BASIC EQUIPMENT IN AUTOMATIC DELIVERY SYSTEMS

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ABSTRACT

This paper presents some of the practical automatic control systems that are available for canals, pressure pipe systems, and farm turnouts. The natural characteristics of feedback control, the elements involved in the feedback path, the modes of control and conditions for stability of control, and the manner in which the input response effects the output (surge wave action for example) are all considerations of basic equipment and are discussed in considerable depth when applied to a simple form of an automatic control system ("Little Man"). Components are gradually added to achieve greater operational flexibility. Finally, the HyFLO method of automatic downstream control of canal check gates is discussed to show an example of how the application of control theory can result in achieving optimal automation with available equipment of relatively simple design. A theoretical ultimate, or more modestly, a penultimate, feedback control system is offered to show that there is more work to be done and that the concepts of feedback control applies to the total system as well as to small systems which maybe components of a large system.

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INTRODUCTION

Irrigation System Engineers (those who are deeply involved in the design and operation of delivery systems) should be aware that a sophisticated control technology, together with a wide variety of control equipment and hardware, is available. The state-of-the-art is directly applicable to the automatic control of dynamic systems such as water conveyance facilities. Application to irrigation systems has been slow because of its orientation towards the space, defense, and electrical power system programs.

The Irrigation System Engineer could capitalize on the spinoff from these other programs by expanding his familiarities with disciplines in the field of control engineering and could stimulate the transition or "technology transfer." He is already familiar with the capabilities, limitations, and the operating characteristics of the delivery system. The combination of this knowledge with a modicum of control engineering background would be of great help in defining the requirements of a practical control system to match a delivery system capabilities and requirements. As a result, the goal of achieving optimum response and efficiency (defined as optimal automation) of a system, beyond what could be accomplished conventionally, can be realized.

A treatise on control engineering which embraces many of the basic sciences, would be inappropriate for this paper and beyond the capabilities of the author. However, some of the typical and basic forms of control systems and equipment that are being applied successfully to delivery systems constructed by the Bureau of Reclamation are described. Typical feedback control systems, the common modes of control, the elements involved in the feedback path, and the conditions required for operational stability are all considered in this paper as constituents of basic equipment in automatic delivery systems as opposed to just the hardware. The approach taken is to first discuss a simple form of an automatic control system ("Little Man") and gradually add components to it that achieve greater flexibility of operation. Finally, the HyFLO method of automatic downstream control of canal check gates is discussed to show an example of how the application of control theory can result in achieving optimal automation with available equipment of relatively simple design. Automatic pipe distribution systems and turnouts are also described.

It is hoped that this paper will stimulate and motivate the Irrigation System Engineer to expand his knowledge in the field of control engineering and accelerate the "technology transfer."

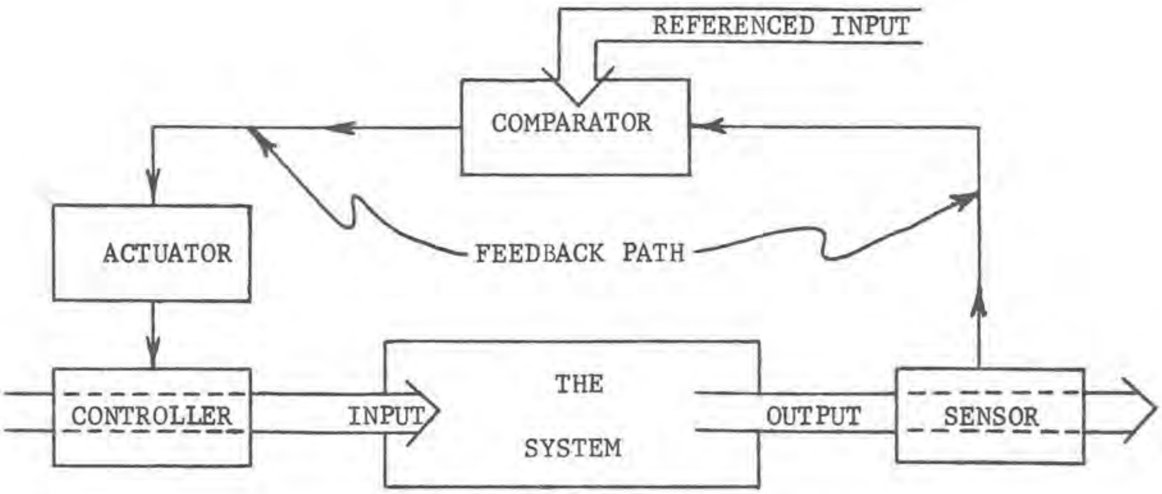
PREREQUISITIES TO SELECTION OF AUTOMATIC SYSTEMS

Identification of the requirements and objectives connected with the purpose of the delivery system and collectively known as the operating criteria is an indispensible prerequisite to the development of practical and effective control schemes. It is in this area where the Irrigation System Engineer should be expert. It should also be his responsibility to define the areas wherein a better match between the system capabilities and requirements is needed to meet the demands of modern irrigation practice to make efficient use of the available water supply and to provide better service to the water user. When all the pertinent criteria have been carefully specified, it is then appropriate to begin to consider, as discussed in the remainder of this paper, the type of control scheme and equipment that would provide the best operation within the constraints placed on the system.

The question of whether or not a delivery system is to be automated should be considered in the early stages of project development. The decision would be developed from a feasibility analysis of the benefits and costs. If automation is selected, it would then be given early and complete consideration in the design of the system.

FEEDBACK CONTROL

A closed-loop control system is one in which the control action is somehow dependent on the output. Feedback is a characteristic of the closed-loop and exists in a system when there is a closed sequence of cause and effect relations among the system variables. The functional arrangement required to adjust the INPUT to restore the OUTPUT of THE SYSTEM to its desired value typically takes the form as shown in figure 1. The FEEDBACK PATH, or loop, links the output, or the controlled variable, to the input and varies from a very complex process down to a simple measuring device.



Block Diagram
Typical Feedback Control System

Figure 1

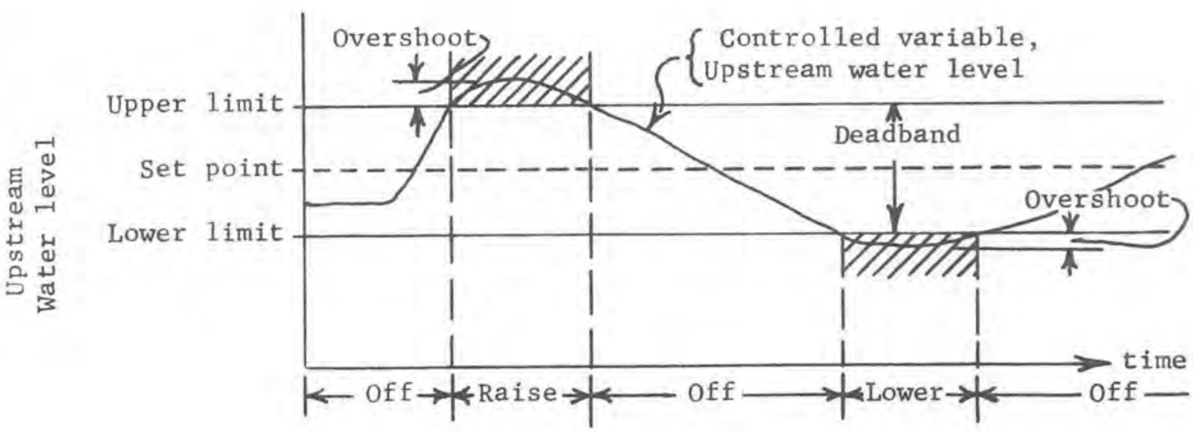
The SENSOR element of the feedback path measures the controlled variable, or the output and provides the primary signal to the COMPARATOR element. In any feedback system a REFERENCE INPUT, or setpoint, is required to establish a difference, or error-signal, between the desired value and the output value as measured by the sensor. The comparator then detects the error and provides the signal to the ACTUATOR which energizes the CONTROLLER to adjust the input to the system. The purpose, therefore, of the automatic feedback system is to reduce the error as rapidly and/or as smoothly as possible by applying a modified error to the input which can manipulate the controlled variable or the output of the system to its desired value. The type of controlled action, or error-signal modification, is called mode of control.

There are two common modes of control in use: (1) ON-OFF and (2) PROPORTIONAL. The on-off mode of control applies, to the system being controlled, corrective signals which are discontinuous functions of the sensed error. The corrective signal can assume only three discrete values corresponding to (1) zero, or no correction, (2) plus, or increase the output correction and (3) minus, or decrease the output correction. This type of system would be three-position control and where only two of the three values are used it would be two-position control. The proportional mode of control applies to the system being controlled corrective signals which vary in some direct proportion to the amount of the error signal. The ratio between the input and output action is usually adjustable and is called the gain or sensitivity of the controller, (1), (2), (3). The mode of control together with the elements which perform the control actions should be carefully selected on the basis of how rapidly and smoothly the feedback system is to respond and adjust the INPUT and restore the OUTPUT of THE SYSTEM to the desired value.

AUTOMATIC CANAL SYSTEMS

Small SYSTEMS (figure 1) may be physical components of a large delivery system such as gates, valves, supply pumps, turnouts, etc., that perform one or more vital functions of the total delivery system. Maintenance of a constant water level immediately upstream of a check structure by adjustment of the controlling check gate is a typical and practical example wherein the fundamental feedback control and the modes of control as discussed above can be illustrated. Also, the certain favorable conditions which must exist to avoid operational instability can be brought out in discussing the example in rather considerable detail.

The output of the system in this example is the upstream water level, or the controlled variable. Its vertical motion is monitored by the sensor. The plus and minus from the set point is detected by the comparator to determine which direction the controller, or gate should move. When the water level rises, the gate opening must increase to cause an opposite effect in the form of a negative surge wave to travel upstream from the gate to the sensor and cancel the initial water level rise. The negative surge wave is the final step of the closed-loop and therefore the input to the system. A reversed control sequence must occur when the water level lowers in order to restore the water level to its desired value. Figure 2 illustrates the on-off, three-position control.



Gate status

On-Off, Three Position Control

Figure 2

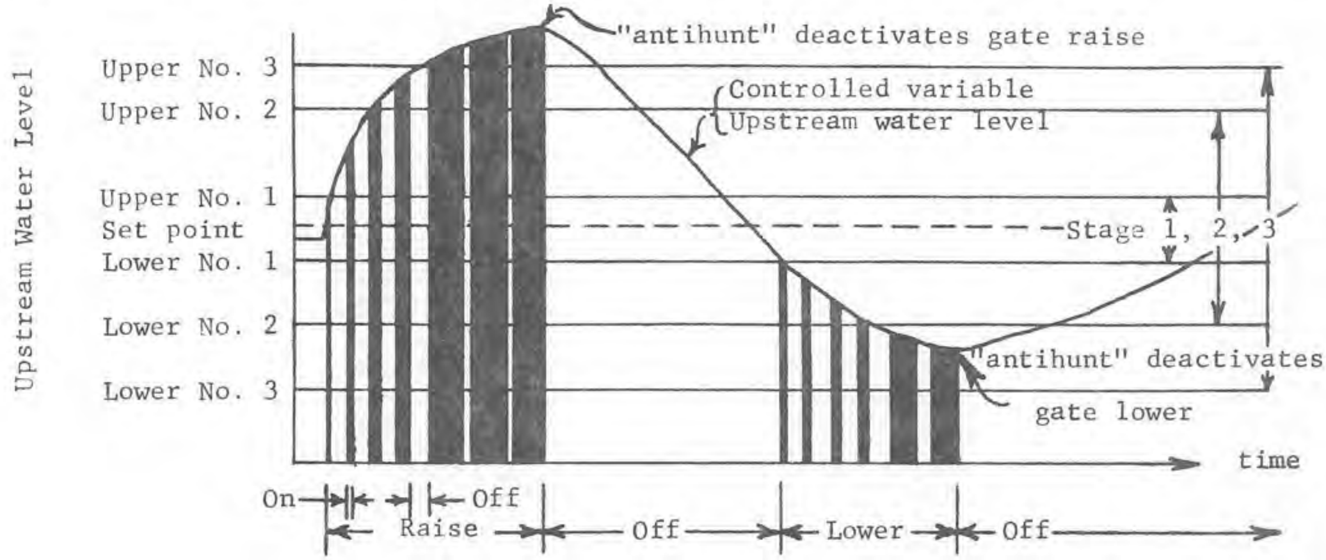
The deadband is an essential part of the on-off mode of control. Whenever the water level is outside of the deadband (figure 2), the gate will continue to either raise or lower if there is no other controlling factor involved until the water level reenters the deadband in which there is no controlled action (hence, three-position control (1) raise, (2) lower, (3) no controlled action). This type of control action is adequate providing certain favorable conditions exist. The ratio of the input response (the negative or positive surge wave caused by the gate rising or lowering) to the initiating disturbance (the initial water level rise or drop which caused the feedback system to move the gate) must not exceed unity. In other words, the correction stimulated by the disturbance must not exceed the disturbance. If this ratio exceeds unity, an initiating disturbance no matter how small will continue to increase in amplitude, (4). To prevent the ratio from exceeding unity, the reaction rate of the controller, or the rate of gate movement, must be slow enough such that the surge wave (negative or positive) produced does not exceed the smallest of initial disturbances (plus or minus) anticipated. The distance between the gate and the location of the sensor should be short so that the time of travel of the surge wave, or the time lag of the system, is minimal. A significant time lag would require an even slower rate of control action to prevent the gate from traveling too far. Excessive gate travel could easily cause the response to exceed the initial disturbance and as a result the amplification effect would occur.

The deadband cannot be too narrow. A narrow deadband would have less off-time, or no-controlled action time, and correspondingly more on-time which would cause excessive cycling of the controller. The smaller the deadband the more sensitive the feedback system is to small disturbances of shorter duration and the rate of controlled action would have to be further reduced. An on-off mode of control without a deadband would be impractical if not impossible because the rate of control action would approach zero since it would have to be extremely slow to prevent amplification of the smallest of disturbances which could be caused even by a slight breeze on the water surface. If the rate of controlled action is set for the minor and slow disturbances, then the feedback system response to the larger and faster disturbances would also be slow and cause the water level to overshoot which could exceed the limits of safety before the controller can restore it to its desired level. Therefore, a feedback system using a simple on-off mode of control is limited to the regulation of minor and slow disturbances if amplification and/or instability of control is to be avoided.

The capabilities of the on-off mode of control could be increased if the rate of the control action were to be made variable so that it would be slow for minor and slow disturbances but fast for large and fast disturbances. However, the check gates are usually designed to travel at a constant speed that is much too fast to provide the slow control action needed to prevent amplification of the disturbances that normally occur in a canal system.

A feedback system which is designed specifically to maintain a constant water level either upstream or downstream of a check structure and is used on many Bureau of Reclamation projects is a device known as the "Little Man." The "Little Man" was developed empirically by field operating personnel and through field experimentation over several years the original design has been modified and improved to increase its capability and to overcome some of the problems that cause instability. The "Little Man" is basically an on-off, three-position mode of control except timers are included in the actuator unit. The timers energize for only a few seconds the raise or lower relays to the motor controller and provide an interval of rest time between the gate movements. The average rate of controlled action, or gate movement, over a period of time can be regulated by adjusting the on-time and/or the rest-time. The timer interrupter sequence works effectively once the operate and rest intervals are properly adjusted to prevent amplification of the smallest operational disturbance anticipated.

Before describing how the "Little Man" capabilities were increased to regulate larger disturbances, it is appropriate to first describe the equipment used in the elements of the feedback path. The sensor consists of a float, tape, pulley, counter-weight assembly. The comparator unit is a simple arrangement of two micro switches. One micro switch is set to trip at the upper limit and the other at the lower limit. The tripping action is accomplished mechanically either by cams attached to the float pulley shaft or by a tripping arm attached to the float tape. The set point is usually the design depth at maximum flow of the canal, and the deadband limits are typically ± 0.02 feet from the set point. The actuator then consists of the two timers, one for raise and one for lower, that are activated by the comparator raise or lower micro switches. When the timers are in the operate portion of the timing sequence a raise or lower relay is activated which in turn energizes the motor controller to raise or lower the gate. The timers are adjustable (manually) and the larger disturbances can be accommodated when anticipated. However, the same flexibility was achieved by adding additional pairs of micro switches and time clocks in parallel to the comparator and actuator units. The additional components sense larger water level deviation increments from the set point which are associated to large disturbances. Each stage or larger deadbands selects a different time clock sequence which increase the operate time of gate travel with shorter rest intervals between gate movements. The average response is then faster and proportional to the magnitude of the disturbance. However, excessive gate travel was still a problem. Field personnel developed another device known by the general term "antihunt device" which was added to the comparator unit. The antihunt device has a stabilizing effect on the feedback system because it prevents excessive gate travel and reduces the possibility of amplifying the disturbance. The antihunt device has taken several forms, but basically it deactivates the actuating unit when the water level stops moving away from the set point and begins to return towards it. The overall mode of control for the "Little Man" can be classified as multistage, on-off, three-position control with adjustable rate of control action capabilities. Figure 3 illustrates the expanded capabilities of the "Little Man" feedback system from that illustrated in figure 2.



Gate Status, Operate, and Rest Times
"Little Man" Mode of Control
Multistage, On-Off, Three Position, Plus Rate

Figure 3

It is well to note that even though the antihunt device significantly reduces the instability of the "Little Man" feedback system, there is a possibility that the water may just return a slight amount towards the set point and hangup in this position. Further control action would stop because of the deactivation by the antihunt device, and therefore, the water level would not return to the desired value. However, in a canal system where disturbances are the rule, the possibility of a steady state condition occurring at that particular moment is remote and it would be of a short duration. Another feature of some "Little Man" installations which also adds further operational flexibility is an adjustable motorized set point. This feature of the "Little Man" is used primarily when the canal is to be unwatered. The set point motor, which is manually activated when desired, slowly and continuously drives the set point downward and the feedback system, in effect, senses a high water level and the gate is signaled to open lowering the water surface, (5).

The above lengthy discussion was deemed appropriate because it deals with the elements of the feedback path in terms of a mode of control which is popular, basic, and has application to many other installations. Despite variations in the feedback system, equipment, and the mode of control in different situations, the basic concept remains the same.

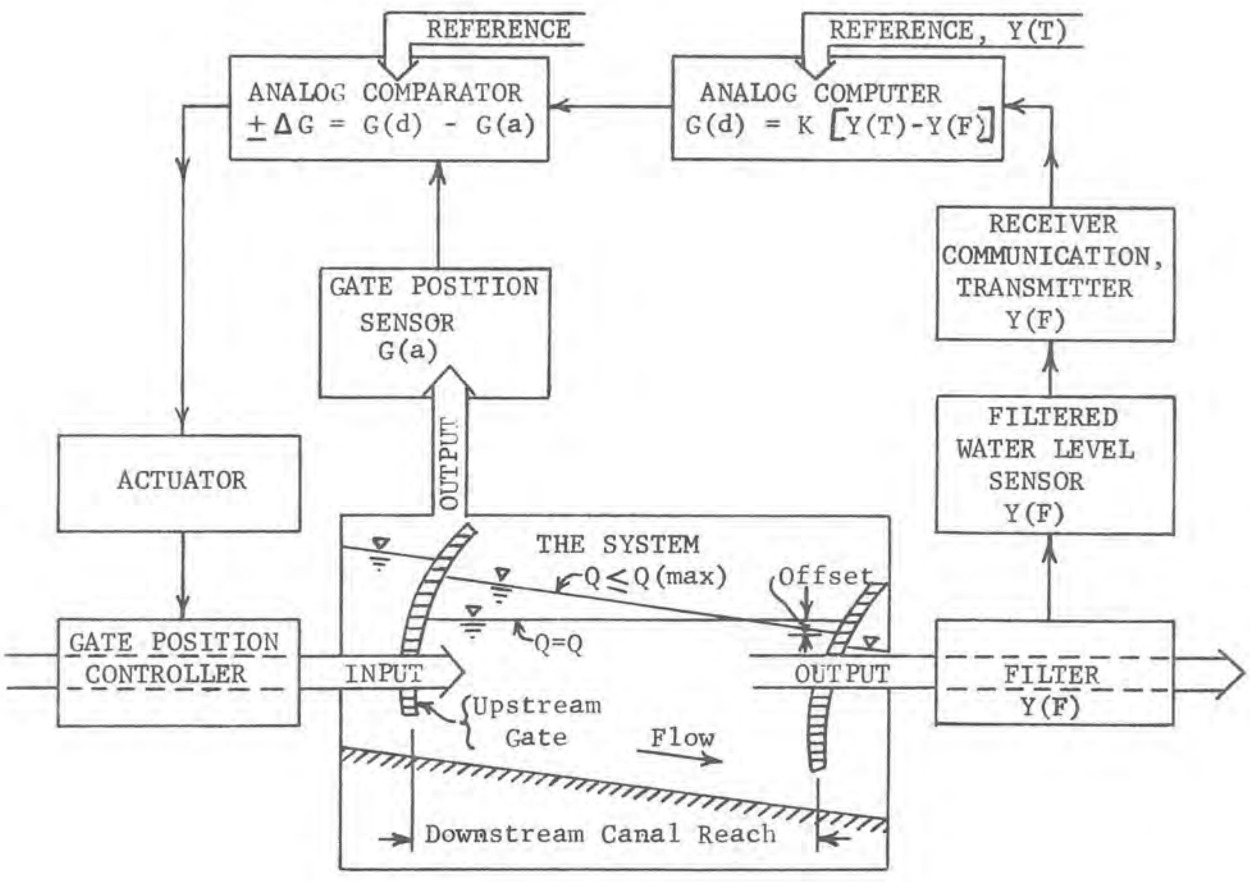
Other applications of the "Little Man" in maintenance of constant water level include Parshall flumes or canal laterals located downstream from a turnout gate or valve. When the downstream water level is used as the controlled variable to adjust the gate upstream the electrical circuitry must be reversed at the controller so that the gate closes when the water level rises and opens when the water level drops.

The "Little Man" is limited to the maintenance of a water level and in only special cases such as Parshall flumes or weirs would it be a flow controller. Flow control in general utilizes commercially available equipment of greater complexity, usually referred to as automatic set point flow controllers to maintain a constant flow. The flow rate desired or set point is dialed by the "ditchrider." The feedback system senses the hydraulic parameters and computes the actual flow through the check gate, as an example, by solving the orifice equation, $Q(\text{actual}) = CA\sqrt{2g\,\Delta H}$. Sensors must measure the magnitude of both the upstream and downstream water level and the actual gate opening. An additional element is included in the feedback path which is the analog computer. The analog computer is designed to solve the orifice equation electronically (the discharge coefficient, C, should also be dialed in by the ditchrider to correspond to the flow setting) based on the signals received from the sensors to obtain the actual flow. The comparator unit compares the computed flow to the set point flow electronically and the actuator, or raise or lower relay, energizes the motor controller to raise or lower the gate to obtain the set point flow. This equipment usually has built-in "antihunt" characteristics in the form of time delay units and resistor and capacitor (RC) circuits.

Greater flexibility of operation can be achieved beyond just the maintenance of constant water levels or constant flows at a check structure when the system to be controlled, figure 1, is expanded and more elements are added into the feedback path. An example of an enlarged system would be one which includes a check gate and the canal reach downstream from it. By moving the water level sensor to the lower end of the downstream canal reach and by adding transmitter, communication channel, and receiver elements between the sensor and the controlling gate upstream (a distance of perhaps several miles), a response to a disturbance at the lower end of the canal reach can be instantaneous at the upper end. The behavior of the canal reach can then be analogous to that of a pressure pipe system. Attempts to apply the "Little Man" to the enlarged system have not been too successful because of the appreciable time lag involved for the surge wave, or input, to arrive at the downstream sensor of the system. Unless the conditions are exactly right, as explained earlier, the "Little Man" feedback control system can easily begin to oscillate.

The results of a recent research program by the University of California and subsequent field tests sponsored by the Bureau of Reclamation has shown that if certain control parameters are incorporated into additional elements of the feedback system, not only can the problems of instability be avoided, but a higher degree of self-regulation can be achieved. The feedback system developed has been labeled the Hydraulic

Filter Level Offset (HyFLO) method. In the HyFLO method, the downstream canal side turnout demand, or its equivalent canal flow, is related to the "offset" (the drop in the canal water surface level as flow increases). The HyFLO feedback system is basically a proportional mode of control. The upstream gate opening is directly proportional to the offset of the downstream water level, the controlled variable, from a target level which is selected as the water level desired when the flow demand is zero. The offset is an essential part of the proportional mode of control and provides a smooth and continuous control action because of the coupling between the controlled variable and the position of the gate. The elements of the HyFLO feedback system as shown in the longitudinally compressed figure 4 are identified before the control parameters for the proportional mode and for stability of control are discussed.

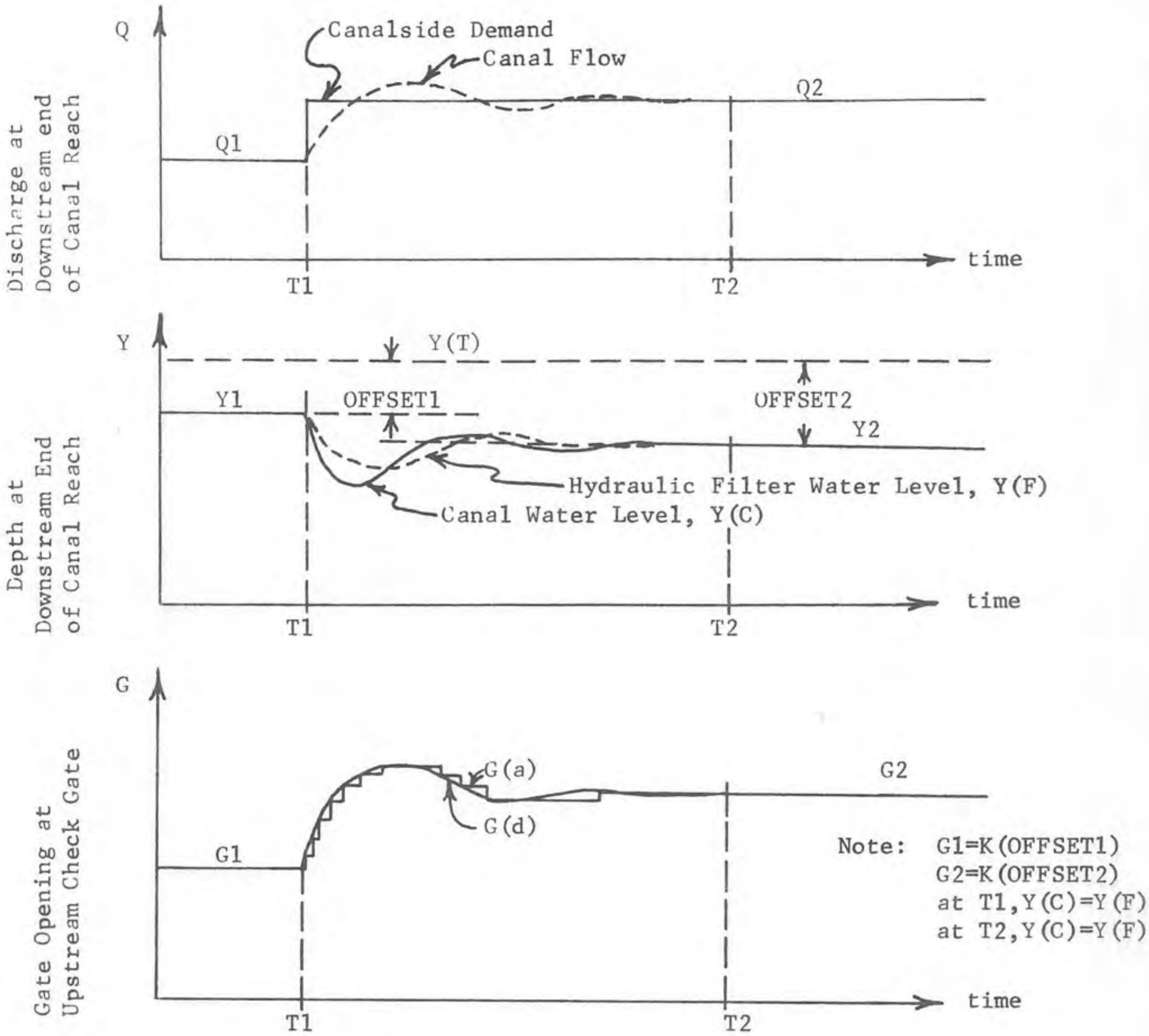


HyFLO Feedback Control System

Figure 4

A special hydraulic analog filter, analogous to an electrical RC circuit develops the necessary long time constant (on the order of 2,000 seconds) and is the first element of the feedback system (figure 4). It consists of a capillary tube connected between the canal (or a normal stilling well) and a secondary or filter well. The linear resistance of the laminar flow produced by the capillary tube represents the resistance and the area of the filter well represents the capacitance of the analogous RC circuit. The sensor element gages the water level inside the filter well and may consist of either a pressure transducer or a potentiometer driven by a float pulley shaft. This measurement is then transmitted to, and received at, the upstream check gate. The output of the receiver is the input to the analog computer which solves the equation G(d) = K(Y(T)-Y(F)) where G(d) is the desired gate opening, K is the proportionality factor or the gain which is constant, Y(T) is the target value, or the referenced input, and Y(F) is an analog of the hydraulic filter well level. The comparator unit electronically sums (or the electronic equivalent of subtraction) the computed gate opening, G(d), and the actual gate opening, G(a), which has an opposite polarity as measured by another potentiometer driven by the gate hoist shaft, to obtain the error signal. All measured and computed valves, of course, must be properly scaled and calibrated if each element is to perform correctly. If the error is greater than the comparator referenced input (typically $\pm$ 0.10 foot of gate opening), the comparator will energize the raise or lower relay of the actuator which will in turn energize the controller to raise or lower the gate depending on whether the comparator signal output is plus or minus. The gate moves in the proper direction until the comparator unit difference is zero, at which time the gate stops. The comparator unit by itself is an on-off, three-position mode of control which is necessary because of the very fast rate of travel of the gate relative to the feedback response of the hydraulic filter well. Figure 5 illustrates a hypothetical response of the HyFLO feedback control system for a canal reach.

Central to the stable operation of the HyFLO system is the selection of three primary control parameters, (1) the hydraulic filter well "time constant," (2) the water level "offset," and (3) the proportionality factor or "gain." These control parameters are selected to eliminate instability inherent in automatic feedback control systems and to give a high degree of self regulation, i.e., the fastest response and recovery of the system to a new steady state without excessive overshooting of the water levels. The system must function over a wide range of canalside demand changes from an instantaneous change of 50 percent of designed capacity to, small less than 1 percent, of designed capacity. The time constant of the hydraulic filter well governs the stability of the control system by filtering out the critical frequencies of disturbances which tend to be amplified by the controller. The selection of the time constant is based on considerations of the hydraulic transient behavior of the open channel under study, the desired rate of control action of the system, or the amount of damping within a period of potential oscillation, as well as the desired magnitude of the offset from the target valve. The magnitude of offset for maximum flow is selected to obtain an optimum balance between the faster system response permissible with a larger offset and the cost of accommodating larger offsets.



Hypothetical Response of the HyFLO
Feedback Control System

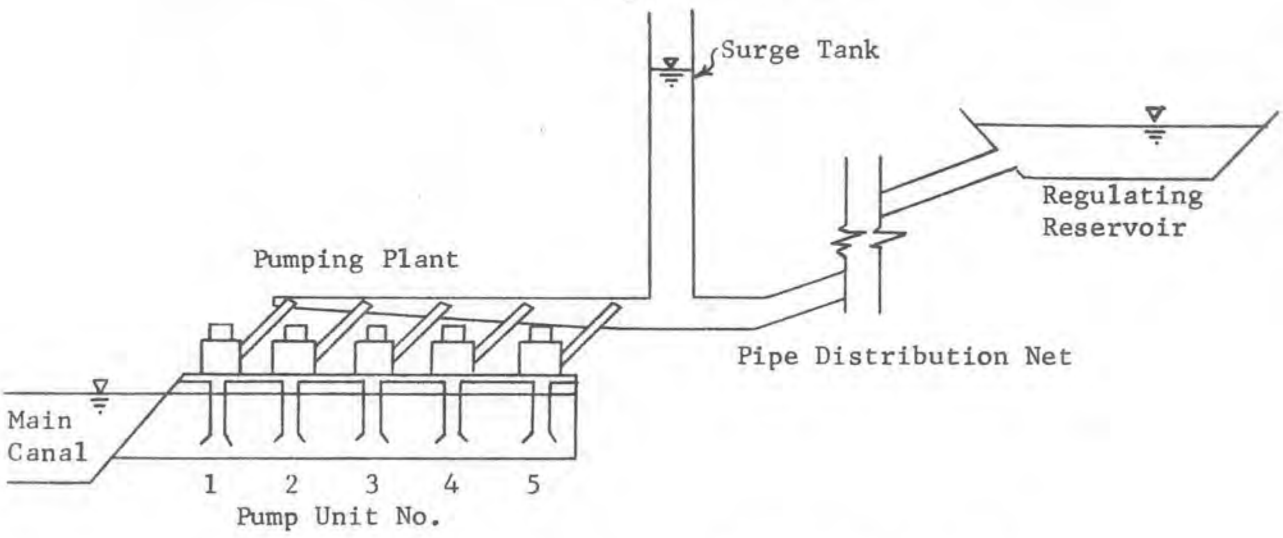
Figure 5

The gain is selected to prevent the amplification of a disturbance as it propagates upstream towards the headworks through the upper canal reaches, which may also have HyFLO control. Amplification of the disturbance upstream is usually the controlling factor when selecting the gain, or proportionality factor, (4).

The three primary control parameters are interdependent and are solved by trial and error using special computer programs developed at the University of California at Berkeley, and are described in greater detail in references 5 and 6. Further information on the need, the general theory, and the application of automatic downstream control systems by the HyFLO method may also be found in a paper presented at the Fifth Technical Conference of the U.S. Committee on Irrigation, Drainage, and Flood Control on October 8 and 9, 1970 (reference 7). The output of the mathematical model simulating a canal system and the HyFLO method of controlling the check gates when demand changes on the simulated canal system were made was the key element in the research program that demonstrated the feasibility of the HyFLO method. The "on-the-computer" analysis was subsequently confirmed by prototype tests. The HyFLO method increases flexibility of operation, has wide application, and meets the demands of modern irrigation practice.

AUTOMATIC PIPE DISTRIBUTION SYSTEMS

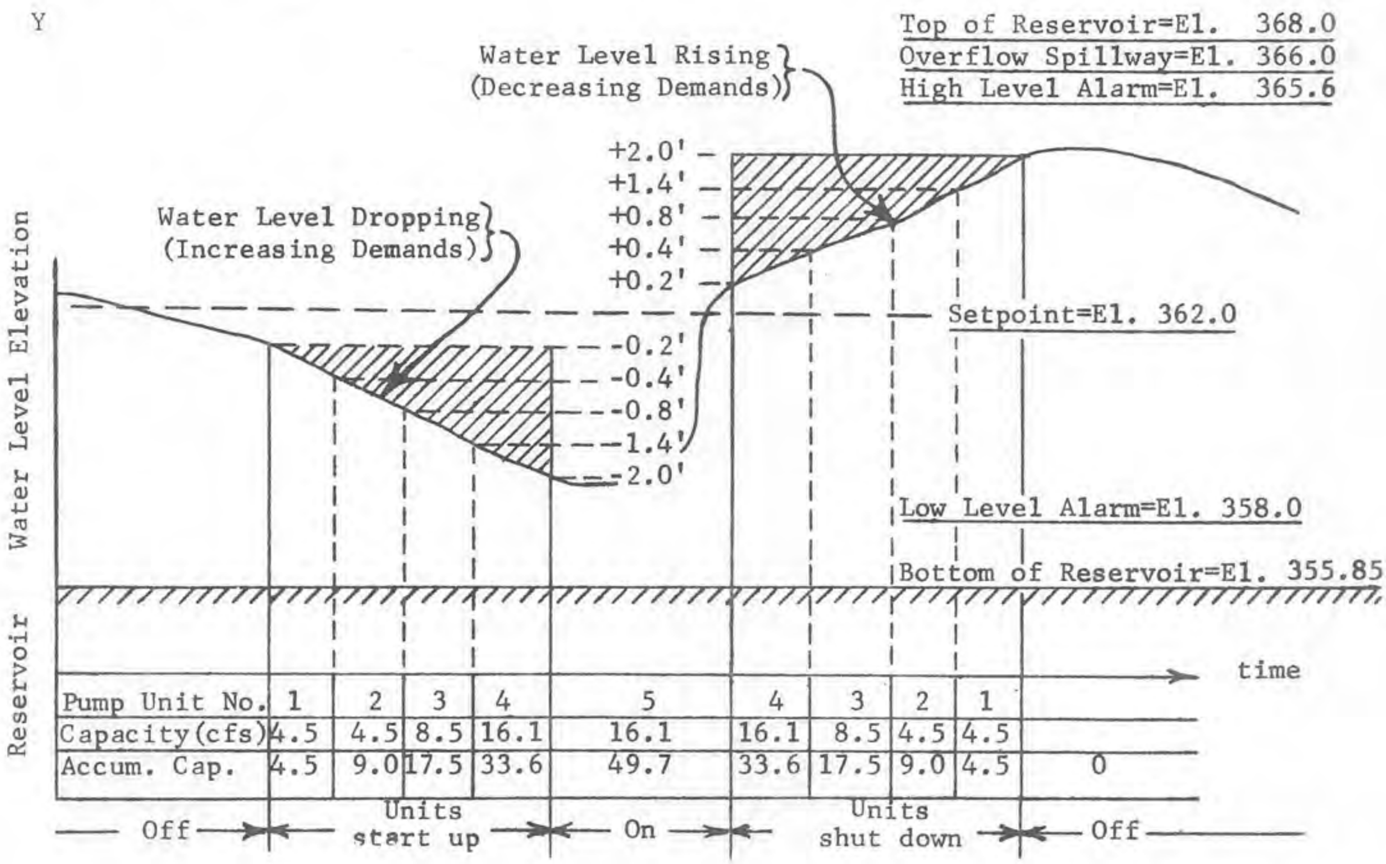
A typical pressure pipe distribution system is shown in figure 6. Each pumping unit is automatically controlled using a water level telemetering system. The sensor is usually a direct float operation where the vertical motion of the float is directly transferred to the transmitter.



Typical Pressure Pipe Distribution System

Figure 6

The output of the transmitter is over a direct-current circuit to the receiver at the pumping plant using the pulse-duration mode of communication. The receiver is equipped with a level indicator and sufficient auxiliary contacts to start and stop each individual pumping unit. Each pair of these contacts is assigned one of the pumping units where one of the pair of contacts starts the pump at a low limit setting and the other stops the pump at an upper limit setting where the settings represent selected water levels in the reservoir. Additional contacts at the float sensor, or transmitting end, are opened by the float sensor when abnormally high or low reservoir levels exist and interrupt the telemetering system which in turn opens a contact at the pumping plant and all the pumping units running will be shut down automatically. Figure 7 shows schematically the sequence of automatic starting and stopping of a five-unit pumping plant. The type of control action involved is the multistage, on-off two-position control.



Pumping Plant Status

Sequence for automatic starting or stopping of a five-unit pumping plant when water demands are increasing or decreasing on a pressure pipe distribution system-multistage, on-off, two-position control.

Figure 7

For two position control, the deadband for each unit is the zone between the upper and lower limits such as 0.02', 0.04', and etc., as shown in figure 7. The pump units are either on or off inside the deadband. The pump units are started up when the water level reaches the lower limit (an indication that the water demands on the system have increased) and continues to run until the water level reaches the upper limit (an indication that the demands have decreased). The unit then stops and remains off until the water level drops to the lower limit. The deadband is relatively wide to reduce sensitivity and the pumping units are of variable size from small to large to give the variable rate of control action necessary to meet small to large demands all of which increases operational control stability and flexibility. The time lag is naturally very short because of the closed pipe system between the pumping plant and the regulating reservoir.

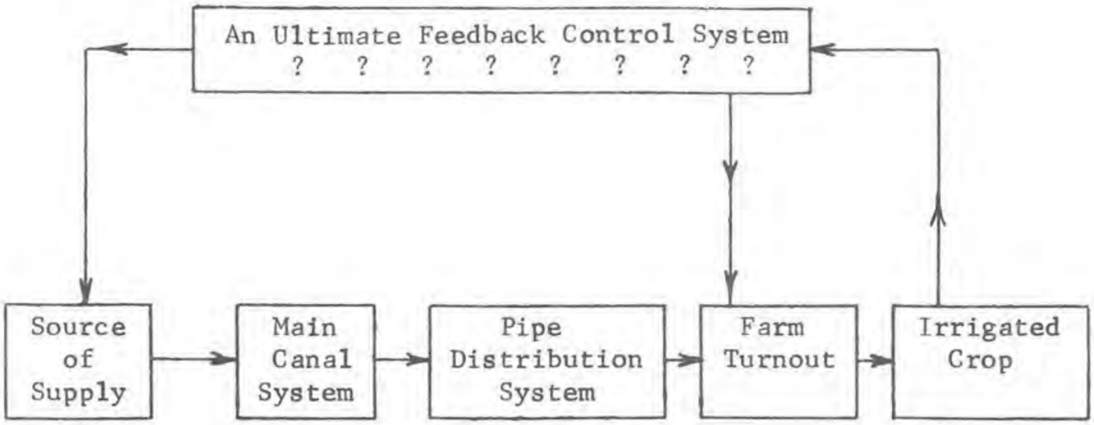
AUTOMATIC TURNOUTS

As mentioned previously the "Little Man" is applicable for automatically controlling a constant water level downstream of a turnout gate from a main canal or canal lateral. Controllers similar to the "Little Man" which are available in commercial configuration are frequently used to regulate the outlet works of diversion dams. Automatic setpoint controllers, as mentioned earlier, for canal check gate control, are also available and are used for automatically controlling turnout gates.

A rotameter-type vertical flowmeter, flow controller, and integrator for farm delivery turnouts has been recently developed and manufactured by the Brooks Instrument Division, Emerson Electric Company, Hatfield, Pennsylvania. The Brooks meter combines the capability for (1) rate-of-flow (c.f.s.), measurement and indication and an integrator for totalized-flow read-out in acre-feet, (2) limiting the flow to a maximum preset rate over a range of head, and (3) a small (1/2-inch) external on-off valve to start and stop the main delivery to the water user, all in a single unit. External power is not required except internal power supplied by batteries is required for the integrator unit. The meter is basically a variable orifice-type. Flow control is essentially a hydraulically actuated servomechanism using the metering float as the sensor and comparator with the setpoint for maximum flow as the referenced input and an internal pressure chamber and sleeve valve as the actuator and controller. Pressure regulator valves are often used at farm turnouts from pressure pipe systems where the pressure head in the distribution system varies significantly. The sensor for this system may be a pressure transducer or float system in the standpipe at the head of the farmer's lateral. The pressure regulator valve maintains a constant head (maximum) in the standpipe by adjusting an internal valve as the pressure varies on the upstream side.

ULTIMATE AUTOMATIC DELIVERY SYSTEMS

Water conveyance is presently or could be readily made automatic from the main canal headworks to the farm turnout. An ultimate or more modestly, a penultimate, feedback control system would be one that links the actual requirements of the irrigated crop or plant to the farm turnout as well as the source of supply as suggested in figure 8.



Ultimate Feedback Control for
Automatic Delivery Systems

Figure 8

Recent advances in irrigation sciences have related irrigation scheduling to the complex climate-crop-soil relationship, (8). Increased knowledge of soil and plant characteristics combined with better methods of measuring current soil moisture content and estimating soil moisture depletion are available to predict with greater accuracy the time and actual quantity of water needed for the next irrigation. The sensor element for measuring the prevailing soil moisture content could be a commercially available instrument or a trained technician. This primary information could then be fed into an automatic data processing digital computer which has available in memory information concerning the characteristic of the soil such as its moisture holding capacity, the type of plant and its maturity, an estimate of evaporation, and many other parameters which may effect the quantity and timing of the next irrigation. The digital computer utilizing many reference inputs determines the schedule for irrigation and the possible alternatives. This information is then furnished to the water user who must select the schedule best suited to his operation. The user, in a sense, performs the function of the comparator element using his other competative farm operations as reference. The final schedule involving the actual water quantity and the time it is needed at the farm turnout should be relayed to the operators of the supply system for release from the storage reservoirs. A feedback system of this nature including the forecasting of the available runoff would enable the scheduling procedure to be done on a yearly, monthly, weekly, and daily basis with reasonably good accuracy. The transfer of large quantities of water to meet turnout demands; to store winter and spring flood runoff in offstream reservoirs; and to attain an optimum power generation and off-peak pumping operations would therefore be accomplished with improved efficiency.

The theoretical ultimate system discussed is intended to show that there is much more work to be done and that the concept of feedback control applies to the total system as well as to small systems which may be components of a large system.

Some of the feedback systems that are already in use could be improved with respect to some of the components. For an example, gate motor controllers could be of variable speed (very slow to fast) which would improve the operation of both the "Little Man" and the HyFLO methods of automatic flow regulation in canals. Similarly, the pumping units for automatic pressure pipe distribution systems could have variable discharge output (probably variable pitch impellers) to more closely match the actual demand. Variable gate speed and pump discharge would provide a smother and more efficient operation and improve operational stability.

SUMMARY

Instead of trying to cover all of the possible applications or all the basic equipment of feedback control systems, emphasis is placed on showing that there are practical automatic control systems for main canals, pressure pipe distributions, and farm turnouts which are being successfully applied.

Elements of a typical feedback control system are identifiable in even the small and simple automatic system such as the "Little Man." Whenever there is an automatic controlled action dependent on a controlled variable such as the gate adjustment to maintain a constant upstream water level, there is a feedback path linking the output to the input. The elements of the feedback path and the mode of control apply corrective signals to the controller to automatically adjust the input to manipulate the output to its desired value. The on-off mode of control lacks flexibility of operation for canal check gate regulation because it is limited to small and slow disturbances if operational stability is to be maintained. For automatic pressure pipe system, the on-off mode of control provides a good method of automatically starting and stopping pumps in accordance with the demand on the system because conditions are usually favorable to operational stability.

The proportional mode of control such as the HyFLO method offers a great deal of versatility and flexibility of operation to automatic flow regulation in canal systems. The large and rapid as well as the small and slow disturbances can be regulated smoothly by the proportional mode of control and operational stability is maintained by including a system-related hydraulic filter-well ahead of the sensor. Both modes of control, on-off, and proportional, have their application and usefulness but certain favorable conditions must exist in each to avoid instability of control.

The natural characteristics of feedback control, the elements involved in the feedback path, the modes of control and conditions for stability of control, and the manner in which input response effects the output (surge wave action for example) are all considerations of basic equipment in automatic delivery systems. Selection of electrical, and/or mechanical, and/or hydraulic components and hardware is a relatively minor, but important, aspect when it comes to developing practical and successful control schemes.

It has been noted that conveyance of irrigation water is presently or could be readily made automatic from the main canal headworks to the farm turnout. Implementation of an ultimate feedback control system (figure 8) would go far towards meeting the demands of modern irrigation practice in providing a better match between the plant requirements and available water supply. What is actually accomplished is limited only by the imagination, the inventiveness, and the ability of the Irrigation Systems Engineer to transfer available technology.

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