A SYSTEM FOR THE AUTOMATIC SENSING AND RECORDING OF A GREENHOUSE ENVIRONMENT USING MOVING SENSORS

by

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We accept this thesis as conforming to the required standard

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ABSTRACT

One of the major problems encountered in collecting data for use in analysing the internal environment of a greenhouse is the time required to read and record the many environmental parameters. This problem severely restricts the analysis of factors affecting the environment by limiting the number of locations that can be conveniently sampled and the frequency with which each location can be sampled. The time and cost factors also limit the number of parameters which can be measured at each location.

A sensor module has been developed which will automatically measure environmental parameters at any number of pre-determined points along a fixed track. The module is capable of sampling 15 variables at a single location and transmitting via one cable all 15 signals for interpretation by a main decoding and recording station.

The module is capable of automatically making 10 stops and measuring 15 parameters at each stop in about 10 minutes; a task which is very time consuming or expensive by other methods.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>i</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>v</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>iv</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>LITERATURE REVIEW</td>
<td>3</td>
</tr>
<tr>
<td>DESIGN APPROACH</td>
<td>9</td>
</tr>
<tr>
<td>Design Criteria</td>
<td>9</td>
</tr>
<tr>
<td>Component Selection</td>
<td>14</td>
</tr>
<tr>
<td>THE MODULE</td>
<td>18</td>
</tr>
<tr>
<td>Overview of Operation</td>
<td>18</td>
</tr>
<tr>
<td>General Description</td>
<td>18</td>
</tr>
<tr>
<td>Details of Operation</td>
<td>27</td>
</tr>
<tr>
<td>RECORDING STATION RECEIVER</td>
<td>41</td>
</tr>
<tr>
<td>Overview of Operation</td>
<td>41</td>
</tr>
<tr>
<td>Details of Operation</td>
<td>41</td>
</tr>
<tr>
<td>TESTING THE SYSTEM</td>
<td>48</td>
</tr>
<tr>
<td>Experiment A</td>
<td>48</td>
</tr>
<tr>
<td>Experiment B</td>
<td>49</td>
</tr>
<tr>
<td>DISCUSSION</td>
<td>51</td>
</tr>
<tr>
<td>RECOMMENDATIONS</td>
<td>55</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>58</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>DESCRIPTION</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Effect of Oil Layer on Mercury Trough Resistance</td>
<td>50</td>
</tr>
<tr>
<td>FIGURE</td>
<td>DESCRIPTION</td>
<td>PAGE</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>A Systems Comparison</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>The Module</td>
<td>19</td>
</tr>
<tr>
<td>3</td>
<td>Fork Connector</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>Main Power Supply</td>
<td>23</td>
</tr>
<tr>
<td>5</td>
<td>Mercury Troughs</td>
<td>24</td>
</tr>
<tr>
<td>6</td>
<td>Recording Station Receiver Circuit Box</td>
<td>26</td>
</tr>
<tr>
<td>7</td>
<td>Module Circuit Block Diagram</td>
<td>29</td>
</tr>
<tr>
<td>8</td>
<td>Microswitch Wedge</td>
<td>30</td>
</tr>
<tr>
<td>9</td>
<td>Module Regulator Supply Wiring Diagram</td>
<td>35</td>
</tr>
<tr>
<td>10</td>
<td>Sensor Equilibration Timer and Variable-Square Wave Generator</td>
<td>36</td>
</tr>
<tr>
<td>11</td>
<td>Module Wiring Diagram, Integrated Circuits only</td>
<td>37</td>
</tr>
<tr>
<td>12</td>
<td>Rotary Switch Wiring Diagram</td>
<td>38</td>
</tr>
<tr>
<td>13</td>
<td>Module Relay Wiring Diagram</td>
<td>39</td>
</tr>
<tr>
<td>14</td>
<td>Automatic Reset for the Module</td>
<td>40</td>
</tr>
<tr>
<td>15</td>
<td>Recording Station Block Diagram</td>
<td>42</td>
</tr>
<tr>
<td>16</td>
<td>Recording Station Receiver Wiring Diagram, Integrated Circuits only</td>
<td>44</td>
</tr>
<tr>
<td>17</td>
<td>Receiver Relays and Relay Drivers</td>
<td>45</td>
</tr>
<tr>
<td>18</td>
<td>Automatic Reset for Recording Station Receiver</td>
<td>46</td>
</tr>
<tr>
<td>19</td>
<td>Main Power Supply Wiring Diagram</td>
<td>47</td>
</tr>
</tbody>
</table>
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INTRODUCTION

There are many variables in the design of a greenhouse which affect plant growth and development. Individual environmental factors such as temperature can be readily measured at a single location, and such measurements can be applied to the control of the greenhouse environment within preset limits. Of course, the environmental conditions at the single location cannot accurately represent the wide variations of environmental conditions experienced by the plants in different parts of a normal greenhouse. These variations in growth conditions at different locations within the greenhouse are due to such factors as building orientation, building design, architectural shape, and construction materials, and they are ultimately reflected by alterations in plant growth rate and productivity.

In testing any new concepts in greenhouse design, or structural material, it is necessary not only to analyse the possible effect theoretically but it must also be possible to support these calculations with actual data collected from prototype greenhouses, and subsequently in the finished structure.

The collection of large amounts of data is required in order to assemble a true representation of the building's climatic conditions. The methods presently available for
this task are either so time consuming that the data obtained is difficult to interpret, or they require very elaborate and expensive equipment.

Until now, few attempts have been made to employ those sensors and measuring devices commonly found in agricultural research stations and universities in a realistic analysis of greenhouse environments. Past trends have been to either ignore climatic gradients completely, or to invest heavily in systems designed solely for data acquisition.

A new system will be introduced which will enable automatic sensing and recording of environmental parameters at many locations throughout a greenhouse using common sensors, amplifiers and recorders. This system differs from other environmental data collection systems in that it contains the latest digital electronics combined with the simplicity and low cost of a minimum number of sensors.
LITERATURE REVIEW

Theoretical analyses of greenhouse environments have been used in evaluating the effect of new structural materials, building orientations, and architectural designs. In all of these cases, the methods have required actual measured data from sensing and recording devices to support calculated results (4, 9, 10, 11, 13, 15, 17). Without such data, application of the theoretical results is not justified. The analysis of this environmental data has also been used to predict or explain variations in plant growth rates and productivity (1, 3, 6, 14).

The approaches to the measurement of the environment inside large enclosures which have been used in the past and are presently being used, may be categorized into four groups of systems:

(a) data acquisition systems (4, 5, 6, 11, 13)
(b) systems using a few sensors to obtain approximations of the environment (1, 2, 7, 9, 14, 15, 16, 17)
(c) telemetry systems (8, 12)
(d) non-automated systems (3).

Examples from each of the groups have been selected and will be cited as being typical of that category. The need for a system which does not fall into one of the above groups should be evident after the discussion of each of the

* Numbers in parentheses refer to appended references.
categories.

(a) Data acquisition systems are those systems which employ a sensor fixed at every location where a measurement is to be taken, and a signal amplifier and recording device which collects the data. Such a system is described by Hahn et al. (5). The system includes a 40 input channel scanner, each channel capable of being connected to only one sensor, a 40 thermocouple input, a magnetic and mechanical print-out, and a small computer. The cost of this system is around $10,000. The cost of the sensors alone is high, since for every parameter and at each location where sampling occurs, a sensor is needed. The main advantages of this system are that the information at any and all sampling points may be obtained almost instantaneously and the frequency of sampling is nearly unlimited.

The disadvantages are twofold. For those researchers who are not solely involved in environmental data acquisition or who are unable or do not wish to invest so heavily, the cost of the data acquisition system is too great. The mobility of the system is also limited, since the wiring of all the sensors back to the recording unit often results in a huge spider web, where the 40 channel scanner becomes the fly! Such a system works only with sensors designed for the amplifying unit, and installations are almost permanent.

Another similar type of system contains at every sampling location, not only a sensor, but also a measuring
instrument and the recorder outputs of each of the instruments is fed into multipoint chart recorders. Such work has been investigated by Hand et al. (6) who measured light and temperature in the following way. "Solar radiation flux density on a horizontal surface immediately above the leaf canopy is measured by means of nine electrically matched Moll-Gurzinsky type solarimeters". On the same topic of light measurement, "a uniformity trial conducted on a bright sunny day in mid-June revealed that at midday there was a significant variation in both N-S and E-W directions". Quite likely nine solarimeters were not enough to give a good picture of the light distribution in the greenhouse.

The measurement of temperature was accomplished with thermocouples "...on a multipoint chart recorder". Multipoint chart recorders suffer from the same drawbacks as the data acquisition systems due to the many wires involved in connecting the thermocouples to them.

(b) Systems using a few sensors, to obtain approximations of the environment are typified by a temperature sensor at the air intake port of the greenhouse, and a second temperature sensor at the exhaust port. The difference in temperature between these two ports represents the gradient in the greenhouse, which because of only two data points must be considered linear. A linear gradient is highly unlikely in any greenhouse.

Thompson et al. (14) describes such a system and
the control obtained through its use in an article entitled "Plastic Covered Greenhouses Supply Controlled Atmospheres to Citrus Trees". "Temperature rise on hot days was 7°F. With outside ambient temperature at 104°F, exhaust air was 111°F". Measurement of the greenhouse environment employing this system neglects to include the possibility that areas in the enclosure are hotter than 111°F and others colder than 104°F.

Campbell et al. (2) describes a poultry building housing an "environmental control system" as follows: "The controlled structure -- a steel building 20 ft by 60 ft -- the range of controlled temperatures is ± 2 deg.". How were such small variations measured and controlled throughout such a large building? "The minimum monitor recordings recommended for an environmental control facility are (a) temperature of the control sensor, (b) humidity measured at the point of temperature control sensor (a)." The implication here is that one temperature control sensor is sufficient to enable a ± 2 deg temperature variation at any location in the enclosure. The temperature and humidity measured at the control sensor is assumed to be representative of conditions throughout the building. It is felt that this limited information is not an acceptable basis for an "environmental control system".

(c) Telemetry systems include some of the attempts which have been made to transmit temperatures from the bodies of
animals through the use of radio signals. The telemetry approach is a very good one, since it eliminates all wires between the sensors and recording unit (8, 12).

These systems are best suited to temperature measurements using thermistors, since the use of more complex sensors is not possible. Due to their simplicity, thermistors may be used in small oscillators or modulators, and a change in temperature will be reflected as either a change in signal frequency or amplitude. Any other sensor, which requires reference currents, such as a hot wire anemometer, would not lend itself easily to these circuits.

The measurement of temperatures at several locations may be accomplished through the use of a different radio frequency for each of the signals transmitted. This allows easy identification of the sensors. Unfortunately a transmitter and receiver is required for every sensor which makes the system costly.

(d) Non-automated systems have probably shown the most promising efforts in realistically measuring the different climatic gradients which exist in the greenhouse. Unfortunately, this approach requires a great deal of labor and time, and because of the temporal element the results are difficult to interpret. The system usually consists of at least two technicians, one holding the sensor and the other the meter and recording pad. Both technicians walk around the greenhouse sampling one variable after the other at
each location. The use of this technique is described by Cotton (3) in the study of the microclimate surrounding tomato plants in the greenhouse. The results of his experiments show that climatic gradients exist throughout the greenhouse and that one location cannot adequately represent the true conditions. He concludes "the present measurements emphasize the large differences of temperature and humidity between the macroclimate and microclimate in the presence of plants ...These differences pose a problem on the siting of instruments for the measurement and control of the glasshouse climate...".

The work involved in taking multiple measurements is tedious and indicates a need for a simple automated system for measuring and recording these climatic gradients.
Design Approach

Design Criteria

As in the case of most designs, the system described here is the result of many compromises. Before the actual design was achieved, it was necessary to model an ideal system which would accomplish the task at hand, with the preset restrictions on cost and complexity. The ideal system would include the following criteria:

a) the ability to measure variables at all sampling points at about the same time, in order to allow direct comparison of results;

b) the ability to measure these variables as often as possible, to allow minute to minute comparisons of results;

c) a minimum amount of wiring within the greenhouse (or other enclosure) to limit cost and interference from equipment;

d) a relatively low cost, of approximately $1000 or less.

The data acquisition system, as described by Hahn et al. (5) well satisfied a) and b) but has limitations due to the extensive wiring requirements and high cost.

A data acquisition system in its simplest and least expensive arrangement is represented by System A in Figure 1. It consists of a number of sensors, corresponding amplifiers, and a multi-input recording unit, having as many inputs as there are sensors (or amplifiers). The sensors
FIGURE 1. A Systems Comparison
SYSTEM A

SENSOR 1

SENSOR 2

SENSOR "N"

CABLE 1

CABLE 2

CABLE "N"

AMP. 1

AMP. 2

AMP. "N"

SAMPLING SITE

RECORDING STATION

SYSTEM B

SENSOR 1

SENSOR 2

SENSOR "N"

SELECTOR SWITCH 1

SELECTOR SWITCH 2

SELECTOR SWITCH 3

CABLE

AMP. 1

AMP. 2

AMP. "N"

SINGLE INPUT RECORD

SYNCHRONIZED

SAMPLING SITE

RECORDING STATION
are located at the sampling site and the amplifiers and recording unit at the recording station.

In System A, there is a cable connecting each sensor to an amplifier. The number of cables and their lengths become important factors as the number of sensors and their distance from the recording station increases. The increased number of inputs to the recording unit adds further complications. The major advantage of the system is that a continuous output from the sensors is obtainable.

System B (Figure 1) operates without a continuous recorder output. It is felt that a continuous output from a sensor is not essential, but rather that a series of measurements over a period of time would suffice in establishing a pattern. For example, 24 to 48 temperature measurements taken over a period of 24 hours would be an adequate indication of the temperature variation at that point for the day. With this in mind, even though criteria a) and b) are not fully satisfied an acceptable system can still be designed.

At first, System B appears to be more complex than System A, but it has the following advantages.

The link between the sampling site and the recording station has been minimized from "n" cables in System A to only one cable in System B. It is important to note that this single cable does not contain the sum of all the 'n' cables. The number of wires in the cable is independent
of the value of "n", and solely dependent on the number of wires going to the sensor having the most electrical connections. As a result, whether one or fifty sensors are employed in System B, only one cable is required. The simplification of the wiring is accomplished by synchronizing the three selector switches, so that only one sensor, one amplifier and the recorder are connected at the same time. All other sensors and amplifiers are at this time not connected. By advancing all selector switches at once, the next sensor, amplifier and the recorder are made operational. Another advantage of System B is the increased mobility of the components of the "sampling site" resulting from the use of a single cable. The sensors and Selector Switch 1 (Figure 1) could be moved as a unit to the first sampling location and after a suitable sensor equilibration time could be used to record at a remote station the temperature and humidity at that point, before repeating the sequence at the next location. Consider the situation of having to measure the temperature and humidity at five locations in the greenhouse. System A would require the following:

(i) five temperature sensors
(ii) five humidity sensors, and
(iii) two cables from each of the five locations to the recording station -- a total of ten cables.

System B could be used to obtain the same data as that from System A if the temperature and humidity sensors
were moved from one location to the other. System B then would require only:

(i) one temperature sensor
(ii) one humidity sensor, and
(iii) one cable,

and this is the key to meeting criterion c).

The movable sensors introduce a temporal error encountered in some of the non-automated systems discussed earlier. The magnitude of the error can be reduced if the sampling is done rapidly. This can be achieved through the use of a fast moving automatic transport mechanism for the sensors and simple electronic circuits to act as the selector switches mentioned in Figure 1. Undoubtedly, time will still be a factor to consider in the comparison of results.

Criterion d) may also be approached by using System B in Figure 1. Because System B has the potential to eliminate all but the minimum number of sensors in the analysis of the environment, it saves many dollars in the cost of sensors alone. The added cost of electronic circuits used in the selector switches of System B is equivalent to the cost of 8 light, 8 humidity and 8 temperature sensors.

In summary, the system which meets all the present criteria would consist of six basic units:

1. a package of sensors, comprised of one sensor type for every parameter to be measured, which is easily moved throughout the greenhouse.
2. an automatic, self-propelled carrier mechanism for the sensor package, travelling preferably in a continuous circuit,
3. three selector switches, the number of switching positions of each equal to the total number of sensors to be used in 1.,
4. sensor amplifiers, one per sensor type in 1.,
5. one cable connecting the sensor package and the moving carrier, 1. and 2., to the sensor amplifiers, and
6. a recording unit.

Component Selection

A brief discussion of the final choice of components for each of the above units follows.

1. It was assumed that in order to get a three dimensional picture of the distribution of climatic variables in the greenhouse, it would be necessary to move the sensor package not only over a horizontal plane throughout the enclosure but also vertically. For example, if measurements at three different horizontal planes are desired, it would require the sensor package to either travel along the same circuit three times, once at each level, or to travel the circuit once and at each stop move the sensors to each of the three levels before proceeding to the next stop. This type of system would have a very low sampling frequency, and for that reason it was decided to have one sensor package at each of the three levels; thus three packages of sensors would move through the greenhouse once per circuit.
2. The carrier mechanism for the sensor packages should be automatically controlled in its movement from one sampling site to another, so that no human supervision is necessary. It should travel throughout the greenhouse avoiding obstructions and guided in such a way as to consistently locate a sampling site.

The best guide for such a carrier would be a fixed track on which cues are mounted for the halting of carrier movement at the sampling site. If after the stopping of the carrier a device is activated that after a fixed time allows the carrier to move to the next site, then the carrier becomes self operating.

3. Mechanical rotary switches were not considered feasible as selector switches, since the synchronizing of all selector switches is vital for the proper operation of the system. To synchronize three mechanical rotary switches, remote from each other, could be a mechanical engineer's nightmare, and a switch "out of step" could be disastrous. Contacts on rotary switches are unreliable electrically because of their dust and corrosive susceptibilities. For these reasons, it was decided that reed relays, which have dust free, enclosed contacts, would be more appropriate. Consequently, for every sensor used a relay is required. The shaft rotation of a mechanical rotary switch is replaced by an electrical impulse which closes the right relay at the right time. Digital electronic circuits have been used for
years in switching circuits (a computer is an example) but only recently have their prices dropped enough to make them readily available.

The selector switch consisting of reed relays and digital integrated circuits would function as a clean, automatically advancing rotary switch. The added advantage of the integrated circuits is that they allow easy electrical synchronizing of several switching circuits. The number of switching positions of the "electronic rotary switch" was chosen to be fifteen, a number divisible by the three sensor packages mentioned in 1., which allows five sensors per package.

The sensors, carrier mechanism, and the first of the three selector switches will be referred to as a sensor module which includes all of the components associated with the "sampling site" of System B (Figure 1).

4. The sensor amplifiers required in the system would be those compatible with the sensors being used in the module. Only one amplifier would be needed for every type of sensor used. Whether one or fifteen temperature sensors are employed, is not important in the selection of the amplifier. What is important is that temperature has been chosen as a sensor type. In both cases, only one temperature amplifier is needed. The same is true of all other sensors used.

5. The single cable, or transmission cable, which
is used in this system could be connected at one end to the module and the other end to the selector switch and amplifiers. However, due to supporting roof structures in most greenhouses, it would be necessary to fix the cable to the track to allow the module to travel without restraint. Allowances would have to be made to permit connection of the sensors to the transmission cable at each sampling site.

The number of wires in the cable will depend on the sensor having the maximum number of electrical connections. If this number were "M", then the number of wires in the cable would be M + 1. The extra wire would be used to transmit the synchronizing signal between the module and the remaining selector switches. The transmission cable should be electrically shielded, in order to minimize stray signal interference at the sensor amplifiers.

6. The recording unit could simply be a single pen chart recorder; its input being connected to the third selector switch of System B (Figure 1).

Selector switches 2 and 3 (Figure 1) will be referred to as the recording station receiver, which including the sensor amplifiers and recorder make up the recording station of System B.
The Module

Overview of Operation

The module consists of a buggy (Figure 2) which transports the sensors from station to station within the greenhouse along a fixed two rail track. The track is 7 cm wide and can be suspended or mounted anywhere preferably to form a closed loop so that the buggy can run continuously.

The module travels along the track until it reaches a sampling site. Upon being stopped by a wedge, the fork connector (Figure 3) drops into the mercury troughs mounted in the track, and makes the module to receiver connection via the transmission cable complete. The sensors equilibrate to their new environment for the length of time (a variable) preset in the module circuit. After equilibration, the sensors are sequentially connected to their respective amplifiers, and the data is recorded. The completion of the recording results in the lifting of the fork from the troughs, and the advancement of the module to the next sampling site.

General Description

The module is basically a trolley which besides the equipment needed for its own locomotion, carries a box (Figure 2(E)) containing the electronic circuits which are
FIGURE 2. The Module

A. Microswitch MS1
B. Motor
C. Motor reversing switch (test model only)
D. Sensor cable connector strip
E. Electronic circuit box
F. Microswitch MS2
G. Timer relay
H. Relay 16
I. Fork lifter solenoid
J. Spring suspension assembly
FIGURE 3. Fork Connector

(i) Fork connector A about to drop into mercury trough B.

(ii) Connection completed.
the heart of the environmental parameter sampling system. The module also carries the packages of sensors, which will be used for the analysis, supported at various elevations under the trolley by rigid plastic tubing. The sensor cables, located in the tubing, are connected to a connector strip (Figure 2(D)), and the sensors can then be positioned at different levels as desired.

The track is constructed by bolting two rails of the type used for large suspended sliding doors together, side by side, to obtain a double railed track. The double rail was chosen over the single rail because it was believed that it would lessen the lateral wavering of the sensor packages by adding to the stability of the module. The track is securely suspended from the ceiling or rafters of the greenhouse.

A windshield wiper motor (Figure 2(B)) from an automobile is used to drive one of the four wheels of the module. With the chain, sprockets and wheels used in this prototype, a forward velocity of approximately one foot per second is obtained. Three of the wheels are idlers, one of which has a spring suspension assembly (Figure 2(J)) which assures that the four wheels are always in contact with the track.

The motor as well as the electronic circuits obtain the power necessary for operation from a small power supply which also rides on the module. This auxiliary supply
is serviced by the main power supply (Figure 4) which is located at the remote recording station, where the data is collected. Transmission of the power from the main to the auxiliary supply is achieved through the use of the track itself as one electrical conductor, and a second conducting strip (Figure 5(A)) running parallel to and on the inside of one of the rails, as the other. Electric motor brushes are used to pick up the current from these two conductors.

The function of the electronic circuits is to connect the fifteen sensors on the module one by one to their respective signal amplifiers which are all situated at the recording station through the use of a minimum number of wires. The fairly recent development of inexpensive integrated circuits commonly used in computers makes an electronic switching device to accomplish this task, simple, cheap and compact.

The transmission cable (Figure 5(B)) which contains the wires that carry the signals from the sensors to their amplifiers is attached midway between the two rails, and runs the full length of the track. It is necessary to tap into this cable at each of the sampling stations along the track in order to make the connection of sensors to amplifiers possible. Sliding contacts could be used to make the electrical connection of the sensors to the transmission cable but the variability of electrical contact
FIGURE 4. Main Power Supply
FIGURE 5. Mercury Troughs

A. Power conducting strip

B. Transmission cable
resistance of open sliding contacts which are susceptible to corrosion and dust collection was considered too great. A solid-liquid-solid connector consisting of two metals joined by a mercury medium replaced the sliding contact approach. Each of the wires of the transmission cable is connected to its own small trough partly filled with mercury at the sampling site (Figure 5). The troughs are machined into a piece of plexiglass and the piece is fastened between the two rails at the site.

A cable from the module's circuitry is terminated at one end by a fork connector -- a terminal strip housing wire prongs (Figure 3). These prongs when dropped into the mercury troughs make the electrical connection of sensors to amplifiers complete. They are lifted out of the troughs by an arm activated by a lifter solenoid (Figure 2(1)) before the module moves to its next sampling site.

The switching of a sensor to its proper amplifier is controlled by the integrated circuits of the module -- the brain of the system. However, once the fifteen sensor signals have been converted into one signal path (the wires of the transmission cable), they must be diverted again to their respective amplifiers at the recording station. For this reason, a similar circuit to the module circuit is required at the recording station and this is the recording station receiver (Figure 6). This unit receives fifteen
FIGURE 6. Recording Station Receiver Circuit Box
signals one after the other and it does the routing of the signal to its proper amplifier. To simplify the receiver circuit, it was arbitrarily decided to divert the first three sensor signals to one amplifier, the next three to another, and so on, up to the fifteenth.

In order for the sensors and amplifiers to be connected at the right time, it is essential that the module's switching circuits are synchronized with those of the receiver's. A synchronizing signal which is transmitted via its own wire in the transmission cable from the module to the receiver, assures that this will occur.

As well as connecting the sensors and amplifiers the receiver connects the individual amplifiers to the recording unit one at a time. This eliminates the interference of the output of one amplifier with that of another. If a pen recorder is used as the recording device, a straight horizontal line will be obtained for the length of time that a sensor is connected to its amplifier. This time may be varied by an adjustment in the module circuit. A digital print-out or magnetic recording device which may be triggered to take a reading at a given instant would be much more convenient since transferring of data from the chart paper would be unnecessary.

Details of Operation

The small regulator power supply mounted on the module is always on, so long as the main power supply is on.
The main supply (Figure 4) offers 18 volts to the module power supply, which produces a regulated 5 volts, via the track on which the module travels and through a metal conducting strip (Figure 5(A)) insulated from the track. This strip is the positive pole, and the track is the negative as well as a ground connection. The current is picked up from the track by carbon brushes, of the type used in electric motors.

All circuits are operated on 5 volts, due to the low voltage requirements of the integrated circuits. The motor as well as the lifter solenoid for the fork connector operate on 5 volts.

Figure 7 shows the block diagram of the module's circuits. While the module is in motion, microswitch MS1 (Figure 2(A), and Figure 7) is in the normally closed (NC) position, and relay 16 (Figure 2(H), and Figure 7) is open. The fork connector is in the "UP" position since the fork lifter solenoid S1 is activated. Due to a mechanical connection, when the fork is up, MS2 (Figure 2(F), and Figure 7) is closed; consequently current is supplied to the motor which is driving the module. Because MS1 is in the NC position, no current is being supplied to any other circuits.

When MS1 is tripped by the wedge (Figure 8(A)) under the track, it assumes its normally open (NO) position.
FIGURE 7. Module Circuit Block Diagram
FIGURE 8. Microswitch Wedge

A. Wedge

B. Mercury troughs, bottom view
As soon as this occurs, no more current is supplied to S1 (Figure 7) or to the motor, which results in the simultaneous stopping of the module and dropping of the connector into the mercury trough. Also, 5 volts are supplied to the equilibration timer. After equilibration, the timer relay (Figure 2(G), and Figure 7) closes and current is supplied to the rest of the circuits.

The instant that current is applied to the automatic reset circuit, the binary counter is reset to a reference count, so that the switching sequence will always occur in the same order. Resetting is essential for the proper operation of the sequence. The square wave generator is the pace setter for the switching sequence, and its frequency will determine the length of time that any sensor is connected to its amplifier. Specifically, it sets the speed at which the binary counter counts. The binary counter counts in sequence from zero to fifteen (in binary form) after resetting, and it is the heart of the switching system. Each count represents a specific function to be executed, in this case the closing of a specific relay to allow a sensor to be connected to the transmission cable and then to its amplifier. This is accomplished through the decoder and inverters.

Relay 16 is not connected to a sensor, but rather to MS1. In the switching sequence, relay 1 closes for the
length of time determined by the square wave generator, and as relay 1 opens, relay 2 closes for the same time span, and so on, until relay 16 closes. The signal which triggers the closing of relay 16 is also connected to the binary counter through a series of "OR" gates. This prevents the counter from starting its count at zero again with the next incoming pulse from the square wave generator. It puts the counter on "hold" and keeps relay 16 closed. The contacts of relay 16 are connected in parallel with MS1, and their closing supplies current to solenoid S1. The motor will not be activated until microswitch MS2 is closed, i.e. when the fork is in the UP position. This prevents damage to the pins of the connector by completely removing the connector from the mercury troughs before advancing the module.

The signal which synchronizes the switching sequence of the module with the receiving station sequence is obtained from the input to the binary counter, consequently when the counter is stopped by the activation of relay 16, the synchronizing signal to the receiving station is also held.

The switching sequence occurs as described above only when the rotary switch (Figure 7) is in position 16. The function of this switch is to add to the versatility of the circuits by making the number of functions variable from
0 to 15. For example, if we were only interested in taking three sensor readings, we would set the rotary switch to position 4, so that on the fourth count, the module would be advanced to the next station. This speeds up the cycle by avoiding unnecessary switching. The rotary switch is not essential, however, and may be omitted.

The detail wiring diagrams and schematics of the module are shown in Figures 9 through 14. The relays shown in Figure 13 are all of the single pole type. The sensors in this case must all have two wires going to them. This is true of sensors such as thermistors and some humidity sensors. If a sensor required three wires to be connected to it (e.g. humidity), a double pole relay would have to be used in place of a single pole. Furthermore, one additional wire would have to be used in the transmission cable, and one additional prong added to the fork connector. However, with proper foresight this is no problem. By settling on the maximum number of wires one would expect for a sensor (a hot wire anemometer requires six) the relays and transmission cable can be chosen beforehand. For example, if a transmission cable of seven wires, a fork connector of seven prongs, and five pole relays are used, up to fifteen hot-wire anemometer sensors could be used. (This added initial expense avoids the great inconvenience of changing wires and relays should one decide to convert from a two
wire sensor to a three or more wire type). With the same arrangement, fifteen thermistors or fifteen light sensor or humidity sensors, or any combination of the above would be possibilities for sampling, as long as the number of wires to each sensor did not exceed six.

The advantage of this system is that the complex wiring is limited to the module and the receiving station rather than the interconnection between the two. This complex wiring can be further simplified through use of printed circuitry.
FIGURE 9. Module Regulator Supply Wiring Diagram
FIGURE 10. Sensor Equilibration Timer and Variable-Square Wave Generator.
NOTE:
ALL RESISTANCES ARE IN OHMS; 1/4 WATT UNLESS SPECIFIED OTHERWISE.
TIMER DELAY: 1.6 - 70 SEC.
FREQ. RANGE: 0.018 - 1.9 Hz.
FIGURE 11. Module Wiring Diagram, Integrated Circuits only
FIGURE 12. Rotary Switch Wiring Diagram
FIGURE 13. Module Relay Wiring Diagram
FIGURE 14. Automatic Reset for the Module
NOTE:
RESISTANCES ARE IN OHMS
RESISTORS ARE 1/4 WATT
UNLESS SPECIFIED
OTHERWISE.
RECORDING STATION RECEIVER

Overview of Operation

The recording station receiver is essentially the slave of the sensor module. Its operation is determined by the synchronizing signal obtained from the module circuit. Because of the present mode of operation, where we assume to have five different types of sensors, three of each, we must have five different types of amplifiers. Three sensors must be connected in sequence to one amplifier, then three more to another amplifier, and so on. The recording station does just that, as well as connecting the amplifier to the recording device, so that at any time only one sensor is hooked to its amplifier, and only that amplifier is connected to the recording device. The recording of the sensor signal occurs as soon as the sensor and amplifier are connected.

Details of Operation

The block diagram for the recording station is shown in Figure 15. With no signal at the "synch." input, the automatic reset circuit keeps the divide by 3 and divide by 5 circuits in their reference positions, i.e. while the module is moving from one sampling location to another. With the first incoming synch. signal the divide by 3 and divide by 5 circuits begin functioning. The divide by 3 circuit advances the divide by 5 circuit (basically a binary counter similar to the one in the module) by one count only

- 41 -
FIGURE 15. Recording Station Block Diagram
at every third synch. signal that comes in. In other words, the switching at the receiver occurs only one third as fast as it does in the module. Thus it allows three similar sensors sequentially to be hooked to one amplifier, and only then will the next group of sensors be connected to their amplifier.

Detailed wiring diagrams and schematics for the receiver are shown in Figures 16 through 18. The main power supply schematic is shown in Figure 19. The integrated circuits in Figure 16 cannot meet the power requirements to operate two relays, so transistor relay drivers (Figure 17) are used. One relay connects the sensor to the amplifier, while the other connects the amplifier to the recording device.
FIGURE 16. Recording Station Receiver Wiring Diagram, Integrated Circuits only
FIGURE 17. Receiver Relays and Relay Drivers
FIGURE 18. Automatic Reset for Recording Station Receiver
NOTE:
RESISTANCES ARE IN OHMS
RESISTORS ARE 1/4 WATT
UNLESS SPECIFIED
OTHERWISE.

\[ R_1 = 220 \text{k}\Omega \]
\[ R_2 = 1 \text{k}\Omega \]
\[ D_1 = \text{IN4005} \]
\[ C_1 = 1 \mu\text{F} \]
\[ C_2 = 10 \mu\text{F} \]

\[ Q_1 = 2N4124 \]
\[ Q_2 = 2N4124 \]

\[ +5V \]
\[ \text{SYNC. IN} \]
\[ \text{RESET OUT} \]
FIGURE 19. Main Power Supply Wiring Diagram
TESTING THE SYSTEM

Experiment A

The only errors which might be encountered in the output data of this system which cannot be corrected by calibration of the sensors are those which might occur as a result of a bad connection between the sensor and its amplifier. Since the mercury connector is the only place where a variation of contact resistance should be found, a test was made on the reproducibility of the resistance of a sensor-to-amplifier connection. A digital ohm meter (Weston 1240) was connected at the receiver station where normally the sensor's amplifier would be. The module was allowed to go through its normal procedure by approaching the mercury connector and dropping the prongs into the troughs, then switching in the sensors and advancing. The resistance of a dummy sensor was measured through the switching system every time the module stopped at the sampling station.

The test was repeated fifteen times. The resistance varied ± 0.5 ohms over the fifteen readings. This does not imply that the variation obtained from station to station will be as small as the variation at a single station. But, any variation in readings due to change in transmission cable length from station to station can be readily corrected mathematically. Sensors connected to the
module, and suspended under it, showed that results from a given sampling station were obtainable in their proper sequence and were reproducible. Calibration of the sensors was omitted in the trial and consequently the results are not reported.

Experiment B

Due to the toxic effect that mercury vapors have on some plants, it was proposed that a layer of thin lubrication oil covering each mercury trough would substantially reduce evaporation of mercury. It was necessary, then, to study the effect of the oil layer addition on the mercury trough resistance reproducibility. A dummy sensor having a 105.5 ohm resistance out of circuit, was placed on the module as in Experiment A. Ten trials were performed using no oil and then ten more with the oil covering the troughs. The lack of reproducibility of the resistances, due to the added oil, is evident by comparing the results listed in Table I.

The results of this experiment indicate that the addition of oil to the mercury produces random increases in the conductor resistance, and should not be used for that reason.
TABLE 1. Effect of Oil Layer on Mercury Trough Resistance

<table>
<thead>
<tr>
<th>Trial</th>
<th>Resistance (ohms) of Dummy Sensor in Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no oil</td>
</tr>
<tr>
<td>1</td>
<td>105.8</td>
</tr>
<tr>
<td>2</td>
<td>105.6</td>
</tr>
<tr>
<td>3</td>
<td>105.7</td>
</tr>
<tr>
<td>4</td>
<td>105.6</td>
</tr>
<tr>
<td>5</td>
<td>105.6</td>
</tr>
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<td>6</td>
<td>105.6</td>
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<td>7</td>
<td>105.6</td>
</tr>
<tr>
<td>8</td>
<td>105.8</td>
</tr>
<tr>
<td>9</td>
<td>105.6</td>
</tr>
<tr>
<td>10</td>
<td>105.6</td>
</tr>
</tbody>
</table>

Mean = 105.6
Std.Deviation = 0.0850
Std.Error of Mean = 0.0269

Mean = 110.8
Std.Deviation = 6.726
Std. Error of Mean = 2.127
DISCUSSION

The sensing module was designed to provide a system for transporting fifteen environmental sensors from location to location in a greenhouse. At each location, after a suitable equilibration time, the module connects the sensors to their appropriate amplifiers located at a remote recording station. The module will function with a wide variety of sensors many of which are normally available in environmental laboratories. The module has been kept as flexible as possible with adjustments being easily made in the number and type of sensors, time allotted for equilibration and the time each sensor is connected to its amplifier.

Originally the design was intended for use in greenhouses, but its versatility should enable its use in other agricultural buildings such as poultry barns, where environmental gradients exist and could be monitored.

The total cost of a complete system cannot be estimated, since it will vary with the sensors, amplifiers, recording devices and length of track used. However, the material cost of the transmitter, receiver and carrier is approximately $500. The cost of the two railed track is about one dollar per foot, not including the transmission cable. The largest percentage of the cost of the
transmitter and receiver is borne by the multiple reed relays.

Although the surface area of the mercury troughs is only $\frac{1}{8}$ sq inch, it is felt that due to evaporative loss of mercury to the greenhouse atmosphere, the system should not be used in buildings containing plants which are very sensitive to mercury vapours, such as roses. Adequate ventilation is presently the best method of preventing the accumulation of mercury vapours.

The temporal errors introduced as the result of sequential sampling of locations throughout the greenhouse could possibly be eliminated. If one were to use a reference set of sensors and compare all other results with this reference, one could eliminate the inherent error resulting from the elapsed time between samples. For example, a light sensor located outside the greenhouse could be used as a reference sensor, which would record the presence of a cloud rapidly passing over the sun. Thus, a darkened area in the greenhouse could be identified as such due to the passing cloud, rather than an area which is always darker than its surroundings. It is also possible to average the results at a given sampling point over part of, or an entire day, and comparing this average with the average at another sampling point, thus showing any trends at the locations.

The sampling frequency of the system is primarily
dependent on the sensors and amplifiers used. The sensor-to-climate equilibration time is solely dependent on the sensor with the greatest time constant, and the switching time from one sensor to another will depend on the amplifier requiring the longest sensor-to-amplifier equilibration time. The sensor-to-amplifier equilibration time is the period measured from the instant the sensor is connected to the point where the amplifier output has reached 99% of its final value. It is conceivable that if all sensors used had a one second time constant or less and a one second sensor-to-amplifier equilibration time, 20 seconds would be ample for the sensors to equilibrate and 15 measurements to be made at the sampling site. If the travelling distance is approximately 10 feet between sites, then at a velocity of one foot per second, 15 samplings of the environment could be obtained every 30 seconds at a new location in the greenhouse. In a small greenhouse, this could mean 150 measurements per travelling circuit, each circuit requiring 5 minutes. The results could almost be interpreted as a continuous output from fixed sensors. More realistically one should expect approximately 30 seconds equilibration time and 10 seconds switching time and 20 seconds travelling time per site. Thus with 10 sites, measurements at a given site are repeated every 10 minutes. The total distance covered in that time would
be 200 feet. The combinations are unlimited; the time values stated here are only some examples rather than fixed values.

The system has approached the ideal environmental parameter sampling system with respect to cost, complexity and versatility more closely than any others mentioned in previous publications. It is believed that the compromises reached are well worth the savings in cost of more complex data acquisition systems, and that this system will allow more researchers to carefully examine their greenhouse environments through the use of instruments which are already at their disposal.
RECOMMENDATIONS

There are some improvements in the design of this system which may be incorporated into a working system. These proposed changes have come from the construction and testing of the prototype.

The mercury trough connector is probably the most controversial design aspect of the system. The results of Experiment A indicate that sensors should be chosen whose calibration is not significantly altered by a $\pm 0.5$ ohm lead wire resistance change. A specific example is the choice of a thermistor which has a 50 ohm change in resistance per degree at 25°C. The error introduced due to the mercury trough connection would be $\pm 0.01$°C. This type of thermistor is common, and ideal. With the same thermistor, and a transmission cable containing 22 gauge (Awg) copper wires, having a resistance of 16.46 ohms per 1000 feet, would produce only a 0.33°C increase over the entire 1000 feet. This means that for this type of sensor and cable, correction for a change in transmission cable length is probably not necessary.

The use of oil to decrease evaporative loss of mercury, in spite of the results of Experiment B, should be studied. It is possible that with a change of material used for the prongs, such as a highly polished stainless steel, the amount of oil adhering to the prongs would
lessen. Also, deepening the troughs and increasing the mercury to oil ratio might help in stripping off the oil as the prongs enter the mercury. Also, the trough surface area of 1/8 sq inch if decreased by a refinement in the connecting procedure or design would certainly lessen evaporation. It is also possible to try a different liquid as the medium or to try a completely different connector.

The prototype module is quite heavy being constructed primarily of steel. Since the module must carry only the transmitter and its own propulsion equipment, rigid plastic would probably suffice as the construction material.

If arrangement of motor, transmitter, connector and cable could be accomplished to allow the module to be supported by a monorail, and lateral waivering could be eliminated, this would simplify the construction of the track, especially the curves, and would reduce the cost of the track by a half.

A major technical improvement in the module would be to operate the motor and lifter solenoid by the main power supply (i.e. use 18 volts as opposed to their operating from the regulated 5 volt supply in the module circuit). Since the maximum current drain is produced by these two electrical devices, the power transistor in the regulated
module power supply could be made smaller and it would operate at a lower temperature requiring a smaller heat dissipation area for the transistor.

The proposed alteration has a second advantage. The cue for the integrated circuits in the module to reset themselves is the turning off and turning on of the power supplied to them. A supply voltage drop below a threshold will be interpreted by the integrated circuits as the reset signal. Such a voltage drop occurs for a fraction of a second when the motor and solenoid are turned on. If these two devices are connected to the same power supply as the integrated circuits, once in a while, the module will send its information to the recording station, advance a fraction of an inch (just far enough so that the forks have passed the mercury troughs) and then stop and drop the fork. The module will "mentally" go through its counts one more time and then advance to the next station. Since the occurrence of such accidental stops is low and the result is only a few extra seconds added to the travelling time from one station to the other, the problem is not considered critical. It may be eliminated by either connecting the motor and solenoid to their own 5 volt supply, or choose these two devices so that they are compatible with the main power supply voltage. In either case, the voltage drop which occurs when the devices are turned on will not affect the sensitive integrated circuits.
REFERENCES


