A Minicomputer-controlled Data Acquisition System

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ABSTRACT

A minicomputer-controlled data system was developed for measuring a wide variety of plant and weather variables in the field. One to 26 sensors were scanned at each of one to eight portable sensor stands placed in field plots. Analog signals from thermocouples, a dewpoint meter, radiation sensing devices, and a hot-wire anemometer were measured with a digital voltmeter. Digital data were accumulated from a cup anemometer, an automatic evaporation pan, and a beta-ray scaler. Data were processed by the computer, and the dimensioned values were recorded on punched paper tape and in a printed form. The software was written in absolute assembler language. The program included routines that would set the initial conditions and control the read, convert, and write operations; drive the peripheral equipment; provide mathematical functions; and handle interrupt signals. A multipoint recorder furnished graphic data from selected sensors.

KEYWORDS: Leaf thermometer, sensor stand, automatic evaporation pan, stepping switch driver.

ACKNOWLEDGMENTS

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A MINICOMPUTER-CONTROLLED DATA ACQUISITION SYSTEM

By K. E. Fry[1]

SYSTEM REQUIREMENTS

Methods of monitoring plant and microclimate variables in field crops are continuously needed.[2] [3] Present solid-state systems offer reasonable flexibility for interfacing with a wide variety of electrical sensors; however, as the demand for flexibility increases, so does the cost of the equipment. As a result of the recent advancements in microprocessor integrated circuits and reasonably simple combinations with peripheral input-output devices, experimenters can assemble highly flexible systems inexpensively.

Although the data acquisition system described here was designed around a minicomputer (Hewlett-Packard Co., Model 2114A, 8K x 16 bit memory locations), the principal organization of the hardware and software (computer programs) is applicable to available microprocessors in combination with adequate random-access-memories (RAM) and input-output peripheral equipment.

The following requirements were incorporated into the total system to collect plant, microclimate, and weather data:

Computer Control of Operation

- Operate the system with computer program (see Appendix A), which is composed of a control loop that selects program subroutines to scan sensors, convert data, and record final data for further analysis.
- Sound a buzzer to warn field help before scans are started.
- Operate multiplexing and measuring devices under program control in the field plots.
- Place the system in a wait mode during periods of power failure.

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[1] Plant physiologist, Western Cotton Research Laboratory, Science and Education Administration, Phoenix, Ariz.

[2] Boving, P. A., and Winterfeld, R. G. A mobile recording and monitoring weather tower. U.S. Dept. Agr., Agr. Res. Serv. ARS W-41, 13 pp. 1976.

[3] Smith, J. W., Stadelbacher, E. A., and Gantt, C. W. A mobile unit for automatic collection of computer-compatible macroclimatic and microclimatic field data. U.S. Dept. Agr., Agr. Res. Serv. ARS S-136, 6 pp. 1976.

Sensor Selection

- Scan 1 to 26 analog sensors at each of one to eight portable sensor stands placed in field plots.
- Record rapidly changing plant and weather parameters at predetermined intervals (1 to 30 min).
- Record slowly changing parameters (for example, soil temperatures) at hourly intervals.
- Accumulate and record pulse counts for preset time periods.
- Be able to change the pattern of scan under program control or manually without halting operations.

Data Processing

- Convert the sensor voltage readings or pulse counts into the desired dimension by using linear, polynomial, or exponential regression equations.
- Utilize multiple sensors and multiple regression equations to calculate the final dimension, when it is influenced by more than one weather or plant variable.

Data Logging

- Print Julian day, hour, and minute.
- Print channel code number and corresponding data in block format for immediate observation.
- Record the above information of punched paper tape in an appropriate format for further processing.
- Print statements indicating the channel and stand number when a malfunction of equipment occurred.
- Print the time when line power was lost and when it returned.

SYSTEM HARDWARE

Computer and Peripheral Equipment

The components of the data acquisition system are shown in figure 1. Only signal lines are shown connecting the components. The plant and microclimate sensors were mounted on field sensor stands (fig. 2), which were usually located near the center of the experimental plots. A 26-position stepping switch at each stand performed the necessary multiplexing of the sensor signals to a common signal line. Appendix B describes a single-step driver, which was used to operate a stepping switch under computer control. Signal, control, and direct current power lines connect the stands to the signal processing equipment, which was located in an air-conditioned trailer.

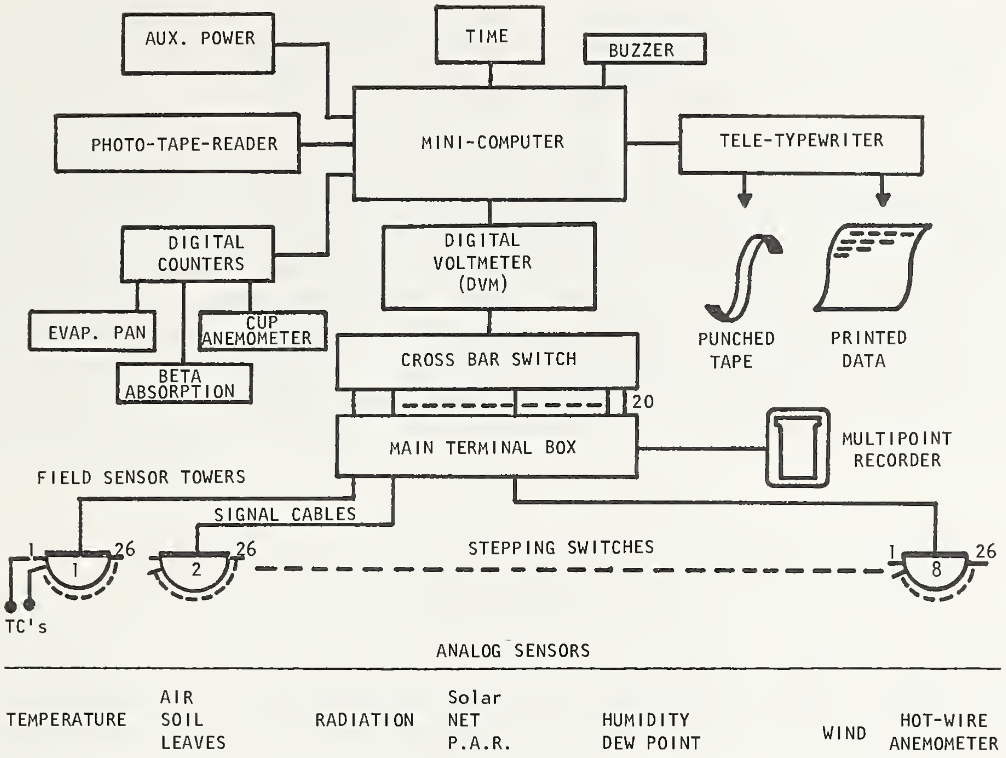

Figure 1.--Relation of system hardware components to minicomputer.

Figure 2.--Sensor stand support for air-temperature manifold and sensor tubes, stepping switch, and terminal board.

In the trailer, a crossbar switch (see Crossbar Switch, Appendix C) multiplexed the signals from the different stepping switches at the sensor stands and also signals from individual sensors located elsewhere. The signals were measured by a digital voltmeter (DVM, Hewlett-Packard Co., Model 2401C), were converted to the desired dimensions in the computer, and, by means of a teletypewriter (Teletype Corp., Model ASR-35), were logged on punched paper tape and as printed data. Each system component was operated by the computer under program control (see Interfacing Peripheral Equipment, Appendix C). A software clock determined the preselected time to sound the warning buzzer and start a scan of the sensors on line. The code numbers of the channels to be scanned were read from paper tape by the photo tape-reader (Hewlett-Packard Co., Model 2753) and were stored in computer memory. Digital counters (four-decade) accumulated the numbers of electrical pulses received from digital-output sensors over preselected time periods. The counts were read and logged by the computer.

Multipoint Recorder

Graphic recordings of selected weather and plant parameters were obtained with a multipoint recorder (Leeds and Northrup, Model H, 1 to 12 channels). Under computer control, a 12-pole relay rerouted the signals from the selected sensors between the scans.

Auxiliary Power

Regulated and uninterruptible alternating current power was supplied to the computer and digital voltmeter through a charger-inverter system connected to seven 12-volt automobile batteries (Elgar Corp., Model UPS1001). In the event of line power failure, the data acquisition system was held in a wait mode; the software clock continued to run. Normal operations were resumed if the line power returned within 45 min; if not, the total system was shut down orderly.

Data Reduction

The field data were printed on folded teletypewriter paper (8.5 by 11 inches), which was conveniently bound in pressboard binders for a quick reference; however, studies of the weather and plant variables, including hourly averages of air and leaf temperature, required further data reduction.

During 1976, a small office computer (Wang Laboratories, Inc., Model 2200S, 32K x 8-bit registers) became available. Computer programs in BASIC were written to read the paper tapes (Photo tape-reader, Wang Model 2203), select specific data, perform statistical treatments, and list and graph the reduced field parameters (Plotter, Wang Model 2212).

ANALOG PARAMETER MEASUREMENTS

Temperature Measurements

The choice of sensors for the air, soil, and leaf temperatures was copper-constantan thermocouples for the following reasons: (1) Thermocouples were inexpensive and easily constructed, (2) sensors for a wide number of uses could be fabricated from commercially available wire with diameters from 1.4 to 0.012 mm (Omega Engineering Inc.), (3) only a single calibration was needed regardless of sensor size for all thermocouples made from the same materials, and (4) inexpensive hand-held meters were available for use with thermocouples.

Air Temperature

At each sensor stand (fig. 2), air temperature was measured at the soil surface, at the height in the densest canopy, and about 1 m higher. Sensors were mounted inside a horizontal polyvinyl tube (1/2-inch diameter, 30 cm long). An outer tube (1-inch diameter) surrounded the sensor tube, and both were wrapped with reflective aluminized polyester tape (Scotch No. 850). Holes were drilled near the base of the inner tube to allow airflow between the tubes. All joints were lubricated with silicone grease to prevent sticking during adjustments and disassembly. The meter-long manifold (1½-inch diameter) supported two sensor tubes and a connection to the third sensor tube through a flexible hair-dryer hose. Aspiration velocities were 508, 330, and 152 cm sec^{-1} for the upper, center, and lower sensor tubes, respectively, when obtained with a small blower (Dayton, No. 40012) attached to the manifold with its exhaust point upward.

Soil Temperature

Copper-constantan thermocouples were inserted to depths of 1, 5, 10, 20, 40, and 100 cm below the soil surface of the cotton rows. The junctions were insulated with several coats of vinyl glue.

Leaf Temperature

A clip-on type of leaf thermometer was developed to obtain maximum convenience in attaching the thermometer to the leaf, minimum influence on the leaf's temperature and movement, and adequate reliability in monitoring leaf surface temperature over extended periods. Figure 3 shows a thermometer clamped to a cotton leaf. A copper-constantan junction bead (about 0.1 mm in diameter, welded from 25 μ wire) was epoxy-glued to the tip of a toothbrush bristle (0.38 mm in diameter) and was held against the leaf surface with a force of about 1 g. The coiled spring and wire arm that holds the bristle was formed from 0.5-mm-diameter phosphorbronze wire. Heavier spring wire (0.8 mm in diameter) was used for the holding loops and arms that were soldered to the jaws of a miniature alligator clip (Mueller, No. 30C). The clamping force of the spring-loaded clip was sufficient to hold the thermometer in place in winds of 670 cm sec^{-1} (15 miles per

Figure 3.--Thermocouple leaf thermometer on cotton leaf (underside).

hour). For use on cotton leaves, holding-loops were 2.7 cm in diameter and the arms were 3 cm long. Flexible thermocouple lead wires (127 μ in diameter, 40 cm long, Teflon insulation, Omega Engineering Inc.) were threaded through polyvinyl tubing (1.3 mm outside diameter) and connected to heavier lead wires (0.5 mm in diameter).

The leaf thermometers were tested for accuracy in measuring surface temperatures by clamping them to wet blotter paper. Their temperature readings were compared with those from fine-wire thermocouples embedded in the blotter. The leaf thermometers were in error about 0.16° Celsius above the blotter temperature for every degree Celsius the ambient air temperature was higher than the blotter temperature.

Possible leaf damage and its influence on the leaf temperature at the point of measurement were tested in the following manner. Thermometers were allowed to remain on field cotton leaves for 5 days. Then, during a period of relatively stable leaf temperature and rapid transpiration, the leaf temperatures were recorded before and after moving the thermometer bead about 5 mm. Usually, no significant mean difference in temperatures was observed, indicating that the 1-g force of the bead against the leaf tissue did not greatly influence the transpiration rate and the resulting leaf temperature.

Dewpoint Temperature

Air was sampled at the temperature sensor tubes and pumped at the sensor stands (not shown in fig. 2) to a solenoid gas multiplexer (three channels) in the trailer. Dewpoint temperatures were measured in a thermoelectric dewpoint hygrometer (Cambridge Systems, Model 880). During stormy weather, condensation in the gas lines invalidated the readings.

Radiation Measurements

Solar Radiation

At an instrument shelter, the solar radiation was monitored with a Kipp and Zonen solarimeter. Because the solarimeter was used at high field temperatures, it was calibrated against a temperature-compensated Epply Black and White pyranometer. Recorded body temperatures, measured on the north side of the Kipp and Zonen solarimeter, were included in the multiple regression analysis along with the radiation measurements. The resulting multiple linear equation was used for the calibration.

Net Radiation

At each sensor stand, net radiation was measured 1 m above the crop and 1 m south of the stand with Fritschen-type net radiometers. Calibrations from the manufacturer were used.

Photosynthetic Active Radiation (PAR)

At the instrument shelter, PAR was measured with a quantum sensor (Lambda Instruments Co., Inc., Model LI-190S). The manufacturer's calibration was used.

Hot-Wire Anemometers

Multiple-junction, hot-wire anemometers (Hastings-Radist Inc., Probe Type N-7B) were used to measure the horizontal air movement in the canopy. Unfortunately, the alternating current in the lead wires often induced in the main signal wires a noise component. The level of this noise was reduced by cabling the anemometer lead wires separately.

DIGITAL PARAMETER MEASUREMENTS

For each 15-min interval, the electrical pulses from sensors were counted by means of solid-state, four-decade counters. At scan time, the count of each unit was sampled in sequence and was logged by the computer. Then the count registers were set to zero and the counters were started again. Three devices were operating currently.

Cup Anemometer

A three-cup anemometer[4] was used to integrate windspeed over 15-min intervals and at 1 m above the crop. For every revolution of the cups, a pulse was generated and counted. The calibration of the anemometer was based on the data of Fritschen.[5]

Automatic Evaporation Pan

A standard (type A) evaporation pan was placed near the center of the field. The water level was regulated at 17.8 cm by automatically adding water at 15-min intervals. Chlorinated water was supplied from an elevated fiberglass tank (capacity 946 liters) at the edge of the field. The pan water level was controlled at a small shelter 2 m east of the pan. A reservoir in the shelter was connected to the pan with a garden hose so that pan water level could be sensed in the shelter with a Styrofoam float. Attached to the float was permanent magnet, which controlled a 6-v solenoid valve in the waterline by means of a reed switch. A tipping-bucket mechanism, taken from a rain gage, triggered an electric pulse to the four-decade counter for every 8 ml of water added to the pan. At 15-min intervals, the count was logged and the counter was reset.

Beta Absorption

Relative leaf water content (RLWC) was estimated from beta absorption.[6] Counts from a Geiger Muller detector were scaled for 10 min (Hamner Electronics, Inc., Scaler Model NS-11). The count was recorded by the computer, and the scaler was reset at 15-min intervals. The high voltage to, and the signal from, each detector were switched consecutively among four detectors by means of high-voltage reed switches at the field plot. In this manner, the thickness of each of four leaves was measured once every hour. The relation of RLWC to leaf thickness was determined in experimental leaves at the end of a run.

SYSTEM OPERATION

The data acquisition system has been in operation since the summer of 1975, primarily for field measurements. Modifications to the hardware and software were made as needed to accomodate different kinds of sensors. The maximum number of channels on line at one time was 125, which were distributed among six stepping switches.

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[4] Fritschen, L. J. A sensitive cup-type anemometer. J. Appl. Meteorol. 6: 695-698. 1976.

[5] See footnote 4.

[6] Nakayama, F. S., and Ehrler, W. L. Beta-ray technique for measuring leaf water content changes and moisture status of plants. Plant Physiol. 39: 95-98. 1964.

The system was used during winter months in the laboratory for logging leaf weight losses. Ten balances were constructed in the laboratory, using miniature strain gages.[7] For each of 10 detached leaves, 10 measurements were taken every 4 minutes for the first hour and every 10 minutes for the next 2 hours. In this operation, a modified computer program was assembled from selected subroutines (Appendix A). The subroutines, labeled LOOP, TBG, and PRINT, were modified to suit the specific task.

DISCUSSION

Analog stripchart recorders log data that are immediately observable, yet the number of channels is severely limited. Digital recording systems will handle large numbers of data channels, but small changes in any parameter are difficult to observe unless the digitized data are graphed. Our data collection system includes some of each advantage.

The greatest advantage of the system is its flexibility and ability to collect data from a wide variety of sensors, to scan different sensors at different intervals, to utilize multiple sensors and mathematical equations to obtain the final dimensions, and to control both the field multiplexers and the sensing devices during a measurement.

The main disadvantages of the system result from operation of the sophisticated equipment, which is necessary for operation. The builder-operator must have knowledge of digital electronics, assembler language programming, and sensor characteristics. Changes made in the method of operation generally require additional digital circuitry and computer program modifications; however, higher levels of sophistication can be obtained when innovations of circuitry and programming become available.

APPENDIX A

Software Program for Data Acquisition System

The computer program is written in assembler language for the Hewlett-Packard 2100 series minicomputers.[8] To reduce memory requirements for the total operational program, absolute (nonrelocatable) expressions were used. The program occupied about 2,000 memory locations (16 bit). For the storage of data from 200 sensors, about 1,500 additional locations were needed. The subroutine symbols and their linkage in the program are shown in figure 4, which is followed by a key to the mission of each subroutine. Four more conversions subroutines may be added without changing the format of the channel codes. In the program listing (not shown), the steps are well documented and are assembled in octal-based integers. A current program listing is available from the author.

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[7] Idle, D. B. An electrical weight transducer designed for the measurement of changes of weight of detached leaves. Ann. Bot. 40: 473-477. 1976.

[8] Anonymous. A Pocket Guide to Hewlett-Packard Computers. Hewlett-Packard Co., Cupertino, Calif., 626 pp., illus. 1972.

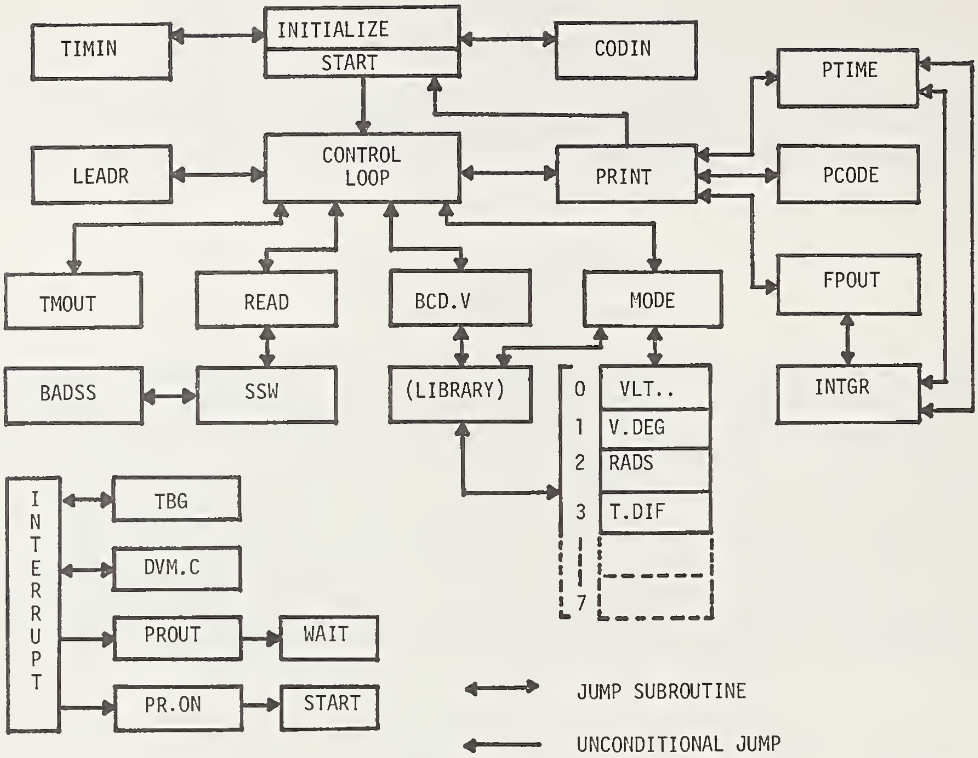

Figure 4.--Subroutines for computer program and their linkage.

Key to Subroutine Labels in Figure 4

INITIALIZE sets the initial conditions for the peripheral equipment.

START clears the storage arrays and resets the pointers.

TIMIN inputs the Julian day, hour, and minute from the keyboard.

CODIN inputs from paper tape the specific channels to be read, the corresponding conversion subroutine code, and the DVM integration time (0.1 or 1.0 sec). The information is stored in array CODE.

LOOP tests for different operational commands that are manually or program controlled. When present, they cause a jump to the corresponding subroutines.

LEADR punches 127 nulls to obtain leader and trailers on data tapes.

TMOUT is called manually to print the current Julian day and time.

READ inputs the channel code, sets the crossbar switch to the requested stepping switch line, calls the stepping switch subroutine (SSW), and initiates the DVM to start a reading.

SSW operates the requested stepping switch to find the requested switch level (see Appendix B).

BADSS prints the channel number at which a malfunction of the stepping switch occurred.

BCD.V converts voltage data from array BCD (see DVM.C below) to a floating-point binary (packed), checks for a DVM overload, and stores the data in array VOLT.

MODE selects a conversion subroutine according to the channel code, gets the data from array VOLT, and stores the converted data in array DATA.

VLT. transfers voltage data without conversion.

V.DEG converts voltage data to degrees Celsius using a quadratic regression equation for copper-constantan thermocouples.

RADS converts voltage to langleys per minute. The temperature of the solarimeter is recalled from the previous reading and is used in a multiple linear regression equation. Coefficients for the equation were determined experimentally.

T.DIF converts voltage data to degrees Celsius using a quadratic regression equation for chromel-constantan-copper thermocouples, which were wired for differential temperature measurements.

PRINT controls the output of day, time, code, and data. After an end statement is printed, the program control is transferred to START.

PTIME outputs the Julian day, hour, and minute at which the scanning started.

PCODE outputs the channel code in decimal integers.

FPOUT outputs a floating-point number. When the number of integers exceeds 6, $$ is printed.

INTGR outputs an integer (decimal) that was stored as an unpacked binary number (manufacturer's software).

LIBRARY includes selected mathematical subroutines (furnished by the manufacturer) that will: (1) convert a binary number of 16 bits to a packed floating-point number of 32 bits; (2) double-store or double-load floating-point numbers; and (3) add, subtract, multiply, and divide integers and floating-point numbers.

BITIN (not shown in fig. 4) is called by READ. It inputs data from the counters and scaler, and stores them in array BIT.

BTOUT (not shown in fig. 4) is called by PRINT. It outputs data from array BIT.

INTERRUPT SUBROUTINES An interrupt is a signal to the computer from an external source, which immediately forces the control of the program to a specific subroutine. At the end of the subroutine, the control is transferred back to the next step in the program at which it was interrupted. The subroutines are listed with decreasing priorities.

TBG A signal from the time-base-generator (every 10 sec) causes a jump to subroutine TBG, in which the software clock is updated. At preselected times, signals are set to sound the warning buzzer, start a scan, scan the hourly readings, punch a leader-trailer, and start a new page on the printer.

DVM.C When the DVM has finished a reading, it causes a jump to subroutine DVM.C, in which the binary coded data (4-2'-2-1) is input from the DVM and is stored in array BCD.

PROUT When the auxiliary power source has signaled that the line power is off, the control jumps to PROUT. The time of day is saved, and the control is locked in a wait loop. Peripheral equipment is turned off, but the software clock continues to operate.

PR.ON A return of line power causes a jump to PR.ON. Peripheral equipment is turned on, the times of day that the power went off and came back on are printed, a leader and new page are obtained, and the program control is transferred to START.

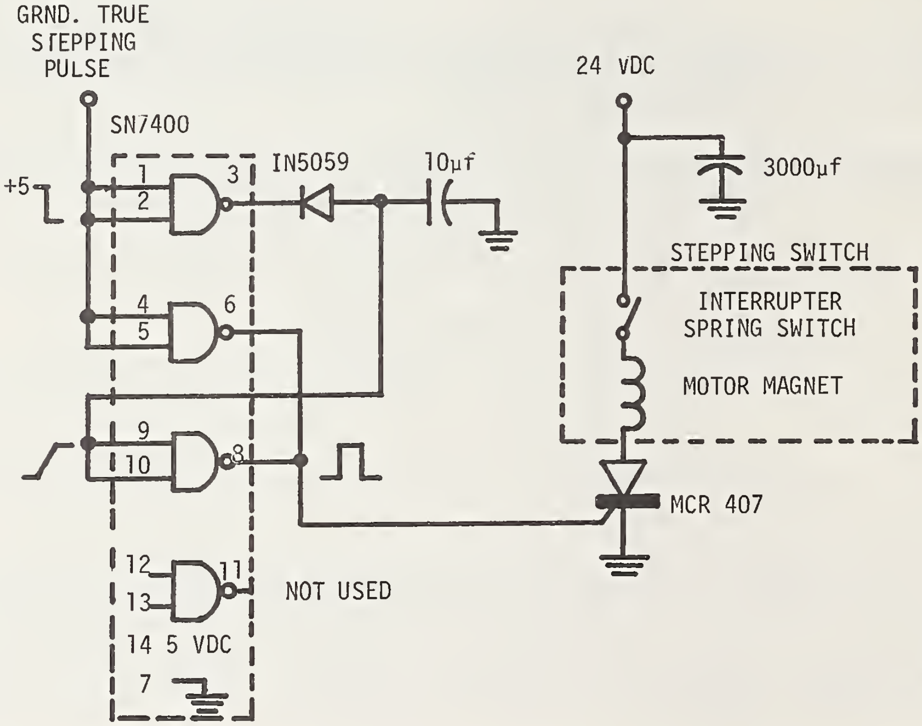

Figure 5.--Schematic diagram of stepping-switch (Type 45), single-step driver.

APPENDIX B

Single-Step Driver for Stepping Switch

The circuit shown in figure 5 causes the stepping switch (GTE Automatic Electric Co., Type 45, 26 switch positions, 6 to 12 banks) to advance one step for every voltage drop at the pulse input terminal. The quad two-input nand gate (SN7400 or MC846) generates a positive pulse that triggers the silicon controlled rectifier (SCR) to energize the magnet motor. Commutation of the SCR is obtained at the interrupter switch on the stepper. The pulse timing is controlled at the computer, which was programmed to send out 8 pulses per second.

The 26 positions of the stepping switch are wired (five banks) to send to the computer the binary equivalent for each position. In operation, the computer tests the binary signal for a requested position. Stepping is commanded until the requested position is reached. When more than 76 stepping commands (three rotations of the wiper assembly) are sent and the requested position is not reached, a malfunction statement is printed.

For three summers, these drivers have operated satisfactorily without attention except for an annual cleaning of the interrupter contacts on the stepping switch. A single powerline carrying 24 volts of direct current (vd-c) was supplied to the drivers. The 5 vd-c power required by the nand gate was furnished through a 7805 voltage regulator, which was mounted on a small heat sink (not shown in fig. 5). An insulated metal dust cover was placed over the switch (not shown in fig. 2).

APPENDIX C

Crossbar Switch

The crossbar switch was a relay switching matrix containing 20 gold-plated switches, each having six levels. It was an experimental model (Cunningham Corp.) acquired from government surplus. The relay driving circuits were designed and wired by us so that the switches would operate under computer control through an interface card.

Interfacing Peripheral Equipment

The peripheral equipment was connected to the computer through interface circuit cards, which were supplied by the manufacturer. These cards permitted the exchange of commands and data signals. Fifty channels were made available for control of the crossbar and stepping switches and to read digital data from the digital counters. One card (not an interface card) furnished crystal-controlled time pulses that were counted in the software clock. We wrote the software to drive all the peripheral equipment.

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