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Microcontrollers in Recirculating Aquaculture Systems[1]

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Closed-system aquaculture presents a new and expanding commercial opportunity; however, presently there are few profitable commercial operations. Intensive aquaculture systems require a sufficient supply of oxygen and nutrients in temperature-controlled water with a means of removing wastes from the system. In properly controlled recirculating aquaculture systems, stocking rates of up to one-half pound of fish per gallon of water can be obtained. However, since failure of any component can cause catastrophic losses within a short period of time, the system must be reliable and constantly monitored. Thus, precise measurements and controls are necessary for the success of an intensive recirculating aquaculture system.

An important component of closed-system aquaculture is the control system which must measure and control all of the critical system parameters. Recent developments in control technology and microcomputers may revolutionize the operation and control of many agricultural and biological production systems. A properly-controlled system will also be energy efficient since production can be optimized with respect to the various inputs.

SYSTEM PARAMETERS

The most important parameters to be monitored and controlled in an aquaculture system are related to water quality, since they directly affect animal health, feed utilization, growth rates and carrying capacities. The primary water quality parameters include temperature, dissolved oxygen (DO), pH, ammonia, nitrites, nitrates, suspended solids, salinity, alkalinity, biochemical oxygen demand (BOD), and water flow rate. Water levels, availability of electric power, means of detecting fire, smoke and the intrusion of vandals should also be monitored.

Due to the cost and/or unreliability of sensors and associated equipment, most automated aquaculture systems do not attempt to monitor and control all of these parameters. It is recommended that temperature, DO, pH and water flow rate be monitored directly on a continuous basis since they tend to change rapidly and have a significant adverse effect on the system if allowed to operate out-of-range. Other parameters change slowly and tend to stay in range if proper flow rate is maintained. For example, ammonia is usually not a problem if the biological filters are properly sized for the loading rate and if adequate flow is maintained. In this case,

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Table 1. Water quality standards for fish culture.

Alkalinity (as $CaCO_3$)	10 to 100	Nitrogen (N)	<110% total gas pressure <103% as nitrogen gas
Aluminum (Al)	<0.02	Nitrate (NO_3)	0 - 3.0
Arsenic (As)	<0.05	Nitrite (NO_2)	0.1 in soft water
Barium (Ba)	5	Nickel (Ni)	<0.1
Cadmium Alkalinity <100 ppm Alkalinity >100 ppm	 0.0005 0.005	PCB (polychlorinated biphenyls)	0.002
Calcium (Ca)	4 to 160	pH	6.5 - 8.0
Carbon dioxide (CO_2)	0 to 10	Potassium (K)	<5.0
Chlorine (Cl)	<0.003	Salinity	<5%
Chromium (Cr)	0.03	Selenium (Se)	<0.01
Copper Alkalinity <100 ppm Alkalinity >100 ppm	 0.006 0.03	Silver (Ag)	<0.003
Dissolved oxygen (DO)	5 to saturation	Sodium (Na)	75
Hardness, total	10 to 400	Sulfate (SO_4)	<50
Hydrogen cyanide (HCN)	<0.005	Sulfur (S)	<1.0
Hydrogen sulfide (H_2S)	<0.003	Total dissolved solids (TDS)	<400
Iron (Fe)	<0.1	Total suspended solids (TSS)	<80
Lead (Pb)	<0.02	Uranium (U)	<0.1
Magnesium (Mg)	<15	Vanadium (V)	<0.1
Manganese (Mn)	<0.01	Zinc (Zn)	<0.005
Mercury (Hg)	<0.2	Zirconium (Z)	<0.01

Source: U.S. Environmental Protection Agency 1979-80
Note: Values are in milligrams per liter unless otherwise noted.

flow rate is the critical parameter that should be monitored continuously, taking only periodic measurements of ammonia. Table 1 gives the general range of water quality standards for fish culture.

In order to maximize production, water temperature must be precisely controlled. The range of temperature for optimum aquacultural production depends on the species being cultured. Some species require a variable range in order to propagate. However, temperature variation can be detrimental to some species and, in most cases, a relatively constant temperature is the goal. The larger the volume of water, the easier it is to control the temperature, because the high specific heat of water creates a high thermal mass that resists rapid changes in temperature.

All aquaculture species depend on oxygen for life and growth. The concentration of molecular oxygen in the water (normally measured in mg/liter) is called dissolved oxygen (DO) and depends on the temperature of the water and the biological demand of the system. Dissolved oxygen is the most critical parameter in a closed recirculating system since it can change rapidly. Fish kills result if DO is allowed to drop below a critical level. DO should be monitored very closely at all times and there should be a backup source of oxygen in case the primary supply is interrupted. If aeration equipment is used to supply oxygen, the air pressure supplied to the aeration equipment can be monitored instead of directly measuring dissolved oxygen. However, since this is such an important parameter, it would be advisable to measure both, thus providing a backup in the system.

Ammonia is a waste product of protein metabolism. In water, it is present in two forms, ionized (NH_4^+) and unionized (NH_3). Unionized ammonia is toxic to most aquatic organisms and occurs in greater proportion at high pH and warmer temperatures. The toxicity of the unionized form is harmful at levels as low as 0.05 milligrams per liter. Nitrite is a byproduct of the biological oxidation of ammonia. Most aquatic organisms can tolerate some traces of nitrites, but as the level increases, productivity goes down. Generally, nitrate is not toxic to fish and is used by plants for food. Nitrite is a difficult parameter to measure and control. Ammonia is also difficult to measure with sensors. However, ammonia is usually not a problem once the biological filters have been properly sized and an adequate flow rate determined. Also, ammonia levels tend to change slowly, making periodic measurements sufficient.

SENSORS AND INSTRUMENTATION

Recirculating aquaculture systems commonly include controls to monitor the water quality parameters of temperature, dissolved oxygen, pH, and water flow rate either directly or by monitoring equipment which maintains the parameter. In the past, only the most sophisticated and expensive instruments were adequate for monitoring and controlling aquaculture systems. However, today there are many new developments in solid state electronics which are bringing down the cost and increasing the reliability of sensors and instruments. The following is a review of several of the sensors and instruments used to monitor some of the parameters of an aquacultural system.

Liquid-Filled Thermometer

The liquid-filled glass thermometer is the simplest and most economical way to measure temperature. The thermometer indicates temperature by the expansion and contraction of mercury or alcohol in a sealed glass column. A common type used in aquaculture is a sealed unit that floats in water. These thermometers are accurate, simple and reliable, but are also prone to breakage and cannot be interfaced with a control system. They are most appropriately used as a back-up to other temperature indicators and for calibration of other temperature sensors.

Bimetallic and Gas Bulb Thermometers

Both of these thermometers are mechanical and can be used to indicate temperature on a dial or used to either open or close an electrical switch such as those used on most common thermostats. These types of thermometers are very simple, reliable and can be interfaced with electronic control systems.

Thermocouple

Two wires of dissimilar metals connected at each end generate a voltage related to the temperature difference between the two junctions. There are six common types of thermocouples depending upon the kinds of metals used to make them. They have wide operating ranges but have very low DC voltage outputs. Due to this low voltage, in the past thermocouples could only be used with very expensive instrumentation; however, advances in solid state electronics have greatly reduced the price of instrumentation to the point where it is a practical method of measuring temperature today. These sensors are very inexpensive if you make your own. Simply cut the wire to the length desired and solder or weld the ends together. Thermocouples are very practical when you want to measure temperature at a number of locations.

Resistant Temperature Detectors (RTDs) and Thermistors

Resistant temperature detectors and thermistors work on the principle of change of resistance with a change in temperature. This resistance can be measured and calibrated to a temperature scale which can be electronically displayed. Although the principle of operation is completely different, RTDs and thermocouples are very similar from a users point of view. Thermocouples usually are more flexible in application and have a better long-term stability than do RTDs. However, RTDs and thermistors have a much higher temperature sensitivity than thermocouples, thus requiring less sophisticated electronics.

Integrated Circuit (IC) Transducer

An integrated circuit transducer is a solid-state microelectronic circuit that is contained in a transistor-like housing and has an output voltage or current proportional to its temperature when supplied with a constant current or voltage. IC transducers are very reliable and simple to use and interface with control circuits. They have the advantage of being a completely packaged temperature indicator in comparison to thermocouples and RTDs which must be connected to some electronic circuit. IC transducers, sometimes called IC sensors, are very linear, are precalibrated and cost about the same as RTDs and thermocouples. They do have a limited temperature range (minus 85° to 125° Celsius). However, this should not be a problem with aquaculture operations.

pH Measurement

The pH measurement is made either chemically or electronically. The chemical method is extremely simple. A reagent is added to a sample and the resulting color change corresponds to the pH value. The electronic method uses an electrode that is placed in the water and has an output voltage which is correlated to pH. These units are commercially available at a moderate cost and can be interfaced with control systems.

Dissolved Oxygen Measurement

Dissolved oxygen (DO) can be measured both chemically and electronically. The electronic measurement for DO simply requires the placement of the probe in the water. The DO probe consists of a gold or platinum element that is surrounded by a reagent solution. This solution is separated from water by a membrane which allows the passage of oxygen into the solution where it reacts with the element and generates a voltage that can be measured and displayed. The DO probe can be interfaced with an electronic control system but has the disadvantage of high cost and high maintenance.

ENVIRONMENT AND ELECTRONICS

An important consideration in aquacultural control systems is the environment in which they are used. The corrosiveness of the water in which the probes are placed can rapidly degrade their effectiveness. Probes can also be fouled by microbial growth. A regular schedule of maintenance and calibration must be used to insure that the probes are functioning properly. Some method of fault detection should be used for each probe to determine its status and calibration. The electronics must be isolated from the high humidity and constant wet environment of the production facility.

Low voltage should be used for control components where possible and a ground fault system should be provided as a safety precaution for the higher voltage components of the system. This is needed for protection of personnel as well as the aquatic animals.

AUTOMATIC CONTROL

Feedback is an important concept in systems control. As an example, consider a heated water tank in which a measurement is taken to determine if the water is at the desired temperature. The controller would interpret the feedback as follows: water above desired temperature — turn heater off; water below desired temperature — turn heater on. The common thermostat operates in this manner; however, it is usually an on-off device which causes temperature fluctuations in the system.

A better system is one that supplies heat proportional to that which is needed, thus minimizing the fluctuations. This is called proportional control. There are also more sophisticated control functions known as derivative and integral control functions which further minimize oscillations in the system. They accomplish this by sensing the rate at which the parameter is changing and by determining the deviation of the measured parameter from the desired set point. This type of control system is usually referred to as PID (proportional-integral-derivative). These types of controllers have been available for many years but have been very expensive and usually were used only in sophisticated industrial operations. The cost of PID controllers is falling, but they may not be a good choice for most agricultural operations since PID controllers are based on complex mathematics and require considerable expertise in order to design, modify and apply to a specific operation.

An alternative to traditional control system theory is based on what is called "fuzzy logic". Its strength in process control lies in its ability to manipulate systems that are complex, nonlinear and, most importantly, lack any mathematical model. Moreover, the input to fuzzy logic control is a set of rules written with linguistic variables, stated in plain English. Thus, no special programming skills are required if a fuzzy logic control code generator or compiler is used. This exotic technique has found a home in applications ranging from autofocus cameras to stock portfolio management. It also lends itself very well to applications in aquaculture since it is based on a simple system of 'if' and 'then' statements. For example, if condition A and condition B exist, then take action C. This basis for control makes it much easier for the aquaculturists to communicate with the engineers and the computer scientists. This new control technology, microcomputers and a new programming language may revolutionize the operation and control of many agricultural and biological production systems.

MICROCONTROLLERS

Industrial automatic controllers have been available for years but have a price tag in the thousands of dollars. In addition, they are not very adaptable to aquacultural operations due to the severe environment in which they operate and the changing requirements of agricultural control systems. On the other hand, microcontroller chips are very inexpensive, usually costing much less than $100. They are very small, can operate under very severe environmental conditions, and lend themselves to new, simplified programming procedures. These features make the microcontroller the preferred choice for embedded control, such as that used in appliances, automotive engine control, camera exposure control and industrial automation.

A microcontroller is an enhanced microprocessor. In addition to the microprocessor, a microcontroller typically contains several parallel and serial ports, system clock generators, data and program memory, timers, counters, interrupt logic, analog-to-digital converters, digital-to-analog converters, and even digital signal processing subsystems on the same chip. Thus, a single-chip microcontroller may be placed in an application to perform as an embedded controller with no other support chips. Only within the last few years have microcontrollers advanced to the point that they can handle a large number of inputs and outputs and accommodate enough memory and processing power to control a complex system such as those used in aquacultural production.

Microcontrollers that can be programmed by means of an interview with the aquaculturist may be available soon. This is due to a new visual programming language being developed by the Industrial and Systems Engineering Department at the University of Florida. This new visual programming language allows the end user (aquaculturist) to sit down at a computer at some convenient location, such as the county Extension office, and describe what parameters are to be controlled, what type of control devices will be used, and tell exactly how the system should operate. This visual programming language provides a menu of choices for all of the system and control parameters. Once the choices have been made and instructions given, the computer automatically writes all of the computer program (source code) for the control system. More detailed information on the visual programming language can be found in *A Visual Language for Microcontrollers*, S. Yerlan, et al., Research Report 93-4, Industrial and Systems Engineering, University of Florida.

As an example of how the visual programming language works, consider a microcontroller system (Figure 1) in which temperature, dissolved oxygen, pH, water level, and water flow rate are to be monitored and/or controlled. Using the visual programming software, the aquaculturists can select these parameters and tell how each is controlled. For example, the temperature is controlled by a heat pump which can heat or cool the water. The dissolved oxygen level is controlled by oxygen injection, the water level is controlled by a valve connected to the main supply line, the flow rate is controlled by the pump speed and the pH is monitored but not controlled. The upper and lower limits of each parameter and the sampling rate for each can be selected. Once all the inputs have been made, the operation of the system may be simulated by the software to insure that it operates as the user intended. Next, the visual programming software writes all of the source code in the appropriate computer control language, then the electronic control circuit is drawn by the computer which can then be burned or etched into the microcontroller. The microcontroller is then ready to be installed into the automatic control system, where the input sensors are connected and the output signals are sent to the control devices (pumps, valves, heat pumps, etc.).

The hardware and software to accomplish the tasks just described are still being developed, but should be available in the near future. In the meantime, microcontrollers can still be developed to monitor and control most parameters in an aquaculture production facility, but may require a considerable cooperative effort among the aquaculturist, engineer and hardware and software suppliers.

POTENTIAL FOR ENERGY SAVINGS

As more reliable and effective sensors become available to measure aquacultural system parameters, more microcontrollers will be used to optimize aquacultural production. An optimized system is both energy efficient and cost effective. Presently, most system components are overdesigned because precise measurement and control are not being utilized. For example, aeration systems usually move a lot more air and use more energy than is necessary because dissolved oxygen is not being directly measured and controlled. In addition, biological filters may be overdesigned and use higher water flow rates and, hence more energy than necessary because the ammonia level is not being directly monitored and controlled.

Microcontrollers allow large amounts of real time data to be collected, providing a basis for improving the efficiency of the production system as it operates. A precisely-controlled environment minimizes stress on the aquatic organism and reduces the grow out period. It also reduces the quantity of energy, labor and water used per production unit. For example, if the system is completely automated with microcontrollers, including the monitoring of feed, growth rate of fish and energy utilization, simple experiments can be run to determine whether it is economically feasible to increase the water temperature in order to increase the growth rate. In other words, the aquaculturist can continually improve the efficiency of the operation by observing its performance under different operating conditions.

Microcontrollers can also be utilized to activate other devices such as switching on back-up power when the main power fails, sounding alarms and making phone calls when system parameters are out of range or when intrusion, smoke, fire or high temperature sensors are activated. To be practical, the monitoring and notification system should allow the production manager to follow a normal daily routine, including travel away from the production facility, while remaining informed about the system's operation. This type of monitoring and response may provide the basis for the greatest energy savings, because system failures result in instant loss of the energy sequestered in the aquatic animal.

A conservative estimate of energy savings for a properly monitored and controlled aquaculture system of 20% would result in ten billion Btus of energy saved annually from ornamental fish production alone. This is based on energy consumption as reported from "The Florida Energy Consumption Model" which indicates that 4.46×10^{11} Btus of energy are consumed annually in aquacultural production in Florida, with 1.16×10^{11} Btus of that used in ornamental fish production.

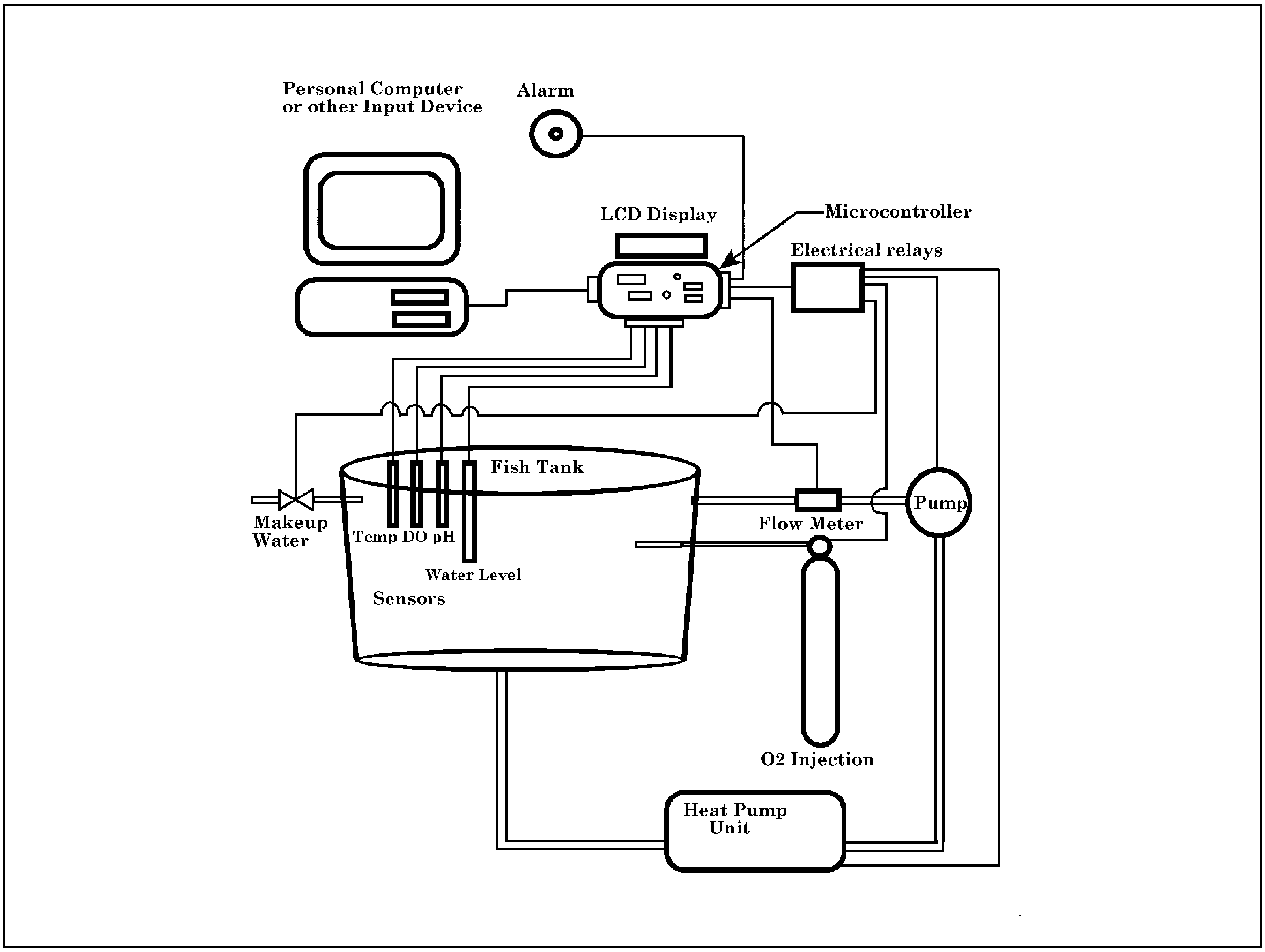

Figure 1. Microcontrolled aquaculture system.