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IRRIGATION AUTOMATION: A SYSTEMS APPROACH

BY

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IRRIGATION AUTOMATION: A SYSTEMS APPROACH

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable as meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

Thesis Adviser Date

Head, Electrical
Engineering Department Date

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E.B.H.

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GLOSSARY OF TERMS

AUTOMATION: Decision-making capability in addition to the use of hardware and energy to replace human labor.

BASIN: An area of nearly level land surrounded by low, flat levees which is flooded to the desired depth when irrigated.

BOOM: A long arm containing several sprinkler heads.

BORDERS: Gently sloping strips of field bound by low earth ridges or levees to contain water during irrigation.

CANAL: A ditch that carries irrigation water from the source of supply to one or more farms.

CAPILLARY ACTION: Movement of water in the soil under unsaturated conditions from a high-moisture potential (moist area) to a low-moisture potential (dry area).

CARRIAGE: A movable support structure for pipe laterals.

CHECKS: Structures placed in a ditch to form adjustable dams to control the elevation of the water surface upstream so that water can be diverted from the ditch.

CONTOUR DITCH: Irrigation water is distributed from ditches running across the slope approximately on the contour.

CORRUGATIONS: Small channels or grooves evenly spaced across the field.

DITCHES: Open channels used to carry water to its point of use.

DIVISION BOX: Device used to divide or direct the flow of water between two or more ditches.

DROPS: Devices which control ditch velocity by lowering the water abruptly from one level to a lower level.

EVAPOTRANSPIRATION: Includes water used by plants in transpiration and growth and that evaporated from adjacent soil and from precipitation intercepted by plant foliage.

FIELD CAPACITY: The moisture percentage, on a dry weight basis, of a soil after rapid drainage has taken place following an application of water, provided there is no water table within capillary reach of the root zone. This moisture percentage usually is reached within two to four days after an irrigation, the time interval depending on the physical characteristics of the soil.

FLOW RATE: The rate at which water flows in a delivery system or onto a field.

FLUIDIC DEVICES: Water handling devices which use fluidic principles involving single or combined fluid phase techniques (air or water or air and water) to perform logic, amplification, and controlling functions.

FLUMES: Artificial channels supported by substructure which carry water across areas where ditches are not practical.

FURROW: A groove or depression between crop rows.

GATED PIPE: Portable metal pipe, usually aluminum, with a number of small gates along one side through which water can be run into corrugations, furrows, and borders.

GATES: Openings in hydraulic structures which permit the passage of water, and in most instances regulate out-flow.

GUN: A high velocity, large volume sprinkler head used on traveler sprinklers.

HEAD: The depth of flow of water over the crest (measured at a specified distance upstream from the bulkhead).

HEAD DITCHES: Used to distribute water in a field for surface irrigation.

HEAD GATE: Gate used to divert the required amount of irrigation water from the source of supply to the field ditches.

HYDRAULIC ROUGHNESS: A measure of the resistance provided by a surface to water flowing over it.

INFILTRATION: The passage of water into the soil surface.

INTAKE RATE: The rate at which water enters the soil.

IRRIGATION EFFICIENCY: The percentage of applied irrigation water that is stored in the soil and available for consumptive use by the crop. When the water is measured at the farm headgate, it is called farm-irrigation efficiency; when measured at the field, it is designated as field-irrigation efficiency, and when measured at the point of diversion, it may be called the project efficiency.

LATERAL: A side ditch or pipe leading from a supply canal or pipe to a set to be irrigated; water is usually applied to the field from a lateral.

LEACHING: The removal of harmful soluble salts from the crop root zone by applying irrigation water in excess of crop needs to flush the salts below the root zone.

LEVEE: A small ridge of earth for confining water during irrigation.

MAINLINE: Conveys water from the supply line to the lateral lines.

MECHANIZATION: The use of hardware and energy to replace human labor.

MOLE DRAINS: Cylindrical channels artifically produced in the subsoil without digging a trench from the surface.

PERCOLATION: The movement of water through the soil profile.

PLANT STRESS: Describes adverse effects on crops from low plant water potential and other factors.

ROOT ZONE: Area in the soil where crop roots are; the depth of this zone varies with crop type.

RUNOFF: That portion of the precipitation that makes its way toward stream channels, lakes, or oceans as surface or subsurface flow.

SET: A part of a field which receives water until it reaches a specified minimum moisture level.

SIPHONS: Small curved pipes that deliver water over the head-ditch to corrugations, furrows, or borders.

SLOPE: The angle of inclination of the soil surface.

SOIL MOISTURE TENSION: A measure of the tenacity with which water is retained in the soil and shows the force per unit-area that must be exerted to remove water from a soil. It is usually expressed in atmospheres, the average air pressure at sea level.

SUMP: A hole or reservoir serving as a water receptacle.

TILE DRAIN: A drain which receives water from the soil; constructed of tiles laid end to end in a trench which is backfilled, water enters the drain through perforations or joints between tiles.

TRAILER LINES: Lines with several sprinkler heads which are attached at intervals to a main lateral to increase the area sprinkled per set. They trail behind the main lateral when the lateral is moved to the next set.

TURNOUT: A gate, valve, or other outlet type which permits transference of water from a conveyance or delivery system to a lesser conveyance or delivery system or onto a field.

VALVE: A structure which controls flow of water within a pipe or out of a pipe.

WATER TABLE: The top surface of the ground water zone; the soil is saturated in the ground water zone.

WILTING POINT: The soil moisture content at which plants can no longer obtain enough moisture to meet transpiration requirements, and the plants wilt.

CHAPTER I

INTRODUCTION

Man continually tries to find an easier way. Labor saving methods, in some instances, have been forced on him by other urgent demands for his time. In other instances, he has simply desired more leisure time. Automation in irrigation is not an exception. Efficient use of land and water resources is essential in this age of increasing population, increasing demands for food, increasing pollution, and decreasing available natural resources. Automating irrigation practices permits greater efficiency in water use. In addition, it fosters new agricultural practices in areas such as climate modification, fertilizer and herbicide application, and waste disposal. As labor costs increase, pollution laws tighten, and water resources dwindle, automation of irrigation quickly becomes a must (1).

For automated equipment to be of value to the individual farmer, such equipment must be reliable, simple to operate and maintain, and fail-safe. It must also be sufficiently inexpensive and sufficiently effective to assure him of a significant chance for increased profits. These goals can be accomplished only through diligent application of state-of-the-art scientific and engineering knowledge and practices to the design of new automated irrigation equipment.

The interdisciplinary approach to irrigation engineering has just barely begun. Interdisciplinary cooperation can produce the effective sensors or transducers, communication systems, and controls required in automatic systems. Inexpensive, reliable, and accurate devices are needed to measure plant stress, soil moisture, soil salinity, evapotranspiration rates, flow rates, pipe pressure, water quality, and other parameters vital to optimum system operation. Automated irrigation system development is also dependent on adapting present or developing new communication systems for error free, dependable transmission of system parameter measurements and system control commands. Little work on communication systems, applicable to individual farm use, has been done. Significant improvements on communication equipment and methods used in large district and state irrigation projects are also possible. Some work is being carried out at the district and state levels in California, Arizona, Nebraska, Oregon, and Washington. A definite lack of valves, gates, meters, pump controls, and other controls specifically designed for use in automatic irrigation systems exists. In many cases automatic controls have simply been tacked on to existing gates, valves, and pumps. This is, perhaps, a necessary first step, but much design is unfinished. Many semi-automatic check gates and turnouts have been built. These units definitely have their place in automatic systems. However, completely automatic gates, valves, and other controls must be developed to complement the semi-automatic units.

Research and development of automatic irrigation systems have been performed principally by three groups: universities, state water projects, and industry. Universities have concentrated resources on solving problems associated with irrigation on the individual farm. State water projects have concentrated on developing automatic water distribution systems capable of supplying water on demand. Industry has used its resources primarily in the development of sprinkler systems. It has also given some attention to surface systems with pipe delivery and to surface systems controlled by fluidic diverters.

An automated system requires a telemetry system to transmit the measurement of necessary parameters to the control center. This same telemetry system may also be used to remotely control the irrigation system. Alarms and system monitoring functions may be performed remotely by a telemetry system. Reliability and maintainability are essentials in such a telemetry system.

This thesis defines areas in which the electrical engineer can assist in developing irrigation automation.

Particular attention is given to a telemetry system for data transmission from soil moisture sensors. Present and future communication requirements in automated irrigation systems are also discussed.

CHAPTER II

HISTORY OF AUTOMATION IN IRRIGATION

Each of the three basic irrigation methods--surface irrigation, sprinkler irrigation, and subsurface irrigation--requires special consideration in automatic system development. Various degrees of automation have been achieved with each method.

Surface irrigation systems are difficult to automate because of the many variables; such as field slope, soil intake rate, soil hydraulic roughness, and runoff; which must be simultaneously considered. Semi-automatic gates, automatically switched turnouts, and fluidic devices comprise most of the automation developments in surface systems with canal delivery. Surface systems with pipe delivery have been controlled with both electric and pneumatic pipe valves.

Sprinkler systems are the easiest to automate and have been automated to the greatest degree. This is a direct result of their wide commercial use for golf course and landscape maintenance as well as in agriculture. Some completely automatic systems have been developed.

Subsurface irrigation systems are still largely experimental. However, when improved, they should be readily automated. Davis and Nelson state that subsurface systems can be easily automated using float valves and moisture measuring devices to control water application (2).

A. DESCRIPTION OF IRRIGATION METHODS

1. Surface Irrigation

Water is applied to the land in surface systems by ordinary flooding, border flooding, check or basin flooding, and furrow irrigating. Ordinary flooding is the application of irrigation water from field ditches which may be nearly on the contour or up and down the slope. After the water leaves the ditches, no attempt is made to control its flow (3). The border method of flooding consists of dividing the field into a series of strips separated by low ridges (4). These ridges confine the water within each individual strip after the water is released from the supply ditch or pipe. The check or basin flooding method delivers water to a check or basin surrounded by small, flat levees which control the water. The furrow irrigation method requires that water be delivered into closely spaced furrows or corrugations running on the contour or down the field depending on the degree of field slope.

Water is delivered to surface irrigated fields by open canal, underground pipe, or portable pipe. A turnout gate, siphon, hole, or valve controls the flow rate of irrigation water from the delivery system onto the field. Automatic remote control of these devices constitutes part of the automation of surface irrigation.

Figure 1 illustrates most of the methods of surface irrigation (5).

2. Sprinkler Irrigation

Sprinkler irrigation systems are as varied as the land they irrigate and the people who operate them. There are at least nine different types of sprinkler systems in current use (6).

1. Handmove portable lateral
2. Tow-line
3. Giant (boom) sprinkler
4. Traveler (gun) sprinkler
5. Side roll
6. Side move
7. Center-pivot, self-propelled, continuously moving
8. Straight lateral, self-propelled, continuously moving
9. Solid set

The last three systems--center-pivot; straight moving, self-propelled; and solid set--are readily adapted for automation. The other six systems will probably always require a significant amount of hand labor and supervision. Some of these systems are highly

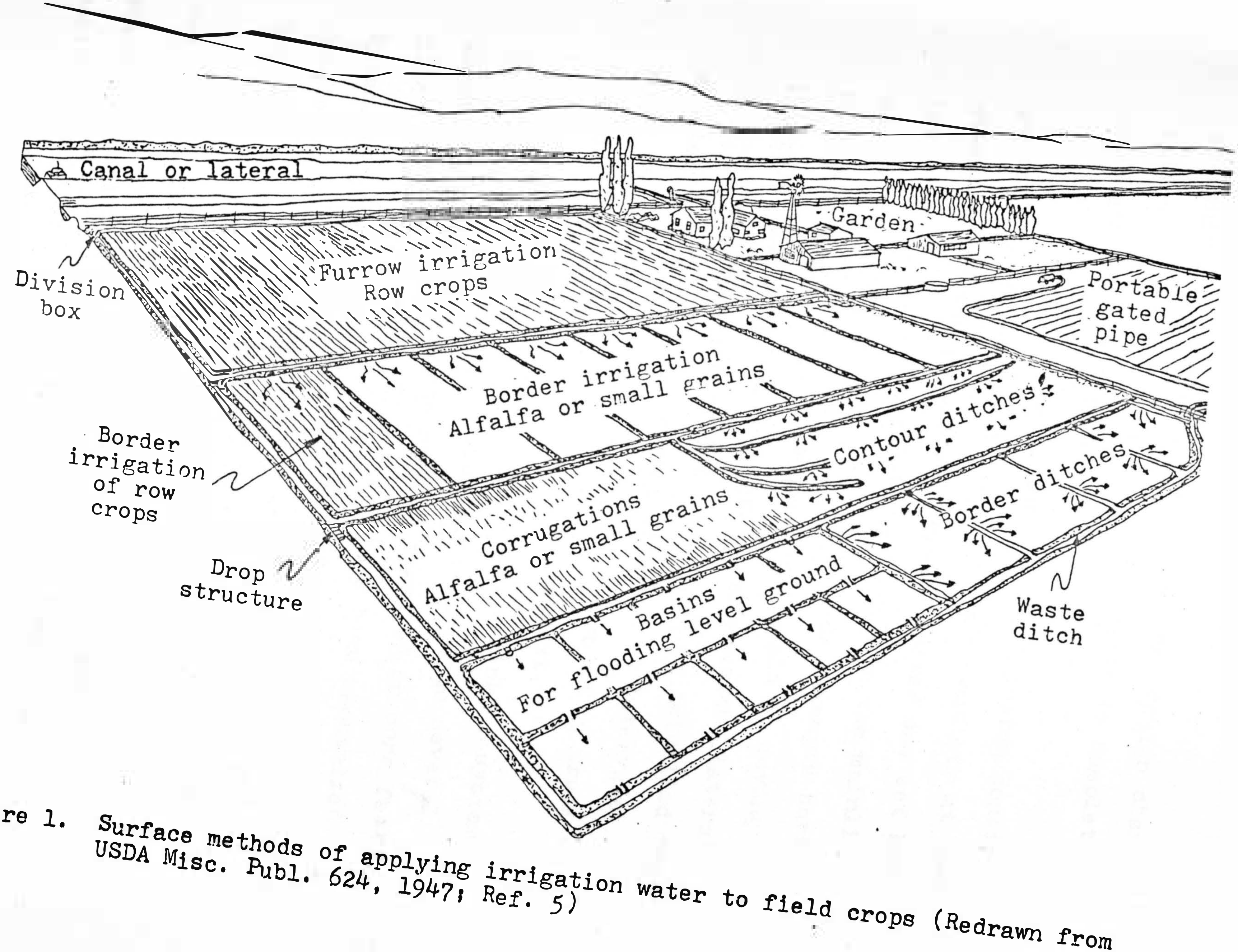

Figure 1. Surface methods of applying irrigation water to field crops (Redrawn from USDA Misc. Publ. 624, 1947; Ref. 5)

mechanized.* However, due to inherent design characteristics, it is impractical or impossible to completely automate these systems.

The handmove portable lateral system consists of portable or buried main line with valve outlets at desired spacings for the portable laterals. After one set has been irrigated, the laterals are moved to the mainline outlet for the next set. Mechanization attempts have included special pipe rack trailers to aid in moving the laterals, and machines to pick up and move the laterals.

The tow-line system uses fixed or swivelled two-wheeled carriages or skid pans attached at intervals along the lateral. The lateral is end-towed by truck or tractor from one irrigation set to the next.

The heart of the giant (boom) sprinkler system is a sprinkler discharging from one hundred to several hundred gallons per minute over an area 200 or more feet in diameter (6). These sprinklers have been mechanized by mounting them on a trailer for towing by truck or tractor. The sprinkler is connected to the mainline with portable connector pipes or flexible high pressure hose.

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*Mechanization: the use of hardware and energy to replace human labor.

*Automation: mechanization plus a decision-making capability.

Traveler systems are giant (gun) sprinklers mounted on carriages. Connected to the water supply by a high-pressure flexible hose, the sprinkler and the hose are towed across the field by a winch mounted on the carriage or stationed at the other end of the field. The winch is powered by a water turbine or by a gasoline or bottled-gas engine. The sprinkler must be pulled from one set to the next.

The side roll system is a further mechanization of the handmove lateral system. Wheels are attached to the coupler ends of each lateral section, a power unit is attached to the lateral center, and the lateral is side rolled from one set to the next. Gasoline engines, electric motors, or hydraulic movers powered by tractors are used to move the lateral.

A side move system is a side roll system further mechanized to permit irrigation of tall crops. The lateral pipeline is supported above the crops by a carriage arrangement with wheels at 50 to 60 foot intervals. The wheels are driven by a drive mechanism operated from a line shaft running the length of the lateral. Gasoline engines or electric motors usually supply the power necessary to move the laterals. Trailer lines on some systems increase the area irrigated per lateral move.

Center-pivot, self-propelled, continuously moving, sprinkler systems consist of a lateral anchored at one end in the center of the field. Water is supplied to the anchored end. The lateral moves in a circle about the center pivot point. Two-wheeled tracks or skid supported towers support the lateral. The lateral is moved by a hydraulic water drive of the piston or sprinkler type, a hydraulic oil drive, an electric drive, or an air drive. In a rectangular field the four corners are left unirrigated.

Straight lateral, self-propelled, continuously moving systems use laterals supported on two-wheeled self-propelled carriages. With the lateral connected to the water supply by a high pressure flexible hose, a hydraulic power drive moves the lateral in one continuous sweep across the field.

All moving lateral systems now have self-aligning mechanisms to keep the laterals straight as they move. If the lateral becomes too far out of line, safety mechanisms shut down the power drive.

Solid set systems have enough lateral pipe and sprinkler heads so that no laterals need be moved after being placed in the field. There are four types of solid set systems:

1. Portable lateral
2. Buried or permanent lateral
3. Sequencing valve lateral
4. Moving lateral

Portable laterals are moved in and out of the field each irrigation season. Buried or permanent laterals are placed 18 to 24 inches underground with riser pipe and sprinkler heads above ground. Sequencing valve laterals may be buried, on the surface, or suspended above the crops. Each sprinkler riser has a valve to turn the sprinkler on or off when a control signal (usually a change in water pressure in the supply line) is received (6). The water is thus switched from an irrigated set to an unirrigated set. Moving solid set laterals reduce pipe requirements by moving sideways over a distance much less than the lateral length. The lateral is pulled by a winch and is connected to the mainline by high-pressure flexible hose.

3. Subsurface Irrigation

Subsurface irrigation is a method of delivering water to the crop below the soil surface into the root zone. Subsurface irrigation is a term sometimes used to describe the control and maintenance of the water table at the root zone level (7). Water is delivered at varying pressure through slotted, drilled, or porous pipe. Water may also be delivered through tile drains, mole drains, or open ditches (3). The water moves up through the root zone by capillary action.

B. NON-IRRIGATION CAPABILITIES OF IRRIGATION SYSTEMS

Each irrigation method has functional capabilities such as frost protection, crop cooling, and fertilizer application in addition to applying water evenly to the field. Some of these capabilities are in the early stages of development, while other capabilities have been utilized for years. The following discussion of systems' non-irrigation capabilities is intended to underscore present and future agricultural practices which may be automated along with water application.

Surface irrigation systems may be used to apply fertilizer, leach the soil, and dispose of liquid wastes (8).

Sprinkler systems can be used to (8, 9, 10, 11, 12):

1. Reduce soil temperature with high frequency irrigation
2. Reduce average and maximum leaf temperatures by very high frequency irrigation
3. Wash dust off plants
4. Prevent freeze damage by continuous sprinkling
5. Apply basic fertilizers through the soil
6. Apply trace elements through the leaves
7. Apply fungicides
8. Apply pesticides
9. Apply herbicides

10. Leach the soil
11. Dispose of liquid wastes

Subsurface irrigation systems are capable of applying fertilizer and warming the soil (7, 13). Warm water, probably from power plants, applied through subsurface systems or circulated through underground pipes warms the soil (14).

For greatest utilization of the capabilities of each system, proper sensor-transducer devices, data communication equipment, and effective controls are required. A control system would sense which irrigation system functions were required and then properly adapt the irrigation system to perform these functions. Sensors capable of measuring plant stress, soil moisture availability, soil salinity, soil temperature, air temperature, leaf surface temperatures, evapotranspiration rates, and soil moisture content can assist in ideal irrigation scheduling (15, 16, 17, 18, 19, 20). Sensors or devices which measure water pressure, water depth, water presence, water quality, water flow rate, and total water quantity delivered are useful in controlling system operation. All this data must be transmitted to a control center without introducing error. An operator or controller then sends the proper control signals to system regulation equipment. This equipment may consist of check gates, valves, turnouts, sprinkler heads, pumps, pressure regulators, flow rate regulators, fertilizer injection meters, other chemical injection meters, and water quality control systems. Properly designing and operating an irrigation system permits greatest water application efficiency and provides the most services to its owner.

Though most of the above measuring devices, controls, and communication equipment are at the experimental stage or are yet to be developed, research on such equipment is vigorous and increasingly widespread as the necessity for irrigation automation becomes more obvious. Providing the incentive for automation are decreasing labor availability, increasing labor price, and decreasing water supply.

C. IRRIGATION AUTOMATION EFFORTS

Insight into problems which must be solved to automate irrigation systems is gained by reviewing past and present automation efforts. The primary function of an automatic system is to apply water evenly and accurately when and where it is needed. Complex problems are encountered in obtaining necessary data and exercising proper system control to fulfill this primary function. The following review presents representative efforts at solving these problems in automating surface, sprinkler, and subsurface irrigation systems.

1. Surface Irrigation Automation Efforts

Surface flooding systems using basins and borders or contour ditches are easiest to automate, because the field is graded to allow the stream of water to distribute itself evenly over the field. Systems with surface delivery by ditch or canal have been semi-automated by mechanizing canal check gates and field turnout gates (21). Mechanical timers, some with escapement releases to permit resetting between applications, have been installed on either canal checks or turnout gates (22). These timers are set for the length of time desired for each set. A small float is used to start each timer. After the time period has elapsed, the timer allows the gate to open or close, depending on gate design and function. A center-of-pressure gate used in conjunction with the timed gate opens when water rises above the center-of-pressure point and remains open until water ceases to flow over it (23). A center-of-pressure gate is used as the canal check and a timed gate as the turnout gate or vice versa. When a border or basin has received sufficient water, the turnout gate closes, the canal water level rises, and the center-of-pressure gate opens allowing water to flow to the next set. See Figure 2 and Figure 3.

Sinking float gates may also be used to time a set (24). When water reaches a gate, it is opened by

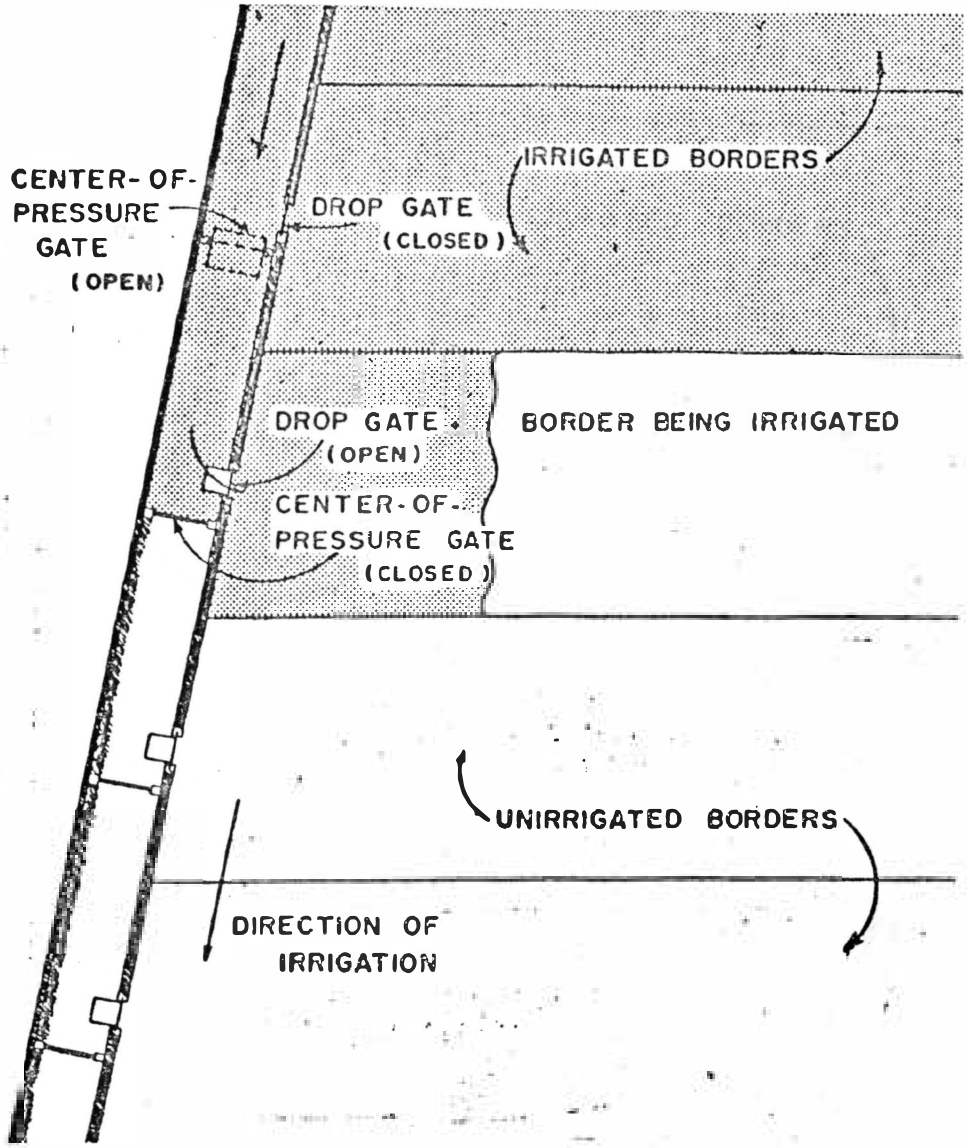

Figure 2. Schematic drawing showing semi-automatic gate installation for irrigating from upper end of ditch to lower end (from Humpherys, Ref. 23)

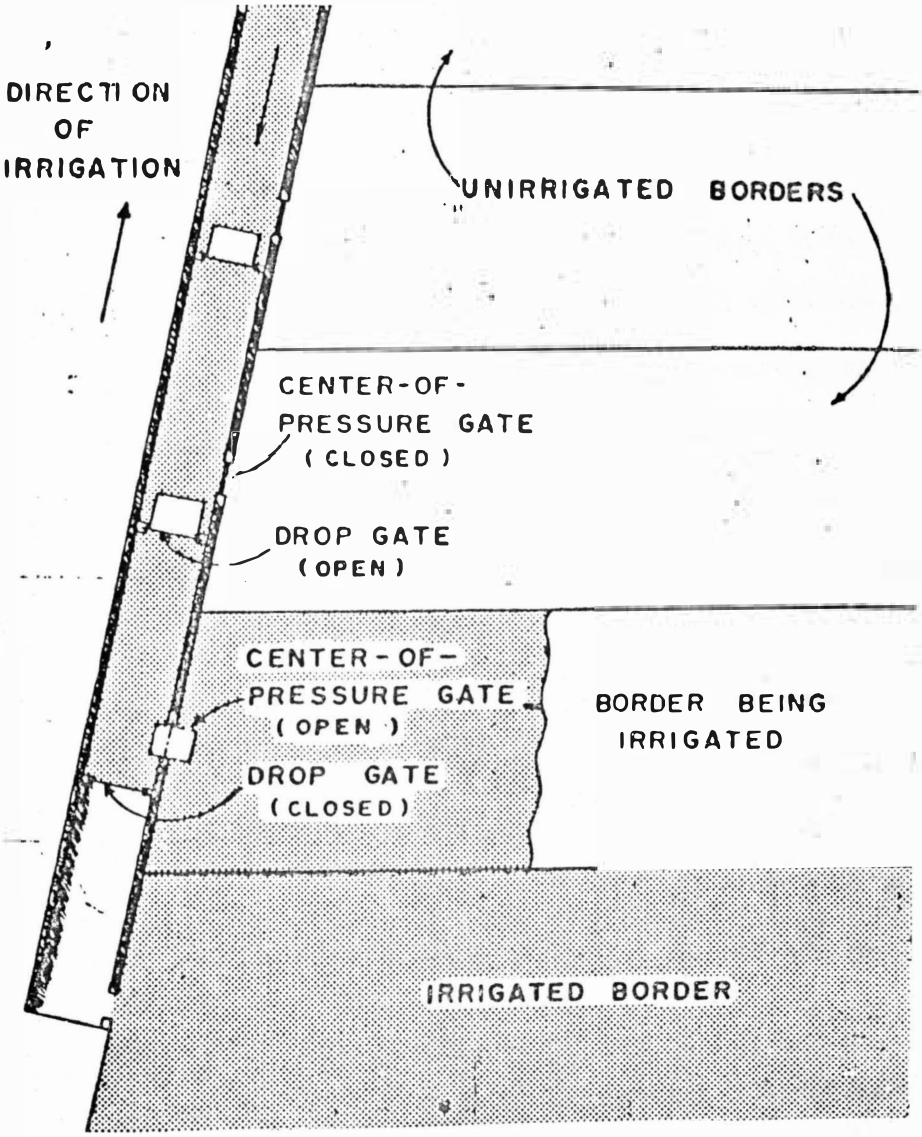

Figure 3. Schematic drawing showing semi-automatic gate installation for irrigating from lower end of ditch to upper end (from Humpherys, Ref. 23)

the rising float. A hole in the float causes the float to fill with water at a predetermined rate. Once full, the float sinks causing the gate to close quickly and remain closed as long as water is in the canal and until the float drains.

These timed drop gates, pressure gates, and sinking float gates are made in various styles for use in lined and unlined ditches. Adaptations permitting portability have also been made (25).

Automating basin and border or contour systems is accomplished through the use of hydraulic or electronic controls to change sets (26). The element that signals the system to change sets is a sensor placed at the far end of the basin, border, or contour away from the canal turnout. The sensor may be a sump float which vents a hydraulic line to the atmosphere when the sump fills with water (27). It may also be an electronic probe which shorts when water contacts it (26). Each basin, border, or contour has a sensor. The sensor signal, indicating that irrigation of a set is complete, is transmitted by a hydraulic line or radio transmitter to the proper turnouts and check gates. Four-way or newer three-way valves (28), solenoids, or motors (26) then open and/or close the proper gates to switch the system to the next set.

Similar approaches are used in other surface systems. Controls, gates, and valves may differ slightly, depending on whether the delivery system is pipe or canal, and whether furrows, borders, or basins are being irrigated. The sensing element that determines when to switch sets may be placed in a representative furrow, when a furrow irrigation system is used (21). If pipe distribution systems are used, pneumatic valves provide a means of switching outlets (29). Set switching may be performed remotely using such pneumatic valves (30). A clock and a programmed sequencer determine when sets should be changed. Control commands are transmitted by radio or wire to the proper valve controls. A different type of hydraulic system, used in Hawaii, utilizes a membrane, controlled by a hydraulic cylinder, to cover holes in the bottom of the distribution pipe (27). To switch sets, the membrane for the next set is raised by a hydraulic cylinder while the membrane for the irrigated set is lowered. Switching is again controlled by sump floats at border, contour, or furrow ends.

Control methods and equipment also depend on the irrigation strategy being practiced. Two of the newer methods are cutback furrow irrigation and water reuse systems (30, 31). The various strategies are attempts to achieve maximum application efficiency and uniformity. The cutback system designed by Garton used semi-automatic or automatic check gates to change sets (32). When water reaches the end of the set furrows, the canal check gate opens, allowing water to flow to the next set. The canal slope and outlet spacings are such that the water continues to flow from the outlets in the first set, but at a decreased rate. When water is delivered to the third set, the water level drops below the outlets of the first set, and irrigation of the first set is complete. An automatic cutback valve for use in pipe delivery systems, which is programmable for high and low flow rates as well as the length of time at each rate, is under experimental evaluation (33). This valve is placed between the main delivery pipe and the pipe with furrow holes.

With reuse systems, water is delivered to the furrows at a rate just below the rate at which erosion occurs (31). Runoff is collected in a storage pond. Water from this pond is pumped back into the main supply line. Starting the collection pond pump at the start of a set and shutting it off when water reaches the end of the field creates a type of cutback system in the reuse system. The reuse system at Mead, Nebraska uses tensiometers to signal moisture deficiences (31). As the tensiometer gauge needle moves upscale with decreasing moisture, it causes a set-point contact to close and complete a relay circuit. Wires connect the tensiometer with the master control. The pipe delivery system uses pneumatic valves controlled by 3-way electric valves switched by the master control.

Fluidic devices present an alternative to mechanical and pneumatic valves (27). Such devices utilize the Coanda (wall attachment) effect to form a bistable diverter capable of switching water flow from conveyance ditches and flumes to field distribution networks. Fluidic devices may be pneumatically, electrically, or hydraulically controlled.

An automatic fluidic system operates essentially the same as any other automatic surface system. Irrigation progresses from the first set to the last, with diverters being switched by sensors at the end of the field. These sensors are bowls connected to their respective diverters by a communication line which apirates air. When water on the field reaches the desired depth, the bowls fill with water. As the bowls fill, aspirated air through the communication lines to the bowls is cut off, and sets are switched. Fluidic devices may also be used for reservoir level control and for operating large gates (27, 34). A fluidically operated siphon for use on fields with slopes less than 1° is in the experimental stage (27, 34).

2. Sprinkler Irrigation Automation Efforts

Sprinkler systems such as the center-pivot and solid set are readily automated. Automating a solid set system requires installation of automatic valves and controllers (9). Center-pivot systems require on-off water control and lateral speed control. In either sprinkler system a moisture sensing device, such as a tensiometer, can turn the system on, and a water application measurement device, such as a probe in a can, can turn the system off (26). Other sprinkler systems are more difficult and somewhat impractical to automate.

3. Subsurface Irrigation Automation Efforts

Automation of subsurface systems appears straightforward. Automatic valves and system controllers will comprise an automatic system. Davis and Nelson describe a moisture application regulation system consisting of float valves and moisture measuring devices (2).

D. IRRIGATION SCHEDULING AND WATER SUPPLY

So far three important aspects of irrigation have received only passing attention:

1. Determining when to irrigate
2. Deciding how much water to apply
3. Getting the water from the supply to the farm

This thesis will not attempt to explain the many variables involved in determining when and how much water to apply. There are, however, three commonly used methods. Visual observation of plant wilt (16, 18) or manual soil inspection are the methods most often used. Soil moisture sensing devices, such as tensiometers (31) or resistance blocks (35, 36), are used by some. The most accurate and complete method is using a computer analysis of soil, crop, and climate data to schedule the time and amount of irrigation (15, 16). Such a service is now being used in the Arizona Salt River Project (15).

Water supplies range from individual wells to dam reservoirs. The individual farmer may control his own well in most cases, if he has one. Otherwise, water is pumped from lakes, rivers, and dam reservoirs. Few farms are located adjacent to any of these supplies. This necessitates using supply canals or pipes controlled by an irrigation district or a state agency to deliver water to turnouts at the individual farms.

Large water delivery projects exist in Arizona (37), California (38, 39, 40), Washington (41), Oregon (42), and Nebraska (43, 44). A considerable amount of automation has been and is being implemented on these projects. This automation has been deemed necessary to provide water to users on demand and to insure adequate flood protection on project canals.

The Salt River Project's digital telemetering and control system, installed in 1962, automated supervision of canal check gates (45). Communications between stations are on a single-frequency VHF radio network operating at

169.525 MHz. Digital information is telemetered by frequency shift keying of an FM carrier. Each station time shares the channel and accepts only messages containing its address code. Forebay depth, gate positions and downstream record readings are monitored and gate positions controlled. An entirely solid state digital system is planned for future expansion of its remote supervisory control.

The Coachella Valley County Water District in California has installed a supervisory remote control system on its main canal system and three domestic water systems (38). The entire system is analog except for check 6-A, which has a digital system. The telemetering equipment is of modular solid state construction and uses AM and FSK encoding techniques.* Microwave, VHF radio, and local land lines provide the paths for telemetry and control. There is a report-back provision of any changes made in the delivery system. An alarm system at all locations sounds an audible alarm and flashes a light at headquarters in case of malfunction. An operator at headquarters makes all decisions connected with system operation. In addition to the supervisory control system, "Little Man"

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*Equipment was manufactured and/or fabricated by the Hersey-Sparling Meter Company, El Monte, California and is of the Quindar type.

controls are used at several gates to maintain constant upstream water level (46). The "Little Man" is an on-off, three position control which uses a float in conjunction with micro-switches and a timer to control canal water level by raising or lowering the canal check gate.

The California State Water Project uses the controlled volume concept (47). This concept requires simultaneous operation of all check gates between an added or deleted load and the source. Such a system allows delivery on demand to water users, something not possible in other canal delivery systems. Water must normally be ordered at least one day in advance and often several days in advance, and delivery must be accepted. The controlled volume concept is, therefore, a great breakthrough. It does, however, require a completely automated delivery system.

The South Bay Aqueduct is controlled by a computer-oriented digital supervisory control system (39). Data from the aqueduct and commands to the aqueduct are carried over four pairs of simplex type 4-A lines. Two lines carry outgoing messages and two carry incoming messages. One outgoing line sends command functions; the second outgoing line sends interrogation signals to a site requesting it to report specific data or status at the site. The third line is reserved for incoming messages and provides for the transmission of the report of status and data from the sites; the fourth is reserved for sites to report as an alarm any failure or impending adverse aqueduct or system condition. The command center is at Sacramento. A similar remote control system is in existence on the California Aqueduct with the control center also in Sacramento.

Another canal water level control system in the experimental stage in California uses the hydraulic filter level offset (HyFLO) method (48). HyFLO relates canal depths associated with downstream flows and turnout diversions to the canal inflow. Since the method gives downstream control, it can accomodate unscheduled demands. Communication with the downstream sensor is by phone wires.

The Columbia Basin Project in Washington is contemplating a supervisory control system for its canal delivery facilities (41). Several "Little Man" controls are presently in use. Radio alarm units indicate trouble at project pumping stations. Other automation efforts are automatic pump shutdown and automatic pump restart after power failure.

The Dalles Irrigation District Project is an automated closed conduit demand system (42). Pumping plants fill reservoirs or tanks which feed and maintain pressure in the pipeline. Many pairs of wires, similar to telephone wire, link pumping stations to float switches and alarm circuits at each station's tanks or reservoirs. Pipeline pressure is controlled by automatic maintenance of proper tank or reservoir levels.

The Central Nebraska Public Power and Irrigation District has scheduled completion of its computerized supervisory control system for the summer of 1971 (43). This is an all digital system capable of monitoring and controlling all important check points in the system. Communication is by VHF radio, microwave, and buried communication cable. All stations also have alarms for abnormal conditions.

There is room for improvement in the semi-automatic and automatic equipment, sensors, controls, and communication techniques now being used in irrigation systems. Few of the sensing, control, and communication techniques, that electrical engineering can provide, have been used. This author believes that there are manifold contributions electrical engineering can make in advancing irrigation system automation.

Irrigation system automation on the individual farm and proper irrigation scheduling are still in the infancy stage. Interdisciplinary cooperation of electrical engineers with others can advance development in automation and scheduling.

CHAPTER III

MOISTURE SENSOR DATA TELEMETRY SYSTEM

Little effort has been devoted toward the development of a telemetry-control communication system capable of reliably and inexpensively transmitting information required for on the farm automation of irrigation. Three groups have addressed this area. Haise and Kruse at Colorado State University built a radio remote control system and a wire tone telemetry control system (29). Bowman at Montana State University has constructed a radio telemetry system to signal turnout gates when water has advanced to the far end of a border being irrigated (26). Fischbach at the University of Nebraska has developed an automatic control system for his reuse irrigation system (31). These systems have seen only limited acceptance with most current effort being concentrated on hydraulic and pneumatic control systems. Communication between remote points in hydraulic and pneumatic systems is over pressurized lines. Rodents and other factors cause damage resulting in line leaks which interrupt system operation and require maintenance. While electronic, hydraulic, and pneumatic systems each have advantages and disadvantages, this author feels electronic systems have been greatly underrated, especially when used in conjunction with hydraulic and pneumatic devices.

A. EXISTING ELECTRONIC SYSTEMS

A more complete description of existing electronic systems is now presented. The radio remote control system, described by Haise and Kruse (29), consists of a 24-hour time clock, a 12-channel citizens' band transmitter, and 12 receivers. The time clock programs set-changes to an accuracy of five minutes. At the end of each irrigation set interval, the time clock activates the transmitter. According to the set sequence programmed, the transmitter first signals the downstream valve(s) to open, and then 30 seconds later signals the upstream valve(s) to close. Any sequence of pneumatic valve operation may be programmed. In an attempt to improve system reliability and simplicity, an industrial timer using wires has been used to open and close the valves instead of the radio system. To reduce the number of wires required, a tone telemetry system using standard encoders and decoders to activate solenoid control valves was also tested. All systems were constructed from off-the-shelf components, and all were field tested. Radio control was rejected due to difficulty of maintaining voltage on standby batteries, possibility of spurious signal interference, and system complexity. The tone telemetry system exhibited high line losses and changes in supply voltage would easily switch sets. Decoders also required frequent adjustment to insure proper decoding. Finally, the industrial switch simply required too many wires. Hence, hydraulic control was turned to. This author feels most of the above problems were a result of using off-the-shelf components not designed for use in the type of environment to which they were subjected and the conditions under which they were forced to operate.

The radio system tested by Bowman was designed specifically for application as a remote water presence telemeter (26). Solid state power switches are incorporated as part of both the transmitter and receiver to permit very low standby power drain. Both transmitter and receiver are crystal controlled and operate at 27.043 MHz. Each transmitter is identified by the tone it transmits. The receiver then switches on the proper gate servomotor to open or close the proper gates, depending on which tone (which transmitter output) was received. By placing the sensing probe in an open can at the desired application depth, this control system can be used to turn off sprinkler systems. This radio control system has been field tested and has performed satisfactorily.

Fischbach has developed a control system for his automatic reuse system (31). System operation is started by the closing of a contact on a tensiometer in the field. This energizes a relay at the control center. Timers, switches, and relays then sequence the system through all sets. All control commands are communicated over wires.

All three systems discussed above are severely limited in their telemetry-control capabilities. Stringing bundles of wires everywhere is certainly inconvenient and expensive. There are instances where a wire carrying telemetry-control commands may be less expensive and more desirable than a radio system. However, many situations occur where only a radio system will adequately meet telemetry-control needs, even though it may be slightly more complex and requires a license. An example of a situation where radio systems are most attractive is in telemetry of data from sensors in various fields to a central location for analysis. In most such instances it would be most inconvenient to run a dedicated wire to each sensor.

B. MOISTURE SENSOR DATA TELEMETRY SYSTEM DESIGN

Due to the lack of effort in the development of telemetry-control communication systems for use on individual farms, this problem is examined further in this thesis. Effort was concentrated on the development of a soil moisture data telemetry system with emphasis on using or at least defining communication methods applicable to reliable and inexpensive data and control communications.

1. Design Objectives

Several objectives were considered while exploring telemetry system design possibilities. These were:

1. The system must be practical for soil moisture data telemetry on individual farms.
2. The systems must be low enough in cost to be attractive to the individual farmer.
3. The system must be simple to operate, reliable, and easy to maintain.
4. The system must operate correctly despite large power supply voltage changes and must have low power requirements permitting operation over extended periods without power supply replenishing.
5. The system must be capable of expansion for use in large data gathering projects.
6. The system must be capable of serving as the communication link in automatic irrigation system control.
7. The above requirements dictate design of a system which may be easily increased or decreased in size and adapted to different uses with little system redesign.

2. Telemetry System Types

With these objectives in mind, three types of telemetry systems were examined:

1. The programmed system
2. The adaptive system
3. The interrogate system

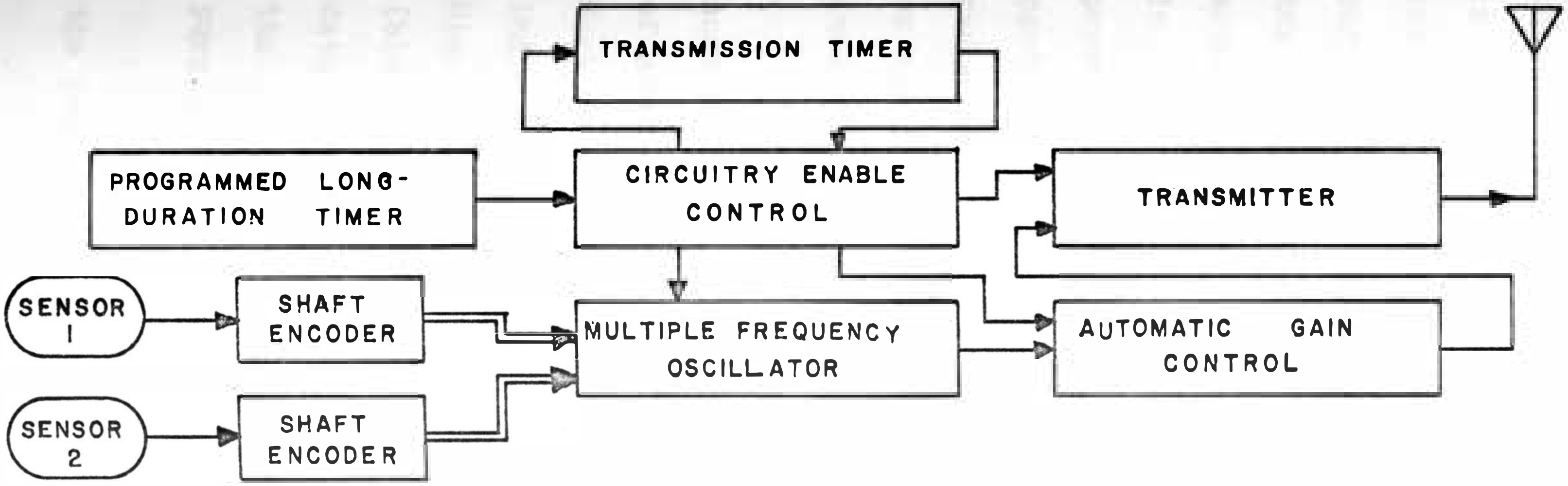
In the programmed system each data station is programmed for a prescribed number of data transmissions per day.

The adaptive system transmits data only if the data has changed more than a set quantity from the previous data transmitted. The interrogate system transmits data only after being interrogated by the control center. Each system has applications for which it is best suited, some of which will be discussed later. The programmed system is probably the cheapest and requires the least power, while the interrogate is the most versatile, with capabilities for error detection and feedback error correction. It is, however, probably the most expensive.

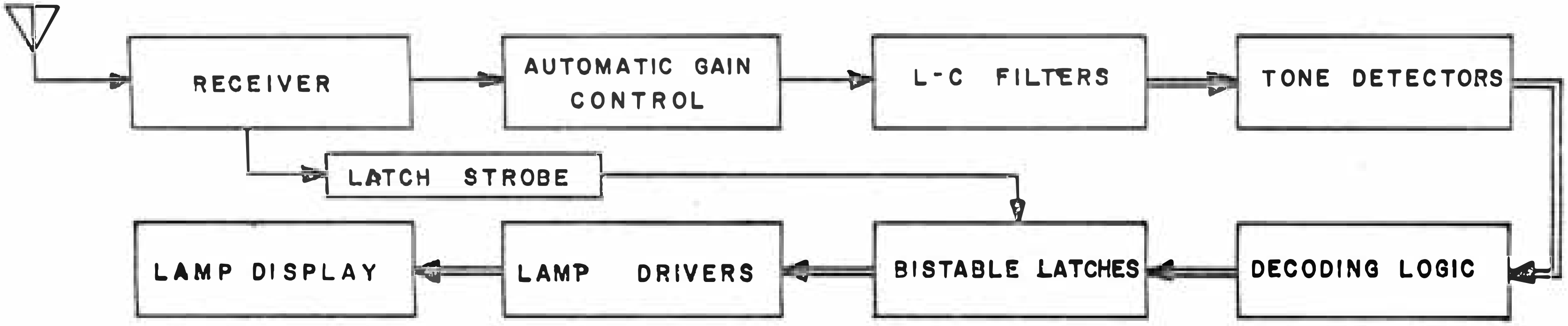
A programmed system was chosen for development. Even though the programmed system has the fewest capabilities, it was chosen for its simpler circuitry requirements and capability of permitting exploration of telemetry problems not evident on a surface examination.

The programmed system, as developed, is controlled by an adjustable, long-duration timer. This timer is set to signal the desired number of data transmissions per day. This data is then stored or recorded at the main or control station. A block diagram of the programmed system is shown in Figure 4.

Tensiometers were chosen as the soil moisture sensors because of their low cost, high reliability, low maintenance requirements, characteristic of not requiring calibration for soil type, and capability of measuring soil moisture availability to plants (49).



a) Programmed system field station



b) Programmed system main (control) station

Figure 4. Block diagram of programmed soil moisture data telemetry system

If a mercury manometer is used as the tensiometer tension indicator, digital encoding of the mercury column position is easily accomplished. This may be done by inserting wires through the tubing at the desired divisions with the mercury as the electrical common. If a vacuum gauge indicator is used, digital encoding without affecting gauge accuracy is difficult. A shaft encoder, designed for use in the vacuum gauge indicator, encoded gauge readings properly. Friction from encoder brushes added significant hysteresis to the gauge movement, thus destroying gauge accuracy. Such a shaft encoder may have to be part of the design parameters used in designing a vacuum gauge indicator.

Transmission of soil moisture data messages is accomplished using a multiple-tone oscillator capable of adding five audio frequencies without distortion. Each tone represents a binary bit: a tone's presence indicates a "one" and its absence indicates a "zero". Since the use of two sensors requires only four tones (bits), the fifth tone (bit) may be used to add error detection in coding, or it may be used to synchronize the serial transmission of several messages of four parallel bits each.

The long-duration timer, as programmed, signals the power switch (circuitry enable control) to turn the transmitter on permitting transmission of soil moisture data to the main (control) station. The transmission timer signals the power switch when data transmission is complete. The power switch then turns all circuitry off, except for the long-duration timer.

Data may be transmitted over any convenient communication link. For this system a crystal controlled radio transmitter and receiver, operating in the citizens' band, were used (50). An automatic gain control was required preceeding the transmitter to ensure operation as close to 100% amplitude modulation as possible without inducing distortion.

After demodulation from the carrier in the receiver at the main (control) station, the audio signal is amplified by an automatic gain controlled amplifier. This provides compensation for variations in received signal strength. The different tones are recovered by tone filters. Inductor-capacitor filters were initially chosen for temperature stability and low power dissipation. Active filters should be considered to reduce cost, bandpass width, and circuit size. Temperature sensitivity and increased power requirements must still be evaluated.

Tone detectors at the tone filters' outputs create logic "one" and "zero" levels. The detectors' outputs are then decoded by integrated circuit logic.

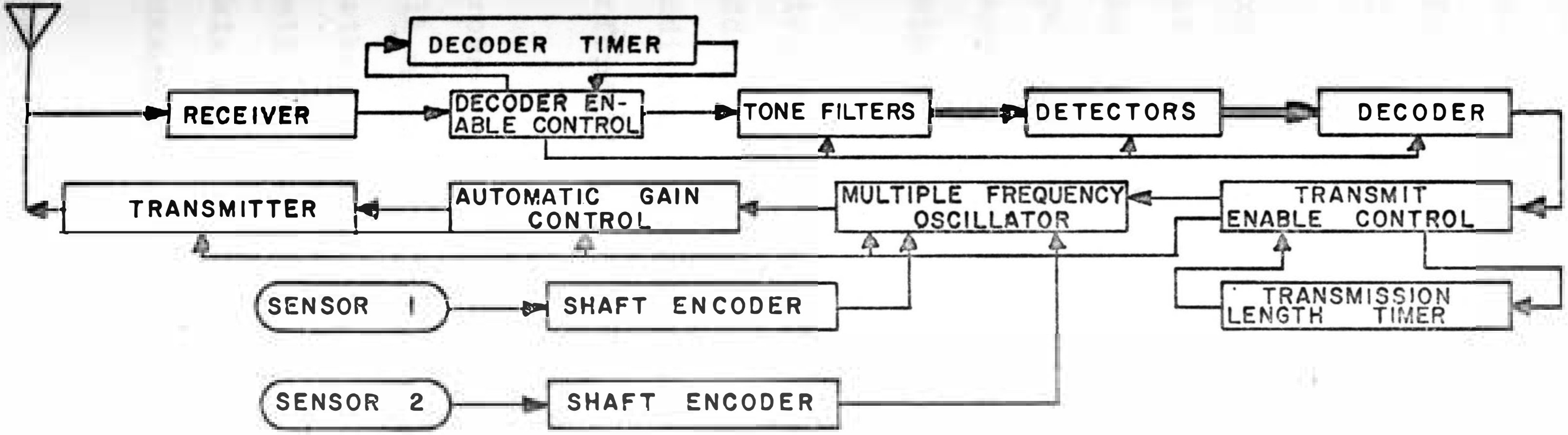
At this point the received data may be either recorded or displayed. The easiest method of recording is probably a digital print out. In the telemetry system model constructed, however, the data is stored in bistable latches and visually displayed. The display consists of one lamp, properly labeled, for each possible data reading. Transistor drivers provide the power necessary to light the lamps. New data is strobed into the memory and displayed upon reception.

An adaptive system is the same as the programmed system with the long-duration timer replaced by a comparator capable of remembering the last data point. The comparator signals for a new data transmission when the quantity monitored changes by more than a specified increment.

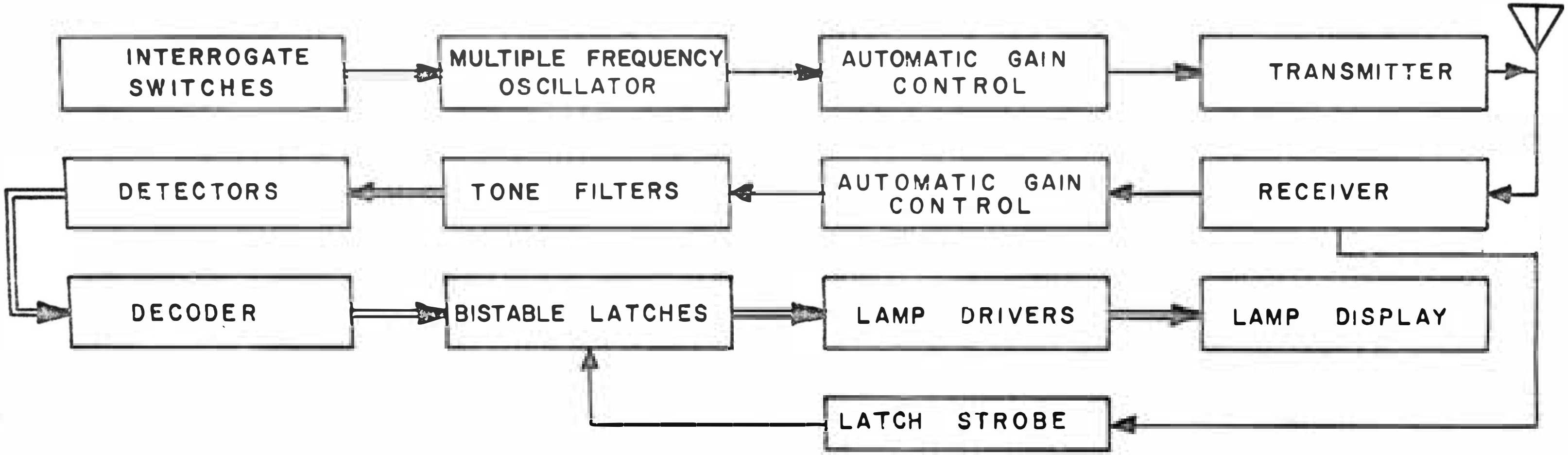
An interrogate system transmits data only upon request from the main (control) station. A block diagram of an interrogate system is shown in Figure 5. Data (field) stations may be interrogated manually or automatically. Similar equipment to that described above is used to implement the interrogate system.

Actual circuits used to implement the programmed system have been reported (51).

New circuit components are being marketed almost daily. As a result, circuit designs are often outdated



a) Interrogate system field station



b) Interrogate system main (control) station

Figure 5. Block diagram of interrogate soil moisture data telemetry system

even before completion. Because of this fact, this thesis will emphasize telemetry-control principles applicable to automatic irrigation systems, rather than discuss circuitry.

The programmed telemetry system appears least expensive to implement. Probability of transmission error is small, because of long message transmission lengths. This protects against false signalling from spurious radio signals, noise, or channel fading. Long message lengths are possible because changes in soil moisture occur slowly.

When more than one field station is used, each field station must transmit its identification code in addition to its soil moisture data. This requires additional message binary bits to accomodate the extra information.

As larger systems are constructed, message size grows rapidly. It soon becomes impractical to transmit all message bits in parallel, and a series transmission method must be selected. A coding scheme particularly well adapted for use in telemetry-control systems where data and control messages occur at random times is discussed in a following section.

If field sensor data is used to automatically start an irrigation system, a synchronization method must be employed to prevent control center confusion because of simultaneous data transmissions from more than one programmed field station. The programmed system does not readily permit synchronization among the various field stations. Theoretically the clocks at each field station could be set to stagger data transmissions from the field stations. No practical clocks are sufficiently accurate to permit this when data transmissions must be closely spaced because of large numbers of field stations. It thus seems that the programmed system is suited only for use in relatively small systems for data gathering or system monitoring purposes where occasional data loss is unimportant, data transmission frequency is not critical, and decisions are operator performed.

An adaptive system transmits no superfluous information; only data changes are transmitted for recording. These data changes are transmitted immediately when they occur, a must in alarm systems. The adaptive system suffers most of the drawbacks of the programmed system. Another negative factor is that comparator design will probably increase power supply drain.

An interrogate system, with its capability of two-way communication, circumvents most of the drawbacks encountered in the programmed and adaptive systems at the sacrifice of increased cost and complexity. Transmitter lockout, while another station is transmitting, may be employed to prevent messages from interfering with each other. Feedback coding methods may be implemented when very low error rates are demanded (52). The uses for systems with two-way communication capabilities are unlimited.

These three types of systems--programmed, adaptive, and interrogate--with adaptations when necesary, should be able to meet the communication needs in automatic irrigation systems. Channel type selection for these systems depends on the application and location of the system as well as economic feasability. Use of error detection and correction coding in these systems depends on penalties resulting from an erroneous transmission, type and amount of noise in the channel, and quantity and speed of information transmissions. Possible solutions to each of these areas will be discussed in the next section.

CHAPTER IV

PRESENT AND ANTICIPATED IRRIGATION NEEDS

There are many ways in which electrical engineering can contribute to irrigation research and automation. Research efforts can be accelerated by new and better sensors which enable detailed study of plant growth parameters. Automatic logging of data from these sensors will permit gathering of more data and faster analysis of the data. Automating irrigation systems requires development of necessary sensors, controls, and communication equipment. Research and development efforts can realize their greatest potential with the least delay through cooperation among groups such as plant and soil scientists, agricultural engineers, mechanical engineers, and electrical engineers.

A. SENSORS

Hite (35) and Hamre (36) have studied methods of soil moisture measurement and have worked on development of new methods of soil moisture measurement. Hite lists nine methods of determining soil moisture:

1. Gravimetric method
2. Chemical methods
3. Tension methods
4. Penetrometer method

5. Lysimeter method
6. Nuclear methods
7. Electrical methods
8. Infrared methods
9. Thermal methods

Hamre explored the practicality of using two other methods:

1. Capacitance method
2. Proton precession method

He concluded that the proton precession method was not useful for in field application. Further investigation of the capacitance method was suggested.

All of these methods have their own specific strengths and weaknesses. Two methods, tension and resistance, have received the greatest acceptance in general use, probably because of their relatively low cost and ease of use.

The tension method has gained wide acceptance in soil moisture measurements for irrigation purposes. Water availability to plant roots is determined by the capillary potential of the water in the surrounding soil and a tensiometer measures capillary potential. A tensiometer requires little or no maintenance, can be remotely located, and measures moisture non-destructively (53). However, rapid changes in percent soil moisture cannot be followed, capillary potentials greater than one atmosphere cannot be measured, and accurate readings immediately after installation cannot be obtained with a tensiometer. A tensiometer must be calibrated for soil type and compaction, if percent soil moisture is desired rather than capillary potential.

The resistance method, using Bouyoucos sorption blocks, rivals use of the tensiometer. The resistance method responds more quickly to percent soil moisture changes than the tensiometer, and it can measure lower levels of percent soil moisture (53). The resistance method must be calibrated for soil type, and it should be calibrated in the field for greatest accuracy. The system must be periodically recalibrated and the wetting, drying cycle exhibits hysteresis. It is, however, readily adapted to automatic, remote-site measurements.

A method to inexpensively measure percent soil moisture and soil moisture availability quickly without frequent recalibration while maintaining system portability is yet to be developed. A soil moisture measurement method with these capabilities could ease the gathering of soil moisture data by irrigation scheduling services as well as by individual farmers. One such irrigation service is available in Arizona (15, 16).

As Carolus (18) indicates, there are many other variables, such as solar radiation, wind, soil salt content, crop type, crop stage of growth, plant and soil temperature that affect plant growth and development.

Each of these factors contributes to plant stress. Different methods of detecting plant stress are being researched, and sensors to detect parameters determined to be critical are needed.

Plants vary in their tolerance of excess dissolved salt and ions in soil (17). To detect rising concentrations of salts and ions before damage to plants results, sensors capable of measuring these quantities in the field would be advantageous.

After a water quality standard for irrigation water is established, sensors to monitor water quality will be desirable. These sensors could enable better determination of when soil leaching may be necessary or when better quality water must be used. Sensing of water solid content, in addition to other water quality parameters, is especially important in subsurface irrigation systems (55).

It is also desirable to know when the level of plant nutrients in the soil falls below the optimum point. Sensors capable of measuring nutrient levels could signal the control center when injection of lacking nutrients into the irrigation water is necessary.

In addition to sensors which measure parameters vital to scheduling the time, amount, and kind of irrigation, sensors capable of monitoring irrigation system operation parameters are required. Reservoir and canal water levels, gate and valve positions, pipeline pressures, rate and amount of water flow, pump operation, and other quantities must be measured by proper sensors, and the data transmitted to a control center. Less expensive, more convenient, more reliable, and more accurate sensors are in demand.

Both sensors with analog output and sensors with digital output have applications in modern irrigation systems. An analog output is useful for showing trends. A digital output is easier to transmit without introducing error.

B. CONTROLS

Once sensors provide the necessary data to determine proper irrigation system operation, controls capable of accurately and reliably carrying out proper system operation are required. If the schedule says to put two inches of water on one field and four inches of water on another field, control equipment must be able to carry this out at the time and in the manner specified. To efficiently and correctly apply this water, automatic irrigation systems must be capable of controlling both the rate of application and the quantity applied.

As discussed earlier, controls to carry out these demands are in the early stages of development.

Much work is yet to be done. In many cases these controls will include system monitor sensors in the feedback loops of the controls.

Meyer discusses three prerequisites that controls must meet (56).

1. The controls should be designed and arranged so that easy inspection and testing of the system is possible. This should include, wherever possible, visible indication of the operating conditions of the system. If these features are designed into the control system, the operator can make a quick survey of the system and detect faults and irregularities before they can be the source of malfunctions that could damage the equipment or the crops. This feature of ease of inspection also provides for rapid trouble-shooting.

2. The controls should be so designed that they allow easy field adjustment of the operating parameters. This particular feature allows one system to be adapted to many different conditions that could exist throughout the growing season.

3. There should be full protection for operators of the system. This should include low voltage control wherever there is the slightest possibility of shock.

This author feels that these requirements must be met for automatic irrigation systems to be accepted by the average farmer.

The water source must be capable of supplying water on demand to enable full realization of benefits from new crop-soil-climate scheduling techniques as they are further developed. A significant development in providing water on demand, as noted earlier, is the canal delivery controlled volume concept being used in the California Water Project (39). Control of water movement is achieved by simultaneous operation of all facilities: turnouts, checks, pumps, and power plants. This requires a completely automatic distribution system with proper controls.

A pump, capable of being controlled to deliver varying amounts of water, would eliminate the need for several different sizes of pumps at irrigation pumping plants and the switching controls needed for them. Such a pump, automatically controlled to meet water demand, could increase efficiency in both canal and pipe delivery systems, if it were developed (46).

Development of variable speed motors for opening and closing check gates would ease the problem of controlling hunting in automatic canal water level control systems (46). Variable gate speed could prevent excessive overshoot for small disturbances by providing slow gate adjustment. For larger disturbances, faster gate movement may provide better control.

Valves and gates, designed to permit quantitative measurement of the amount of water delivered as well as controlling the rate of delivery, would ease design of automatic irrigation systems (57). Accurate regulation of water deliveries and accurate assessments for water used are other benefits of such valves and gates.

Metering devices for injecting fertilizers, herbicides, fungicides, pesticides, and other chemicals into the irrigation water are required in the newer, more versatile systems (8). These devices must insure thorough mixing of the chemicals with the water. Metering devices are also necessary for mixing high quality and low quality water, in areas where this is necessary, for maximum utilization of available water resources (17). Development of controls to permit remote adjustment of these devices is necessary in automatic irrigation systems.

Ground speed controllers for traveling sprinklers and laterals are at the present time inadequate (58). An electrical ground speed sensor in a feedback control system could control an electric or hydraulic drive. Power to operate the control might possibly be obtained from the water supply with a hydraulic drive turning a generator to maintain voltage on a storage battery.

Electronic and mechanical timers designed for irrigation applications are in demand. Such timers must be immune to corrosion, moisture, dust, heat, shock, and supply voltage variations. Timers must be capable of being reset between irrigations, preferably remotely or automatically. They must also be easily adjusted for length of period timed as well as be capable of timing both long and short periods.

Valves and gates, capable of being remotely controlled, are essentials in automatic irrigation systems. Included in this category are fluidic devices. Remote control may be accomplished electrically, pneumatically, hydraulically or by using some combination of these approaches. Very few valves and gates capable of being continuously controlled have been developed; most valves and gates are either open or closed. Continuous control is advantageous in cutback furrow irrigation systems. It also permits easy system adjustments for varying field and crop conditions.

Better controls for maintaining alignment on moving lateral and center-pivot systems may be required (57). Such controls would compensate the system for changes in field slope, changes in traction, changes in wind, and sudden changes in field roughness, if not excessive.

Future solid set systems will require controls, operated from a remote location, to retract risers and sprinkler heads below the ground level during land preparation, seeding, cultivating and harvesting (6). The same controls will raise the risers and sprinklers when irrigation is required.

Automatically adjustable nozzles, adjustable for nozzle size and trajectory angle, when developed will permit best system adaptation for frost control, environmental control, wind compensation, and normal irrigation (6, 58). Such nozzle controls would make sprinkler systems more versatile and effective.

Reliable and inexpensive power sources for in field operation of sensor, control, and communication devices and equipment are a must. The sources must not present shock hazards to operators. As a consequence, they will probably be low voltage sources.

Batteries and wires are the sources usually used, but often leave much to be desired. Battery voltage drops with use. Long wires dissipate power and have a voltage drop from source to load depending on line length. Wires are also generally in the way.

Power might possibly be obtained from the moving water in the delivery system. A water wheel assembly for use on open canals has been built to provide operating pressure for a hydraulic control system (21). The same type of approach, possibly using a small water wheel to drive a generator, could be used to maintain battery supply voltage. It is also conceivable that entirely new types of power sources will be developed in the future.

Control center command systems are, and probably will continue to be, of three types: human decision control, sensor indicated demand control, and computer decision control. Obviously there is an overlap in these types, since human decisions are inescapable. Someone must decide what parameters are important, design the sensors, and program the computer.

Various combinations of these types may be used as the control center command system, depending on irrigation system type, application, and degree of automation. Data from sensors may be used by both human and computer in making decisions. Computers are likely to be utilized in highly automated systems performing other functions in addition to irrigation.

Human decision alone, without the aid of soil-plant-climate data, is usually an inefficient method of controlling irrigation systems. If the system is not automated, people tend to irrigate to their convenience, ignoring efficiency of water application. If the system is automated, people often over-irrigate, simply because it is so easy to apply water. Development of inexpensive sensors, enabling necessary scheduling data to be easily obtained, will greatly improve the achievable quality of control command decisions made by human operators.

Such data, along with crop type, crop stage of growth, and meteorlogical data, are effectively analyzed by computer. A computer scheduling service may be widely accepted by irrigators in the future.

C. COMMUNICATION TELEMETRY AND CONTROL

A reliable and secure telemetry-control system is required to communicate data from sensors to a control center, and to communicate control commands from a control center to the proper controls. This telemetry-control system should be as inexpensive as possible, while meeting all performance requirements. Some of the factors to be considered in designing such a system are: the quantity of information to be transmitted, the rate of transmission, the type of information, the expected channel noise, and the type of data processing to be used.

Irrigation system telemetry and control deals almost entirely with relatively slowly varying quantities. Changes in plant stress, soil moisture, reservoir water levels, and canal water levels occur at the quickest in seconds, usually not less than in minutes, and most of the time in hours. The quickest parameter changes will probably occur in closed delivery systems. Even here, valve and pump response times will probably be in terms of at least seconds. It is unlikely that a system capable of transmitting several thousand bits-per-second will be necessary to meet information requirements of even the most rapidly varying irrigation parameters.

The amount of information at one sensor or one control point is small; information quantity is more a function of the number of points from which data is received and the number of points controlled. Only a fraction of these points will be transmitting data or receiving commands at any particular time. Unless a system grows to a very large size or the status of many points must be rapidly scanned, a system with a fairly slow transmission rate, perhaps 10 bits-per-second to 100 bits-per-second, will be more than adequate to meet irrigation system demands.

In discussing information transmission rates, it has been assumed that the telemetry-control system would be digital. While an analog system may in some instances be less expensive and may more easily show trends of a variable, the several analog-analog translations normally used to telemeter analog information introduce additive errors (59). Analog signals are dependent on wave form magnitude and shape, both of thich are easily affected by channel noise (60). Thus, analog signals are inherently suceptible to noise induced error. A digital telemetry-control system is preferred for its greater intrinsic accuracy, direct suitability for data logging and computer control, and capability of high information rates or large number of multiplexed narrow bandwidth channels carrying information at low rates (59, 61).

The communication link selected determines the maximum possible data transmission rate. For a channel of bandwidth W, the maximum data rate is 2W (62, 63). This assumes an ideally square transmission channel: all frequencies are passed with the same attenuation in the bandwidth W and all frequencies are infinitely attenuated outside this bandwidth. Variation in bandwidth attenuation and necessary guard bands usually limit the signalling rate to W or less (64). However, very high transmission rates are not necessary. Nearly any communication link may be used, providing it is economical. One may choose among teletype and telegraph, voice-grade telephone, power-line carrier, VHF radio, UHF radio, microwave, or simple wire pairs. Wire pair, radio, and voice-grade telephone will probably be the communication links used most in irrigation telemetry-control systems.

Many techniques are available to encode information for transmission. Most such techniques may be grouped into the general classes: PAM (pulse amplitude modulation), PDM (pulse duration modulation), PPM (pulse position modulation), and PCM (pulse code modulation) (65, 66). PAM, PDM, and PPM are suitable for use in both analog and digital systems. PCM is suitable only for digital systems.

PAM conveys information in terms of a pulse train in which each pulse is characterized by a voltage, current, or differential phase (65). This technique, while primarily used in analog telemetry, can be used to concentrate information in digital systems with high channel signal-to-noise ratios. However, PAM is highly susceptible to channel noise, difficult to protect against noise, and requires low keying rates to maintain pulse integrity on narrow bandwidth channels (65).

PDM conveys information in the form of a pulse train in which each pulse is characterized by a time duration (65). Also extensively used in analog telemetry, PDM has two basic forms in digital use (65).

1. RZ (return-to-zero) in which each positive half cycle of a rectangular wave train carries an information bit
2. NRZ (non-return-to-zero) in which each successive half-cycle of a pseudo-rectangular wave train carries an information bit

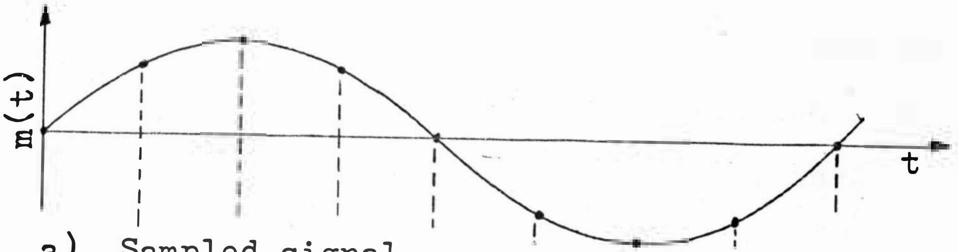
PDM is also susceptible to channel noise induced error. PDM of the RZ type may be safeguarded to a predictable limit by the inclusion of redundant information. PDM also requires low keying rates to maintain pulse integrity on narrow bandwidth channels (65).

PPM conveys information in terms of a pulse train where the instantaneous value of the modulating wave displaces the pulse from its normal position by an amount proportional to the amplitude of the modulating wave (60). All pulses are of the same size and shape. The pulse leading edge, trailing edge or both edges may be timed. PPM is often used in analog telemetry. Narrow bandwidth channels require a low keying rate to permit maintenance of pulse integrity.

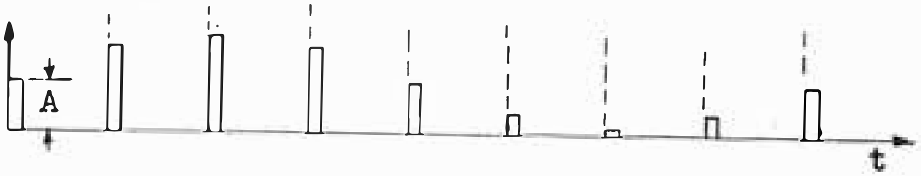
PCM conveys information in terms of a binary pulse train where 1-bits are designated by their explicit presence and 0-bits by their absence in the alternate half cycles of a rectangular pulse train (65). Both the transmitter and receiver must be synchronized by an accurate clocking system. PCM is a digital technique only. Since PCM emphasizes independence of any amplitude property of a pulse, and bit recognition is on a minimum amount of information, PCM can accomodate high information rates, closely spaced multiplexed channels, and low error rates with inclusion of redundancy. Figure 6 pictorially compares PAM, PDM, PPM, and PCM.

PAM is analogous to AM (amplitude modulation) and has the same noise immunity. PDM and PPM are analogous to FM (frequency modulation) and give the same type of noise immunity improvement over PAM that FM gives over AM. PCM gives a much better noise immunity improvement with bandwidth than PAM, PDM, or PPM (61).

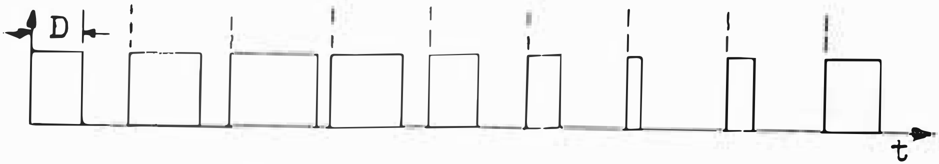
Signal modulating equipment prepares digital or analog data for transmission over a communication link. It performs encoding, multiplexing, and other necessary operations required for data transmission.



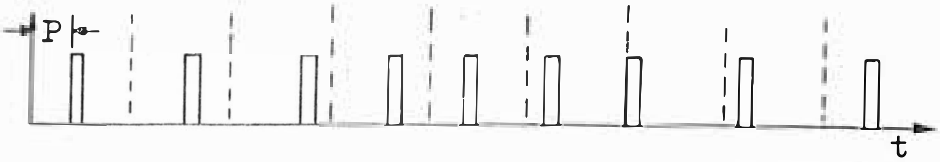
a) Sampled signal



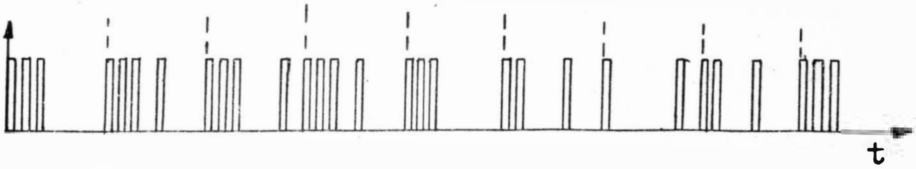
b) PAM--Information contained in magnitude of A



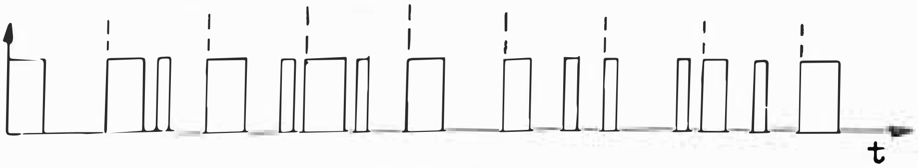
c) PDM--Information contained in length of D



d) PPM--Information contained in length of P



e) Return-to-zero PCM--Information encoded as 1's and 0's



f) Non-return-to-zero PCM--Information encoded as 1's and 0's

Figure 6. Pictorial comparison of PAM, PDM, PPM and PCM.

Signal modulating equipment injects information into and receives information from a communication link. While other signal modulating equipment exists, three main types are in common use:

1. AM or ON-OFF equipment
2. FSK (frequency-shift) equipment
3. PSK (phase-shift) equipment

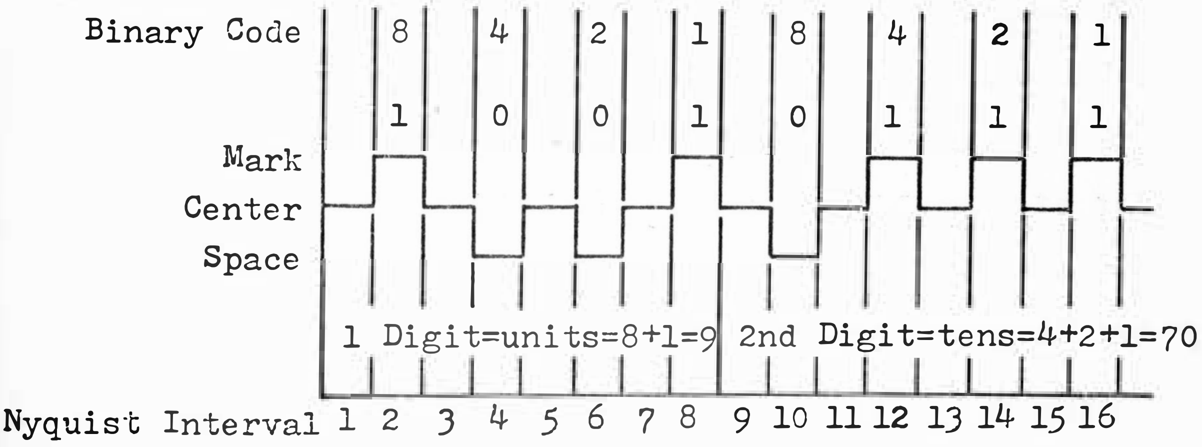
Since telephone lines are used as the communication link in many telemetry-control systems, audio or tone equipment is used to process the data at the transmitter and receiver. Telephone lines or their equivalent will probably be used a great deal in irrigation telemetry-control systems also. The following discussion of signal modulating equipment will concentrate on tone equipment for this reason. AM tone equipment is driven between its two switched states, ON and OFF, by rectangular keying pulses. FSK equipment is driven from a "space" to a "mark" frequency by the rectangular keying pulses. PSK uses the rectangular keying pulse to shift from a "space" quiescent reference phasing, to a "mark" phase shift (65).

While FSK requires the greatest bandwidth of the three types, it is not necessary to keep track of amplitude or phase relations at the receiver. This is especially advantageous in fading channels.

Recall that it was decided that in irrigation telemetry-control systems a fairly low information transmission rate will probably be adequate to meet normal requirements. It was also decided that the telemetry system must be simple, inexpensive, reliable, and secure. This author proposes that a trinary (three-state signal) adaptation of FSK be used in future irrigation telemetry-control system development. Such a system has been used in at least two previous instances (45, 67).

This system uses a "mark"/"space"/"center" three-state signalling (68). This is a return-to-zero (RTZ) type of signalling where the center frequency is transmitted between every "mark" or "space" frequency. The "mark" frequency represents a 1, and the "space" frequency represents a 0. See Figure 7.

The system requires two Nyquist intervals to transmit one bit of information, since the code requires a return to the center frequency for one Nyquist interval after transmission of each "mark" or "space" frequency for one Nyquist interval (67). A Nyquist interval is $\frac{1}{2W}$ seconds long, where W is the channel bandwidth. Use of such a trinary signal to transmit binary information permits greater system flexibility. The return to the neutral or center condition after each bit clearly defines the end of each bit. This permits the system to rest



Total Binary Code and Decimal, BCD, Digit-79

Figure 7. Binary coding using 8 bit word in trinary signalling system

between blocks of bits or between each bit. In fact, no clock is needed at the receiver, since "mark" or "space" decisions can be made as soon as the difference in the outputs of matched "mark" and "space" filters exceeds a certain threshold.

Another function this type of coding permits is proportioning control by the transmission of a "mark" or "space" of any duration. In other words, digital and analog data may be transmitted using the same equipment. For instance, after a remote station receives its address code, a certain length pulse could be sent to signal proper gate or valve position.

Using this trinary code to transmit binary information means that the maximum transmission rate is one-half of the theoretical Nyquist rate of $\frac{1}{2W}$ bits-per-second. Using three states (frequencies) also means the channel bandwidth must be greater for a given data rate than in a two state system. Such restrictions are not likely to hamper telemetry-control system effectiveness in irrigation systems.

A method of assuring channel security against noise is needed. In a channel of limited bandwidth, and a particular level of gaussian noise, a three-state signal is somewhat more susceptible to noise than a two-state signal (68). This increased noise susceptibility may be countered by a slight lengthening of the

Nyquist interval (68). In fact, a step in the direction of increasing M (number of states) and T (length of Nyquist interval) will actually result in an error rate decrease. Error rate may also be decreased by the inclusion of redundancy in the coded information to enable error detection. The type of encoding used is determined by the amount of channel efficiency that one is willing to sacrifice, the type of noise to be guarded against, the cost of making an error, the cost of equipment to implement a code, and the type of information being transmitted (69).

Wilson discusses many of the most commonly used error control techniques (70).

1. Single parity (SP)
2. Double parity--1 and 0 (DP-10)
3. Double parity--staggered (DP-S)
4. Constant ratio
5. Double transmission (DT)
6. Bose-Chaudhuri (B-C)
7. Composite coding--combining DT with other techniques

The single parity technique adds an additional bit to the string of information bits. The additional bit is made either a 1 or a 0 so that the total number of 1's in the message will be an even number (for even parity).

The double parity 1-0 technique involves a string of information bits of length four and two additional parity bits. One of the parity bits is either a 1 or a 0 so that the total number of 1's will be an even number. The other parity bit is made a 1 or a 0 so that the total number of 0's will be an even number. In each case the parity bits do not consider the status of the other parity bits.

The double parity-staggered technique again appends the two parity bits to the four information bits. One parity bit provides an even parity of 1's in association with the first three bits of the four information bits. The second parity bit provides an even 1's parity considering only the last three information bits.

The constant ratio technique utilizes a constant ratio of 1 to 0 bits in a constant length message. For example, a 2-out-of-5 word structure may be used with two, and only two, bits being 1's in every code group. Each code group is checked at the receiver to see if it contains the correct number of 1's.

The double transmission technique transmits the information bits twice. At the receiver, the repeated bits are compared on a bit-by-bit basis.

The Bose-Chaudhuri technique involves a family of cyclic codes. One of these codes is the 31/26 code.

With this particular code, 26 information bits are transmitted with five parity bits appended at the end. This encoding operation may be described by considering the 26 information bits as a binary number, which is divided by a prime number "stored" in the transmitting terminal. The result of this division provides a remainder of five bits which become the appended parity bits. This process is repeated at the receiving terminal using the same prime number. The remainders are then compared, and if they match, the data transmission is assumed to have been errorless.

Composite coding (combining double transmission with other techniques) can be used when additional security is required.

Table 1 gives examples of the above codes, and Table 2 compares the error detection effectiveness and encoding efficiency of all the codes. The Bose-Chaudhuri technique is found to have the highest error detection effectiveness and the highest encoding efficiency. Wilson also states that it is an economical code to implement.

Many other codes have been developed in an effort to correct errors in addition to detecting them. These range from cyclic codes to feedback codes (52, 71). Error correcting codes cannot correct every conceivable

TABLE I

EXAMPLES OF SOME COMMON ERROR CONTROL TECHNIQUES

Simple Parity (SP)

SP Example: $0110\underline{0}$ $1011\underline{1}$ $1000\underline{1}$ $1111\underline{0}$

(The underscored bits are the even parity bits.)

Double Parity -1 and 0 (DP-10)

DP-10 Example: $1110\underline{1}\overline{0}$ $0110\underline{0}\overline{1}$

(The underscored bit is the 1's parity and the overscored bit is the 0's parity.)

Double Parity Staggered (DP-S)

DP-S Example: $\underline{111}0\underline{1}0$ $\underline{011000}$ $\underline{100}1\underline{1}1$

(The first parity bit provides even parity for the first three information bits, and the second parity bit provides even parity for the last three bits.)

Constant Ratio (2/5)

2/5 Example: 01100 00101 10001

(Each message or word structure has only 2 of the five bits as 1's.)

Double Transmission (DT)

DT Example: 11010 11010

(The message is completely retransmitted.)

Bose-Chaudhuri (B-C)

B-C Example: $01110100100010001111000111\underline{10010}$

(The underscored bits are the check bits for a 31/26 code.)

Composite Coding

DT + SP Example: $0110\underline{0}$ $0110\underline{0}$

(The underscored bit is the even parity bit, and the message is transmitted twice.)

(Some examples are from Wilson, 1970; Ref. 70)

TABLE II

THE ERROR DETECTION EFFECTIVENESS AND ENCODING EFFICIENCY OF SOME COMMON ERROR CONTROL TECHNIQUES

Encoding Technique	Error Detection Effectiveness	Encoding Efficiency
B-C (worst case)*	97.0%	83.9%
B-C (fair lines)	99.9+%	83.9%
DT (5-bit word)	97.0%	50.0%
DT (4-bit word)	93.8%	50.0%
DP-S (96 bits)	73.0%	66.7%
2/5	71.0%	66.6%
DP-10 (6-bits)	63.0%	66.7%
SP (5 bits)	51.6%	80.0%
DT + B-C (worst case)	100.0%	42.0%
DT + DP-S	99.6%	33.3%
DT + DP-10	99.4%	33.3%
DT + 2/5	99.1%	33.3%
DT + SP (5 bits)	98.5%	40.0%

*Worst case here refers to the equal probability of each bit transmitted being in error--a completely impractical transmission lines operating condition. (From Wilson, 1970; Ref. 70) pattern of errors, but must be designed to correct the most likely patterns for the channel used. As attempts to correct errors are made, equipment expense rapidly increases and transmission efficiency decreases.

This author feels that further investigation of the use of the trinary signalling method proposed earlier is warranted. This method may be able to meet the telemetry-control requirements of automatic irrigation systems.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

As automation of irrigation becomes a necessity to meet water application efficiency requirements, all disciplines should cooperate in developing the best irrigation systems possible. These systems must be reliable, maintainable, efficient, and as inexpensive as possible.

Non-irrigation capabilities of irrigation systems may be automated along with water application. This may save several field operations required to apply fertilizers and other chemicals. Climate control and crop frost protection will also be practical in automated systems.

Sensors, controls, and communication systems must be developed to implement automation. Few electrical engineering techniques have been applied in designing such sensors, controls, and communication systems. This author feels electrical engineering techniques have much to offer in enabling meeting of automated system goals.

All controls and telemetry-control communication systems should be designed so that if they fail, they will fail safely. Irrigation equipment is expensive, and a failure of one or more components should not jeopardize the entire system or the crops irrigated.

Further effort in developing power sources for automated system electrical equipment is necessary. This power might be obtained from moving water in the supply lines.

Further investigation of the trinary signalling method is suggested as a solution to automatic irrigation system communication requirements. Security coding techniques may be used in the trinary system to help prevent false signalling.

Great care must be exercised at all times to design and build systems which will be readily accepted by the irrigators using them. A large degree of good salesmanship by those promoting conservation of water through use of automatic irrigation systems will be needed. The individual farmer must not be alienated. His welfare must be high on the design priority list.

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