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MICROPROCESSOR-BASED DATA ACQUISITION AND CONTROL SOFTWARE FOR THE SPAR SYSTEM

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SUMMARY:

Software was developed for a microcomputer system to perform data acquisition and environmental control of the SPAR system. Feedback information was utilized to control CO_2 levels, humidity, and air temperature. An analysis of the performance of the software is presented.

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MICROPROCESSOR-BASED DATA ACQUISITION AND CONTROL SOFTWARE FOR THE SPAR SYSTEM[1/]

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ABSTRACT

Computer software has been developed for a microprocessor-based data acquisition and control system to monitor 64 transducers and to maintain closed loop environmental control for the sunlit Soil-Plant-Atmosphere Research (SPAR) units at Florence, S.C. An assembly language program and a BASIC program were written to run concurrently by using a real-time interrupt. The assembly language program performs the data acquisition, real time control, and time keeping. The dynamic signal conditioning, the computation of control parameters, and the conversion and output of the acquired data in engineering units are performed by the BASIC program.

Environmental control algorithms were implemented in software to control temperature, CO_2 concentration, and relative humidity. The BASIC program utilizes the history of the absolute deviation from the control levels to compute the control parameters for the assembly language program to implement. The temperature control algorithm enabled control within $\pm 0.2^oC$ for control temperatures ranging from 15^oC to 35^oC with ambient temperatures ranging from 20^oC to 32^oC. A proportional control algorithm written in BASIC enabled CO_2 control for three SPAR units within ± 10 ppm under changing radiative load with full canopy closure using one infrared gas analyzer. A CO_2 control algorithm using light response curves to project CO_2 uptake and absolute deviations from the control level to correct the coefficients of light response curves is derived.

Dynamic environmental control of the SPAR units can be obtained using an inexpensive microprocessor-based system when process feedback is influenced by random climatic variations. This enables researchers to conduct precise experiments involving climatic variables to provide the necessary inputs for crop simulation modeling.

Index words: Microprocessors, computer software, control algorithms, crops simulation modeling, controlled environment growth chambers, photosynthesis.

1/This research was conducted at the Coastal Plains Soil and Water Conservation Research Center in cooperation with Clemson University and South Carolina Agriculture Experiment Stations. All reported conclusions, opinions, or recommendations are those of the authors and not those of the USDA or the cooperators.

INTRODUCTION

The emphasis of more precise research needed for crop growth simulation modeling has led researchers to the construction of more complicated controlled environment growth units. Microprocessor technology has provided solutions to some of the problems of cost and implementation of the data acquisition and environmental control in these units.

The Soil-Plant-Atmosphere Research (SPAR) units were designed and constructed at Florence, S.C. (Phene et al (1978)). The SPAR units were designed to collect data needed to develop crop growth simulation models (Hesketh et al (1976)). These models require varying certain environmental factors, such as air temperature, and measuring the effects on crop growth responses such as photosynthesis (Musgrave et al (1961)), (Peters et al 1974)). The initial microprocessor-based data system for the SPAR units was implemented in 1976. The system was used to monitor meteorological data in the SPAR units (McKinion et al (1978)).

The objective of this paper is to discuss software which has been developed for data acquisition and environment control. The discussion of the software will include the microcomputer system description, an overview of the system software, and the environmental control algorithms.

SYSTEM DESCRIPTION

The microprocessor-based data acquisition system consists of an Altair 8080A 1/ microcomputer with 32k bytes of memory and the necessary input-output (I/O) cards, a minifloppy disc drive (FD), video display terminal (CRT), a Teletype model ASR 35 (TTY), and a 12 bit analog to digital (A/D) based data acquisition system (DAS). The DAS consists of a Burr Brown SDM 853 12 bit A/D converter with the necessary support electronics to multiplex 64 channels of data from various voltage transducers with outputs in two ranges, 0-5 v anc 0-5 mv. A schematic of the various components in relation to the SPAR units is shown in Fig. 1.

The microcomputer system is interfaced to three SPAR units using a parallel I/O card containing 8 parallel 8 bit I/O ports (Mits 88-4 P10 Board); and relay driving electronics (Dunlap et al (1978)). Three ports are used to control the A/D converter and read the input measurements.

The heater, air conditioner, humidifier, and CO_2 control circuitry is implemented using relay driver circuits and one 8-bit parallel I/O port (environment byte) for each SPAR unit. Each of 5 bits of the parallel port (environment I/O (Fig. 1)) is connected to relay circuit which enables on/off control of the air conditioner, heater, humidifier, CO_2 output and CO_2 sampling as follows:

bit 3: air conditioner on,

bit 4: heater on,

bit 5: humidifier on,

1/ Mention of product names is for description only, and not an endorsement by USDA-SEA-FR.

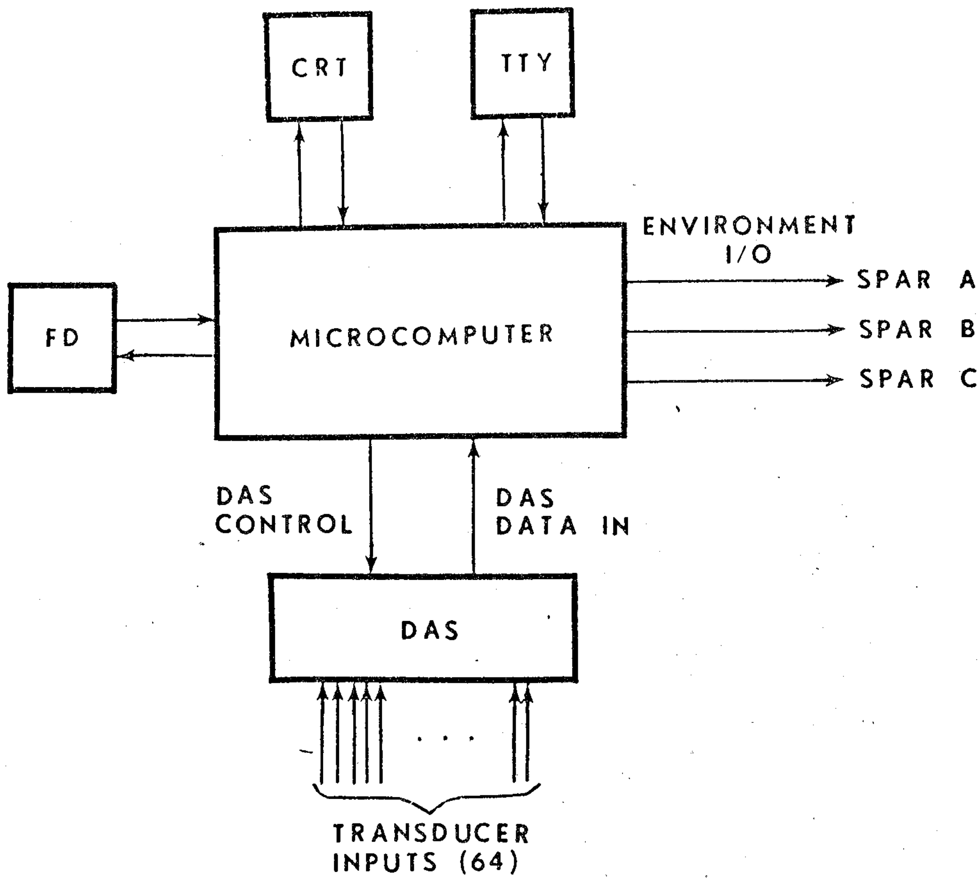

Figure 1. A schematic of the microcomputer and data acquisition system in relation to the SPAR units.

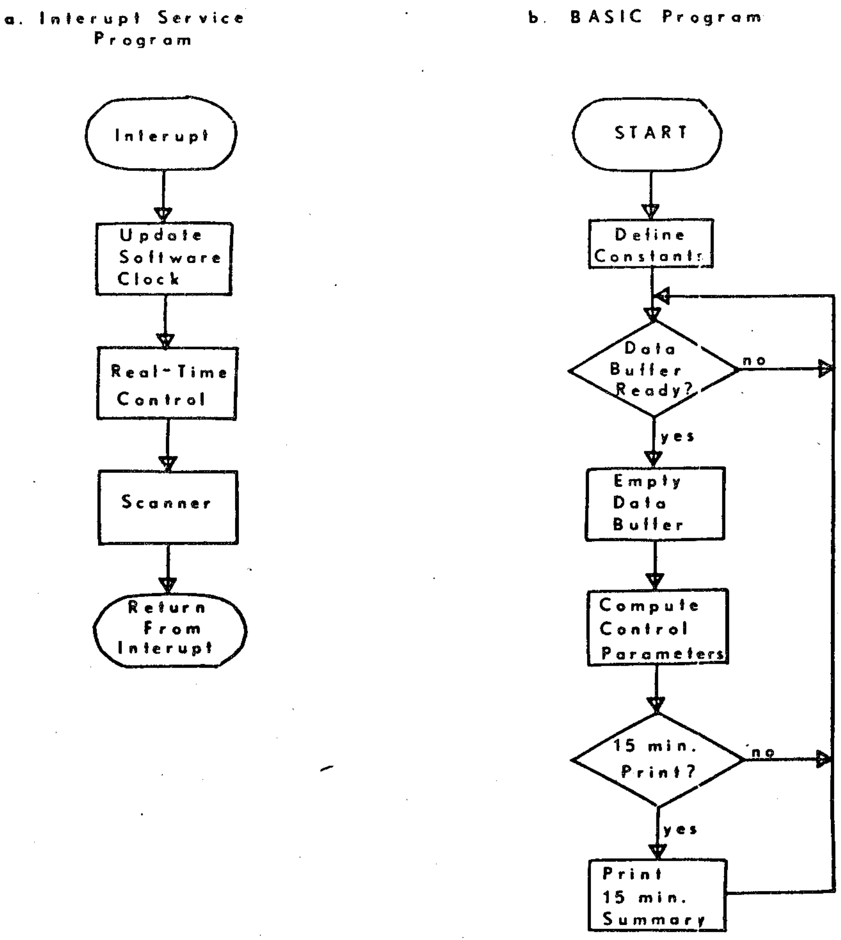

Figure 2. Flow charts of the interrupt service program (assembly language) and the BASIC program.

constants are checked daily with a digital voltmeter (DVM) (Hewlett Packard Model 3955 A). The following algorithm was used to correct each low level signal.

$$X_o = X_1 - L,$$

A2) $X_2 = X_3 - H$

A3) $D_x = (X_2 - X_o)/(H-L)$

A4) $\hat{C}_i = C_i + D_x\ (C_i - X_1),$

where L, H = actual low and high standards in mv, respectively,

X_3 = measured output in mv from the low and high mv standards, respectively,

X_2 = deviation from low and high standards in mv, respectively,

D_x = discrete estimate of the drift error rate in mv/mv,

C_i = output of low level channel i in mv, and

$\hat{C}_i$ = corrected output of channel i in mv.

The computed $\hat{C}_i$ is used as the output of channel i for that BASIC scan. Table 1 shows a comparison of the standard deviations of the absolute deviation of the DAS measured data from the DVM values for the SPAR temperature thermocouples. The reduction in the standard deviations after implementation of the autocorrection routine indicates a reduction in the variation from the DVM readings.

After completing this, the BASIC program changes the buffer ready memory location to initiate another scan. Next, the BASIC program branches to routines which compute the temperature, humidity, and CO_2 control duty cycles.

The BASIC program outputs the acquired data as 15 min averages of the acquired scans. The data is converted to engineering units and CO_2 uptake for each SPAR unit is computed along with other parameters such as transpiration, and is printed on the TTY with a punched paper tape to enable further offline processing of the data. On the basis of 8 samples per BASIC scan, there are 40 scans per 15 min output period.

Control Algorithms

The CO_2 level in each of the three SPAR units is sampled once per minute for 20 sec and measured electronically using one infrared gas analyzer. A large continous gas sampling loop is circulated by gas pumps located in the return ducts of the heating and cooling system to enable a current gas sample from each SPAR unit to be available at the CO_2 analyzer. The measured CO_2 level is used to calculate the amount of CO_2 needed after the gas law corrections

Table 1: Analysis of the performance of the autocorrection routine using the standard deviation of the actual reading minus the DAS reading.

Channel Description	Before Autocorrection	After Autocorrection
	Standard deviation of the differences in the DVM and DAS readings in mv.	
SPAR A Temperature	± 0.009	± 0.003
SPAR B Temperature	± 0.008	± 0.002
SPAR C Temperature	± 0.009	± 0.004
0.300 mv 1/ Standard	2/	± 0.004
1.822 mv 1/ Standard	± 0.018	± 0.012

1/ Not corrected with the autocorrection routine.
2/ Not measured prior to implementation of the autocorrection routine.

for pressure and temperature. The CO_2 output hardware consists of solenoid valves for on/off control, needle valves for regulating the flow rates, and rotometers and electronic gas flowmeters in line for measurement of flow. The solenoid valves are interfaced to a parallel L/O port on the computer via relay driving electronics. The physical CO_2 system and associated hardware are discussed in more detail by Phene et al (1978) and Dunlap et al (1978). Once a CO_2 level is measured, the BASIC program changes a memory location to alert the interrupt service program to begin sampling the gas from the next SPAR unit. This involves the computer turning off the gas sample from the SPAR unit previously being sampled and allowing the gas sample from the next SPAR unit to flow to the infrared gas analyzer.

The first algorithm for CO_2 control was implemented in the BASIC program. This algorithm turned the CO_2 on for 0, 1, 2 or 3 periods of 20 sec-based on the absolute deviation from the CO_2 control level. For this algorithm the absolute deviation was compared to control ranges corresponding to the four possible time intervals. In Table 2, the standard deviation from the mean control level of 320 ppm, and the integrated solar radiation are presented for representative 15 min output periods for the SPAR units. These data were obtained on Julian Date 119, 1978 with a full canopy of winter wheat growing. This method of CO_2 control requires critical monitoring and selection of the flow rate of the CO_2 being added to the SPAR units since the minimum input period is 20 sec.

Hardware was implemented to allow the implementation of shorter CO_2 input periods. A new CO_2 control algorithm was written based on previous research findings for photosynthesis rates in relation to solar radiation in the SPAR units. The proposed algorithm is based upon two assumptions: 1) There is no CO_2 uptake when there is no positive solar flux, and 2) Photosynthetic rate responds as a quadratic function of positive solar flux (Phene et al 1978)). With these assumptions, the light response curves are of the form:

$$= a + bF \qquad (1)$$

where

P = photosynthethic rate in mg of CO_2 m^{-2} of soil surface min^{-1}

F = solar flux in W m^{-2}

a = dynamic constant in mg of CO_2 W^{-1} min^{-1}, and

b = dynamic constant in mg of CO_2 W^{-2} m^2

The proposed CO_2 control routine is based upon the deviation from the control level and the light response equation (1). The SPAR units are a closed system with respect to gases. The volume of the atmospheric portion of the SPAR system is estimated to be 2.75 m^3. Using this estimate of the volume, the calculation of the amount of CO_2 removed due to the photosynthesis is possible using the CO_2 readings in ppm.

The difficulty in using equation (1) to determine CO_2 uptake is the lack of a method of finding the solar flux during the next measurement period. Therefore, a feedback relationship is also used. This utilizes the information of the deviation from the CO_2 control level. The feedback relationship is a finite difference equation based on the first and second order time variations from the control level. The equation is

$$= C_n / \Delta t_n + (C_n - C_{n-1}) / \Delta t_n \qquad (2)$$

Table 2: Standard deviation from the mean control level (320 ppm) under different radiation loads for a full canopy of winter wheat (JD 119). Based on 15 observations from a 15-minute period.

SPAR	Standard Deviation (ppm)	Incoming Radiation (W/m^2)
A	6.7	732.4
C	10.6	732.4
A	7.5	676.6
B	6.7	676.6
C	9.3	676.6
A	9.3	788.2
B	8.7	788.2
A	10.6	809.1
C	5.4	809.1
A	9.6	823.1
B	9.8	823.1
C	7.7	823.1

= rate of deficit of CO_2 in cm^3/min at time n,

C_n = deficit of CO_2 at time n in cm^3, and

Δt_n = time since the last CO_2 reading in min

Equation (2) represents the rate of CO_2 required to maintain the control level which was not supplied in previous estimates of Equation (1). The errors induced by the estimates of the coefficients, a and b, in equation (1) and the solar flux estimates are corrected by equation (2).

The estimates of a and b are found by least squares using the past instantaneous solar fluxes and previous estimates of equation (1) plus the C_{dn} values of the day, i.e., the actual CO_2 uptake. The presunrise initial values of a and b are assumed to be 1. Estimates of the next instantaneous solar flux are obtained using the weighted average of the 5 previous instantaneous solar fluxes. This control algorithm has not been tested.

The temperature control algorithm is based on forward projection proportional control. The implementation of the environment byte in the assembly language control routines enable the heaters to be turned on for multiples of 0.016 sec up to 4.25 sec. The air conditioner system is run continously to enable collection of transpiration (Phene et al (1978)) and to maintain a minimum relative humidity at a given control temperature.

The amount of time the heaters are on during the 4.25 sec period is computed in BASIC. The computation of the fraction of the total period (duty cycle) is done using the following nonlinear finite difference equation.

$$D_i = \bar{D}_i + A_1 \tau i + A_2 (\tau i - \tau i\text{-}1) + B_1 \quad \tau i/(B_2 \quad \tau i\text{-}1)^2\text{-}1) \qquad (3)$$

where, i = discrete control time,

D_i = new duty cycle,

$\bar{D}_i$ = weighted average of the 5 previous duty cycles, i.e.,

$\bar{D}_i = (1/9)*D_{i-5} + (2/9)* D_{i-4} + (3/9)*D_{i-3} + (2/9)*D_{i-2} + (1/9)*D_{i-1}$,

τi = deviation of temperature from the control temperature at time i in mv,

= deviation of the temperature from the control temperature at time i-1 in mv,

A_1, A_2 = first and second order estimates of duty cycle per deviation from the control temperature in duty cycle/mv, and

B_1, B_2 = stabilizing coefficients fro nonequilibrium approaches to the control temperatures in duty cycle/mv.

The new duty cycle is computed by equation (3) after each BASIC scan and limited to a minimum duty cycle of 0 sec, heater always off, and a maximum duty cycle of 4.25 sec, heaters always on.

Tests were run to determine the responsiveness of the routine to changes in the control temperature. At different control temperatures, the system was allowed to equilibrate and then the control temperature was changed. This was done over control temperatures ranging from 20° C to 35° C. The results of this are given in Figure 3. The response was independent of the beginning control temperature over this range. In all cases, the system equilibrated to the new control temperature within 10 min with one overshoot and undershoot.

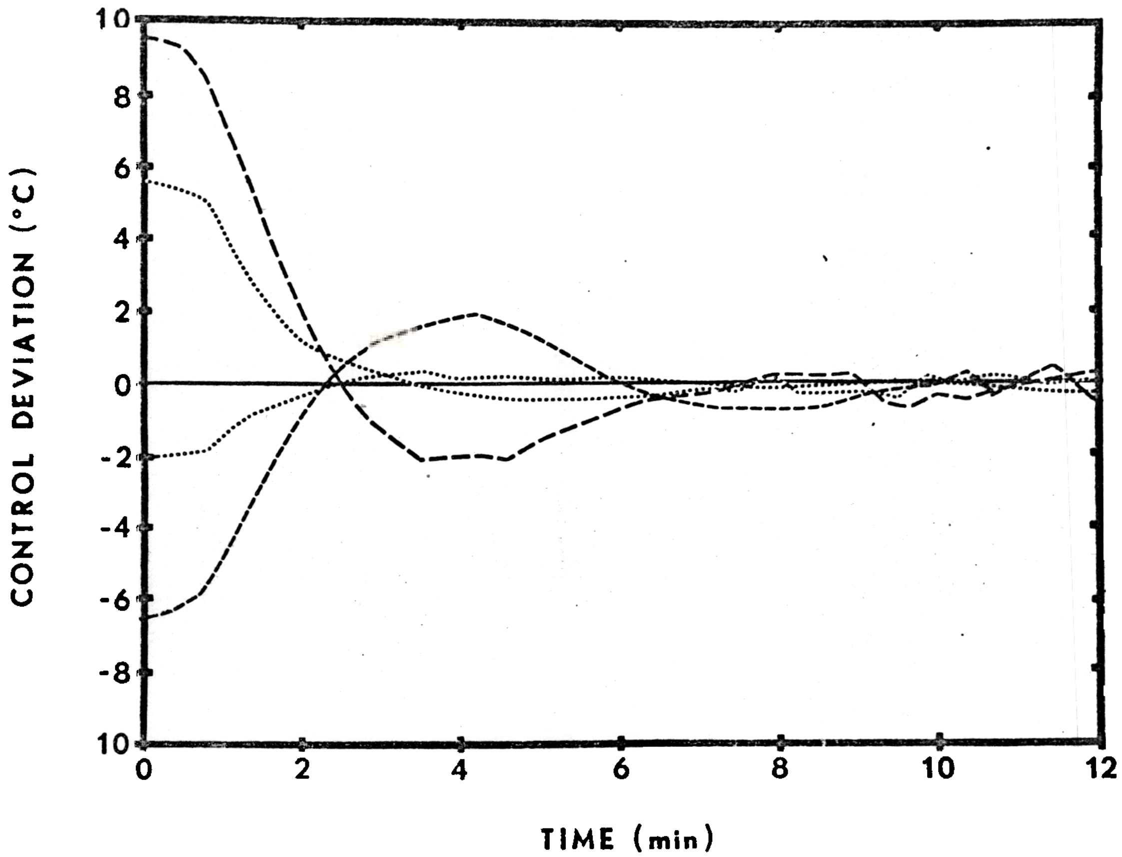

Figure 3. Response of the temperature control algorithm to step changes.

The main limitation of continuous air conditioning was found to be the freezing of the air conditioner coils at low control temperatures, i. e. below 12° C. This required implementation of defrost cycles. The defrost cycle was initiated after the air conditioner coil temperature remained below 1° C for 15 min. The air conditioner was turned off until the coil temperature reached 5° C. This allows the frost on the coil to melt. With the defrost cycles, temperature control was not as good for these lower control temperatures. For maximum ambient temperatures above 30° C, the heater-air conditioner system was able to maintain a minimum control temperature of 15° C without defrost cycles. As the maximum ambient temperature decreased, the minimum temperature obtainable without defrost cycle remained between 9° C and 12° C. The range of constant temperatures attainable without defrost cycles are shown in Figure 4. These were maintained for days with maximum ambient temperatures of 30° C and minimum ambient temperatures of 20° C. The minimum relative humidity corresponding to the constant temperatures ranged from 40% to 75%.

To simulate a diurnally changing temperature, the temperature control routine in BASIC was modified to compute a new control temperature after each BASIC scan. The function is

$$T = T_{min} + (T_{max} - T_{min}) \sin (h-t)$$

where T_{min} = minimum temperature for the day in °C,

T_{max} = maximum temperature for the day in °C,

h = time in hours,

t = time minimum temperature is to occur in hours.

Figure 5 shows the response of the SPAR system with T_{max} = 38.4°C, T_{min} = 10°C, and t = 2 AM. The maximum ambient temperature was 31°C and the minimum ambient temperature for this day was 18.5° C.

Humidity control is maintained by injecting a water vapor into the duct after the air has been heated. The injection rate of the water is implemented in a similar fashion to the CO_2 and heater control techniques, using a duty cycle to simulate proportional control. Tests on this method of changing relative humidity indicate that a high initial injection rate produces rapid changes in relative humidity. After 1 to 2 min, the changes in relative humidity are much slower. Therefore, an algorithm to take this into account is used.

The equation to compute the injection time for humidity control is

$$T_H = T_n + K_1 E_n + K_2 (E_n - E_{n-1})$$

where

T_H = injection time for the next sample interval in sec,

T_n = integrated injection time over the previous five sample periods in sec,

K_1 = proportionality constant for the absolute error from the control point in sec per percent relative humidity,

E_n = error from the control point at time n, and

K_2 = proportionality constant for the rate of change of the error.

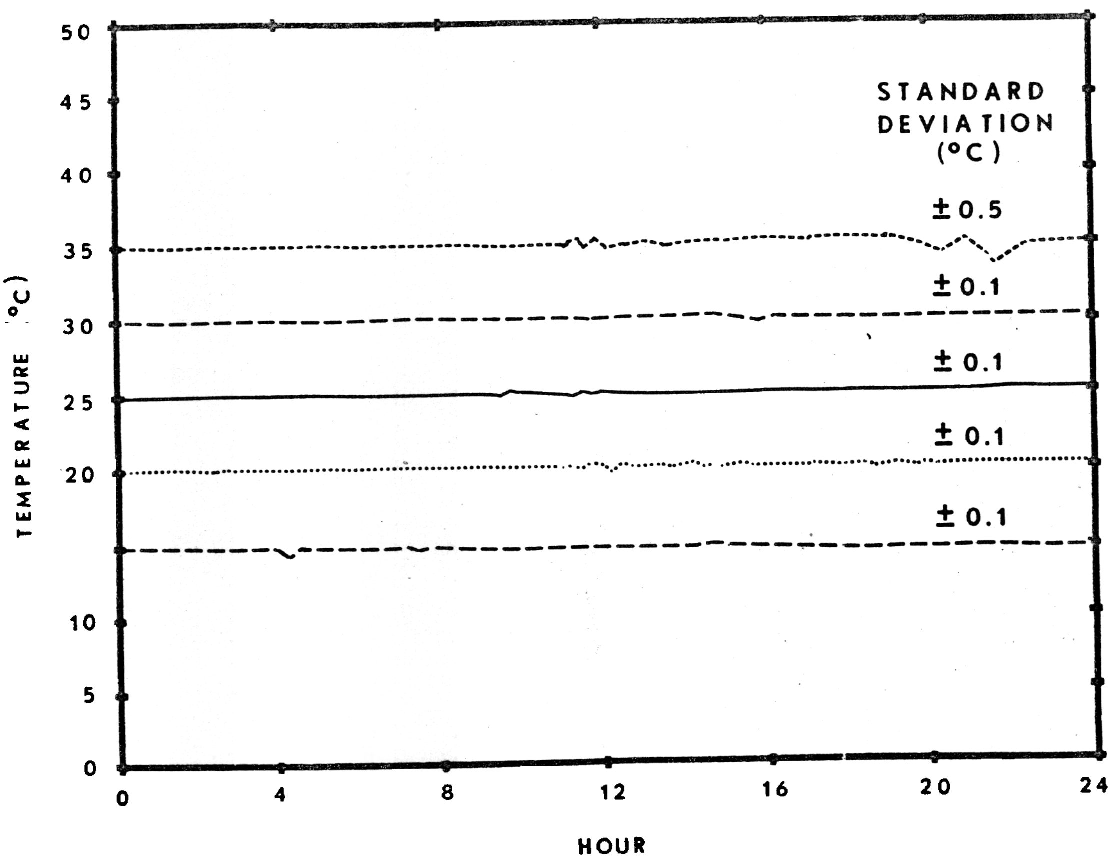

Figure 4. Performance of the temperature control algorithm at constant temperatures.

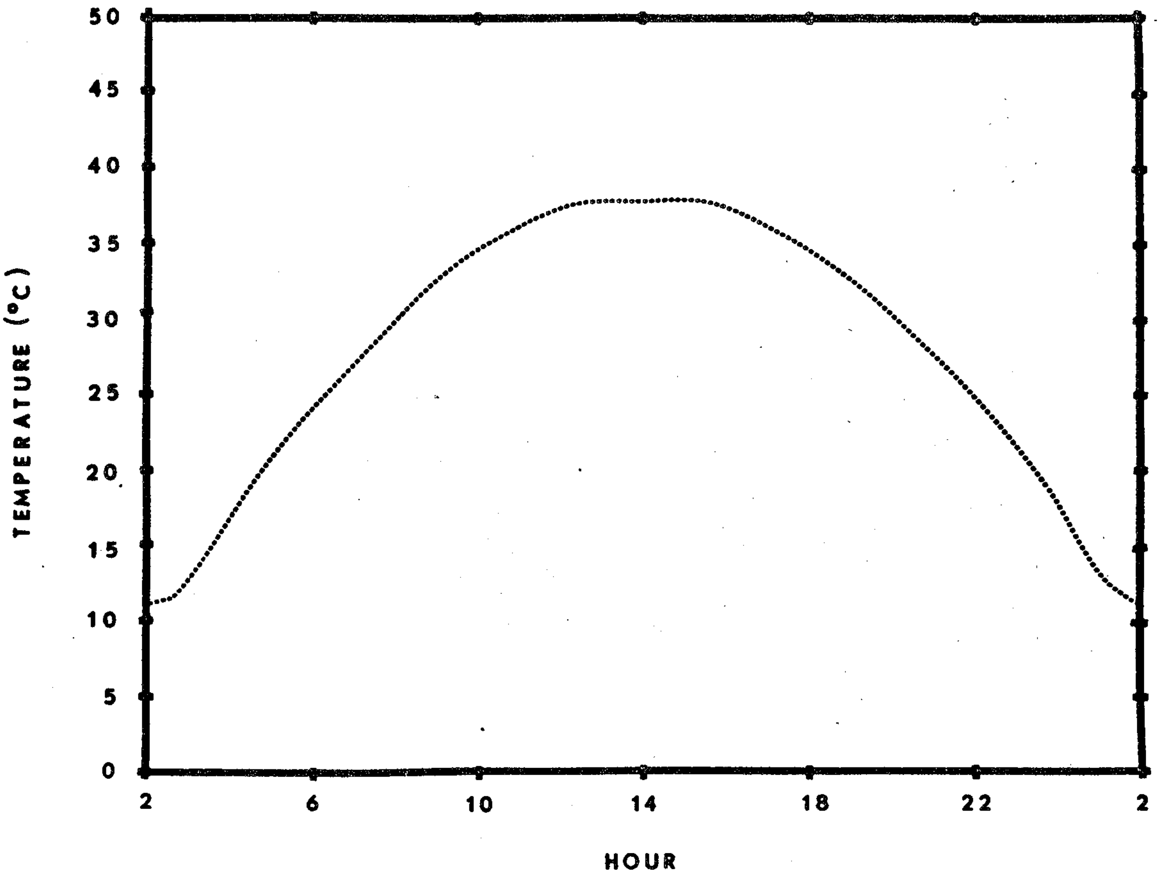

Figure 5. Response of the temperature control algorithm to sinuousoidally changing control temperatures.

Equation (5) is of the same general form as the heater control algorithm (equation (3)). The integrated injection time T_n acts as a stabilizing term which converges to the stable constant rate to maintain a given control level. The error rate term and the rate of change of the error controls the approach to the control point via the constants K_1 and K_2. To compute K_1 and K_2, values of the rate of change given a series of injections times would be required. Let E_m be the deviation induced from a constant injection time, T_c, for sample interval time t_c from a given steady state humidity. Then K_1 would be computed by using

$$T_c = K_1 E_m \tag{6}$$

The constant K_2 would be computed by sampling over the range of humidities and integrating the consecutive terms, K_2 found from

$$T_c = K_2 (E_m - E_{m-1}) \tag{7}$$

Temperature distribution patterns within the SPAR system were investigated using 9 shielded thermocouples in a rectangular array as shown in Figure 6. For empty SPAR units operating within the range of control temperatures tested, the temperatures measured at these thermocouples were within $\pm 2^\circ$ C of the control temperature with a standard deviation less than 2° C (Table 3). These data indicate that air flow within the SPAR units provides uniform temperature distribution at the control temperatures tested. At 25° C, the mean temperatures of the nine thermocouples ranged from 25.8°C to 26.8°C with the largest standard deviation of 1.5°C (Table 3).

SUMMARY

A microprocessor-based data acquisition and control system was implemented for the SPAR system. The hardware and software were designed to monitor 64 transducers and control the air temperature, relative humidity, and CO_2 level in the three SPAR units.

The software consisted of an 8080 assembly language program and a BASIC program operating concurrently through a real-time clock interrupt every 1/60 sec. At each interrupt, the assembly language program updates the software clock, performs real-time implementation of control of the SPAR heaters, the humidifiers, and the CO_2 output hardware by on/off relays enabled the simulation of proportional control. The BASIC program was written to compute the control parameters required by the assembly language routine, convert the acquired data to engineering units, and output the data every 15 min.

The CO_2 control algorithm, implemented in the BASIC program, computes the CO_2 uptake based upon the solar flux and utilizes the feedback to continously correct the light response curves. The time required to output this amount of CO_2 is implemented by the assembly language routine.

Temperature control of the aerial portion of the SPAR units was achieved utilizing the BASIC program to calculate the proportion of time the heaters would be on. The algorithm incorporates forward projection techniques to estimate the deviation from the control level based on the previous history of the system. Tests of the responsiveness of this algorithm indicated that complete recovery from step changes in the control level occurred within 10 min with one damped overshoot and undershoot. For days with ambient temperatures ranging from 20° C to 32° C, temperature control within the SPAR units was obtainable for control temperatures ranging from 15° C to 35° C. The standard deviation for control within this range was $\pm 0.2^\circ$ C for a 24-hour period.

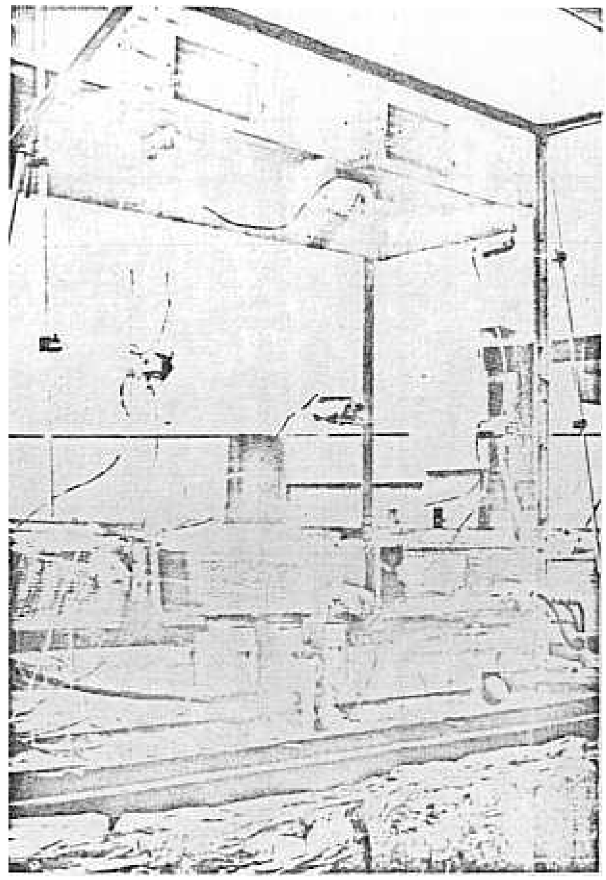

Figure 6. Thermocouple placement for measurement of temperature distribution within the SPAR units.

Table 3: Summary of Spatial Variability Test

MEAN TEMPERATURE ± STANDARD DEVIATION, °C

Control Temperature, °C	Row	Column 1	Column 2	Column 3
10.3 + 0.7	1	12.0 ±	10.8 ± 1.4	10.7 ± 1.3
	2	11.8 ±	10.9 ± 1.5	10.1 ± 1.1
	3	11.8 ±	10.7 ± 1.5	10.6 ± 1.4
15.0 + 0.1	1	16.5 ± 1.2	15.8 ± 0.8	15.9 ± 0.9
	2	16.3 ± 1.4	15.8 ± 0.9	15.2 ± 0.6
	3	16.5 ± 1.6	15.7 ± 1.0	15.7 ± 0.9
20.0 + 0.0	1	20.7 ± 0.8	22.2 ± 0.4	20.6 ± 0.4
	2	20.6 ± 0.8	21.1 ± 0.5	20.4 ± 0.2
	3	20.5 ± 0.7	21.0 ± 0.3	20.6 + 0.3
25.0 ± 0.0	1	26.3 ± 1.2	26.8 ± 0.8	26.3 ± 0.9
	2	26.4 ± 1.4	26.7 ± 0.9	25.8 ± 0.5
	3	26.3 ± 1.5	26.7 ± 1.0	26.1 + 0.8
30.0 + 0.2	1	31.2 ± 1.5	31. ± 1.	31.7 ± 1.0
	2	31.4 ± 1.4	32. ± 0.	31.3 ± 0.4
	3	31.3 ± 1.6	32. ± 0.	31.4 ± 0.8
34.4 + 0.9	1	35.1 ± 1.8	36.3 ± 1.6	36.0 ± 1.5
	2	35.6 ± 1.7	36.6 ± 1.3	35.9 ± 1.0
	3	35.3 ± 1.8	36.4 ± 1.4	35.8 ± 1.3

Temperature distribution patterns within the empty SPAR units, measured on a 3x3 grid, revealed that the temperatures within the aerial portion were within ±2° C of the control levels ranging between 10° C and 35° C.

For control temperatures ranging from 10° C to 35° C, minimum relative humidities ranged from 40% to 75%. The control algorithm for relative humidity involved the BASIC program's computation of the amount of time a fine mist was being injected into the supply duct of the SPAR unit. The time was computed using the history of the absolute deviations from the relative humidity control level with a finite difference equation using the first and second order time rate changes in the absolute deviation from the control levels and a stabilizing integrated time of injection.

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