A MICROPROCESSOR-CONTROLLED WATER-POLLUTION MONITORING SYSTEM*

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A water-quality monitor was designed and built to sample water flowing over a weir in White Oak Creek near the Oak Ridge National Laboratory (ORNL). ORNL is required to sample the water at regular volume intervals to determine whether it meets federal water-quality standards. Because the monitor must yield a high accuracy (0.1%) in measuring water-volume and high repeatability (0.1%) of sample size and demonstrate long-term stability (low-drift), a digital control system using a microprocessor was developed to replace the analog controller in an existing monitor.

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I. INTRODUCTION

The Environmental Protection Agency (EPA) requires that the Oak Ridge National Laboratory (ORNL) monitor the quality and quantity of the effluent ORNL discharges into White Oak Creek, which flows through the Laboratory, to determine whether the water meets federal water-quality standards. The procedure is to analyze samples taken from White Oak Creek as the water flows over a weir in White Oak Dam and thence to public waterways.

The microprocessor-controlled sampling system takes an equal sample of water for each 10,000 ft³ of water that flows over the weir. Two requirements of the system are that (1) the measurement of 10,000 ft³ of water be accurate to within 0.1% (10 ft³), and (2) the water samples be repeatable to within 0.1% at all anticipated flows. The computation of volume of water involves two different nonlinear relationships between water height and water flow and requires integration. A microprocessor-controlled system was de-

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signed rather than an analog system to accomplish the nonlinear conversion and integration with the required precision.

The Intel SIM8-01 microcomputer-on-a-board utilizing the 8008-1 microprocessor was used for this system. It was interfaced to an analog input signal, a mechanical water-sampler, and three control switches. The control program performs a nonlinear conversion from water height to water flow and numerically integrates flow. The program also controls the mechanical sampler and can test most of the system, including itself, for proper operation.

II. DESIGN PHILOSOPHY

The microprocessor-controlled system utilizes an existing water-height measurement system. Water height is measured by a float inside a stilling well. The float is connected to a pulley that translates the vertical movement of the water level to rotation of the pulley shaft. The shaft is connected to a potentiometer to create an analog voltage proportional to water height. The relation of water height (H) to water flow (F) is shown in Fig. 1 and expressed mathematically as

$$F = K[H-744.997]^{3/2} \text{ for } H \leq 750 \text{ ft} \quad (1)$$

and

$$F = K_0 + K_1[H-750] + K_2[H-750]^2 + K_3[H-750]^3 + K_4[H-750]^4 \text{ for } H > 750 \text{ ft}, \quad (2)$$

where $K = 12.6068$, $K_0 = 141.072$, $K_1 = 102.202$, $K_2 = 556.163$, $K_3 = -858.337$, and $K_4 = 476.768$. The units of H are feet above sea level and of F are cubic feet per second. The reason for the point of discontinuity in the first derivative of F with respect to H, dF/dH , at $H = 750$ ft is that the top of the dam is 750 ft above sea level. The water actually spills over the dam during heavy rains, thus changing the relation of F to H.

Because the overall F to H relation is nonlinear and in two distinct pieces and the stability and calibration accuracy of analog function generators are not sufficient for this application, digital conversion is more accurate and repeatable than analog conversion. Typical water flow rates

might be anywhere from <3 cfs in dry weather to >300 cfs in spring flooding. This dynamic range of $>100:1$ is more accurately accommodated by a digital system than an analog system. Furthermore, considering that the flow must be integrated over times as long as an hour between samples, digital integration is preferred to analog integration because a digital integrator does not decay or drift over long periods of time.

For the reasons just given, that is, 0.1% precision in calculation, $>100:1$ in dynamic range of flow signal, and long-term stability in integration, a digital system was developed in preference to an analog system. In light of recent developments in microprocessors, a second choice had to be made between hard-wired logic and programmable logic. We selected a microprocessor instead of hard-wired logic because a microprocessor has programmable arithmetic capability and a lower cost of hardware construction. Also, the microprocessor can be salvaged and reprogrammed for use in another system when this system is removed or replaced. The ability to salvage the microprocessor is important because most designs of instruments and control systems by ORNL are for unique application at the Laboratory.

Use of microprocessors rather than hard-wired logic reduces the amount of hardware design required. The only new hardware required for a new design is the interface to transducers and peripheral devices.

The Intel SIM8-01 microcomputer-on-a-board, utilizing the 8008-1 microprocessor, was used for this system because it was available and equipped with 1K of RAM (random access memory) and 2K of PROM (programmable read only memory) on one printed-circuit board. These features minimized hardware design.

III. COMPUTATIONAL METHODS

The major computational tasks for this system are the conversion from height to flow and the numerical integration of flow. The integration process is to sample the flow signal and, therefore, the height at a 10-Hz rate and then approximate the integration by summation. The 10-Hz rate is high enough that the flow rate cannot change more than 0.0003% between samples, even during the fastest anticipated flow changes. Therefore, the approximation of integration by summation is accurate within $<0.0003\%$.

To satisfy the 0.1% accuracy requirement, a $3\frac{1}{2}$ digit voltmeter was used for analog to digital data conversion. The $3\frac{1}{2}$ digits resolve height data to 0.05%. To maintain this precision internally in the microprocessor, all height, flow-rate, and integrated-flow values are scaled to binary integers of at least 11 bits. Since the 8008-1 microprocessor uses 8-bit words, the 11-bit requirement necessitated some double-word operations.

The 10-Hz signal sampling rate requires that the program execute within 100 msec. To satisfy this requirement, H is converted to F by a table-lookup and linear interpolation method rather than by a time-consuming floating-point solution of Eqs. (1) and (2). The lookup table of flow values corresponding to 251 equally spaced height values is stored in one 256×8 PROM. The high eight bits of each height datum are used as an address at which the corresponding flow datum resides. The low three bits are used for interpolation. Only the least significant 8 bits of each flow datum are stored in PROM. The high 3 bits are calculated by knowing in which of eight areas the height lies.

The linear interpolation requires one binary integer multiplication of an 8-bit difference between two flow data by a number between zero and seven inclusive, and one division by eight. The multiplication is done by successive addition, and the division by right shifting. The maximum error due to interpolation for any flow is $<0.0012\%$ of span.

IV. DESCRIPTION OF FINISHED DESIGN

Figure 2 is a block diagram of the completed system. The digital voltmeter accepts voltages in a range from 0 to 2 V. The analog voltage proportional to water height is scaled to this range. The gain and zero can be adjusted to allow for a nonideal potentiometer. The analog voltage is converted to $3\frac{1}{2}$ -digit, binary-coded-decimal (BCD) form by the voltmeter. This BCD height datum is converted to an 11-bit binary height and then to an 11-bit binary flow by the table-lookup method described. Flow data are summed to an integrated water volume of $10,000 \text{ ft}^3$, at which point a pulse actuates a digital timer that controls the mechanical water sampler. The water is sampled by diverting a constant flow of thoroughly stirred water pumped from the stream into a container for 3.3 sec. Since the 3.3-sec

timer is derived from the 60-Hz power frequency by decade counters, the uncertainty of the 3.3 sec is dependent on the uncertainty of the power frequency. The error of the 60-Hz power line never exceeds 0.05 Hz, or 0.083%, even during extreme load changes or frequency readjustment. When the integrated water volume exceeds 10,000 ft³, this value is subtracted from the integrated value and the process is repeated.

A scaled water-flow number is indicated by a 3½-digit, gas-discharge, panel-mounted display. Front-panel controls include a "manual-sample" switch to allow an operator to take a water sample at any time, a "display-inhibit" switch which turns the water-height and water-flow displays on or off, a switch to reset the integrated water volume to zero to initialize the system, and a "test" switch.

When the "test" switch is depressed, the microprocessor performs several checks of the system hardware and the program. During these checks the water-flow display should be a calibrated value known to the operator. If the value is correct, the operator knows that the power supplies, the voltmeter, the program, and the displays are working properly. Normal program execution is completed in <10 msec; program execution during testing is completed in <40 msec.

V. SUMMARY

A microprocessor-controlled water-pollution monitor using an Intel 8008-1 microprocessor was designed, built, and installed at ORNL. The monitor samples water at precisely measured intervals of integrated volume. Water height is converted to water flow by table-lookup and linear interpolation. Flow is sampled and integrated numerically. The microprocessor controls all system functions by monitoring a 10-Hz clock, a BCD water-height number, and several switches.

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Figure Captions

Fig. 1. Relation of water-flow (F) as a function of water-height (H).

Fig. 2. Finished water-quality monitor.

Figure 1.