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ADVANCES IN PLC-BASED CANAL AUTOMATION

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ABSTRACT

A short history of canal automation is given. PLC-based canal automation is relatively new. Advances in PLC-based canal automation are listed. Also listed are some of the remaining challenges. Recent advances have been made in understanding unsteady flow simulation procedures, the form of the control algorithms used, the tuning procedures for these control algorithms, and the field programming of the algorithms into PLCs. The experiences of the Cal Poly Irrigation Training and Research Center (ITRC) in automating a variety of canals with upstream and downstream control are given.

INTRODUCTION

Canal Automation History

Canal automation in this paper refers to closed-loop control in which a gate or pump changes its position/setting in response to a water level, flow rate, or pressure because that level/rate/pressure is different from the intended target value. "Closed loop" means that the action is performed without any human intervention. The automation may be performed through hydraulic, electrical, electronic, or a combination of these, means.

Early canal automation (pre-1950's) was characterized by the use of hydraulic gates. Flap gates were investigated in The Netherlands by Vlugter (1940). Cal Poly ITRC has recently reported the history of these gates and a new design procedure for them (Burt et al., 2001). Danaidean gates have been used in California since the 1930's and are still used in many irrigation districts for both automatic upstream control and downstream control.

The Nerytec Company from France became famous in the 1950's and 1960's for its hydraulic gates, such as the AVIS, AVIO, and AMIL models. These robust gates have been used around the world for upstream control and level top downstream control (Goussard, 1987).

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In the 1960's and 1970's, canal automation in the U.S.A. proceeded in 4 aspects:

1. Electro-mechanical controllers (commonly called "Littlemen") were developed and installed on projects throughout the western U.S. The legacy of these controllers continues, as many new automated sites with PLCs retain the old Littleman logic – with its inherent simplicity and limitations.
2. A few large water conveyance canals were installed with remote monitoring and remote manual control. Most notable is the California Aqueduct, which has been mistakenly identified as an automated facility for decades.
3. With the advent of computers, a few researchers were able to develop unsteady open channel flow simulation models – which began to open up possibilities for studying new methods of canal automation.
4. A few engineers and researchers began to try to apply control theory to the actual automation of canals. Perhaps most notable are the early attempts by staff from the US Bureau of Reclamation to install HY-FLO and EL-FLO on several canals for downstream control.

In 1987, a landmark American Society of Civil Engineers (ASCE) specialty conference was held in Portland, Oregon. Entitled "Planning, Operation, Rehabilitation and Automation of Irrigation Water Delivery Systems", this conference brought together specialists from around the world to discuss various canal automation techniques.

Since 1987, there has been an evolution in the understanding of the nature of canal automation. This evolution has been assisted through various specialty conferences, primarily sponsored by the former Irrigation and Drainage Division (now the Water Resources Division) of ASCE. The evolution can be describes as follows:

1. In 1987, we had a simplistic view of automation. We understood the basic ideas of upstream and downstream control, and simulation models were becoming popular. Furthermore, personal computers were becoming common and there was a general feeling that computer-based automation would rapidly sweep the irrigation world.
2. In 1991, an ASCE specialty conference was held in Honolulu to discuss the challenges with selecting an unsteady flow simulation model. We were beginning to understand that the problem of simulation was more challenging than we had previously thought, and that there were substantial differences between simulation models. Partly as result of this awareness, authors of these programs began to make them more user-friendly and flexible.
3. By the mid-1990's, the interest in downstream control of many forms and in centralized control was quite strong – at least in theory. Numerous papers were published with various algorithms that had been simulated. But very few successful PLC-based automation schemes had been

successfully implemented. In fact, it appeared that most PLC-based automation schemes were failures rather than successes.

4. By the mid-1990's we also began to realize that, although the automation of the gate was very important, we had not paid sufficient attention to how the harmonics of flow disturbances in individual pools could cause instabilities in control. Therefore, attention shifted to understanding pool dynamics, with the hope that standard control theory (used in other industries) could be applied to irrigation canals. Terminology such as "PID" (Proportional-Integral-Derivative control logic) was heard much more frequently.
5. Upon arrival of the late 1990's we recognized that:
    a. There were very few successful applications of PLC (Programmable Logic Control) based automation systems. Certainly there were good examples of individual gates being automated with the use of PLCs, but there were very few whole systems with gates in series.
    b. SCADA (Supervisory Control and Data Acquisition) had advanced tremendously in the past 5-10 years, and the equipment and communications were much better than before. However, it was difficult to locate a good integrator company (a company that is responsible for the selection of all components, the installation, and commissioning of a SCADA system) even in the U.S.
    c. We had underestimated the complexities of going from an algorithm to actual implementation in the field.
    d. In spite of all of the tremendous theoretical work on downstream control, we still did not have adequate control algorithms for the most simple canal automation procedure – upstream control. Or if we had the algorithms, we were missing essential ingredients and we did not have good ways to tune the controller constants.
    e. The bottom line is that we did not have a package for local upstream or downstream control with PLCs that was easy and quick to implement in irrigation district canals for gates in series.

ITRC CANAL AUTOMATION WORK

The California Polytechnic State University Irrigation Training and Research Center (ITRC) has been involved in canal automation training, technical assistance, and research since the 1980's. ITRC believes in the "Keep It Simple" rule, and continues to recommend simple solutions such as hydraulic gates, long-crested weirs, regulating reservoirs, and remote monitoring where appropriate. But there is an increased need for tighter and more flexible control that often cannot be accomplished with those simple techniques. Therefore, ITRC has actively participated in PLC-based irrigation district automation implementation since the mid-1990's.

With PLC-based control, ITRC has attempted to work with excellent companies, and has tried to incorporate the best simulation models, equipment, control algorithms, HMI (Human-Machine Interface) software, and training that is available commercially and theoretically. There are so many challenges to successful implementation of PLC-based control that it would be fool-hardy for ITRC to work with anything but the best in cooperators, hardware, and software. In general, ITRC's role is to:

1. Select the control logic to be used for a particular project.
2. Select, develop and tune the control algorithm that dictates the gate movement.
3. Assist the irrigation district in specifying the SCADA system characteristics.
4. Work with the district in locating a good SCADA integrator.

Our ultimate objective is to make the technology much more user-friendly, simple to implement, and robust, so that commercial companies can implement it rapidly and effectively in irrigation districts.

Working in this way with the USBR and individual irrigation districts, we have helped to implement the following types of PLC-based canal automation:

1. Upstream control
    a. With overshot gates in series
    b. With radial gates in series
2. Flow rate control
    a. With Replogle flumes
    b. With Acoustic-Doppler Flow meters (ADFM)
3. Downstream control with the control point at the heads of the pools (i.e., level top control)
    a. With overshot gates in series
    b. With pumps in series
    c. For a single pool.
4. Downstream control with the control point at an intermediate location within the pools, with pumps in series

Each case has been different. These cases represent the majority of conditions that can be encountered for distributed control – our preferred method of automation at this time. Distributed control utilizes a PLC at each control structure/pump. The PLCs operate automatically and independently (one per site), but they are remotely monitored via a SCADA system at the irrigation district office. From the office, a person can switch any device to "manual" operation, or can change target water levels/pressures/flow rates.

The three points below summarize our understanding of PLC-based automation at this point in time.

1. Canal automation is much more complex than we had earlier believed.

2. Significant challenges remain in meeting our goal of developing simple procedures and guidelines for automation of irrigation district canals.
3. We have abandoned the dream of developing "simple" procedures for PLC-based canal automation. Our focus is now on developing a transferable procedure – one that irrigation districts and consulting engineers can successfully use without needing a tremendous theoretical background in control theory and hydraulics.

Having stated the challenges, it is also clear that over the past 3 years there have been significant improvements in our understanding of PLC-based canal automation. In addition to having learned from actual field implementations, funding through the California Energy Commission has allowed us to work with others to improve the theoretical understanding of the PLC-based canal automation process. In the remainder of this paper, we will share some of what we have recently learned for each of these PLC-based components:

1. Simulation models
2. Simulation procedures
3. Algorithms
4. Tuning of algorithms
5. PLC and sensor constraints
6. PLC programming by integrators

PLC-BASED CANAL AUTOMATION COMPONENTS

Simulation Model

ITRC presently uses CanalCAD, which utilizes the simulation technology based on algorithms developed by Cunge, Preissmann, Chevereau, Holly, and others at SOGREAH of France. CanalCAD has a user interface that was developed through a combined effort of ITRC, Imperial Irrigation District, and the Iowa Hydraulic Research Institute. We are examining other models for their suitability as a replacement.

In the past 2 years, CanalCAD has been upgraded at ITRC expense so that we can select any location within a pool as the "target" control location. This means that in our control algorithm subroutine, we can extract water levels or flow rates from any designated point. In the past, we were limited to 5 specific locations within any pool.

Key ingredients for any acceptable model include:

- Hydraulic correctness of steady and unsteady flow conditions.
- One second simulation timesteps
- Capability to simulate at least 20 pools in series.

- Capability to solve for initial steady state conditions automatically, including all water surfaces, flow rates, and gate positions.
- Ability to program the control algorithm within the simulator, as a subroutine.
- Ability to model a wide range of structure combinations at any single location.
- Quick computational speed.

With the type of work ITRC does, we have never needed or wished for a simulation program that includes branching canals.

We have occasionally seen discrepancies between actual canal hydraulics and CanalCAD-simulated hydraulics. These discrepancies have been noticed during extreme conditions, but in fact we do not know how extensive they are. We know that in most cases, the control that we have predicted with CanalCAD is what we have obtained. We have also verified some basic facts, such as wave travel characteristics in long canals.

In practice, it is difficult to obtain good data for comparison of simulated versus actual hydraulics because of the uncertainties of actual flow rates, canal dimensions and roughnesses, and water levels. We have recently revised our "commissioning" procedures for new installations so that we can obtain better checks on actual vs. simulated values. We now utilize a specific step-by-step procedure for testing PLC control at each structure, one at a time, for a new installation. Each structure must be "commissioned" by testing the algorithm's ability to maintain a steady state condition, and then progressing into small flow rate changes, and then to larger flow rate changes. This process requires several days. We monitor the actual water levels and the control response of the PLC and then duplicate the control response in CanalCAD. In part, we do this to confirm that there has been no programming error in the PLC.

Figure 1 shows an example of a discrepancy that we cannot yet explain. It is for a single pool that has downstream control at Sutter Mutual Water Company. The water level is controlled at about 82% of the distance down the pool, and a variable-frequency drive (VFD) pump controls the inflow to the pool. The commissioning of the installation required that a flow rate change be made at the far downstream end of the pool. Figure 1 shows that the actual control is better than what was predicted in CanalCAD.

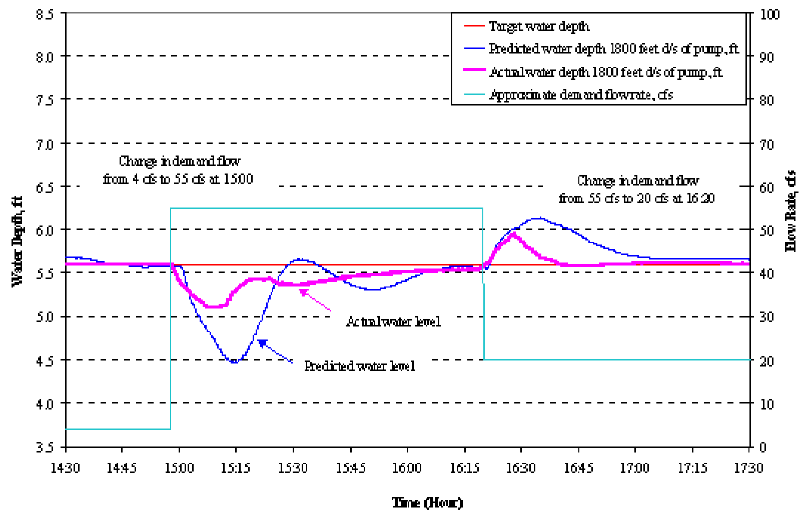

Fig. 1. Simulated and Actual Water Level Changes at Portugese Bend Canal, Sutter Mutual Water Company.

Another discrepancy that we have noticed occurs at conditions of low flow rates. In several canals, the irrigation district personnel have noticed a slow oscillation of gates or pumps with downstream control. We have not been able to duplicate the oscillation in CanalCAD. Our immediate solution is to reduce the magnitude of the response at very low flow rate conditions (e.g., at 5% of the maximum flow rate).

Simulation Procedures

An important lesson we have learned is that on some canals the simulation timestep must be as small as one second. In prior literature and our own previous experiences, it appeared that one-minute simulation timesteps were adequate. The case that first caught our attention was the Stanfield-Furnish Branch (SFB) Canal near Umatilla, Oregon. This is a relatively short canal of 4 pools with minimal storage, having very large flow rate changes (greater than 50%) at the tail end. The gates are overshot bottom-hinged gates, with the exception of radial gates at the head of the canal. The control technique was local downstream control, with the target located immediately downstream of each gate. Control was to be executed once/minute.

With the SFB Canal, we tuned a PI (described later in this paper) algorithm for downstream control in CanalCAD using a one-minute simulation timestep (Figure 2). When the algorithm was implemented in the field, the gates had such excessive movement that the panel heaters overheated and prevented more gate movement. Fortunately, when we heard about this problem it coincided with some observations we had made when doing some other development work that indicated a need for smaller simulation timesteps. When we simulated the operation again, but with a 1 second timestep, the oscillations appeared (Figure 3). It was obvious that we had missed the pool resonance problems in our prior simulations. Using a 1-second timestep to simulate one-minute control, we retuned our control algorithm and added a filter (making it PIF control), with the results seen in Figure 4.

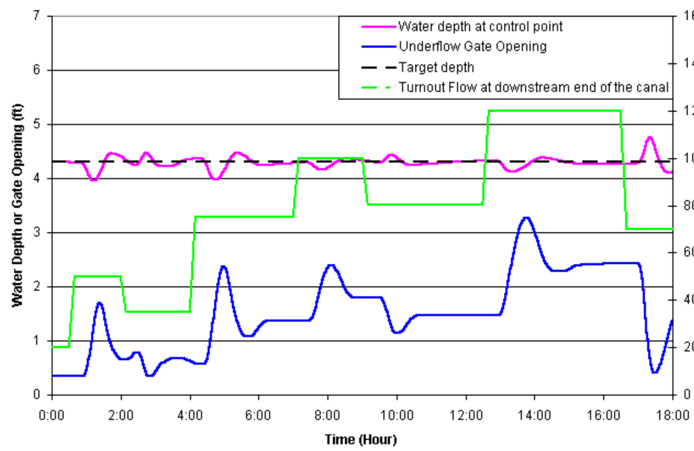

Fig. 2. Downstream Control Simulation Results of Initial Tuning of PI Algorithms on the SFB Canal Using a 1-Minute Simulation Timestep and a 1-Minute Control Timestep.

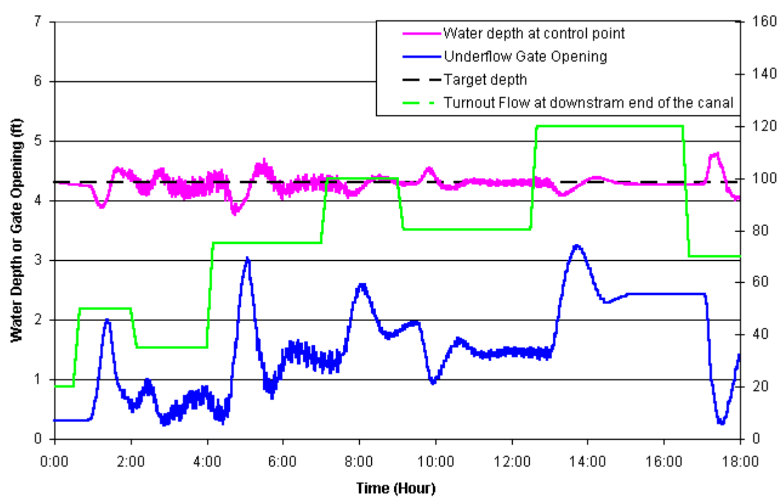

Fig. 3. Downstream Control Simulation Results on the SFB Canal Using a 1-Second Simulation Timestep and a 1-Minute Control Timestep, Using the Original PI Algorithm.

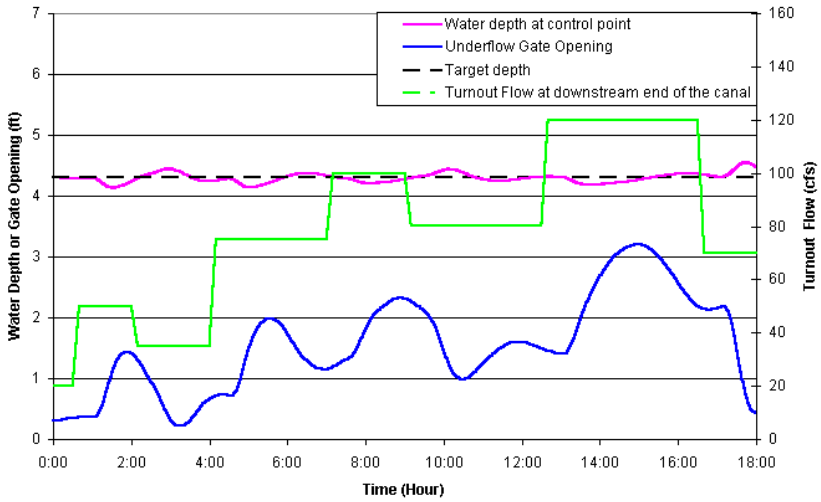

Fig. 4. Downstream Control Simulation Results on the SFB Canal Using a 1-Second Simulation Timestep and a 1-Minute Control Timestep, Using a New PIF Algorithm.

Algorithms

ITRC uses PI (Proportional-Integral) for many cases, PIF (Proportional-Integral plus Filter) equation when it encounters conditions with resonance problems, and once or twice we have used PID – which includes the derivative component. With PIF, the filter accounts for the previous error, and all previous errors, but as the errors become more distant in time, their influence is less and less. The form of the PIF equation can be described as follows:

$$\Delta u = UD \cdot UF \cdot [-KP \cdot (FE1 - FE2) - (KI \cdot FE1)]$$

where

Δu = change in gate position, feet

KP is the first PI constant, determined in MatLab

KI is the second PI constant, determined in MatLab

FE1 = The filtered error for the present timestep

$$FE1 = (FC \cdot FE2) + [(1 - FC) \cdot ENOW]$$

where

FC = a filter constant

FE2 = the value of FE1 for the previous timestep

ENOW = present unfiltered error

= (Actual water level - Target water level)

where

Actual water level is the average of at least 60 measurements taken over the last minute.

UF is a factor that determines how much the gate must be opened for a certain flow rate change. Its value depends on the gate position. It is generally of the form:

$$UF = [a1 \cdot (a2 \cdot u^2 + a3 \cdot u + a4) + a5]$$

UD is a factor (+1 or –1) that depends on whether the gate is an overshot gate or undershot gate

Tuning of Algorithms

We continue to try to develop or locate a procedure that tunes the PI or PIF algorithms satisfactorily and quickly. Historically, we systematically ran simulations starting with one set of KP and KI constants, and step-by-step varied the KP and KI constants in an attempt to bracket the best values. This was a trial-and-error technique that was complicated by the need to use different KP and KI constants for each pool. Because of pool and gate interactions, the tuning of all controllers must be done simultaneously.

The KP and KI combination that produced a quick stabilization with minimal overshoot was chosen if adjacent KP and KI combinations also provided stable solutions. Because of our uncertainties regarding simulated versus true results, we never want to select tuning constants that are on the verge of causing instability. This procedure typically required a minimum of one month of systematic tuning using CanalCAD, and often took longer.

Recently, ITRC has been working with Jan Schuurmans and Peter-Jules van Overloop from The Netherlands to develop a systematic tuning procedure that will be better and also much quicker. The procedure is to first determine resonance and wedge storage characteristics for each individual pool using CanalCAD, and then to use a special MatLab® routine to simultaneously tune the unique PI or PIF constants for each gate or pump controller. To date, we must still do about a week's worth of manual trial-and-error procedure to fine tune the MatLab results. However, we are optimistic that this tuning procedure can be improved further.

PLC and Sensor Constraints

We have encountered several PLC and sensor constraints. On the PLC side, we have learned that many PLCs require a significant part of a minute just to run through various checks of equipment, to read values from sensors, and to communicate with SCADA systems. Furthermore, the manufacturers are often unable to tell us how much time is required. Because our simulations should duplicate the actual computations, this is problematic. We have also found that some brands will take 60 sensor values per minute and provide an average, but those 60 sensor values are all read within the last 1-5 seconds of a minute.

For applications, we now insist on redundancy of key items. Specifically, we state that all of the key sensors be duplicated, plus the sensors must be wired into different power supplies and A/D converter modules in the PLCs. We assume that it is not a question of "if" a sensor will fail, but a question of "when". Although there are numerous techniques to use software to check for problems with single sensors, we have found out that this adds a tremendous complexity to the programming of the PLC that is unnecessary if redundancy exists.

On the sensor side, there are the classic problems with accuracy, calibration, and resolution. But a new challenge is presented when one uses an ADFM or similar device to measure flow rates at the head of a canal (for control purposes). Figure 5 shows that there is tremendous noise in their signals. We have examined numerous filtering techniques, but in the end we have concluded that we need at least 10 minutes of continuous readings before we can use an average value for a control decision. This complicates the control of headworks on some canals. In contrast, using a Replogle flume to measure flows at the head of a canal has the advantages of (i) little or no random noise in the signal, (ii) inexpensive redundancy of the water level sensor, and very importantly for control (iii) because the Replogle flume is a critical flow device, the new flow rate stabilizes very rapidly, so it is easy to determine how much to change the flow control device.

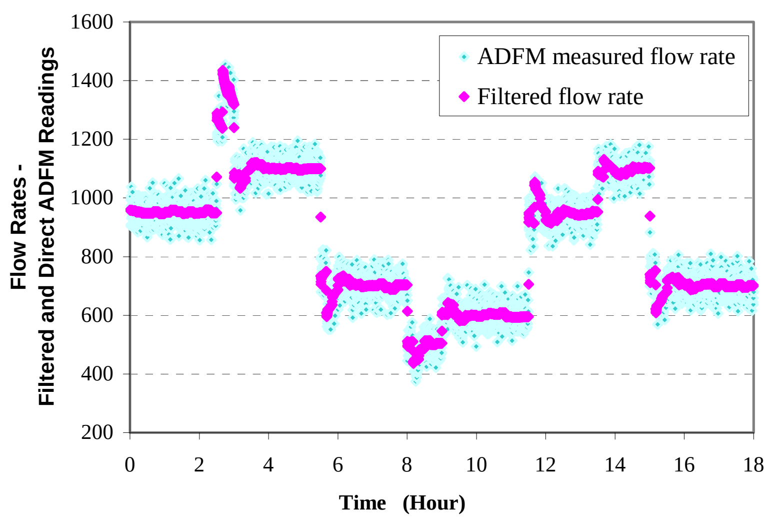

Fig. 5. ADFM and Filtered Signals at Headgate Rock Dam – CRIT Irrigation Project, Arizona.

PLC Programming by Integrators

The complexity of dealing with integrators has been a surprise. Integrator companies in the irrigation market have been quite independent, with little independent review of their work. Their procedures for documentation of programming, their neatness of organizing wiring and panels, their usage of programming languages, and their exposure to PI algorithms for canal automation are quite varied. This means that nothing can be taken for granted – even if an integrator can list numerous completed projects.

Three items are of particular concern to us:

1. A good integrator will always understand hardware, installation, communications, and programming quite well. But it is rare that an integrator is familiar with modern canal control algorithms, and how they are tuned within a simulation model. This can be a problem if the integrators take unwarranted liberties in the programming of the control algorithms that we supply as well as with the tuning constants that we provide.
2. Integrators sometimes embed numerous checks into their code with various hidden constants (of their own selection) that can shut down a gate or pump operation. The irrigation district operators (i) do not know these constants exist, (ii) do not know how to access them, (iii) must generally personally visit the PLC to change the constants, and (iv) do not really understand how the constants should be changed. We believe all constants and alarms should be transparent and changeable from within the office via the SCADA system. A portable PC with a copy of the office HMI (Human-Machine-Interface) software can be used in the field to change constants if it is desired to make in-field adjustments.
3. The "control algorithm" for a gate (the algorithms that are published in irrigation literature) may only occupy 10% of the total programming that most integrators put into the PLC. The remainder of the programming handles numerous checks of equipment and sensors, consideration of gate inertia, and other factors. We are working on specifications that will minimize unnecessary programming.

SUMMARY

In summary, what we started out thinking was a simple algorithm challenge is in fact quite complex. As a profession, we underestimated the complexity of automating canals with PLCs – even with simple upstream control. We now understand that there are challenges in equipment, simulation models, tuning procedures, and field programming. Having identified the weaknesses, we are systematically solving each one.

REFERENCES

Burt, C.M., R. Angold, M. Lehmkuhl, and S. Styles. 2001. Flap gate design for automatic upstream canal water level control. Journal of Irrigation and Drainage Engr. ASCE 127(2):84-91.

Goussard, J. 1987. Neyrtec automatic equipment for irrigation canals. In "Planning, Operation, Rehabilitation and Automation of Irrigation Water Delivery Systems", D. Zimbelman, ed. Proceedings of a symposium sponsored by the Irrigation and Drainage Division of ASCE in Portland, Oregon. pp. 121-132. ISBN 0-87262-608-3.

Vlugter, H. 1940. Over zelfwerkende peilregelaars bij den Waterstaat in Nederlandsch-Indië. De Ingenier in Ned.-Indië., No. 6. 11.84 – 11.93.