- Pool 1: delay time 5min, wave period 15min, length 1600m,
- Pool 2: delay time 3 min, wave period 10min, length 900m,
- Pool 3: delay time 11min, wave period 29min, length 3200m.

The maximum flow capacity in the channel is 270Ml/day.

Four different management strategies (the details are described in [5]) are compared:

- Manual[4], where the regulators are set to a constant position over a period of one day, and the requested demand is rescheduled to minimize wastage.
- TCC™ without feed forward compensation, only using a feedback strategy.
- TCC™ as described above, using both feed forward and feedback.
- Globally optimal scheduling and control.

The actual events in the Scenario 1 are presented in Table 1. No water off-take is required on Pool 2, and hence Pool 2 does not play a role in the computation of the figures of merit. The maximum water demand is 67Ml/day, well below the maximum capacity in the channel. Scenario 1 does not explore the capacity limits of the channel.

[4] The Manual regime considered in the Scenarios is actually an open loop optimal strategy; i.e. from all possible responses characterized by constant regulator positions over 24h periods, this response that achieves the best quality of service is selected.

The figures of merit for the different management strategies are presented in Table 2.

On the basis of the figures of merit in Table 2, it is not possible to distinguish between the various automation strategies. The improvement over the manual regime is significant. Notice that the requested off-takes were scheduled in such a manner as to not require rescheduling under the manual regime.

The time that there is a flood on the canal is due to the rain event occurring at a time where there is major demand on the canal. (The flood event only affects pool 3.) The 24h time between regulator changes in the manual regime cannot cope with the excess water, and a significant flood event is simply unavoidable. In the automated regime, all water off-takes on the farm are stopped. The fact that no flood occurs and that the water efficiency is still 100%, is due to the fact that the available canal storage (freeboard) is sufficient to cope with the rain event. In case the rain event would be so significant that the canal storage is insufficient, the automated regime will spill water as to avoid floods along the canal.

Table 1. Event list for Scenario 1.

Activity	Pool	Start time (min)	Duration (min)	Finish (min)	Size
Rain	1,2,3	3300	600	3900	25mm
Off-take	1	2040	1260	3300	22Ml/day
	1	3900	5820	9720	22 Ml/day
	1	2700	600	3300	25 Ml/day
	1	3900	960	4860	25 Ml/day
	1	7500	2160	9660	13 Ml/day
	3	600	2700	3300	20 Ml/day
	3	3900	2700	6600	20 Ml/day
Off-take refused	3	6000	600	6600	-20 Ml/day

In order to distinguish between the various forms of automation, the actual response time and actuation effort has to be considered. The global optimal management strategy wins in terms of response time and also in terms of overall regulation accuracy but this performance comes at a price. Global optimal management requires substantially more control effort[5] than either form of TCC™.

[5] It is possible to formulate a global optimal control strategy with stringent constraints on the actuation effort. However this was not considered. Instead an unconstrained optimization was performed. This leads to better overall performance, which is however cannot be realised in practice.

TCC™ with feed forward action comes very close to the global optimum but requires less control action than the globally optimal strategy. TCC™ without feed forward action is significantly less responsive, and requires substantially more control actuation than TCC™ with feed forward, but less than the globally optimal control strategy.

Table 2. Scenario 1 Figures of Merit.

Management strategy	Efficiency	QST	CT
Manual	78%	78%	210%
TCC™ (without feed forward)	100%	100%	0%
TCC™ (with feed forward)	100%	100%	0%
Global optimum	100%	100%	0%

Scenario 2: Eight Pools

On the basis of the outcomes in Scenario 1, Scenario 2 is limited to a comparison between the manual control strategy and the two TCC™ strategies. The Scenario 2 activities are listed in Table 3, and the figures of merit are listed in Table 4.

The channel consists of 8 pools in line; Pools 1, 2 and 6 in Scenario 2 have the same characteristics as Pool 1 in Scenario 1, Pools 3 and 7 in Scenario 2 have the same characteristics as Pool 2 in Scenario 2 and Pools 4, 5, and 8 in Scenario 2 are like Pool 3 in Scenario 1.

Under this Scenario, TCC™ with feed forward is the best strategy. It clearly outperforms both TCC™ without feed forward and is vastly superior to the manual management regime. The manual regime achieves good efficiency, but set point regulation requirements are only met over less than half the simulation span. As a consequence water orders are poorly met, and the actual water delivered to the farmers is less than what is requested.

A more careful analysis of the individual pool responses shows that for the manual regime, the most downstream pools are most difficult to manage, whereas for TCC™ the most upstream pool is most difficult to manage. Under this Scenario, using the manual management regime, Pools 5 to 8 receive reasonably poor water level regulation, whereas the first 4 Pools are very well managed. Pool 5 is the worst managed in terms of meeting water demand, and Pool 8 experiences a flood condition during the rain event (for about half the time of the actual rain event).

Table 3. Simulated events under Scenario 2.

Activity	Start (min)	Duration (min)	Finish (min)	Size
Rain (all pools)	3300	600	3900	2.5cm
Off-take Pool 1	6000	2160	8160	15Ml/day
Off-take Pool 4	1200	2100	3300	8 Ml/day
Off-take Pool 4	9600	1800	11400	15 Ml/day
Off-take Pool 5	2100	1200	3300	5 Ml/day
Off-take Pool 5	5700	2880	8580	7 Ml/day
Off-take Pool 6	1440	1860	3300	15 Ml/day
Off-take Pool 6	3900	4620	8520	15 Ml/day
Off-take Pool 6	2400	900	3300	25 Ml/day
Off-take Pool 6	3900	660	4560	25 Ml/day
Off-take Pool 6	6900	2160	9060	13 Ml/day
Off-take Pool 8	600	2700	3300	20 Ml/day
Off-take Pool 8	3900	2700	6600	20 Ml/day
Off-take refused Pool 8	6000	600	6600	-20 Ml/day

In TCC™ mode the only pool where water delivery is not met 100% on-demand is in Pool 1. Allowing for a 4h delay in meeting the water orders would have realized 100% efficiency with 100% of all demand met.

Table 4. Figures of merit for Scenario 2.

Strategy	Efficiency	QST	CT
Manual	90%	45%	50%
TCC™ with feed forward	100%	99.9%	0%
TCC™ without feed forward	100%	98%	0%

CONCLUSION

The simulation scenarios presented show the success of TCC™ in implementing near on-demand (see Figure 3) water delivery.

It may be observed that the two scenarios do not explore the physical limits of water flow capacity of the channel. Rather a low demand scenario is explored, which presents indeed a significant advantage for the manual regime. The situation of high water demand is also not very interesting from a comparison point of view, because when demand is close to full flow capacity the potential for automation is rather limited. This is clear because automation does not provide for extra flow capacity in the channel. More importantly however, rain events and refused water orders would show even greater advantages for the automated regimes in a high demand regime as compared to the presented scenarios in a low demand exploitation situation. Indeed a manual regime simply does not have the responsiveness of the automated regimes to cope with a large rain event, which essentially demands the management of a significant transient. Because, transient phenomena underscore the flexibility of the automated regimes, a low demand scenario is preferred in the comparison. It places the manual regime in the best possible situation. Therefore it is clear that the advantage of automation is very significant indeed.

This is consistent with the experience in the various pilot and commercial implementations thus far in Victoria. TCC™ is water efficient, and rejects disturbances such as rain events, or refused water orders extremely well. Compared to manual control (an idealized optimally computed open-loop scheduling) significant improvement in water distribution efficiency is achieved, combined with much better water level regulation.

The observation made in Scenario 2 that under TCC™ the most upstream pool is most difficult to manage is explained in [3,4]. It is a consequence of the upstream disturbance propagation, which is an unavoidable consequence of the combination of the delay on the channel and the feed forward action. It is this disturbance effect that essentially determines the limits of TCC™ performance.

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