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# A PLANT MORPHOLOGY INTEGRATOR

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Ruixiu Sui

December 1987

To: My parents, Mr. Qijie Sui and Mrs. Wenying Jia,
my wife, Weihua Jiang, and my daughter, Yu Sui
for their love and support.

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## ABSTRACT

A microcomputer-based measurement system has been developed for plant morphology measurement. Seven ultrasonic sensors and an ultrasonic ranging module were used to scan the plant row for distance-to-plant measurements at three different vertical positions and the top of plant row. An optical incremental encoder was used as a position sensor to measure the forward travel distance of the instrument. The selected horizontal interval between two sample collections was 31 mm. An interface was designed to connect a single board computer (SBC) with the ultrasonic sensor system for data acquisition. The storage capacity of this measurement system is 7,000 data values. A key pad was interfaced with the SBC to input the operation commands. A liquid crystal display (LCD) unit was used to display all results, including cumulative plant volume, maximum and average plant widths at three vertical positions, and maximum and average plant height.

The measurement system was tested both in the laboratory and in the field. The results indicate that the unit can be used to obtain accurate measurements for plant morphology analysis.

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# CHAPTER I

# INTRODUCTION

## Background

Evaluation of plant morphology is often desired in research related to crop production. Many diverse factors affect plant morphology. Fertilization, irrigation, tillage methods, pesticide applications, and other production-related treatments would be greatly aided by the ability to rapidly and conveniently measure their plant growth effects. However, measuring the morphology of non-uniform plants is difficult and time consuming. The avialability of inexpensive ultrasonic sensors offers promise of automating this process of plant morphology characterization.

Ultrasonic measurement has been widely used in distance determinations. Distance is measured by transmitting a burst of high frequency sound, then waiting for the echo to return. The elapsed time is directly related to the distance from the ultrasonic sensor to the closest object. That distance can be computed by using the speed of sound and the elapsed time.

Several of these ultrasonic sensors could be interfaced to a microprocessor instrumentation system providing a three-dimensional measurement package. This technique appears feasible for measurement of a variety of "bush" type plants such as cotton, soybeans, various vegetable crops, and small ornamental plants.

## Objective

The primary objective of this project was to design and construct a plant morphology measurement system. The system would use a single board computer (SBC) as the central control unit and seven ultrasonic transducers as the sensors to obtain an integrated plant morphology measurement for a plant row or row segment. Specifically, the system would measure cumulative plant volume, maximum and average plant widths at three vertical positions, and maximum and average plant height.

# CHAPTER II

## REVIEW OF LITERATURE

Jensen (1972) noted that shortly after Linnaeus began cataloging the world's plant species, scientists began an intensive study of their gross morphology (shape or form). This was done primarily to discover features that may be diagnostic in classification. One began simply by measuring the size of a plant and plotting the results as a function of time. The resulting graph might have features that suggest something about growth mechanisms. Other measurements might include the height of a plant, its weight, or its volume. What was actually measured depended upon the point of view.

Albertsen (1983) used two sets of isogenic soybean lines to study fasciation inheritance and to compare growth morphology between fasciated and non-fasciated genotypes. Plant growth measurements were taken on field-grown plants. These measurements included height, developmental stage, number of leaves, stem circumference, and dry weight of the main stem and branches. All measurements were taken twice weekly from 13 days after planting for 12 weeks.

Dasilva (1985) developed a technique for in-situ, non-destructive plant growth evaluation using computer image processing. Three photographs of a plant were taken 90 degrees apart, such that top, front, and side views were obtained. The photographs were then digitized using image processing equipment. The image data was then transfered to a mainframe computer where the images were aligned, rotated and scaled to create a three dimensional graphic reconstruction of the plant. The total plant volume, plant mass, and leaf area could then be calculated.

Meyer (1985) designed and constructed a single and dual camera image measurement system for in-situ leaf area, stem and petiole length, and other geometric features of canopy archtecture. The system worked for determination of in-situ leaf area expansion, internode elongation, and stem diameter. Image processing was accomplished using an IBM PC/XT.

McConnell (1983) presented a paper to describe a tree-row-volume measurement system tested in the laboratory but not yet used in the field. An Apple computer was used in the system to control ultrasonic distance measurement devices scanning the volumetric outline of one side of a tree. The measurement devices were mounted at the required spacing on a vertical mast attached to a tractor. As the tractor traversed a row between the trees, the transducers took distance measurements to the surface of trees in the row. Data points were stored in the computer memory for later calaculations.

Zaerr (1976) developed a technique for measuring shoot elongation in seedlings of Douglas-fir under various levels of water potential. The seedlings were grown from seed in plastic pots. A recording micrometer, with two displacement-sensing transducers, was attached to the shoot of one seedling in a pot. Changes in shoot length were measured and recorded continuously before and after soil in the pot was watered.

Milne (1977) designed a device to measure the shoot length of sitka spruce. The principle of the device was to periodically reposition a light transmitter-receiver assembly and an associated multiturn potentiometer so that the light beam was just clear of the top of the shoot. A framework was used to support a cage assembly holding a light emitting diode (LED) on one side of the shoot opposite a light receiver-amplifer unit on the other side. After a period of growth, a repositioning signal was generated in the electronics. If the control circuit detected no light, extension was implied and the cage was driven upwards until light was received. Thus the new position of the shoot tip was infered from the changed potentiometer resistance. The output voltage from the changed potentimeter had a linear relationship to the optical head position. That voltage represented the measurement of the shoot length.

Chisholm (1983) described a seedling morphometer developed by Weyerhaeuser Instrumentation Research Group.

The morphometer performed rapid morphological measurement for characterization of seedlings to be used in field plantations. The height and stem diameter of plug or bare root nursery seedlings could be measured using that instrument. The dimensions of the morphometer were 50 cm wide, 51 cm deep, 64 cm high, and it weighed approximately 13.6 kg. The morphometer operated on 110 VAC, 60 Hz power. The instrument was operated by moving the height measuring bar to the tip of the seedling's terminal bud. That bar was attached to a pulley which turned a 10-turn potentiometer. Moving the height bar produced a linear voltage change between the potentimeter wiper and ground. The stem diameter measurement was made by a linear transducer in the active leg of a bridge circuit. Movement of the transducer produced a linear change in the output voltage of the bridge circuit. Both height and diameter measurements were output to a digital panel meter providing a visual check as a printer provided hard copy.

Liang Dexin (1986) studied the effect of potash on growth and morphology of soybean plants. Plant heights, leaf numbers per plant, and the dimensions of the leaves were measured from the soybeans with different potash treatments. The results indicated that certain amounts of potash fertilization could make the soybeans grow higher, produce more leaves, and contain more cells.

CHAPTER III

# SYSTEM DESIGN

## Introduction

The measurement system described herein employs seven ultrasonic sensors mounted on a frame to scan the volumetric outline of a plant row from both sides and the top (Figure 1). Output from the sensors is used to calculate enclosed plant volume, maximum and average widths at three vertical positions, and maximum and average height. An optical incremental encoder, which produces 512 digital pulses per revolution of the encoder shaft, measures travel distance along the row (Figure 2). A one-to-one gear ratio between the encoder and a 508-mm diameter wheel on the cart described below provides distance resolution of 3.1 mm.

The electronic portion of the measurement system and the seven ultrasonic sensors are fixed on a special cart (Figure 3). The space between the sensors can be adjusted both vertically and horizontally. As the operator pushes the cart along a plant row, the ultrasonic sensors operate under control of a single board computer (SBC) to sequentially scan the plant row and take distance measurements at selected horizontal intervals. The data acquisition system collects and stores the measurement

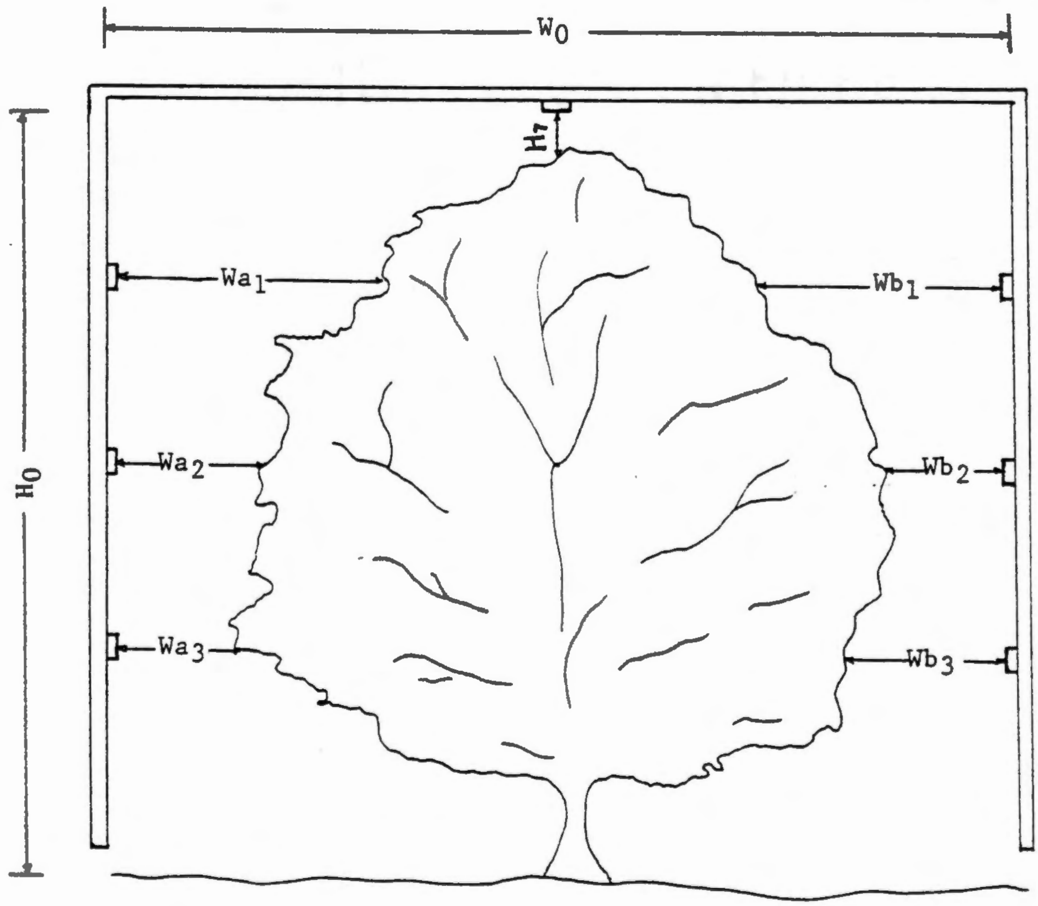


Figure 1. Scan arrangement showing the positions of the seven ultrasonic sensors and the cross section of plant row.

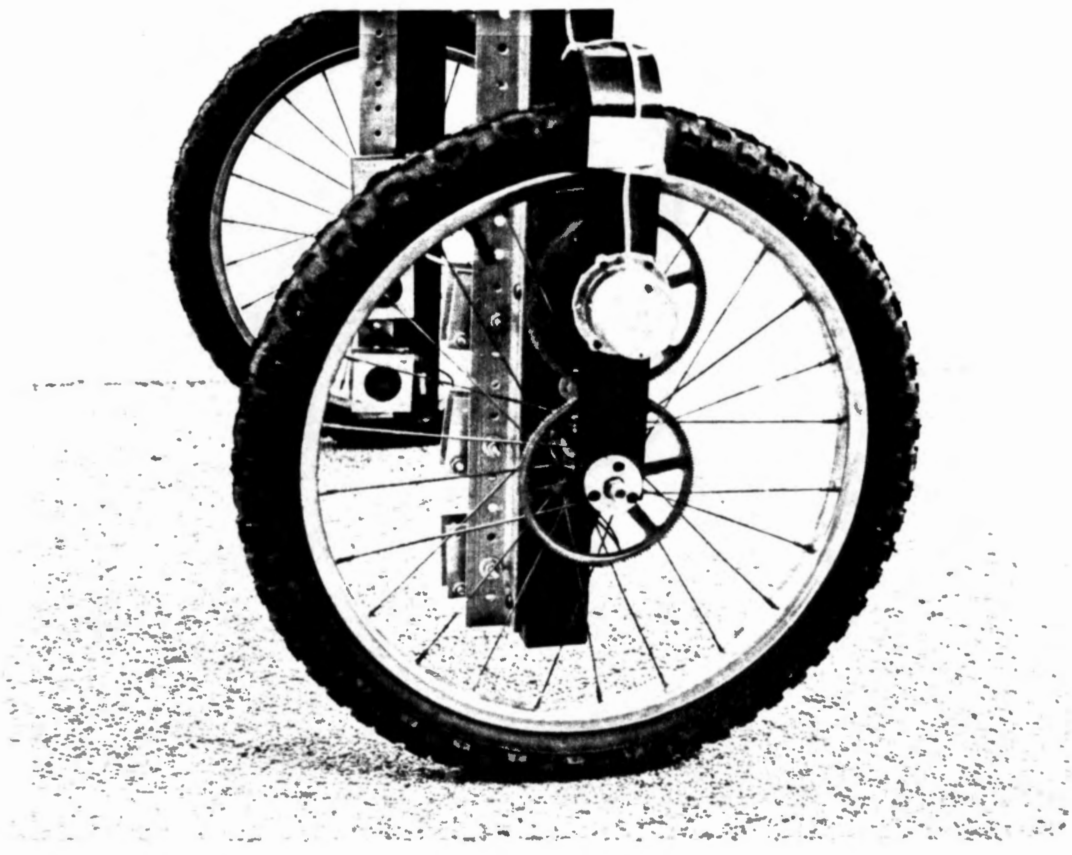

Figure 2. The optical incremental encoder with drive gears mounted on the front left wheel.

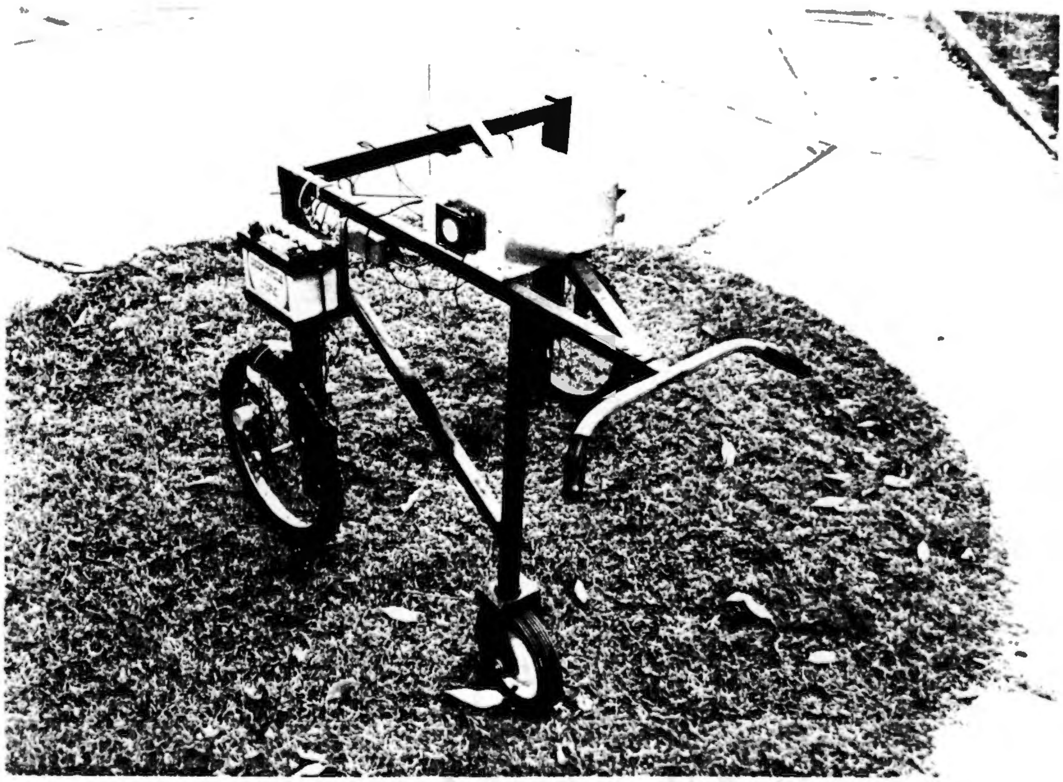

Figure 3. Photograph of the plant morphology integrator unit showing the optical encoder and the ultrasonic sensors. The microprocessor-controlled data acquisition system is housed in the box mounted on top of the cart.

values in the SBC memory for later computations. This measurement system has a storage capacity of 7000 data values. Power for the system is provided by a 12-volt rechargable battery. A voltage regulator converts the supply voltage to the 5 volts DC needed for the instrumentation.

## Ultrasonic Sensor System

Seven ultrasonic transducers and a ranging module, manufactured by Polaroid Corporation and Texas Instruments respectively, are used as the scanning devices in this measurement system.

Each ultrasonic sensor is 38 mm in diameter and consists of 3-mm gold-plated foil stretched over a concentrically grooved aluminum disc (Figure 4). The foil is the moving element in the sensor that converts electrical energy into sound and the returning echo into electrical energy. The Polaroid ultrasonic sensor is larger than other available 50-KHz sensors. This sensor is more directional than the smaller ones because the directional sensitivity of the sensor has a close relationship with the diameter.

The ultrasonic sensors are driven by the ultrasonic ranging module. After the module is triggered by an initiation signal (INIT), provided by the computer, the module generates a set of pulses and sends them to an

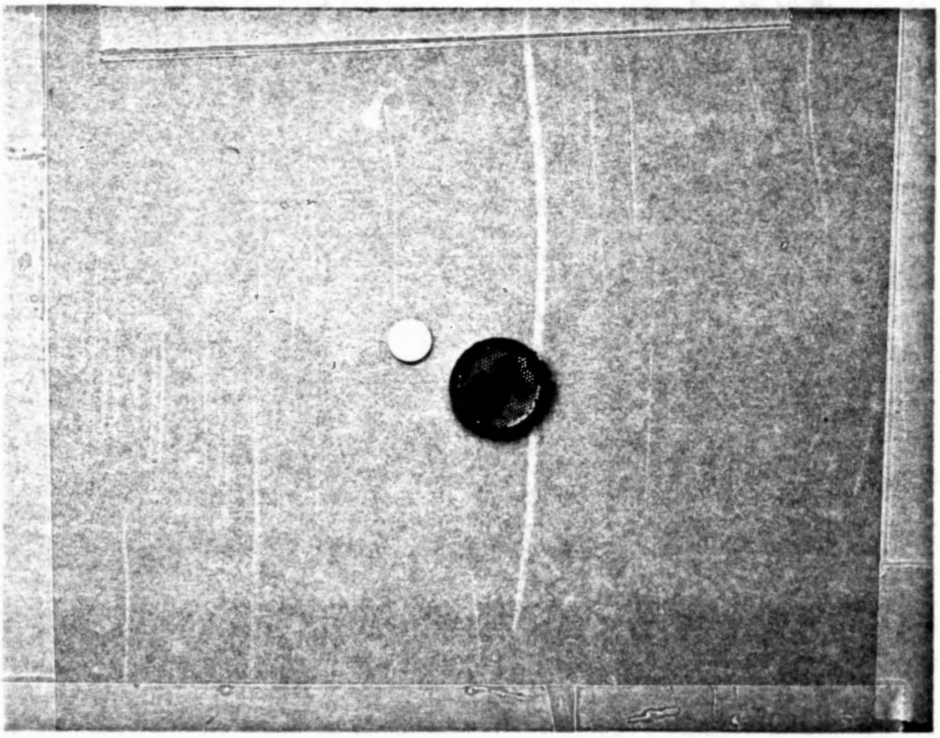

Figure 4.  Photograph of the ultrasonic sensor showing its relative size to a penny.

ultrasonic sensor. Through that sensor a set of ultrasonic pulses are transmitted toward the plant row at a speed of about 350 meters per second. When the first ultrasonic pulse is echoed back to the sensor, the module detects the returning echo and sends an echo signal to the computer. The difference in time between initial and echo signals is a measure of the distance from the ultrasonic sensor to the plant surface (Figure 5). The elapsed time is measured in hardware by a 1-MHz clock connected to an 8-bit counter circuit which interfaces to the SBC through a parallel I/O port (Figure 6). The sensor "window" is a 15 degree cone rotated about the axis of the sensor. Thus, the sensor will detect the nearest surface within that window.

In the ultrasonic ranging module, the receive input of the ranging control IC (integrated circuit) is inhibited by an internal blanking signal for 2.38 ms. This blanking interval corresponds to 416.5 mm which is the minimum distance that the ranging module can sense without external control intervention (Ciarcia, 1984). The typical spacing of plant rows is about one meter. Thus, the distance from the sensor to the plants in the row can sometimes be less than 416.5 mm. To solve this problem, a external control circuit was used (Figure 7) to reduce the ranging module limitation. Two SN74LS221 monostable multivibrators (Texas Instruments, 1976) are used for this purpose. On the rising edge of the INIT signal, the first monostable multivibrator

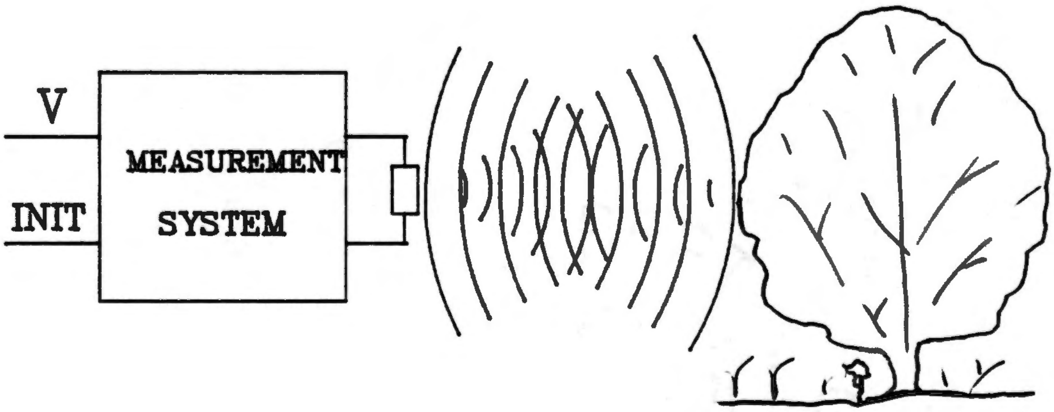


Figure 5. Principle of the ultrasonic measurement system.

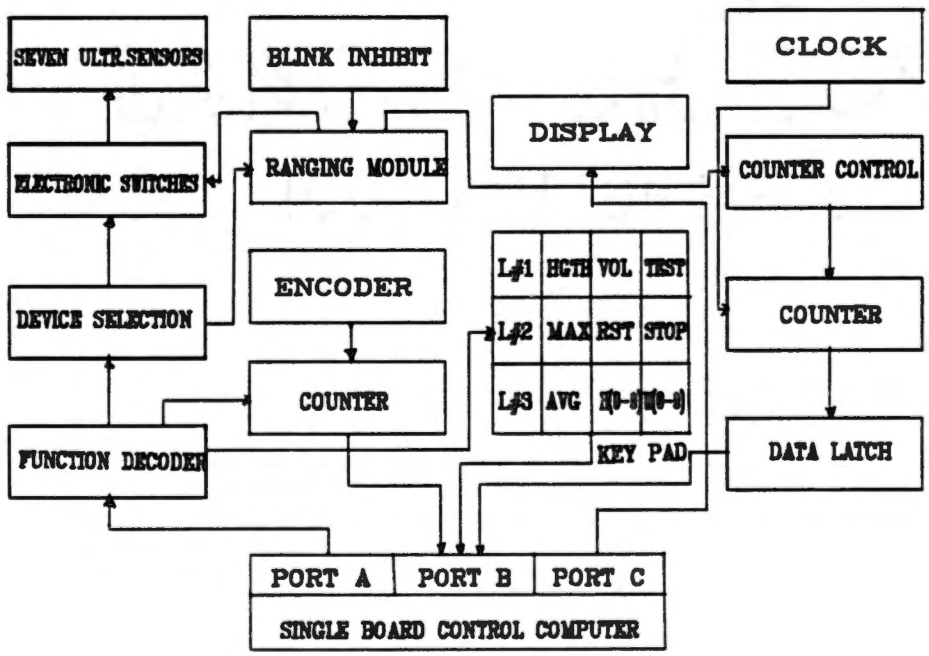


Figure 6. Schematic diagram of the measurement system showing a SBC controlling twelve outside devices (7 ultrasonic sensors, the ultrasonic ranging system, the input keypad, the counter circuit for optical encoder, the counter for sensor data, and the data latch).

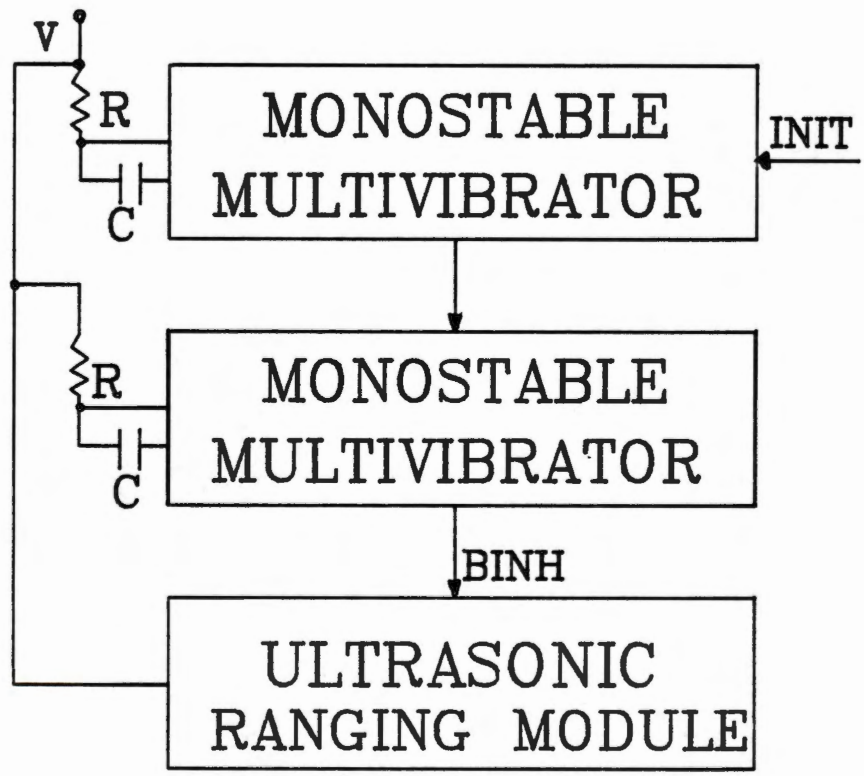


Figure 7. Blank inhibition circuit for the ultrasonic ranging system. Output of this circuit is shown in Figure 8.

(one-shot) outputs an active low pulse of 0.80 ms (Figure 8). The rising edge of this pulse triggers the second monostable multivibrator. The blanking inhibit line, BINH, is taken high by the output of the second monostable multivibrator prior to 2.38 ms to enable the receiver in the ranging module. After adding this external control circuit, the minimum distance that the ranging module can sense is reduced to 140 mm.

## Single Board Computer (SBC)

The measurement system is based on a Model SYS-3Z single board computer (SBC) manufactured by Octagon System Corporation. The SYS-3Z SBC (Figure 9) is a complete computer system, requiring only a 5 volts power supply for system operation. An additional low current 25 volts supply is needed during EPROM programming.

A Z80A CPU with 4MHz clock speed is used in this SBC. The SBC has 8K RAM, 16K EPROM, 16K system ROM and the 24 programmable I/O lines which are divided into 3 addressable ports of 8 bits each (Ports A, B, and C). A fourth addressable location (control register) contains a control word that determines the configuration of these three I/O ports. Each port can be designated for either input or output by writing an appropriate control command to the control register. In this measurement system Port A and

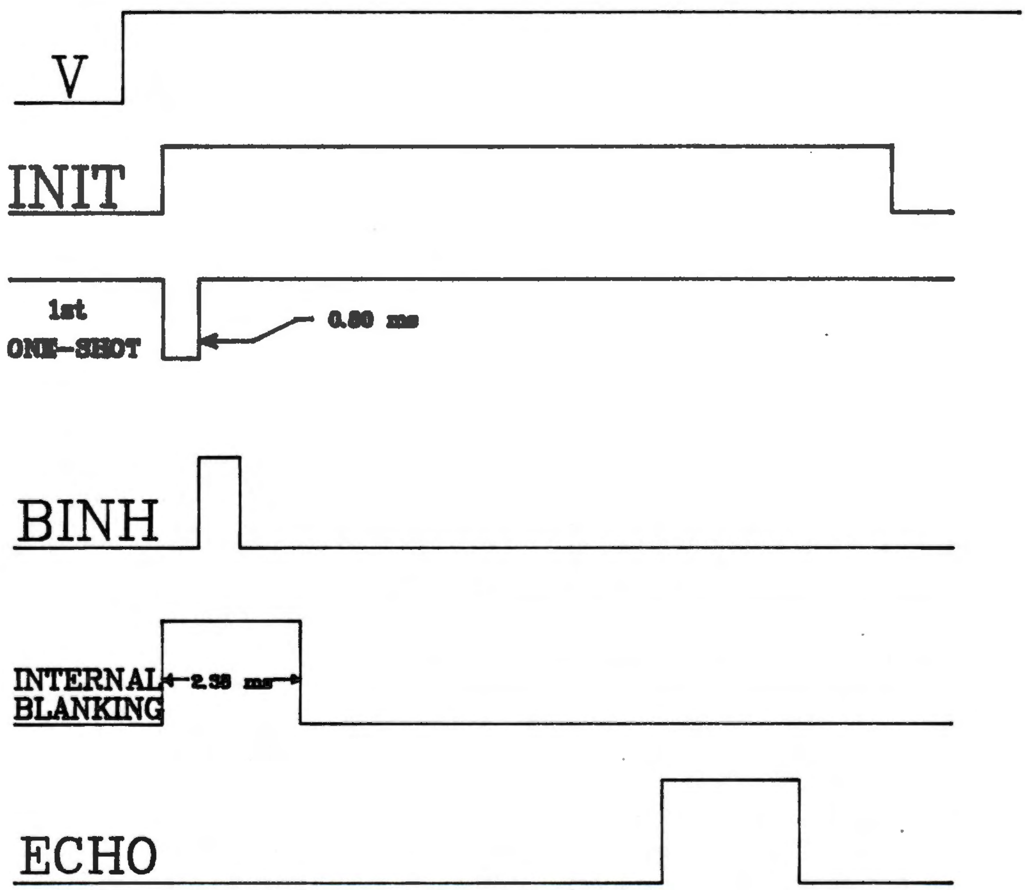


Figure 8. Timing diagram of the ultrasonic ranging system after blanking inhibition showing BINH goes high prior to 2.38 ms.

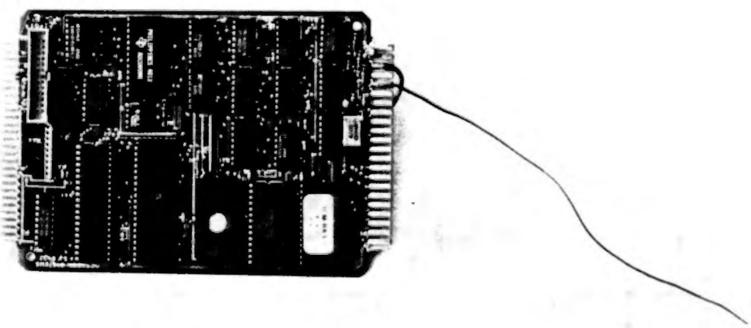

Figure 9. Photograph of the Single Board Computer used in the measurement system.

C are set for output, and Port B for input. Port A is the control port which communicates via a 4-to-16 function decoder (Figure 6) with any of 12 associated devices (7 ultrasonic sensors, the ultrasonic ranging system, the input keypad, the counter circuit for the optical incremental encoder, the counter for sensor data, and the data latch). Port B is the data input port. Through Port B the SBC reads the data from the optical incremental encoder, the counter for sensor data and the keypad. Use of Port B for multiple inputs is accomplished by operating the port as a "data bus" with Port A providing control lines for selecting inputs to use the bus. Port C is used as the data output port. After data processing, the SBC outputs all results to the display unit through Port C.

The SBC uses OEM-BASIC developed by Robasic Corporation (Octagon System Corporation, 1986). OEM-BASIC was specifically written for real-time control and data acquisition. It is similar to the Basic languages found on personal computers. However, it runs faster than "business" BASIC. All OEM-BASIC programs may be stored and run from EPROM as well as RAM. A program run from EPROM frees all but 512 bytes of RAM for other uses.

## Interface Design

### Forward Distance Measurement

An optical incremental encoder is used as a position sensor to determine the horizontal interval between sample collections (Wilkerson et al., 1986). This encoder uses a light emitting diode and a photodetector. The resolution is 512 increments per 360 degree shaft rotation. It operates at 5 volts and generates a TTL binary output. The encoder is housed in a heavy duty case (Figure 10).

The optical incremental encoder produces two output signals which are 90 degree out of phase. If the direction of rotation of the encoder shaft changes, the output pulses will change 180 degree in phase (Figure 11). As shown in Figures 11 and 12, a D-type flip-flop (74 family) is used to latch the logic level on output A by triggering on the rising edge of output B. Then, output B is connected to the clock line of the SN74LS191 counter circuit. Output of the D-type flip-flop is used as the direction line to connected with an up/down line of the counter. If the encoder shaft rotates in clockwise, the counter circuit counts down. If the encoder shaft turns in counterclockwise, the counter circuit counts up (Wilkerson et al., 1986).

The counter circuit for interfacing the optical incremental encoder is composed of a 4-bit up/down counter and a SN74LS244 buffer. When the measurement begins, the 4-

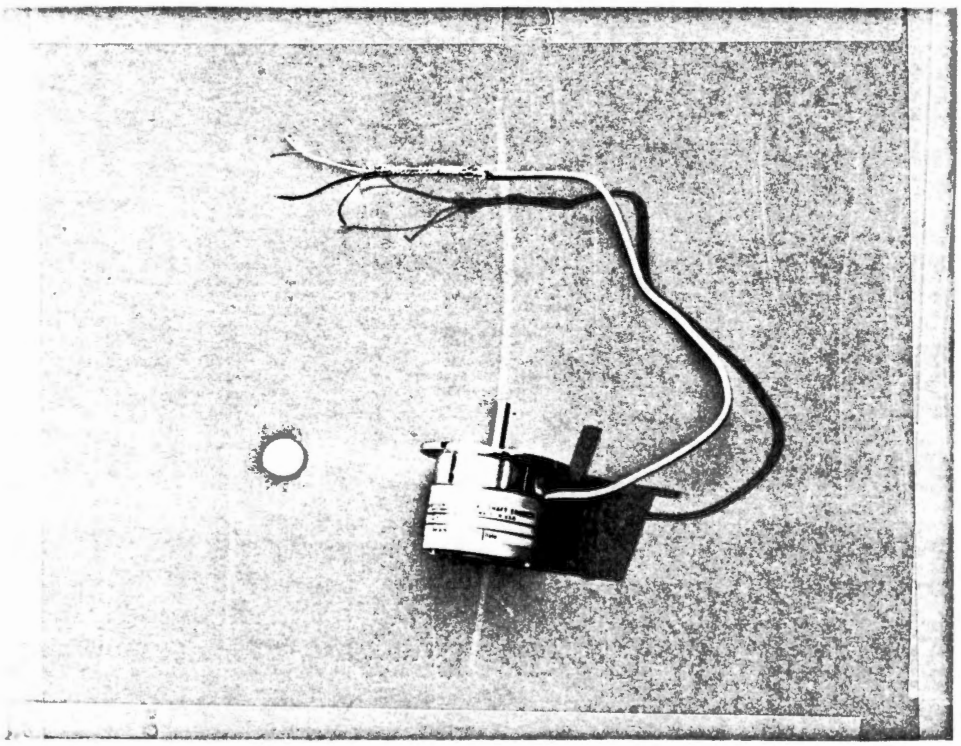

Figure 10. Photograph of the optical incremental encoder.

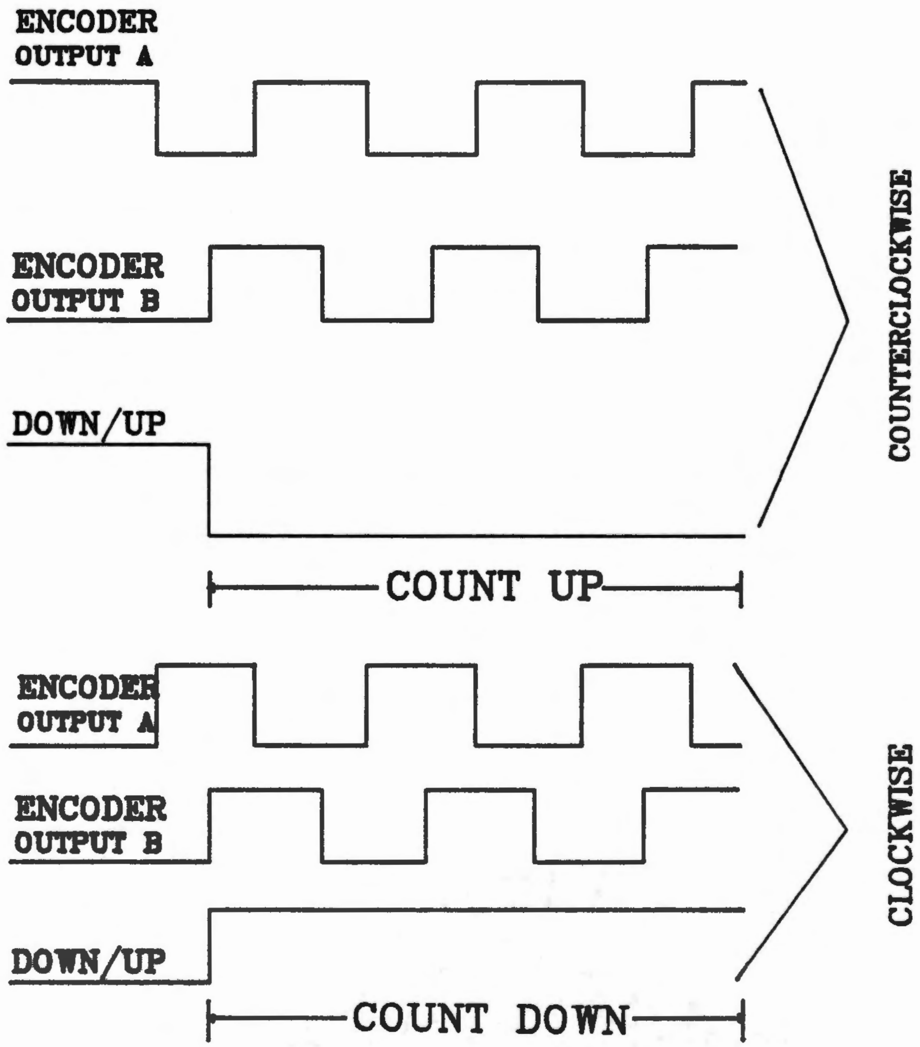


Figure 11. Digital output from the optical incremental encoder during clockwise and counterclockwise shaft rotation.

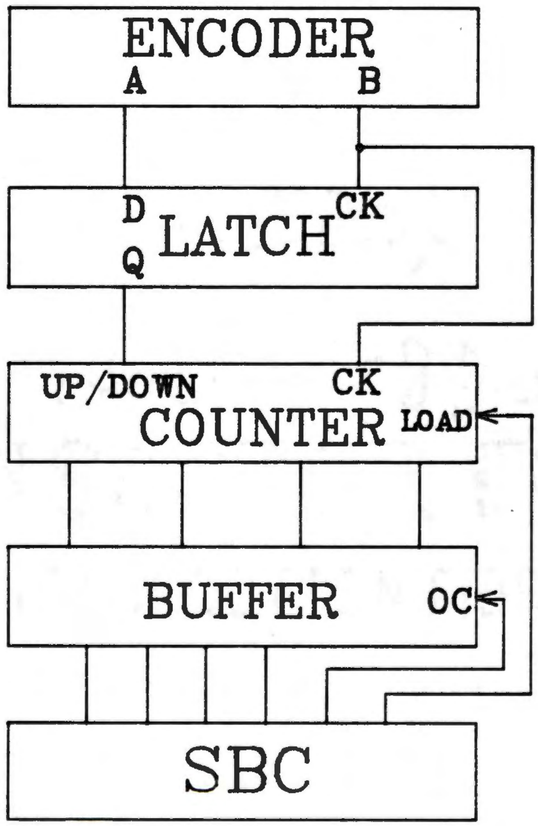


Figure 12. Interface of the optical incremental encoder to the SBC.

bit counter sequentially receives pulses generated by the optical incremental encoder until a pulse from the SBC latches the data from the counter. The data latch retains the binary value which represents the number of pulses received since the last reset. In this measurement system the horizontal interval between data collections is set at 31.1 mm.

Electronic Switching Between Sensors

To reduce cost, seven ultrasonic sensors share a single ultrasonic ranging module. Electronic switches and relays are designed on the interface board to connect the ultrasonic sensors with the ultrasonic ranging module (Figure 13). The SN74L154 function decoder controls the electronic switches by latching one of seven D-type flip-flops (74 family). Upon selection by the decoder, an ultrasonic sensor is connected to the ranging module and fired. When an echo is received, that sensor is disconnected from the ranging module by opening the corresponding electronic switch. If no echo is received in about 0.01 second (sufficient time for the echo to be received from a surface 1750 mm away), the electronic switch connects the next ultrasonic sensor to the ranging module. This process is continued until all ultrasonic sensors have been triggered.

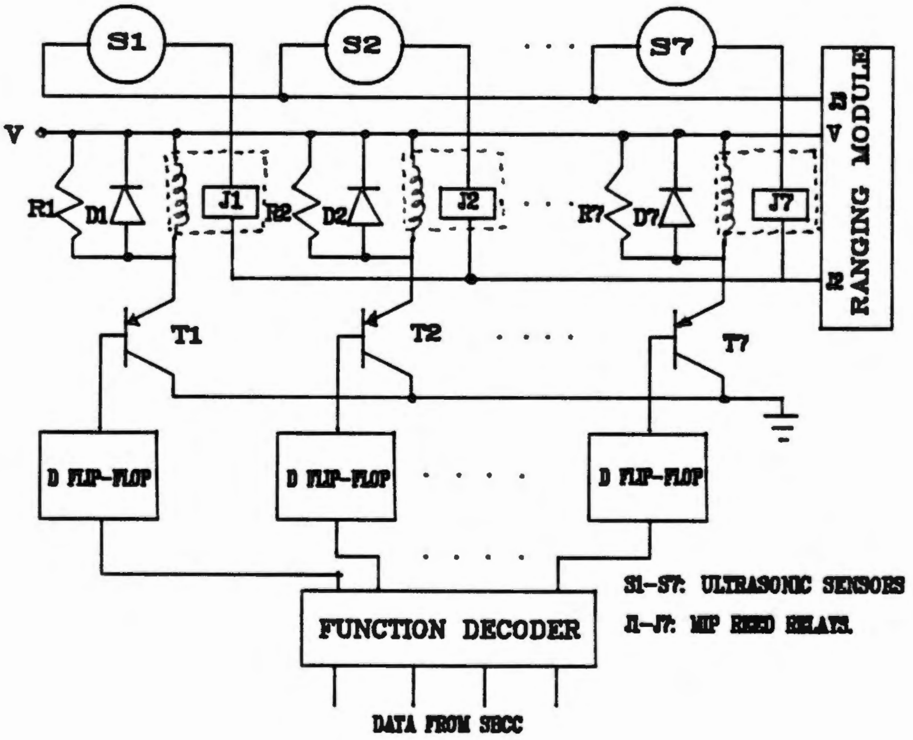


Figure 13. Circuit showing electronic switching to control seven sensors with one ranging module.

Data Acquisition

The distance from the ultrasonic sensor to the plant row surface can be computed by using the following equation:

$$D = Q * S / F \qquad (3-1)$$

where

D = distance from the sensor to the surface of the plant row (mm);

Q = reading value of the counter (pulses);

F = clock frequency (pulses per second);

S = sound speed (mm per second).

The data acquisition circuit (Figure 14) is designed around a clock generator to measure the distance from the ultrasonic sensor to the surface of the plant row. A 50-KHz clock is obtained by using the RDD104 clock chip and a synchronous 4-bit counter. To provide the time base, A 1-MHz external crystal is used with the clock chip.

The output of the clock circuit is connected with the inputs of two SN74LS160A 4-bit synchronous counters. The "enable" pin on the least significant nibble of the counter circuit is connected to the output of the D-type flip-flop (74 family) (Figure 14). When the ranging module is triggered by the initiation signal (INIT), this D-type flip-flop is initiated by the function decoder. This causes the output line of the D-type flip-flop to go high, enabling the counters to start summing the pulses from the clock circuit. When the ECHO signal is received, the D-type flip-

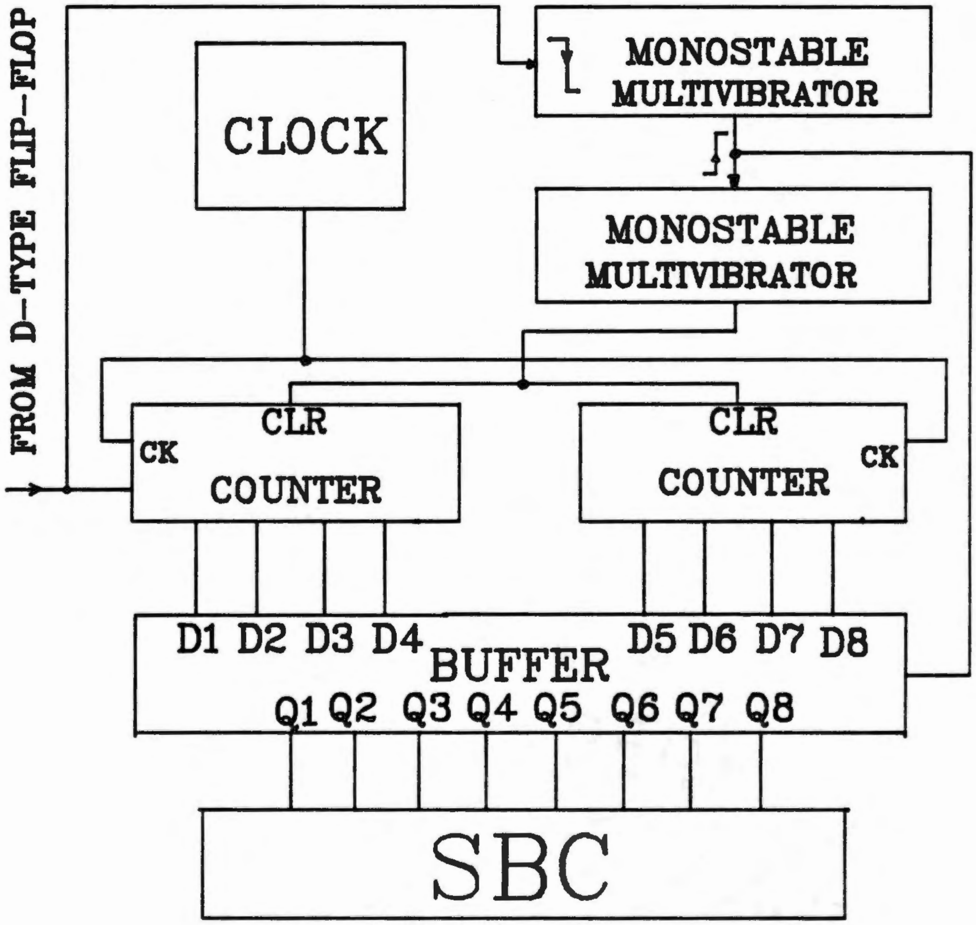


Figure 14. Ultrasonic sensor data acquisition circuit.

flop outputs low, and the counters are stopped. The number, between 0 and 255, stored in two 4-bit counters, is a measure of the time required for the ultrasonic signal to travel round-trip between the ultrasonic sensor and the surface of the plant row. The distance between the sensor and the surface of the plant row can then be easily computed by Equation (3-1).

The number held by the counter circuit must be stored as soon as possible so that another sample collection can be made. This storage is initiated by latching the output of the counters into an SN74LS373 8-bit tri-state latch. The counters are then cleared, permitting the measurement process to be repeated. The SBC can read the value stored in the latch any time before the next ultrasonic echo signal is received.

The function of latching the output and clearing the counters is realized by using two SN74LS221 monostable multivibrators (Wilkerson et al., 1985). The output line of the first monostable multivibrator is connected to the "enable" line of the 8-bit tri-state latch. The output line of the second monostable multivibrator is connected with the "clear" line of the counters. On the falling edge of the output of the D-type flip-flop, the first monostable multivibrator gives an active low pulse (Figure 15). This pulse will latch the output of the counters into the tri-state latch. The rising edge of the first monostable

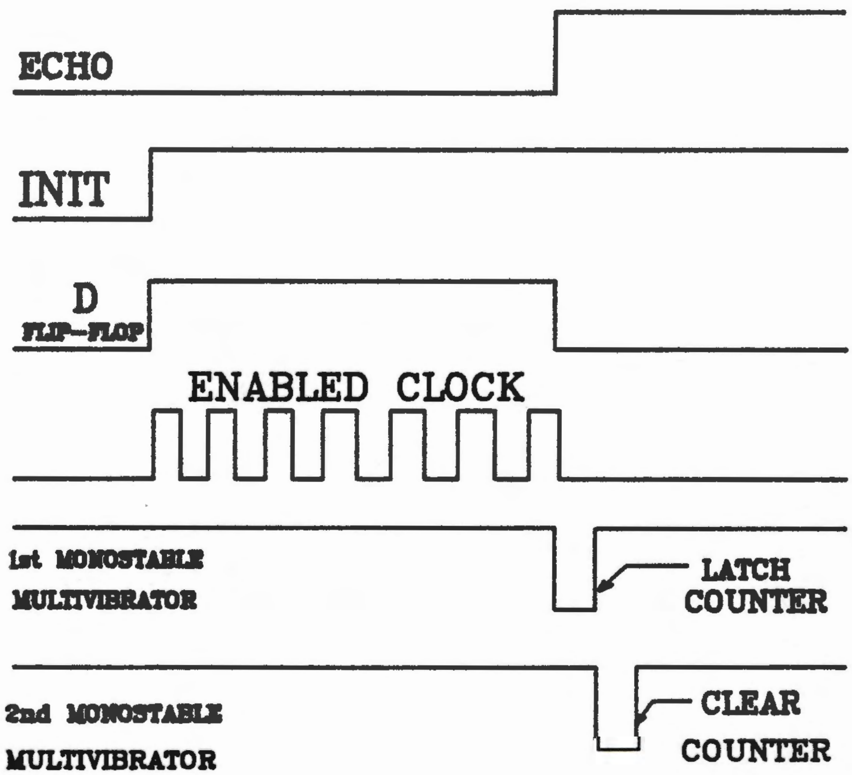


Figure 15. Timing diagram for ultrasonic sensor data aquisition system.

multivibrator triggers the second monostable multivibrator which in turn provides a active low pulse to clear the counters. The entire procedure can then be repeated for another sampling.

Keypad Unit

Control input to the computer is accomplished using a 3 x 4 matrix keypad manufactured by Grayhill (Peatman, 1980). The interface circuit for the keypad is shown in Figure 16. When reading the keypad, the SBC activates one keypad row at a time via the command port (Port A). Port B is then used to read the columns for a depressed key. Each key on the keypad is assigned to perform one function. The function assignments for these keys are as follows:

RST — Reset the measurement system.

W(0-9) — Input the set-up width.

H(0-9) — Input the set-up height.

TEST — Initiate a measurement.

STOP — Stop the measurement.

VOL — Display the volume of plant row measured.

MAX — Used in conjunction with the HGT and L# keys to display the maximum values of the widths and height of the plant row.

AVG — Used in conjunction with the HGT and L# keys to display the average values of the widths and height of the plant row.

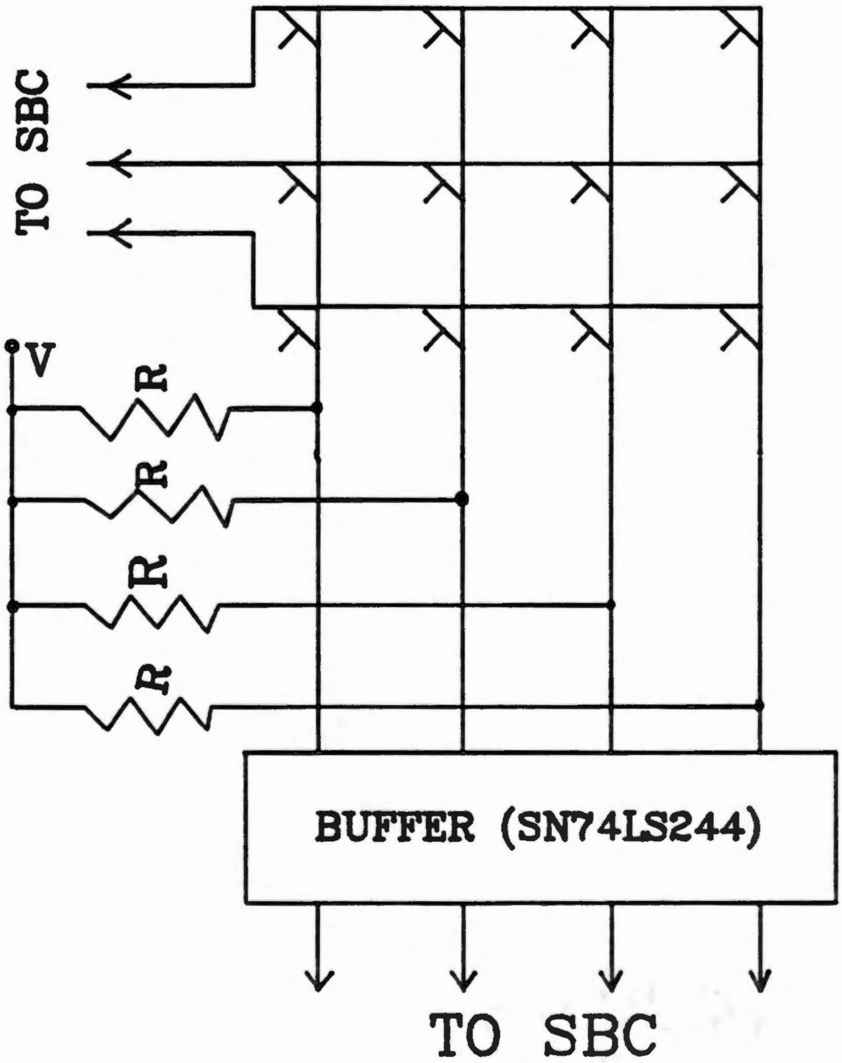


Figure 16. Interface of keypad to the SBC.

HGT Display the maximum and average height of the plant row when used with the MAX and AVG keys respectively.

L#1 Display the maximum and average widths of the plant row at the first level when used with the MAX and AVG keys respectively.

L#2 Display the maximum and average widths of the plant row at the second level when used with the MAX and AVG keys respectively.

L#3 Display the maximum and average widths of the plant row at the third level when used with the MAX and AVG keys respectively.

Display

The display unit is interfaced to Port C of the SBC (Figure 17). This unit consists of a 3 1/2 digit liquid crystal display (LCD) manufactured by Epson, Inc., four BCD-to-7-segment latch/decoder/drivers, and an oscillator. Measured data and operator input parameters are displayed on this unit.

The BCD-to-7-segment latch/decoder/driver is a chip specifically made for LCD operation. The BCD data from Port C of the SBC, applied to the inputs of these chips, are latched into the internal flip-flop when the "load" input is high. If the input data changes while the "load" line is high, the flip-flops will follow the input data. When the

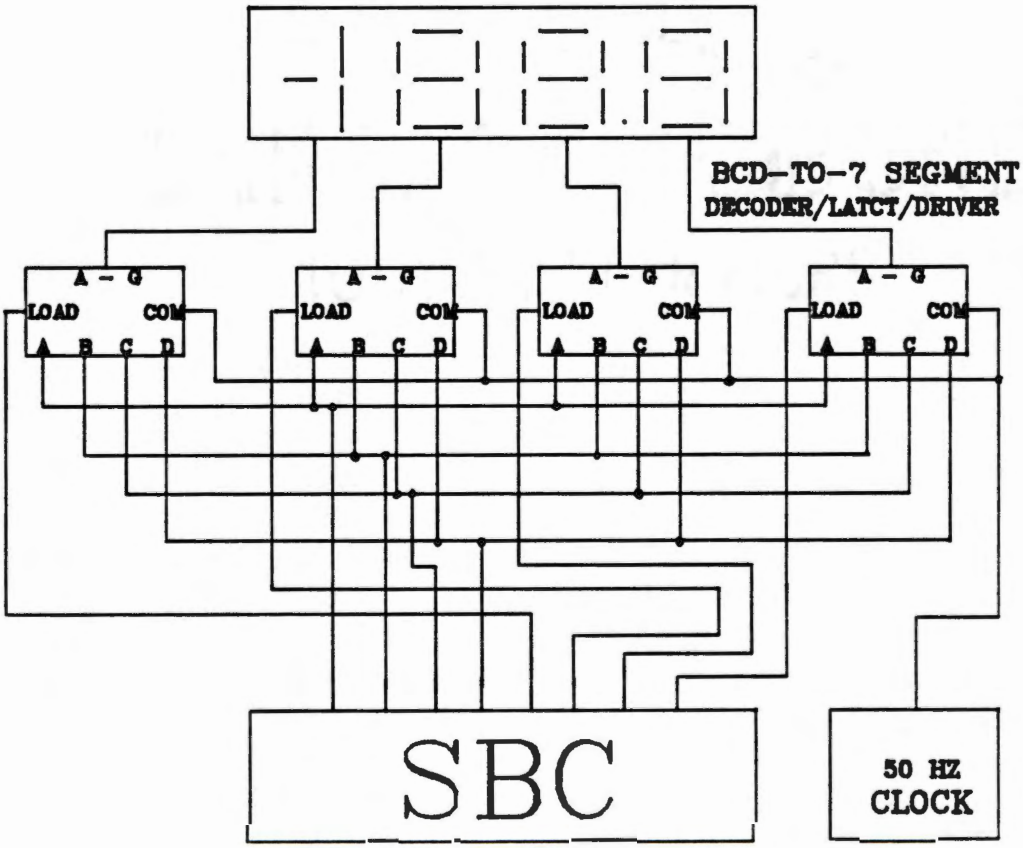


Figure 17. Schematic of LCD display unit with associated components.

"load" is low, the inputs are isolated from the flip-flops. The latched data are decoded to 7-segments to control the opening and closing of the segment switch outputs. Each BCD to 7-segment Latch/Decoder/Driver has its own "load" line which is activated by Port C of the SBC.

To provide an AC signal for the LCD, an oscillator was designed to generate a square wave with an amplitude of 0 to 5 volts and frequency of 50 Hz. The oscillator is composed of two CMOS NAND gates, a resistor and a capacitor.

## Mechanics

### Cabinet

An aluminum cabinet (Figure 18) was constructed to house the interface board, display board, and the SBC. Six edge card guides and three edge card connectors are used inside the cabinet to support the boards and provide the connection for communications between the boards.

The SBC is installed in the bottom of the cabinet. The interface board (Figure 19) is placed between the SBC and display board which is mounted directly below the cabinet top (Figure 20). The LCD and the keypad are mounted on the display board (Figure 21). Two openings cut in the top of the face plate allow installation of the display and keypad.

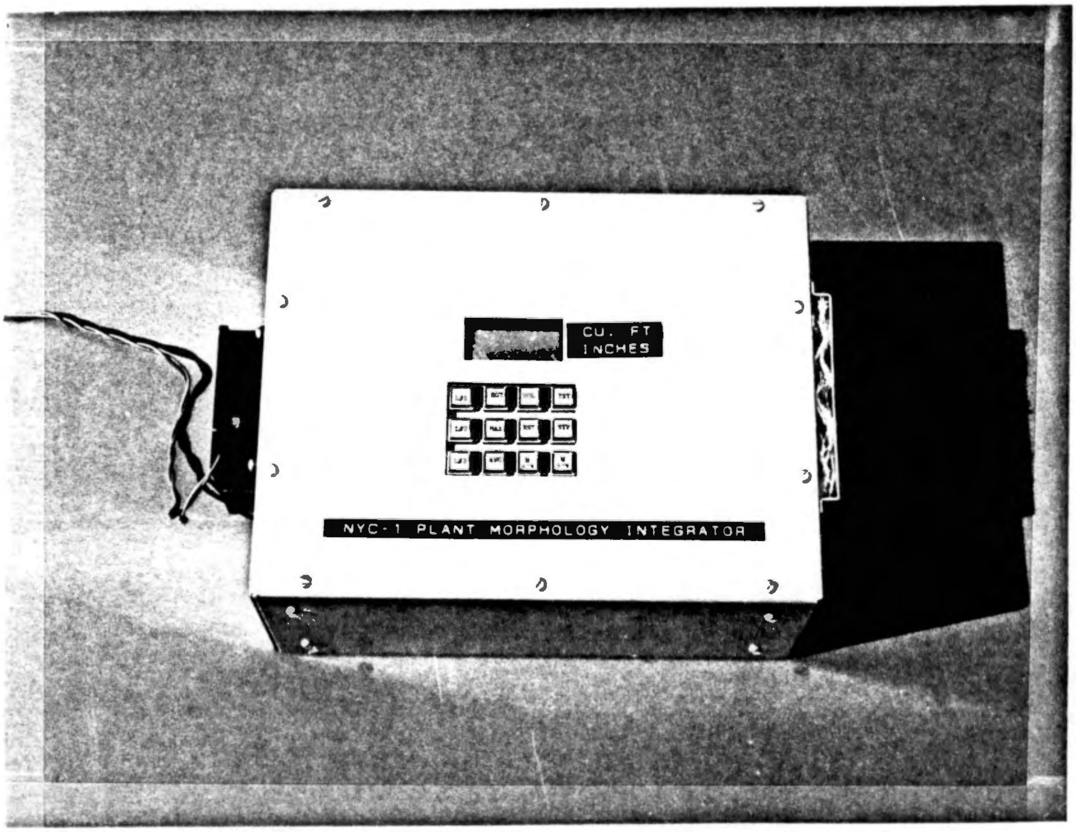


Figure 18. Electronic cabinet showing placement of LCD display unit and keypad.

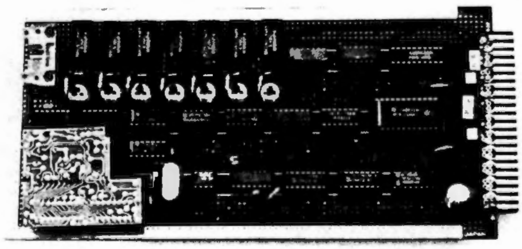

Figure 19. Interface board of the measurement system.

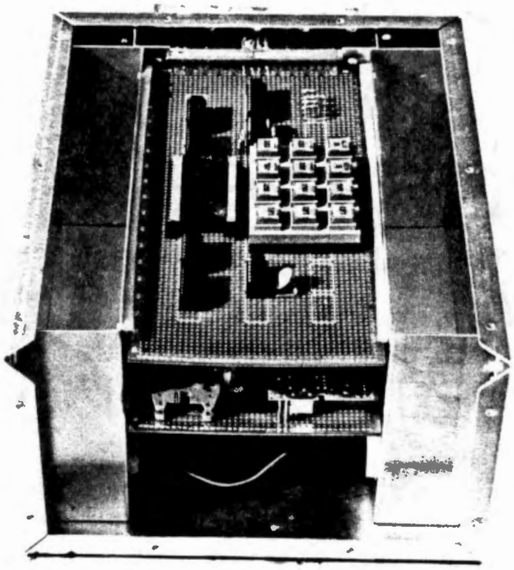

Figure 20. Electronic cabinet showing placement of the display board and interface board. The SBC board, not visible in this photograph, is located directly below the interface board.

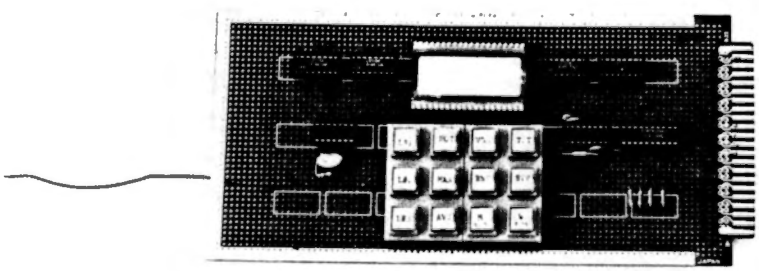

Figure 21. Display board showing placement of LCD unit and keypad.

The digital signals from the ultrasonic sensors and the incremental optical encoder are transmitted via shielded cables. These shielded cables are connected with the electronic components inside the cabinet by using two connectors mounted on the back of the cabinet.

A power supply provides +5 volts DC for the operation of the measurement system, and +12 volts DC for the cooling device. A power regulator (Figure 22) was constructed to convert the 12 volts provided by the rechargable battery supply to 5 volts. A cooling device, discussed later, is directly connected with the battery of 12 volts DC.

Support Cart

A special cart (Figure 3) was constructed for supporting the electronic components, rechargable battery and ultrasonic sensors. The cart, 1200 mm long and 1000 mm high, consists of a frame supported by three wheels. The two front wheels are 508 mm in diameter. The rear pivot wheel is 180 mm in diameter. The width of the cart is adjustable between 625 mm and 1050 mm to satisfy different plant row spacings. Seven ultrasonic sensors are mounted on the frame with three of them on the each side and one on the top (Figure 23). To adjust the sensors vertically, holes are made on the both sides of the frame at a spacing

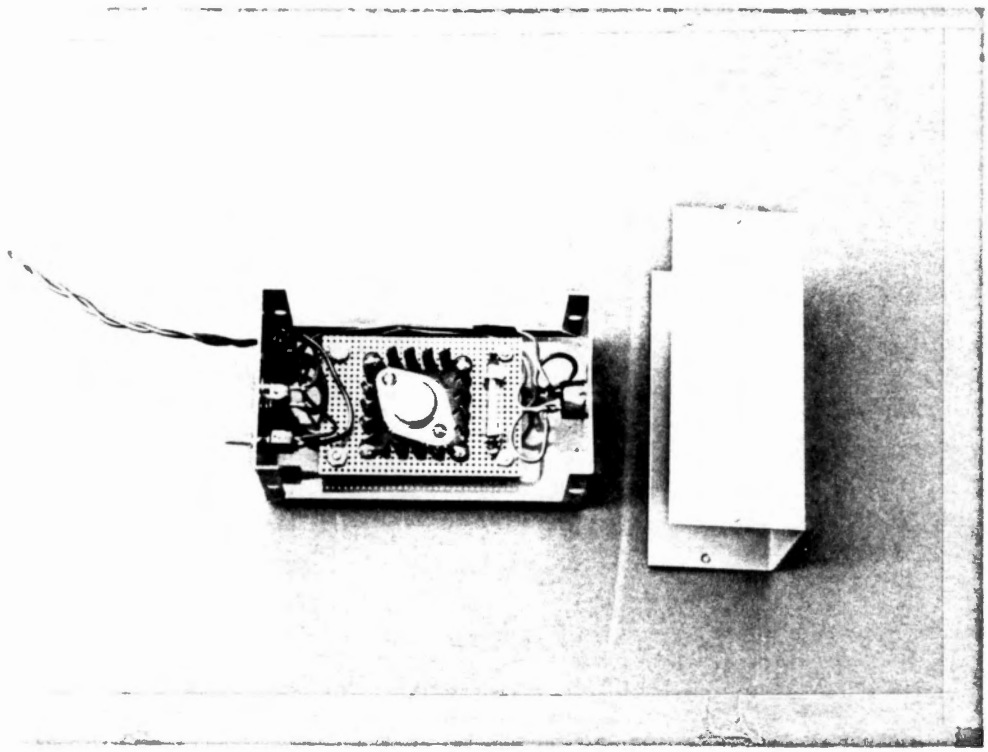

Figure 22. Power regulator.

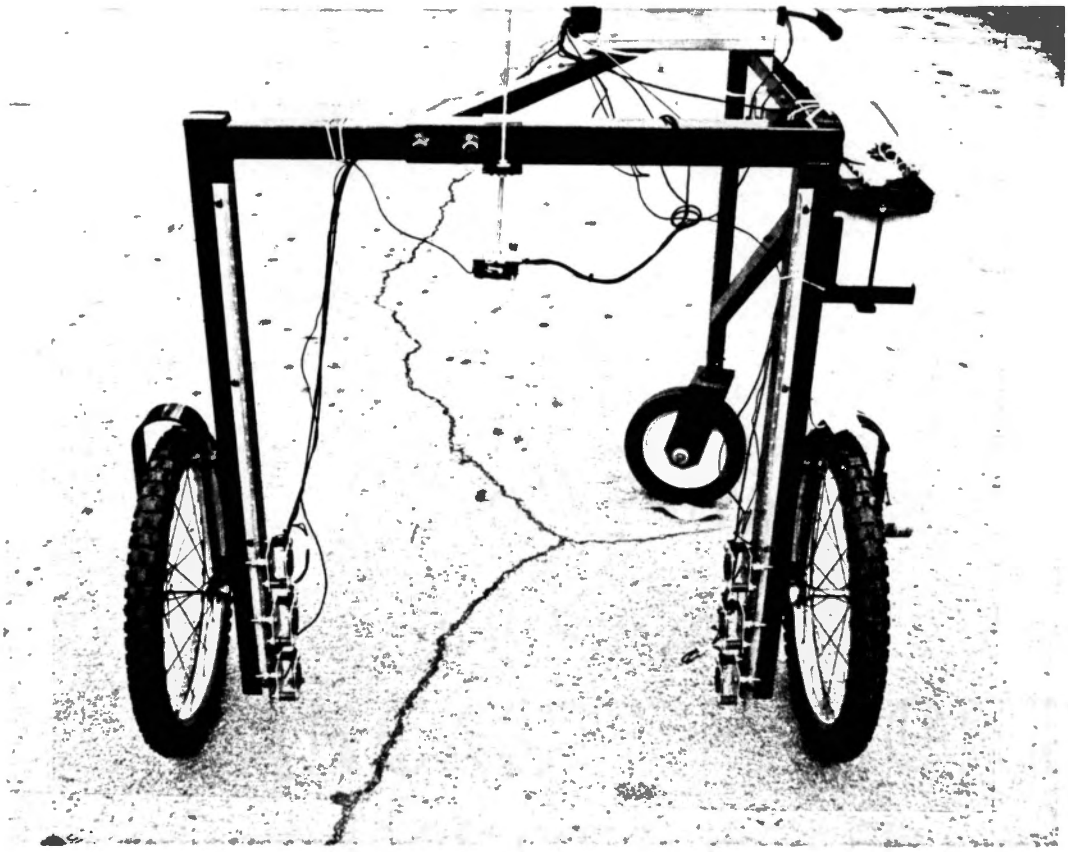

Figure 23. Front view of the plant morphology integrator showing sensor frame and placement of sensors.

of 25 mm. The incremental optical encoder is mounted beside the left front wheel.

## Temperature Control

After preliminary tests in the laboratory, the measurement system was tested on the Plant Science Field Laboratory Farm of The University of Tennessee. Initially, the system worked well; However, after 30 minutes, it began to produce erratic results.

It was found that the erratic results were caused by high temperature in the cabinet. When the environmental temperature was above 33 degree centigrade, the combination of heat from direct sunlight and heat generated by electronic chips inside the cabinet resulted in a temperature too high for proper operation of electronic components in the measurement system.

To solve the temperature problem, a fan was installed on one side of the cabinet (Figure 24) to provide forced ventilation. A filter on the opposite side prevented dust from entering the cabinet. The fan, manufactured by Tandy Corp., required 0.15 AMP at 12 VDC. With this cooling method, the measurement system was satisfactorily tested under an environmental temperature of 36 °C for two hours. Additionally, continuous field operation for up to 6 hours verified satisfactory performance of the cooling device.

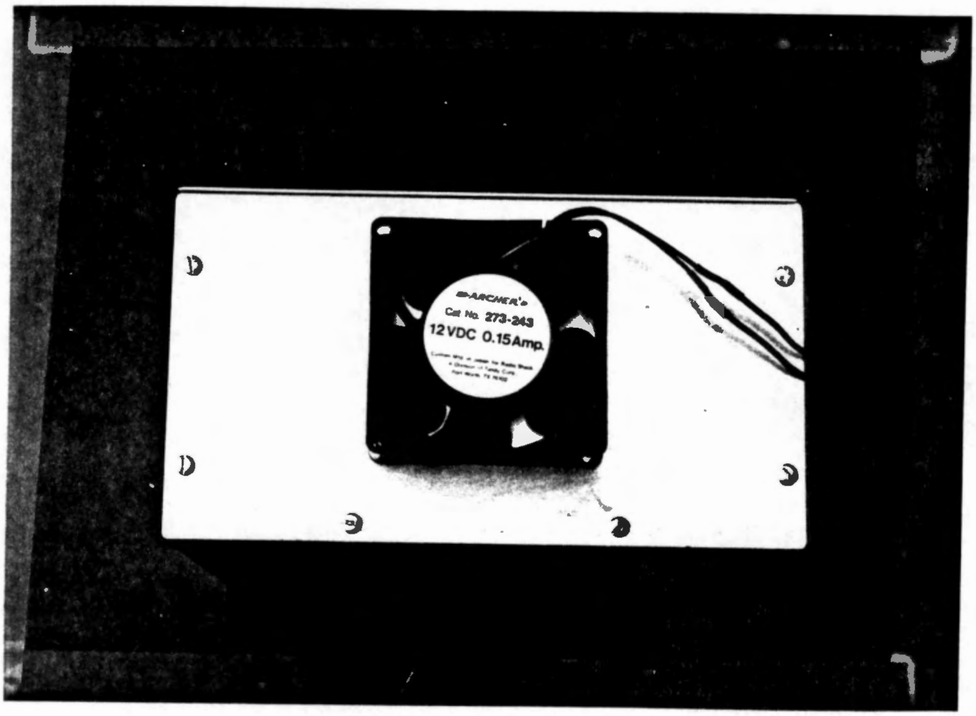


Figure 24. Fan mounted on the electronic cabinet.

# CHAPTER IV

# SOFTWARE

## Introduction

Software to control operation of the system was written in a ROM-based language devoloped by ROBASIC Corporation specifically for control and data acquisition applications. After development and testing, the software was permanently stored in EPROM on the SBC. Program execution is done from the EPROM, leaving the RAM for data storage.

The program is composed of 14 subroutines, including the MONITOR subroutine, the TEST subroutine, DISPLAY subroutine, two parameter inputs subroutines, and eight subroutines for measured data computations. The display subroutine can be called when it is needed. The complete program is listed in the Appendix B, C, D, and E.

## MONITOR Subroutine

When power is initially supplied to the system, the SBC automatically begins to execute the MONITOR subroutine. The MONITOR subroutine monitors the keypad for command inputs and responds with appropriate actions. A flowchart of this subroutine is shown in Figure 25. Initialization of parameters, starting and stopping tests, and display of measured data are performed by this routine.

## TEST Subroutine

Subroutine TEST is one of the major elements of the program. The flowchart of this subroutine is shown in Figure 26. Subroutine TEST can be initiated by pressing the TEST key on the keypad. This subroutine performs the actual data acquisition and storage for the system. The storage capacity is 7,000 data values. If the STOP key is pressed or if 1000 data scan cycles (7,000 data values) have been completed, The execution of TEST subroutine will be stopped, and program execution will revert to the MONITOR subroutine.

## Parameter Input Subroutines

Two parameter input subroutines are included in the software. One, initiated by pressing the W(0-9) key on the keypad, is used for input of the width setting. The other, initiated by pressing the H(0-9) key inputs the height setting. The value of the setting, incremented at a rate of 3 per second during the setting process, is shown on the display and stored in memory. The upper limits of both the width and height settings are 1,700 mm. If the operator

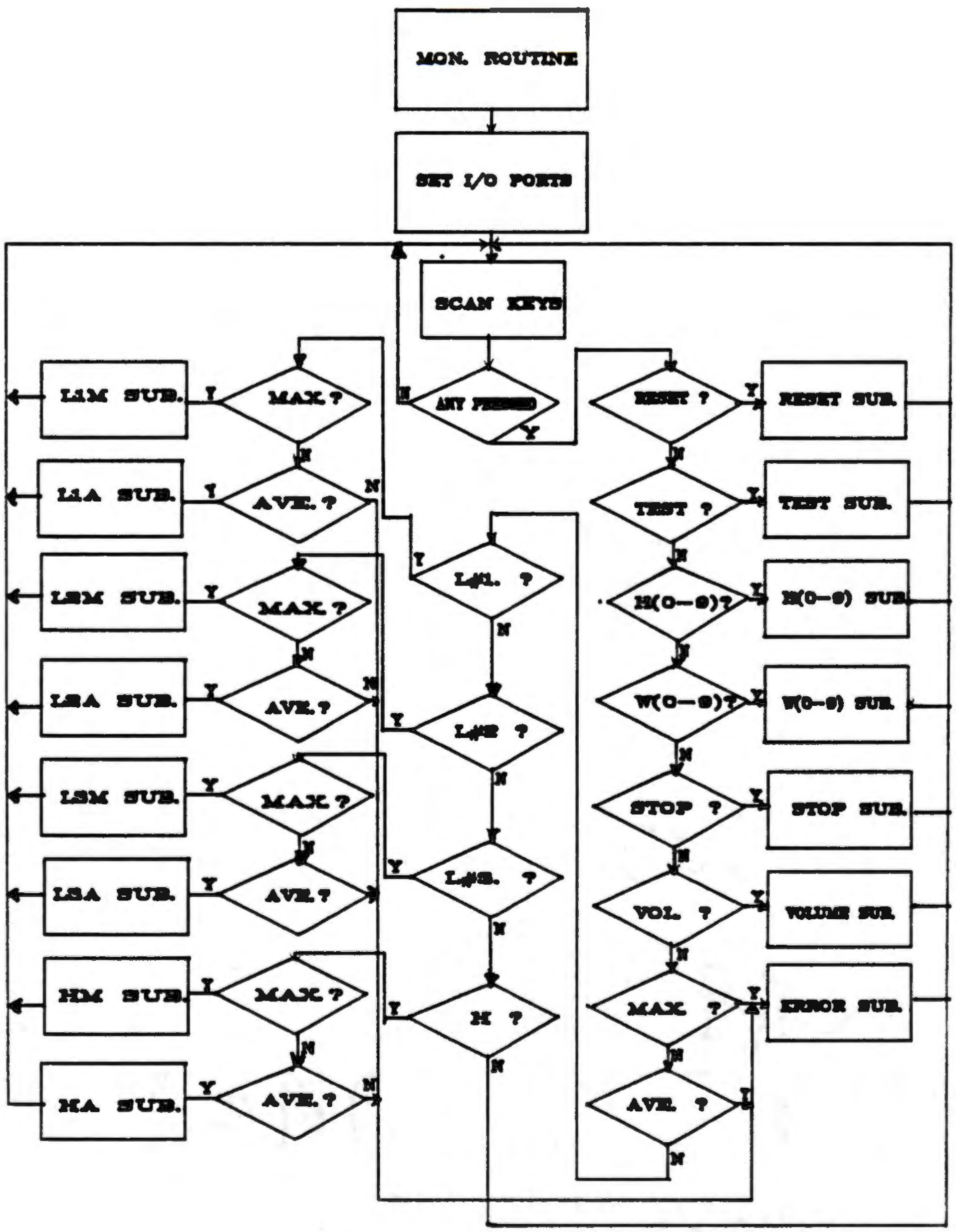


Figure 25. Flowchart for Monitor Program.

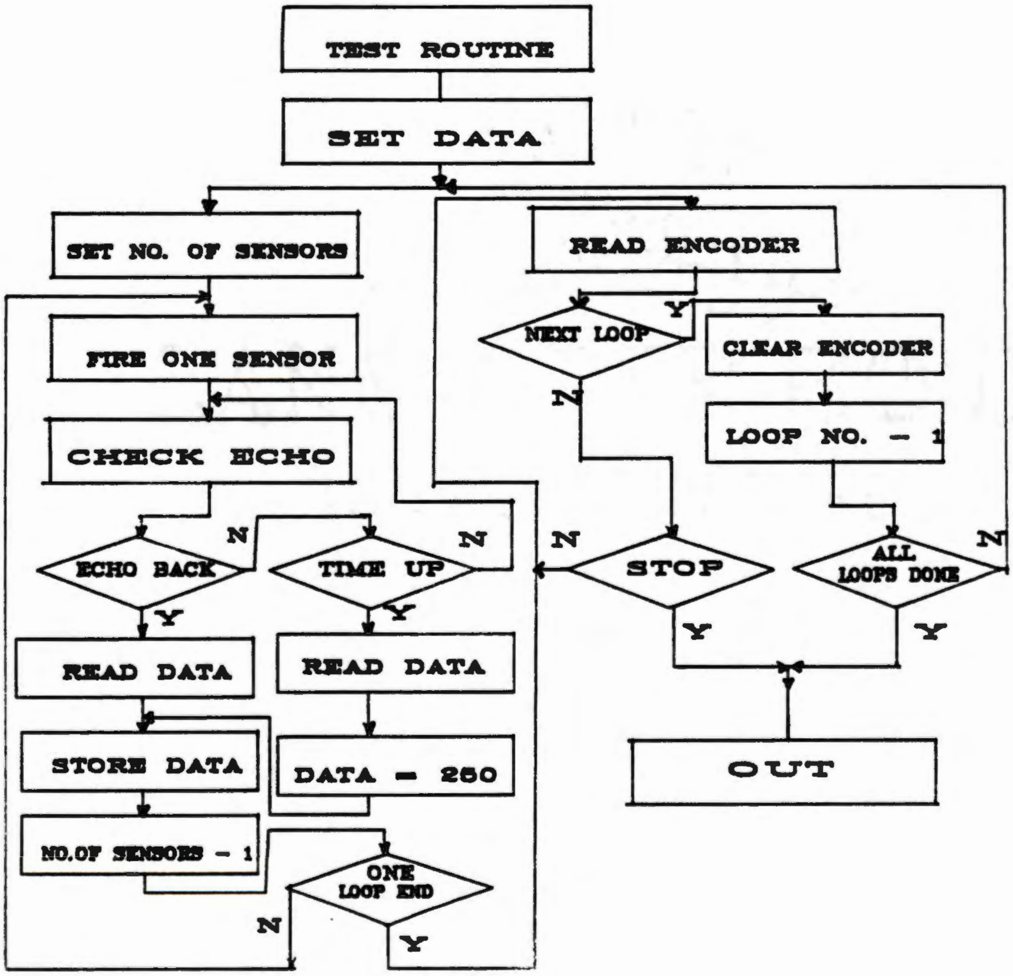


Figure 26. Flowchart for Test Subroutine.

attempts to increment the value over the upper limit, it will be reset to zero and the incrementing process will continue.

## Computation Subroutines

When the test is completed by pressing the STOP key, all of data collected has been stored in memory. The system is then ready for the computation of plant morphology data.

The cumulative plant volume is the major parameter of interest. It is computed by using the equation:

$$V = L * \sum_{n=1}^{N} A_n \qquad (4\text{-}1)$$

where

$A_n$= the cross section area of location n (Figure 1), given by

$A_n=((H_0-H_{7n})/4)(3W_0-(W_{a1n}+W_{a2n}+W_{a3n}+W_{b1n}+W_{b2n}+W_{b3n}))$,

L = the sampling interval,

N = the number of row cross sections measured,

$W_0$= the width setting,

$H_0$= the height setting,

$H_{7n}$= the measured distance from the top sensor to the surface of the plant row at location n, and

$W_{ijn}$= the measured distances from the sensors to the surface of the plant row at side i and elevation j at location n.

This computation represents each cross section of the plant row by a combination of two parallelograms and two triangles (from the $W_1$ level to the top of the plant and from the $W_3$ level to the ground). Other shapes could have been assumed; however, this formula offered a good volume approximation for the bush-type plants of interest in this study.

The following equations are used in the computation subroutines for the calculations of the height and the average widths at three vertical positions of the plant row.

$$H = 1/N \sum_{n=1}^{N} (H_0 - H_{7n}) \qquad (4\text{-}2)$$

where

H = the measured average height of the plant row.

$$W_1 = 1/N \sum_{n=1}^{N} (W_0 - (W_{a1n} + W_{b1n})) \qquad (4\text{-}3)$$

where

$W_1$ = the measured average width of the plant row at level 1.

$$W_2 = 1/N \sum_{n=1}^{N} (W_0 - (W_{a2n} + W_{b2n})) \qquad (4\text{-}4)$$

where

$W_2$ = the measured average width of the plant row at level 2.

$$W_3 = 1/N \sum_{n=1}^{N} (W_0 - (W_{a3n} + W_{b3n})) \qquad (4\text{-}5)$$

where

$W_3$ = the measured average width of the plant row at level 3.

## DISPLAY Subroutine

The DISPLAY subroutine is used for communication between the display unit and Port C of the SBC. The lower 4-bits of Port C output a BCD value to the display data bus while the upper 4-bits select the digit to receive the data. In this subroutine the binary datum from the memory is converted into tenths, units, tens and hundreds. Then, each of these data is combined with digital selection value to form a datum placed on the display data bus.

# CHAPTER V

# SYSTEM OPERATION

Before turning on the system, the positions of ultrasonic sensors should be adjusted for the plant to be measured. The top sensor should be kept directly above the plant row while the three horizontal pairs of sensors (No.a1 and No.b1, No.a2 and No.b2, No.a3 and No.b3) should be located at the vertical positions of interest. To permit accurate measurement, all sensors must be at least 140 mm from the plants.

The power switch of the system is at the back of the cabinet. Upon power up, the MONITOR subroutine is automatically executed. The MONITOR subroutine prepares the system for data acquisition, and contiunously scans the keypad for a depressed key.

Before each test series, the operator must input the height and width settings indicating the ultrasonic sensor positions. These are accomplished by pressing the <u>H(0-9)</u> key and the <u>W(0-9)</u> key respectively. When the operator keeps the <u>H(0-9)</u> key or the <u>W(0-9)</u> key depressed, an incresing number will be displayed on the LCD. When the displayed number reaches the desired value, the key is released. The value displayed by the LCD is also stored in the memory. The height and width settings are necessary for the system to compute the plant morphology data. The system is ready for testing after these settings have been made.

Testing is initiated by pressing the TEST key on the keypad. Data acquisition continues until the STOP key is depressed or 1000 data scan cycles have been completed. This is equivalent to measurements taken at 31-mm intervals over a row length of 31 meters.

The first scan is initiated immediately when the TEST key is pressed. The seven sensors are fired sequentially. The SBC continuously reads the encoder counter, which indicates the travel distance, and compares the value of the encoder counter to the set increment value. When a sufficient distance has been traversed, the scan cycle is repeated. This sequence is followed until the test ends. During the test period the TEST subroutine remains active to determine if a stop command has been issued.

Data from each scan is stored in the SBC memory for processing at the end of the test. Each scan/storage cycle requires approximately 0.04 second. Thus, forward speed affects the scan interval along the row. To achieve the scan interval of 31.1 mm desired for this study, forward speed was limited to 0.6 m/s. While program execution contributes slightly to the delay, the major time limitation is the send/echo cycle for each scanner. The time required to send a pulse and receive the echo is about 0.003 second per meter of distance sensed. A maximum sensing distance of

1.75 m, resulting in a send/echo cycle time of 0.01 second, was used in this study. Exceeding speed of 0.6 m/s will cause erratic volume measurement.

When data acquisition for the row segment is completed, the operator can compute and examine the results by pressing appropriate keys on the keypad. The major parameter of interest is the cumulative plant volume. Maximum and average values for plant width, at each sensor elevation, and plant height are also available.

The following instructions should be followed for examining the plant morphology data.

1. Press the <u>VOL</u> key to obtain the <u>cumulative volume</u> of the plant row;

2. First press the <u>HGT</u> key, then press the <u>MAX</u> key to obtain the <u>maximum height</u> of the plant row.

3. First press the <u>HGT</u> key, then press the <u>AVG</u> key to obtain the <u>average height</u> of the plant row.

4. First press the <u>L#1</u> key, then press the <u>Max</u> key to obtain the <u>maximum width</u> of the plant row at level No. 1.

5. First press the <u>L#1</u> key, then press the <u>AVG</u> key to obtain the <u>average width</u> of the plant row at level No. 1.

6. First press the <u>L#2</u> key, then press the <u>MAX</u> key to obtain the <u>maximum width</u> of the plant row at level No. 2.

7. First press the <u>L#2</u> key, then press the <u>AVG</u> key to obtain the <u>average width</u> of the plant row at level NO. 2.

8. First press the L#3 key, then press the MAX key to obtain the maximum width of the plant row at level No. 3.

9. First press the L#3 key, then press the AVG key to obtain the average width of the plant row at level No. 3.

For a 6-meter row segment test, it takes about 100 seconds for the SBC to perform the computations and the operator to record the data on data sheets.

# CHAPTER VI

# TESTING OF SYSTEM

## Calibration

The value of the sensor data count represents the distance between the ultrasonic sensor and the surface of the plant row. That value is recorded as the count of pulses generated by the oscillator during the transmitting time of the ultrasonic signal. It must be changed to the actual distance measured by using an appropriate conversion. This conversion was determined by measuring known distances and comparing them to the corresponding values of the sensor data counter. The result of the conversion coefficient calculation is shown in Figure 27. The value of the coefficient is 0.2953 count per mm.

## Test procedure

### Laboratory test

The system was initially tested in a series of laboratory experiments which moved progressively from boxes of uniform size to rows of artificial plants placed at various intervals along a row. For all tests, the plant morphology integrator unit was pushed over the row with at

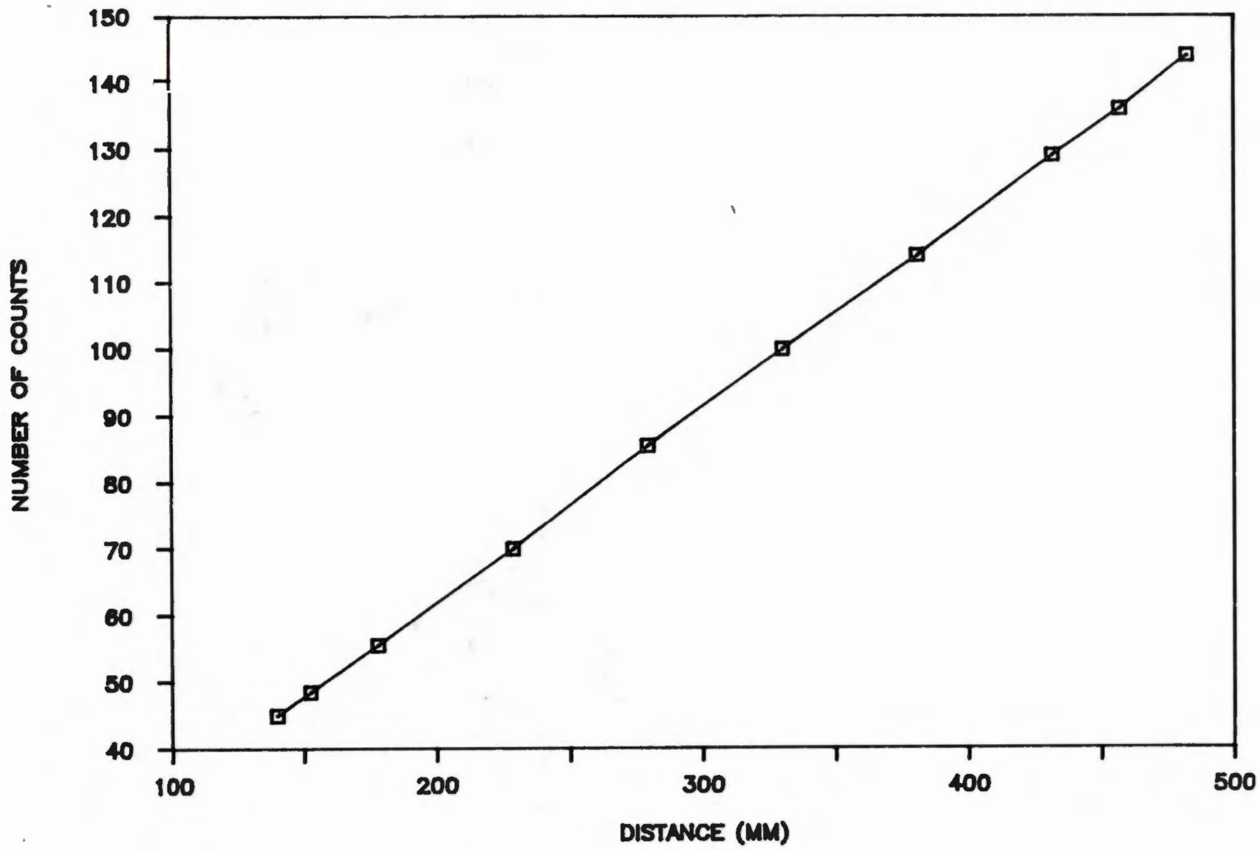


Figure 27. Ultrasonic sensor calibration showing the number of pulse counts versus measured distance. Calibration temperature was 28$^0$C.

least two replications in each direction. The specific row arrangements were as follows:

1. A 1.64-m row of identical cardboard boxes placed end to end.

2. A 2.02-m row of cardboard boxes placed end to end. These boxes ranged from 284 mm to 457 mm in height and 199 mm to 292 mm in width. They were positioned in the row to maximize the variation in size along the row.

3. A 3.66-m row of simulated plants placed at 460-mm increments along the row (Figure 28). These plants were all of the same style; however, they could be individually shaped to conform to a desired pattern. Thus, no two plants were identical in size or shape. The plants had a maximum height and width of approximately 460 mm and 400 mm, respectively. The plant spacing was such that an open space was present between each plant.

4. The same artificial plants used in Test 3 above but spaced at unequal increments along the 3.66-m row. Spacings varied from approximately 380 mm to 530 mm.

5. The plants used in Tests 3 and 4, plus additional plants to provide plant spacing of 230 mm along the 3.66-m row. This spacing eleminated all open space between plants.

Figure 28. System test configuration using artificial plants.

Field test

After being tested in the laboratory, the system was taken to The University of Tennessee Plant Sciences Farm in Knoxville and the Milan Experiment Station of The University of Tennessee for extensive field measurements. Cotton and soybean plant were measured (Figures 29 and 30). Four 6-meter row segments were selected for each type of plant. For each row segment 6 passes over the row were done with 3 passes in each direction. Additional tests were made to test the relationship between the volume of the plant row segment, as measured by the device, against and the weight of plants in the segment. The following tests were conducted in field.

1. Three 6-meter row segments of soybeans on the Plant Science Farm were used for measurements on 2 September 1987. The three row segments had 80, 108 and 99 plants respectively. Some plants were very small, but there were no completely open spaces in the rows.

2. Four 6-meter row segments of cotton were tested on the Milan Experiment Station on 9 September 1987. The cotton was planted on 24 July 1987. The cotton was quite small, and varied greatly in size. Open spaces existed in the rows.

3. Four 6-meter row segments of soybeans were measured on the Milan Experiment Station on 9 September

Figure 29. System test using cotton on Milan Experiment Station, The University of Tennessee, Milan, Tennessee.

Figure 30. System test using soybeans on Milan Experiment Station, The University of Tennessee, Milan, Tennessee.

1987. These soybeans were planted on 14 July 1987. The sizes of the plants varied. Some leaves of the plants had been eaten by deer.

4. Test 2 was repeated using the same plant row segments on 16 and 22 September 1987.

5. Test 3 was repeated using the same plant row segments on 16 September 1987. This test was not repeated on 22 September 1987 due to extensive plant damage by deer.

6. Ten 1.5-meter row segments of cotton characterized as noted for Test 2 were measured, then cut and weighed on 9 September 1987. 3-passes were made for each sample, then averaged to obtain the volume measurement.

7. Ten 1.5-meter row segments of soybeans characterized as noted for Test 3 were tested, then cut and weighed on 9 September 1987. 3-passes were made for each sample, then averaged to obtain the volume measurement.

8. Test 6 and Test 7 were repeated on 16 and 22 September 1987. However, lengths of the row segments were varied from 0.9 meter to 3 meters to obtain variation of the volumes in the row segments.

# CHAPTER VII

# RESULTS AND DISCUSSION

All results of the measuerment system tests both in the laboratory and in the field are included in Appendix A.

Results of the laboratory test using boxes of uniform size (Test 1) are shown in Table 1. The measurements were consistent, showing a maximum variation of 7.6 mm in width measurements. Comparison of the row volume determined by the system to the true value, adjusted to be consistent with Equation (4-1), showed a maximum difference of less than five percent. The difference in the average of six measurements was slightly over one percent.

Results of the maximum measurements from Test 2 (non-uniform boxes) were also very close to the correct values. However, the averages and volume determined by the device were consistently higher than the true values. This difference was due to the conical window of the sensor. Since the window covered an area 15 degrees on each side of the sensor axis (Ciarcia, 1984), each box of a larger size was detected before the sensor axis reached the box, and that box remained detected until the cone had passed beyond it. Thus, the volume, average height, and average widths measured by the device would be increased by an amount proportional to the added dimensions sensed within the cone of view. Results of these measurements are shown in Table 2. Again, the measurements are consistent and in close agreement with the actual values, when adjusted to account for the cone of view. This cone of view could be expected to present measurement problems where step changes in width or height occurred. The effect, while present, would be less pronounced where such changes are gradual. However, the cone avoids the problem of "seeing through" small openings which often occur in actual plants.

Results of the tests with artificial plants are shown in Tables 3, 4, and 5. True volume measurements could not readily be obtained for comparison. Thus, other approaches were used to evaluate the performance of the system. Comparison of the fixed versus variable spacing measurements revealed only slight differences in measured values. Doubling the number of plants (Table 5), thus filling in the empty spaces between plants, doubled the measured volume.

The first field test of the system was conducted on the UTK Plant Science Farm using soybeans. Results of the test are shown in Tables 6, 7, and 8. The measurement consistency was comparable to the laboratory tests.

Tables 9, 10, 11, and 12 show the results of Field Test 2 with cotton. The values of the volume, average height, and average width measured are quite small. The size of the cotton had increased noticably when Field Test 4 was conducted one week later (Tables 13, 14, 15, and 16). The volume increase for the four 6-meter row segments was 43.4 %. The average height increase was 20.2%. The average widths, $W_1$, $W_2$, and $W_3$, increased 51.7%, 14%, and 13.4% respectively. Results shown in Table 17, 18, 19, and 20 were obtained from measurements taken one week after Field Test 4 using the same row segments of cotton. Compared with the data taken in Field Test 4, in this one-week period, the volume increased 26.9%, the average height increased 6.3 %; and the average widths, $W_1$, $W_2$, and $W_3$, increased 18.7 %, 20.5 %, and 21.6% respectively. All measurements of these three tests using cotton were quite consistent.

Results of tests using four 6 meters row segments of soybeans are shown in Tables 21, 22, 23, 24, 25, 26, 27, and 28. The measurements for the first test (Tables 21, 22, 23, and 24) were more consistent than those for the second (25, 26, 27, and 28). The wind was blowing when the second test series was made. The wind moves the plant canopy. Thus, this measurement system would not work correctly when the environment is very windy. Comparing the volume values of the first test with the volume values measured one week later, the volume of these four 6-meter row segments of soybeans did not change much since the soybean plants had achieved near maximum growth when the first test was conducted. Thus, the plants grew very little in the one week period.

Results of Tests 6, 7, and 8 are shown in Tables 29, 30, 31, 32, 33, and 34. The purpose of these tests was to find the relationship between the volume of the plants row and the weight of plant in the row. Figure 31 presents the plots of the total mass versus the total volume for the cotton plants. The data points in Figure 31 appear to show a linear relationship between the total mass and the total volume for cotton plants. The equation of the least square regression line is included on the graph. The correlation coefficient (R square value) for this test is 0.9387 which is quite good. Figure 32 presents similar data for the soybeans. The data for soybeans are somewhat scattered, and the correlation coefficient (R square value) is 0.8160 which is lower than that for cotton. For both cotton and soybeans, the weight generally increased with the volume. However, the correlation is much better for the cotton plants. When these tests were conducted for soybeans, some soybean leaves were damaged by deer, and wind was blowing. That might have affected the correlation. More measurements are needed before determining the exact relationship between the volume and the weight for a specific type of plant.

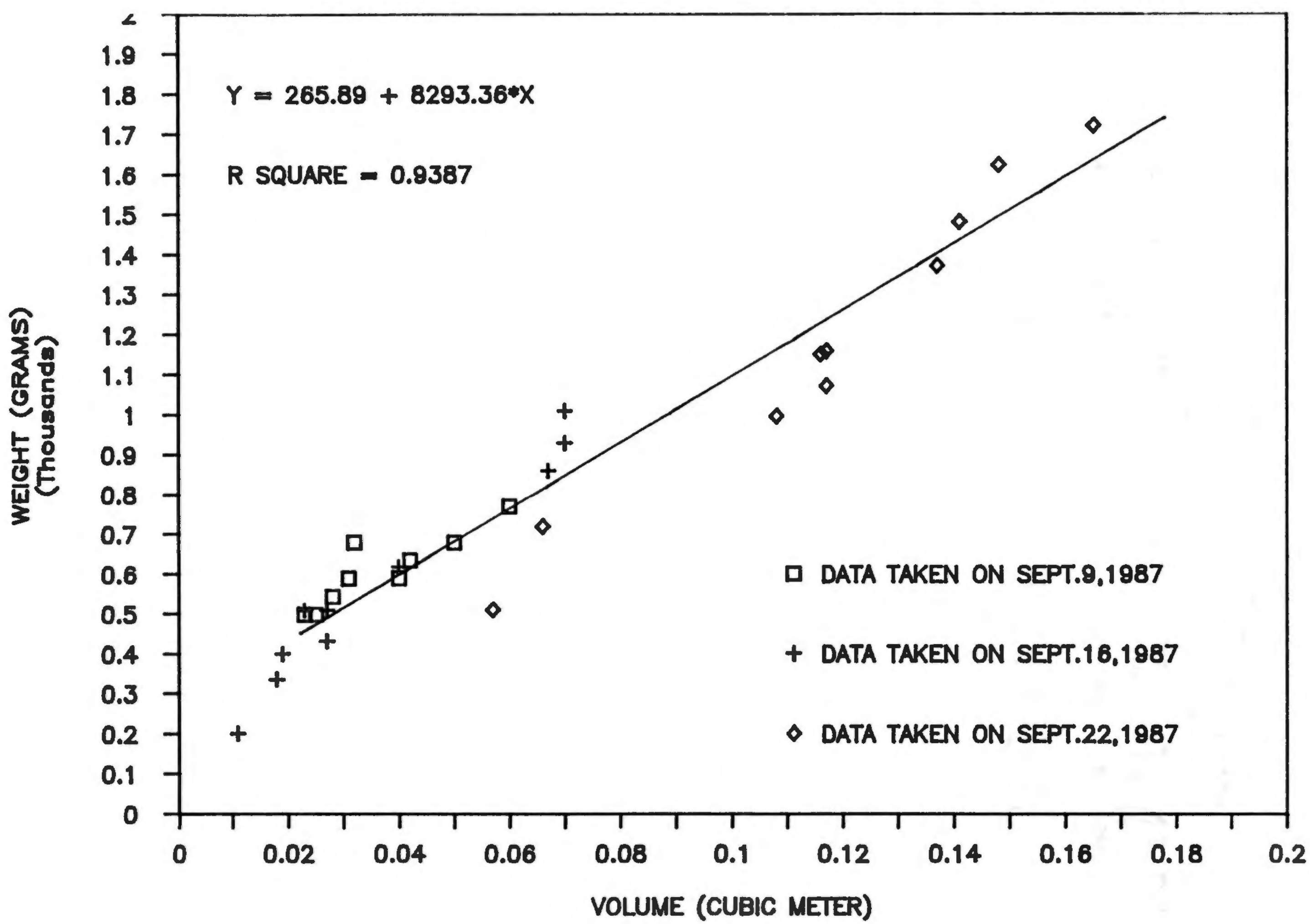


Figure 31. Plots of total mass versus total volume for cotton.

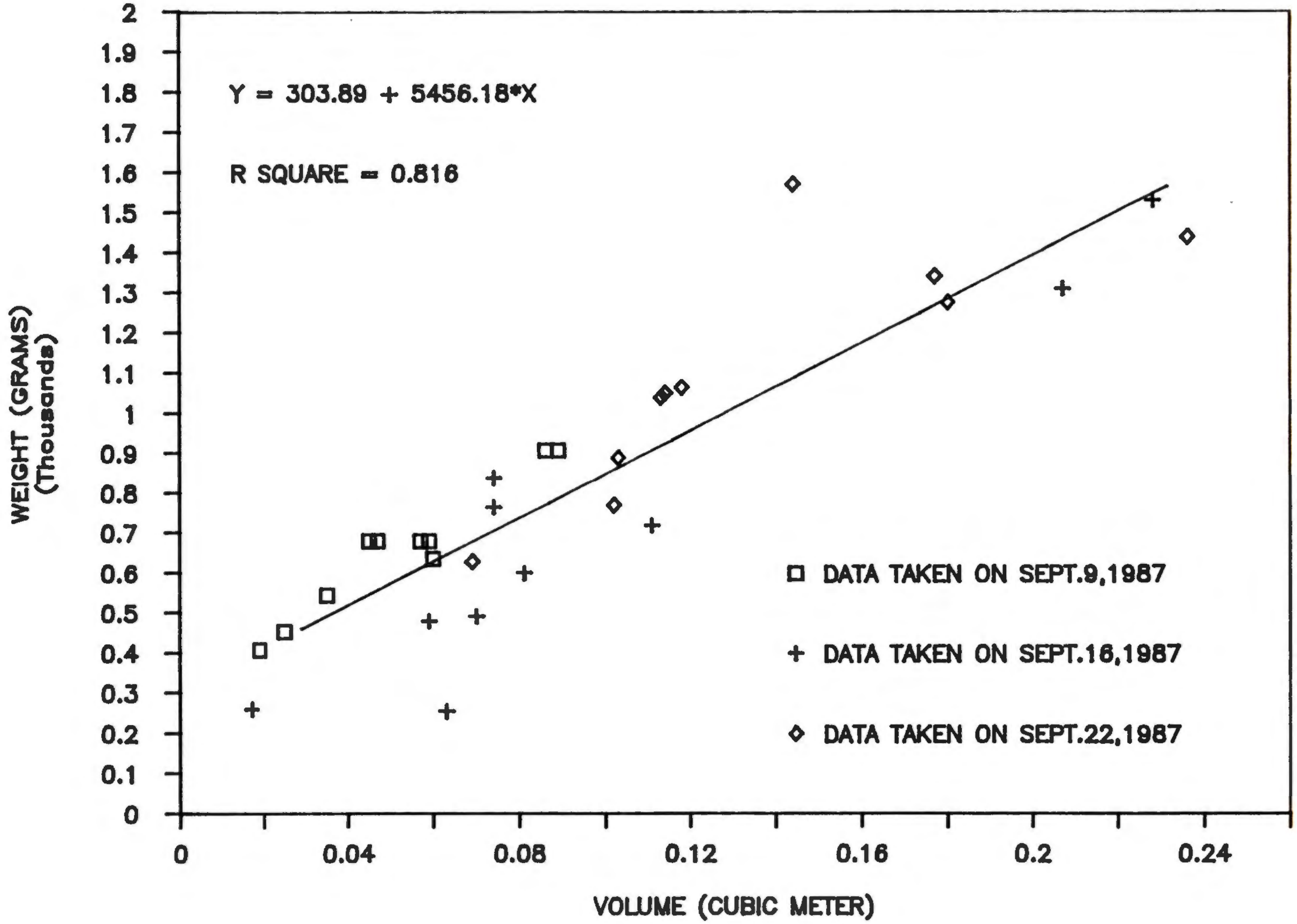


Figure 32. Plots of total mass versus total volume for soybeans.

# CHAPTER VIII

# SUMMARY AND CONCLUSIONS

## Summary

Evaluation of plant morphology is often desired in research related to crop production. However, measuring the morphology of non-uniform plants is difficult and time consuming.

A microcomputer-based measurement system has been developed for plant morphology measurement. Seven ultrasonic sensors and an ultrasonic ranging module were used to scan the plant row for distance-to-plant measurements at three different vertical positions. The space between the ultrasonic sensors can be adjusted both vertically and horizontally. An optical incremental encoder was used as a position sensor to measure the forward travel distance of the instrument. The selected horizontal interval between sample collections was 31 mm. An interface was designed to connect a SBC with the ultrasonic sensor system for data acquisition. The storage capacity of this measurement system is 7000 data values. A key pad was interfaced with the SBC to input the operation commands. An LCD unit was constructed to display all results, including cumulative plant volume, maximum and average plant widths at three vertical positions, and maximum and average plant height.

Laboratory tests of the system indicate that the unit provides accurate measurements of plant dimensions. Measurement of step changes of height or width are slightly biased due to the conical viewing window of the sensors. However, this conical window also prevents certain errors by insuring that a sensor does not "look through" small openings in plant canopies and produce erroneous volume computations as a result.

The system was tested on the Milan Experiment Station of The University of Tennessee. Four 6-meter row segments of cotton and four 6-meter row segments of soybeans were used in the system tests. The measurements of each test were consistent. The growth rate of the plants can be easily calculated using the results of the tests. Correlation of measured plant volume and actual plant mass was very good for cotton. The correlation for soybeans was not as good as for cotton.

## Conclusions and Recommendations

1. A Field Plant Morphology Integrator was designed and constructed by interfacing seven ultrasonic sensors and an optical incremental encoder with a microcomputer.

2. This instrument can measure cumulative plant volume, maximum and average plant widths at three vertical positions, and maximum and average plant height for a plant row or row segment.

3. The results of the laboratory and field tests of this instrument indicate that this measurement system can provide accurate and consistent morphology measurements for a variety of "bush" type plants such as cottons, soybeans, various vegetable crops, and small ornamental plants.

4. This instrument is relatively inexpensive. With minor modification and improvement, it can be manufactured, and used in the research areas requiring plant morphology measurement.

5. Since most of the time is spent on the ultrasonic signal transmitting during a data acquisition cycle, the speed of the measurement system can be increased if several ultrasonic sensors are fired at one time instead of sequentially. In this operation, the ultrasonic signals from different sensors might interfer with each other. Thus, further study of this problem is needed.

6. The sensor frame should be rebuilt to make it easier to adjust the sensor position.

7. A proper shield should be constructed to protect the ultrasonic sensor.

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## BIBLIOGRAPHY

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APPENDIXES

APPENDIX A

TABLES

Table 1. Results of system test using a continuous row of boxes. Box dimensions were uniform along the 1.64-m row. Six passes were made with three passes in each direction.

| Parameter | Max. Value | Min. Value | Avg. Value | Correct Value | Error %* | Max. Error %** |
|---|---|---|---|---|---|---|
| Volume (Cu. m) | 0.119 | 0.113 | 0.116 | 0.118 | 1.69 | 4.24 |
| Max. Height (mm) | 338 | 335 | 337 | 338 | 0.30 | 0.89 |
| Avg. Height (mm) | 330 | 330 | 330 | 330 | 0.00 | 0.00 |
| Maximum $W_1$ (mm) | 290 | 282 | 285 | 287 | 0.70 | 1.74 |
| Average $W_1$ (mm) | 282 | 279 | 281 | 287 | 2.09 | 2.79 |
| Maximum $W_2$ (mm) | 292 | 287 | 291 | 287 | -1.39 | -1.74 |
| Average $W_2$ (mm) | 284 | 282 | 283 | 287 | 1.39 | 1.74 |
| Maximum $W_3$ (mm) | 302 | 292 | 297 | 300 | 1.00 | 2.67 |
| Average $W_3$ (mm) | 292 | 287 | 288 | 295 | 2.37 | 2.71 |

*Percentage error of the six-pass average.

**Maximum percentage error for any pass.

Table 2. Results of system test using a continuous row of non-uniform boxes. Box dimensions varied along the 2.02-m row length. Six passes were made with three passes in each direction.

| Parameter | Max. Value | Min. Value | Avg. Value | Correct Value* | Error %** | Max. Error %*** |
|---|---|---|---|---|---|---|
| Volume (Cu.m) | 0.164 | 0.159 | 0.160 | 0.161 | 0.62 | 3.11 |
| Max. Height (mm) | 457 | 455 | 457 | 460 | 0.65 | 1.09 |
| Avg. Height (mm) | 399 | 396 | 396 | 397 | 0.25 | 0.25 |
| Maximum $W_1$ (mm) | 297 | 297 | 297 | 295 | -0.68 | -0.68 |
| Average $W_1$ (mm) | 262 | 262 | 262 | 268 | 2.24 | 2.24 |
| Maximum $W_2$ (mm) | 302 | 297 | 300 | 298 | -0.67 | -1.34 |
| Average $W_2$ (mm) | 264 | 264 | 264 | 268 | 1.49 | 1.49 |
| Maximum $W_3$ (mm) | 290 | 290 | 290 | 292 | 0.68 | 0.68 |
| Average $W_3$ (mm) | 257 | 257 | 257 | 268 | 4.10 | 4.10 |

*Adjusted to account for the sensor cone of view.

**Percentage error of the six-pass average.

***Maximum percentage error for any pass.

Table 3. Results of system test using artificial plants spaced 460 mm apart along a 3.66-m row.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu.m) | 0.065 | 0.065 | 0.067 | 0.070 | 0.070 | 0.068 | 0.068 |
| Max. Height (mm) | 455 | 450 | 455 | 449 | 447 | 445 | 450 |
| Avg. Height (mm) | 259 | 259 | 267 | 274 | 274 | 272 | 268 |
| Maximum $W_1$ (mm) | 401 | 391 | 368 | 371 | 391 | 389 | 385 |
| Average $W_1$ (mm) | 97 | 101 | 101 | 99 | 99 | 97 | 99 |
| Maximum $W_2$ (mm) | 320 | 290 | 290 | 282 | 310 | 287 | 297 |
| Average $W_2$ (mm) | 109 | 107 | 104 | 109 | 109 | 107 | 108 |
| Maximum $W_3$ (mm) | 193 | 183 | 191 | 193 | 193 | 193 | 191 |
| Average $W_3$ (mm) | 36 | 36 | 36 | 36 | 41 | 38 | 37 |

Table 4. Results of system test using artificial plants spaced 380 mm to 530 mm apart along a 3.66-m row.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.065 | 0.059 | 0.065 | 0.068 | 0.065 | 0.065 | 0.065 |
| Max. Height (mm) | 452 | 455 | 457 | 452 | 450 | 447 | 452 |
| Avg. Height (mm) | 251 | 246 | 269 | 272 | 257 | 264 | 260 |
| Maximum $W_1$ (mm) | 399 | 394 | 399 | 394 | 399 | 394 | 397 |
| Average $W_1$ (mm) | 99 | 91 | 97 | 97 | 94 | 99 | 96 |
| Maximum $W_2$ (mm) | 328 | 307 | 310 | 327 | 330 | 307 | 318 |
| Average $W_2$ (mm) | 104 | 104 | 104 | 109 | 107 | 104 | 105 |
| Maximum $W_3$ (mm) | 178 | 188 | 191 | 178 | 191 | 188 | 186 |
| Average $W_3$ (mm) | 36 | 36 | 30 | 38 | 38 | 38 | 36 |

Table 5. Results of system test using artificial plants spaced 230 mm apart along a 3.66-m row.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu.m) | 0.130 | 0.127 | 0.127 | 0.127 | 0.133 | 0.133 | 0.130 |
| Max. Height (mm) | 437 | 455 | 432 | 439 | 434 | 434 | 439 |
| Avg. Height (mm) | 323 | 325 | 323 | 323 | 323 | 314 | 322 |
| Maximum $W_1$ (mm) | 274 | 277 | 279 | 267 | 287 | 284 | 278 |
| Average $W_1$ (mm) | 155 | 152 | 150 | 150 | 157 | 157 | 154 |
| Maximum $W_2$ (mm) | 279 | 272 | 272 | 267 | 277 | 282 | 275 |
| Average $W_2$ (mm) | 155 | 155 | 150 | 152 | 155 | 157 | 154 |
| Maximum $W_3$ (mm) | 173 | 180 | 173 | 170 | 180 | 175 | 175 |
| Average $W_3$ (mm) | 76 | 74 | 74 | 79 | 81 | 81 | 78 |

Table 6. Results of system test using the first 6-meter row segment of soybeans on the UTK Plant Science Field Laboratory Farm, 2 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu.m) | 0.821 | 0.824 | 0.830 | 0.816 | 0.824 | 0.824 | 0.823 |
| Max. Height (mm) | 706 | 709 | 706 | 709 | 711 | 711 | 709 |
| Avg. Height (mm) | 554 | 556 | 561 | 551 | 561 | 554 | 556 |
| Maximum $W_1$ (mm) | 422 | 437 | 447 | 422 | 417 | 424 | 428 |
| Average $W_1$ (mm) | 231 | 241 | 239 | 241 | 234 | 234 | 237 |
| Maximum $W_2$ (mm) | 625 | 648 | 617 | 640 | 640 | 640 | 635 |
| Average $W_2$ (mm) | 386 | 389 | 386 | 381 | 381 | 381 | 384 |
| Maximum $W_3$ (mm) | 607 | 587 | 584 | 579 | 638 | 605 | 600 |
| Average $W_3$ (mm) | 335 | 338 | 340 | 338 | 340 | 340 | 339 |

Table 7. Results of system test using the second 6-meter row segment of soybeans on the UTK Plant Science Field Laboratory Farm, 2 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu.m) | 0.824 | 0.869 | 0.875 | 0.943 | 0.892 | 0.954 | 0.893 |
| Max. Height (mm) | 711 | 711 | 709 | 711 | 716 | 721 | 713 |
| Avg. Height (mm) | 531 | 554 | 556 | 605 | 577 | 597 | 570 |
| Maximum $W_1$ (mm) | 493 | 495 | 503 | 526 | 523 | 498 | 506 |
| Average $W_1$ (mm) | 262 | 262 | 264 | 269 | 269 | 279 | 268 |
| Maximum $W_2$ (mm) | 648 | 658 | 658 | 648 | 645 | 648 | 651 |
| Average $W_2$ (mm) | 387 | 387 | 391 | 394 | 394 | 396 | 392 |
| Maximum $W_3$ (mm) | 645 | 650 | 645 | 630 | 627 | 589 | 631 |
| Average $W_3$ (mm) | 351 | 356 | 353 | 351 | 351 | 353 | 353 |

Table 8. Results of system test using the third 6-meter row segment of soybeans on the UTK Plant Science Field Laboratory Farm, 2 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 1.017 | 0.986 | 1.034 | 1.059 | 1.020 | 1.017 | 1.022 |
| Max. Height (mm) | 716 | 716 | 711 | 719 | 721 | 719 | 717 |
| Avg. Height (mm) | 579 | 572 | 594 | 599 | 605 | 587 | 589 |
| Maximum $W_1$ (mm) | 559 | 549 | 533 | 569 | 597 | 810 | 603 |
| Average $W_1$ (mm) | 312 | 305 | 310 | 318 | 315 | 318 | 313 |
| Maximum $W_2$ (mm) | 668 | 640 | 650 | 655 | 620 | 635 | 645 |
| Average $W_2$ (mm) | 434 | 434 | 434 | 434 | 437 | 434 | 435 |
| Maximum $W_3$ (mm) | 665 | 676 | 676 | 630 | 627 | 678 | 659 |
| Average $W_3$ (mm) | 404 | 401 | 404 | 399 | 389 | 394 | 399 |

Table 9. Results of system test using the first 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.269 | 0.269 | 0.272 | 0.269 | 0.261 | 0.272 | 0.269 |
| Max. Height (mm) | 450 | 452 | 457 | 442 | 460 | 462 | 454 |
| Avg. Height (mm) | 361 | 361 | 361 | 358 | 361 | 361 | 361 |
| Maximum $W_1$ (mm) | 414 | 399 | 414 | 378 | 414 | 399 | 403 |
| Average $W_1$ (mm) | 208 | 203 | 203 | 208 | 201 | 208 | 205 |
| Maximum $W_2$ (mm) | 386 | 386 | 389 | 406 | 366 | 378 | 385 |
| Average $W_2$ (mm) | 201 | 196 | 196 | 201 | 196 | 203 | 199 |
| Maximum $W_3$ (mm) | 318 | 318 | 282 | 231 | 259 | 272 | 280 |
| Average $W_3$ (mm) | 99 | 94 | 94 | 84 | 79 | 89 | 90 |

Table 10. Results of system test using the second 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.178 | 0.181 | 0.184 | 0.173 | 0.178 | 0.181 | 0.179 |
| Max. Height (mm) | 389 | 378 | 391 | 373 | 378 | 378 | 381 |
| Avg. Height (mm) | 310 | 310 | 305 | 310 | 307 | 312 | 309 |
| Maximum $W_1$ (mm) | 338 | 338 | 356 | 356 | 343 | 348 | 347 |
| Average $W_1$ (mm) | 109 | 109 | 102 | 97 | 109 | 109 | 106 |
| Maximum $W_2$ (mm) | 417 | 434 | 427 | 399 | 414 | 427 | 420 |
| Average $W_2$ (mm) | 173 | 173 | 188 | 175 | 175 | 170 | 176 |
| Maximum $W_3$ (mm) | 287 | 282 | 274 | 272 | 257 | 292 | 277 |
| Average $W_3$ (mm) | 99 | 107 | 109 | 99 | 107 | 102 | 104 |

Table 11. Results of system test using the third 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.212 | 0.221 | 0.227 | 0.227 | 0.229 | 0.218 | 0.222 |
| Max. Height (mm) | 465 | 465 | 470 | 439 | 447 | 434 | 453 |
| Avg. Height (mm) | 361 | 361 | 361 | 361 | 358 | 358 | 360 |
| Maximum $W_1$ (mm) | 389 | 376 | 376 | 366 | 368 | 368 | 374 |
| Average $W_1$ (mm) | 175 | 180 | 180 | 183 | 191 | 183 | 182 |
| Maximum $W_2$ (mm) | 356 | 335 | 358 | 361 | 345 | 338 | 349 |
| Average $W_2$ (mm) | 157 | 157 | 163 | 163 | 167 | 167 | 162 |
| Maximum $W_3$ (mm) | 234 | 196 | 236 | 249 | 249 | 246 | 235 |
| Average $W_3$ (mm) | 56 | 69 | 69 | 71 | 76 | 74 | 69 |

Table 12. Results of system test using the fourth 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| Parameter | Passes Over Row 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
|---|---|---|---|---|---|---|---|
| Volume (Cu. m) | 0.122 | 0.125 | 0.122 | 0.105 | 0.108 | 0.125 | 0.118 |
| Max. Height (mm) | 340 | 348 | 351 | 353 | 343 | 351 | 348 |
| Avg. Height (mm) | 282 | 284 | 287 | 287 | 282 | 290 | 285 |
| Maximum $W_1$ (mm) | 203 | 206 | 203 | 224 | 206 | 216 | 210 |
| Average $W_1$ (mm) | 58 | 53 | 53 | 41 | 38 | 56 | 50 |
| Maximum $W_2$ (mm) | 343 | 318 | 315 | 325 | 333 | 310 | 324 |
| Average $W_2$ (mm) | 135 | 137 | 137 | 132 | 130 | 135 | 134 |
| Maximum $W_3$ (mm) | 358 | 310 | 315 | 351 | 348 | 368 | 342 |
| Average $W_3$ (mm) | 104 | 102 | 91 | 84 | 94 | 102 | 96 |

Table 13. Results of system test using the first 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 16 September 1987

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.337 | 0.357 | 0.348 | 0.329 | 0.331 | 0.343 | 0.341 |
| Max. Height (mm) | 521 | 505 | 513 | 526 | 521 | 523 | 518 |
| Avg. Height (mm) | 404 | 406 | 409 | 406 | 406 | 406 | 406 |
| Maximum $W_1$ (mm) | 396 | 389 | 406 | 376 | 389 | 396 | 392 |
| Average $W_1$ (mm) | 236 | 234 | 239 | 241 | 244 | 246 | 240 |
| Maximum $W_2$ (mm) | 396 | 371 | 406 | 427 | 396 | 406 | 400 |
| Average $W_2$ (mm) | 226 | 231 | 218 | 231 | 234 | 234 | 229 |
| Maximum $W_3$ (mm) | 333 | 333 | 330 | 287 | 282 | 234 | 300 |
| Average $W_3$ (mm) | 122 | 119 | 109 | 107 | 109 | 104 | 112 |

Table 14. Results of system test using the second 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 16 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.255 | 0.238 | 0.252 | 0.252 | 0.246 | 0.255 | 0.250 |
| Max. Height (mm) | 455 | 452 | 450 | 475 | 472 | 460 | 461 |
| Avg. Height (mm) | 376 | 373 | 373 | 381 | 381 | 381 | 378 |
| Maximum $W_1$ (mm) | 371 | 361 | 414 | 366 | 417 | 353 | 380 |
| Average $W_1$ (mm) | 178 | 178 | 183 | 185 | 183 | 185 | 182 |
| Maximum $W_2$ (mm) | 381 | 361 | 404 | 376 | 401 | 384 | 385 |
| Average $W_2$ (mm) | 180 | 173 | 183 | 180 | 175 | 183 | 179 |
| Maximum $W_3$ (mm) | 295 | 325 | 356 | 343 | 315 | 287 | 320 |
| Average $W_3$ (mm) | 114 | 99 | 102 | 114 | 117 | 117 | 111 |

Table 15. Results of system test using the third 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 16 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.309 | 0.289 | 0.289 | 0.309 | 0.297 | 0.306 | 0.300 |
| Max. Height (mm) | 490 | 493 | 490 | 536 | 536 | 544 | 515 |
| Avg. Height (mm) | 411 | 417 | 414 | 424 | 422 | 424 | 419 |
| Maximum $W_1$ (mm) | 411 | 389 | 394 | 404 | 394 | 386 | 396 |
| Average $W_1$ (mm) | 234 | 224 | 224 | 221 | 226 | 218 | 225 |
| Maximum $W_2$ (mm) | 356 | 353 | 376 | 381 | 381 | 356 | 367 |
| Average $W_2$ (mm) | 198 | 185 | 191 | 183 | 183 | 188 | 188 |
| Maximum $W_3$ (mm) | 251 | 315 | 241 | 333 | 312 | 323 | 296 |
| Average $W_3$ (mm) | 91 | 76 | 74 | 81 | 74 | 74 | 78 |

Table 16. Results of system test using the fourth 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 16 September, 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.249 | 0.238 | 0.229 | 0.227 | 0.244 | 0.244 | 0.239 |
| Max. Height (mm) | 452 | 452 | 452 | 455 | 460 | 462 | 456 |
| Avg. Height (mm) | 376 | 373 | 373 | 378 | 381 | 381 | 377 |
| Maximum $W_1$ (mm) | 373 | 356 | 356 | 394 | 371 | 389 | 373 |
| Average $W_1$ (mm) | 175 | 183 | 180 | 173 | 173 | 175 | 177 |
| Maximum $W_2$ (mm) | 384 | 366 | 338 | 335 | 361 | 366 | 358 |
| Average $W_2$ (mm) | 173 | 173 | 170 | 165 | 165 | 165 | 169 |
| Maximum $W_3$ (mm) | 323 | 325 | 302 | 406 | 381 | 325 | 344 |
| Average $W_3$ (mm) | 114 | 107 | 102 | 99 | 109 | 104 | 106 |

Table 17. Results of system test using the first 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 22 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.394 | 0.396 | 0.399 | 0.385 | 0.382 | 0.396 | 0.392 |
| Max. Height (mm) | 531 | 475 | 531 | 541 | 541 | 538 | 526 |
| Avg. Height (mm) | 414 | 414 | 414 | 417 | 417 | 419 | 416 |
| Maximum $W_1$ (mm) | 467 | 475 | 467 | 427 | 447 | 434 | 453 |
| Average $W_1$ (mm) | 269 | 269 | 267 | 269 | 267 | 272 | 269 |
| Maximum $W_2$ (mm) | 422 | 424 | 414 | 404 | 422 | 406 | 415 |
| Average $W_2$ (mm) | 251 | 259 | 246 | 259 | 251 | 249 | 253 |
| Maximum $W_3$ (mm) | 335 | 371 | 345 | 287 | 305 | 320 | 327 |
| Average $W_3$ (mm) | 124 | 135 | 130 | 130 | 130 | 122 | 129 |

Table 18. Results of system test using the second 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 22 September 1987.

| | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| Parameter | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.306 | 0.323 | 0.303 | 0.300 | 0.314 | 0.312 | 0.310 |
| Max. Height (mm) | 493 | 490 | 490 | 498 | 498 | 500 | 495 |
| Avg. Height (mm) | 396 | 399 | 406 | 409 | 406 | 409 | 404 |
| Maximum $W_1$ (mm) | 452 | 434 | 445 | 434 | 462 | 445 | 445 |
| Average $W_1$ (mm) | 208 | 216 | 213 | 213 | 211 | 211 | 212 |
| Maximum $W_2$ (mm) | 424 | 417 | 439 | 432 | 455 | 457 | 437 |
| Average $W_2$ (mm) | 216 | 224 | 226 | 224 | 221 | 224 | 223 |
| Maximum $W_3$ (mm) | 333 | 335 | 325 | 348 | 323 | 348 | 335 |
| Average $W_3$ (mm) | 124 | 124 | 124 | 124 | 127 | 124 | 125 |

Table 19. Results of system test using the third 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 22 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.377 | 0.365 | 0.371 | 0.346 | 0.379 | 0.357 | 0.366 |
| Max. Height (mm) | 513 | 503 | 561 | 523 | 521 | 493 | 519 |
| Avg. Height (mm) | 422 | 424 | 422 | 419 | 422 | 411 | 420 |
| Maximum $W_1$ (mm) | 437 | 434 | 432 | 414 | 447 | 437 | 434 |
| Average $W_1$ (mm) | 241 | 239 | 234 | 234 | 236 | 236 | 237 |
| Maximum $W_2$ (mm) | 406 | 406 | 376 | 381 | 401 | 396 | 394 |
| Average $W_2$ (mm) | 236 | 239 | 236 | 234 | 226 | 224 | 233 |
| Maximum $W_3$ (mm) | 297 | 335 | 312 | 284 | 284 | 302 | 302 |
| Average $W_3$ (mm) | 152 | 152 | 147 | 142 | 147 | 142 | 147 |

Table 20. Results of system test using the fourth 6-meter row segment of cotton on the Milan Experiment Station of The University of Tennessee, 22 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.363 | 0.374 | 0.357 | 0.377 | 0.368 | 0.357 | 0.366 |
| Max. Height (mm) | 533 | 541 | 523 | 561 | 561 | 554 | 546 |
| Avg. Height (mm) | 434 | 437 | 437 | 442 | 442 | 445 | 440 |
| Maximum $W_1$ (mm) | 406 | 417 | 422 | 417 | 411 | 424 | 416 |
| Average $W_1$ (mm) | 264 | 264 | 259 | 259 | 254 | 257 | 260 |
| Maximum $W_2$ (mm) | 361 | 371 | 371 | 373 | 376 | 376 | 371 |
| Average $W_2$ (mm) | 213 | 213 | 208 | 213 | 211 | 218 | 213 |
| Maximum $W_3$ (mm) | 292 | 279 | 279 | 302 | 284 | 292 | 288 |
| Average $W_3$ (mm) | 94 | 89 | 94 | 97 | 97 | 94 | 94 |

Table 21. Results of system test using the first 6-meter row segment of soybeans on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.212 | 0.224 | 0.224 | 0.215 | 0.215 | 0.210 | 0.217 |
| Max. Height (mm) | 523 | 521 | 521 | 518 | 531 | 518 | 522 |
| Avg. Height (mm) | 391 | 368 | 384 | 361 | 368 | 366 | 373 |
| Maximum $W_1$ (mm) | 333 | 330 | 351 | 292 | 333 | 302 | 324 |
| Average $W_1$ (mm) | 79 | 79 | 79 | 79 | 71 | 69 | 76 |
| Maximum $W_2$ (mm) | 394 | 391 | 371 | 399 | 371 | 373 | 383 |
| Average $W_2$ (mm) | 178 | 178 | 178 | 175 | 173 | 170 | 175 |
| Maximum $W_3$ (mm) | 391 | 368 | 394 | 363 | 391 | 361 | 378 |
| Average $W_3$ (mm) | 175 | 178 | 175 | 173 | 170 | 168 | 173 |

Table 22. Results of system test using the second 6-meter row segment of soybeans on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.357 | 0.363 | 0.354 | 0.368 | 0.360 | 0.360 | 0.360 |
| Max. Height (mm) | 650 | 640 | 650 | 673 | 671 | 663 | 658 |
| Avg. Height (mm) | 417 | 427 | 422 | 457 | 460 | 452 | 439 |
| Maximum $W_1$ (mm) | 434 | 500 | 493 | 432 | 470 | 511 | 473 |
| Average $W_1$ (mm) | 145 | 145 | 140 | 142 | 140 | 140 | 142 |
| Maximum $W_2$ (mm) | 533 | 516 | 490 | 516 | 526 | 523 | 517 |
| Average $W_2$ (mm) | 264 | 269 | 254 | 254 | 251 | 249 | 257 |
| Maximum $W_3$ (mm) | 485 | 462 | 572 | 483 | 480 | 523 | 501 |
| Average $W_3$ (mm) | 183 | 180 | 179 | 183 | 175 | 183 | 181 |

Table 23. Results of system test using the third 6-meter row segment of soybeans on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| Parameter | Passes Over Row 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
|---|---|---|---|---|---|---|---|
| Volume (Cu. m) | 0.391 | 0.385 | 0.379 | 0.405 | 0.419 | 0.405 | 0.397 |
| Max. Height (mm) | 711 | 673 | 671 | 686 | 686 | 686 | 686 |
| Avg. Height (mm) | 485 | 452 | 467 | 505 | 503 | 508 | 487 |
| Maximum $W_1$ (mm) | 470 | 511 | 495 | 521 | 516 | 493 | 501 |
| Average $W_1$ (mm) | 231 | 229 | 234 | 218 | 226 | 216 | 226 |
| Maximum $W_2$ (mm) | 511 | 472 | 505 | 521 | 531 | 516 | 509 |
| Average $W_2$ (mm) | 231 | 231 | 226 | 216 | 226 | 229 | 227 |
| Maximum $W_3$ (mm) | 378 | 371 | 381 | 363 | 368 | 371 | 372 |
| Average $W_3$ (mm) | 130 | 137 | 135 | 127 | 132 | 124 | 131 |

Table 24. Results of system test using the fourth 6-meter row segment of soybeans on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.280 | 0.278 | 0.306 | 0.261 | 0.278 | 0.283 | 0.281 |
| Max. Height (mm) | 599 | 612 | 632 | 693 | 671 | 683 | 648 |
| Avg. Height (mm) | 465 | 478 | 485 | 483 | 478 | 475 | 477 |
| Maximum $W_1$ (mm) | 445 | 452 | 485 | 500 | 511 | 480 | 479 |
| Average $W_1$ (mm) | 170 | 170 | 173 | 168 | 163 | 160 | 167 |
| Maximum $W_2$ (mm) | 404 | 442 | 434 | 411 | 439 | 450 | 430 |
| Average $W_2$ (mm) | 183 | 183 | 178 | 185 | 180 | 188 | 183 |
| Maximum $W_3$ (mm) | 320 | 236 | 257 | 249 | 282 | 287 | 272 |
| Average $W_3$ (mm) | 84 | 81 | 84 | 69 | 66 | 71 | 76 |

Table 25. Results of system test using the first 6-meter row segment of soybeans on the Milan Experiment Station of The University of Tennessee, 16 September 1987.*

| Parameter | Passes Over Row 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
|---|---|---|---|---|---|---|---|
| Volume (Cu. m) | 0.212 | 0.272 | 0.238 | 0.232 | 0.241 | 0.246 | 0.240 |
| Max. Height (mm) | 511 | 579 | 582 | 538 | 579 | 561 | 558 |
| Avg. Height (mm) | 401 | 411 | 422 | 401 | 384 | 411 | 405 |
| Maximum $W_1$ (mm) | 274 | 478 | 297 | 297 | 272 | 257 | 313 |
| Average $W_1$ (mm) | 84 | 76 | 81 | 76 | 84 | 74 | 79 |
| Maximum $W_2$ (mm) | 475 | 470 | 447 | 437 | 452 | 470 | 459 |
| Average $W_2$ (mm) | 180 | 185 | 183 | 188 | 188 | 188 | 185 |
| Maximum $W_3$ (mm) | 368 | 452 | 406 | 411 | 373 | 445 | 409 |
| Average $W_3$ (mm) | 185 | 183 | 185 | 180 | 188 | 175 | 183 |

*Wind was blowing when this test was conducted.

Table 26. Results of system test using the second 6-meter row segment of soybeans on the Milan Experiment Station of The University of Tennessee, 16 September 1987.*

| Parameter | Passes Over Row 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
|---|---|---|---|---|---|---|---|
| Volume (Cu. m) | 0.351 | 0.343 | 0.371 | 0.331 | 0.363 | 0.368 | 0.355 |
| Max. Height (mm) | 843 | 607 | 668 | 627 | 638 | 632 | 669 |
| Avg. Height (mm) | 439 | 439 | 434 | 483 | 475 | 475 | 458 |
| Maximum $W_1$ (mm) | 419 | 485 | 389 | 389 | 445 | 411 | 423 |
| Average $W_1$ (mm) | 147 | 145 | 150 | 137 | 132 | 132 | 141 |
| Maximum $W_2$ (mm) | 480 | 551 | 490 | 470 | 495 | 485 | 495 |
| Average $W_2$ (mm) | 259 | 259 | 257 | 241 | 236 | 239 | 249 |
| Maximum $W_3$ (mm) | 480 | 434 | 467 | 478 | 495 | 511 | 478 |
| Average $W_3$ (mm) | 170 | 168 | 178 | 180 | 165 | 183 | 174 |

*Wind was blowing when this test was conducted.

Table 27. Results of system test using the third 6-meter row segment of soybeans on the Milan Experiment Station of The University of Tennessee, 16 September 1987.*

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.368 | 0.408 | 0.408 | 0.385 | 0.419 | 0.396 | 0.397 |
| Max. Height (mm) | 714 | 693 | 706 | 701 | 714 | 714 | 707 |
| Avg. Height (mm) | 493 | 495 | 511 | 508 | 526 | 528 | 510 |
| Maximum $W_1$ (mm) | 538 | 541 | 551 | 546 | 526 | 559 | 544 |
| Average $W_1$ (mm) | 206 | 201 | 183 | 198 | 201 | 196 | 198 |
| Maximum $W_2$ (mm) | 508 | 508 | 508 | 566 | 541 | 480 | 519 |
| Average $W_2$ (mm) | 234 | 239 | 241 | 239 | 236 | 234 | 237 |
| Maximum $W_3$ (mm) | 399 | 485 | 434 | 526 | 396 | 373 | 436 |
| Average $W_3$ (mm) | 124 | 127 | 122 | 127 | 132 | 122 | 126 |

*Wind was blowing when this test was conducted.

Table 28. Results of system test using the fourth 6-meter row segment of soybeans on the Milan Experiment Station of The University of Tennessee, 16 September 1987.*

| Parameter | Passes Over Row | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Avg. |
| Volume (Cu. m) | 0.272 | 0.269 | 0.323 | 0.289 | 0.306 | 0.314 | 0.296 |
| Max. Height (mm) | 648 | 696 | 706 | 681 | 693 | 711 | 689 |
| Avg. Height (mm) | 500 | 495 | 495 | 498 | 495 | 488 | 495 |
| Maximum $W_1$ (mm) | 427 | 419 | 434 | 434 | 460 | 445 | 437 |
| Average $W_1$ (mm) | 145 | 152 | 160 | 173 | 175 | 178 | 164 |
| Maximum $W_2$ (mm) | 406 | 399 | 434 | 401 | 409 | 445 | 416 |
| Average $W_2$ (mm) | 180 | 188 | 201 | 198 | 198 | 201 | 194 |
| Maximum $W_3$ (mm) | 495 | 297 | 307 | 348 | 318 | 318 | 347 |
| Average $W_3$ (mm) | 81 | 76 | 91 | 86 | 84 | 89 | 85 |

*Wind was blowing when this test was conducted.

Table 29. Results of system test using the 1.5-meter row segments of cotton on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| TEST No. | VOLUME (Cu. m) | WEIGHT (Grams) |
|---|---|---|
| 1 | 0.050 | 680 |
| 2 | 0.028 | 544 |
| 3 | 0.031 | 590 |
| 4 | 0.025 | 499 |
| 5 | 0.031 | 590 |
| 6 | 0.032 | 680 |
| 7 | 0.023 | 499 |
| 8 | 0.042 | 635 |
| 9 | 0.040 | 590 |
| 10 | 0.060 | 771 |

Table 30. Results of system test using the 1.5-meter row segment of soybeans on the Milan Experiment Station of The University of Tennessee, 9 September 1987.

| TEST No. | VOLUME (Cu. m) | WEIGHT (Grams) |
|---|---|---|
| 1 | 0.019 | 408 |
| 2 | 0.035 | 544 |
| 3 | 0.060 | 635 |
| 4 | 0.025 | 454 |
| 5 | 0.057 | 680 |
| 6 | 0.047 | 680 |
| 7 | 0.089 | 907 |
| 8 | 0.059 | 680 |
| 9 | 0.086 | 907 |
| 10 | 0.045 | 680 |

Table 31. Results of system test using cotton on the Milan Experiment Station of The University of Tennessee, 16 September 1987. The length of row segments varied from 0.9 meter to 3 meters.

| TEST No. | VOLUME (Cu. m) | WEIGHT (Grams) |
|---|---|---|
| 1 | 0.011 | 202 |
| 2 | 0.018 | 337 |
| 3 | 0.019 | 401 |
| 4 | 0.027 | 510 |
| 5 | 0.040 | 620 |
| 6 | 0.070 | 930 |
| 7 | 0.067 | 860 |
| 8 | 0.070 | 1010 |
| 9 | 0.027 | 432 |
| 10 | 0.023 | 510 |

Table 32. Results of system test using soybeans on the Milan Experiment Station of The University of Tennessee, 16 September 1987. The length of row segments varied from 0.9 meter to 3 meters.

| TEST No. | VOLUME (Cu. m) | WEIGHT (Grams) |
|---|---|---|
| 1* | 0.063 | 255 |
| 2 | 0.059 | 481 |
| 3** | 0.074 | 839 |
| 4 | 0.228 | 1530 |
| 5 | 0.207 | 1310 |
| 6 | 0.070 | 493 |
| 7 | 0.111 | 719 |
| 8 | 0.017 | 260 |
| 9 | 0.081 | 600 |
| 10 | 0.074 | 765 |

*Wind was blowing when this test was conducted.

**Some leaves of the plants in this segment were eaten by deer.

Table 33. Results of system test using cotton on the Milan Experiment Station of The University of Tennessee, 22 September 1987. The length of of row segments varied from 0.9 meter to 3.3 meters.

| TEST No. | VOLUME (Cu. m) | WEIGHT (Grams) |
|---|---|---|
| 1 | 0.057 | 509 |
| 2 | 0.066 | 718 |
| 3 | 0.117 | 1070 |
| 4 | 0.116 | 1150 |
| 5 | 0.117 | 1157 |
| 6 | 0.137 | 1370 |
| 7 | 0.141 | 1480 |
| 8 | 0.148 | 1622 |
| 9 | 0.165 | 1720 |
| 10 | 0.108 | 995 |

Table 34. Results of system test using soybeans on the Milan Experiment Station of The University of Tennessee, 22 September 1987. The length of row segments varied from 1.2 meters to 2.8 meters.

| TEST No. | VOLUME (Cu. m) | WEIGHT (Grams) |
|---|---|---|
| 1 | 0.177 | 1341 |
| 2 | 0.102 | 770 |
| 3 | 0.114 | 1050 |
| 4 | 0.103 | 890 |
| 5 | 0.236 | 1438 |
| 6 | 0.069 | 630 |
| 7 | 0.113 | 1040 |
| 8 | 0.180 | 1275 |
| 9 | 0.118 | 1065 |
| 10 | 0.144 | 1570 |

APPENDIX B

MONITOR SUBROUTINE

```
***************************************************************
                     MONITOR SUBROUTINE
         This subroutine is used to monitor the keypad to
check if any key is depressed.  When a key is depressed, it
goes to a corresponding subroutine.
***************************************************************
10 DIM W(1)                     ;Reserve memory locations for
20 DIM S(8)                     ;variables: W=width setting;
30 DIM H(1)                     ;H=height setting; S=cross
40 DIM Y(8)                     ;section area of row; X and Y
50 DIM X(8)                     ;are temporary variables.
---------------------------------------------------------------
 ;Scanning keypad for a depressed key.
---------------------------------------------------------------
60 POKE &D003,130               ;Initialize I/O ports.
70 POKE &D000,103               ;Allow keypad buffer.
80 POKE &D000,96                ;Activate all rows of keypad.
90 P=PEEK(&D001)                ;Read keypad buffer.
100 K=P AND 240                 ;Maintain 4 MSB.
110 IF K<240 THEN 130           ;Any key pressed?
120 GOTO 70                     ;No, repeat scanning.
---------------------------------------------------------------
  ;Scan the keys on the 1st. row of keypad, which are
  ;L#1, HGT, VOL, and TEST.
---------------------------------------------------------------
130 POKE &D000,99               ;Activate 1st.row of keypad.
140 P1=PEEK(&D001)              ;Read keypad buffer.
150 K1=P1 AND 240               ;Maintain 4 MSB of reading.
160 IF K1=224 THEN 330          ;Key L#1 is depressed.
170 IF K1=208 THEN 690          ;Key HGT is depressed.
180 IF K1=176 THEN 1070         ;Key VOL is depressed.
190 IF K1=112 THEN 1370         ;Key TEST is depressed.
---------------------------------------------------------------
  ;Scan the keys on the 2nd. row of keypad, which are
  ;L#2, MAX, RST, and STOP.
---------------------------------------------------------------
200 POKE &D000,101              ;Activate 2nd. row of keypad.
210 P2=PEEK(&D001)              ;Read keypad buffer.
220 K2=P2 AND 240               ;Maintain 4 MSB of reading.
230 IF K2=224 THEN 450          ;Key L#2 is depressed.
240 IF K2=208 THEN 2240         ;Key MAX is depressed by
                                ;mistake.
--------------------------------------------------------------
  ;Scan the keys on third row of the keypad, which are
  ;L#3, AVG, H(0-9), and W(0-9).
--------------------------------------------------------------
250 POKE &D000,102              ;Activate 3rd. row of keypad.
260 P3=PEEK(&D001)              ;Read keypad buffer.
270 K3=P3 AND 240               ;Maintain 4 MSB of reading.
280 IF K3=224 THEN 570          ;Key L#3 is depressed.
290 IF K3=208 THEN 2240         ;Key AVG is depressed wrongly.
```

```
300 IF K3=176 THEN 1880        ;Key H(0-9) is depressed.
310 IF K3=112 THEN 2060        ;Key W(0-9) is depressed.
-------------------------------------------------------------
320 GOTO 80                    ;Repeat scanning.
-------------------------------------------------------------
  ;After L#1 key is depressed, either MAX or AVG key
  ;should be depressed in a certain time period. Otherwise
  ;it is treated as a wrong operation.
  ;C1 = time delay counter.
-------------------------------------------------------------
330 C1=0                       ;Clear C1.
340 C1=C1+1                    ;Sum C1.
350 POKE &D000,101             ;Activate 2nd.row of keypad.
360 M1=PEEK(&D001)             ;Read keypad buffer.
370 MW1=M1 AND 240             ;Maintain 4 MSB of reading.
380 IF MW1=208 THEN 3560       ;MAX key is depressed.
                               ;Go to L#1.MAX subroutine.
390 POKE &D000,102             ;Activate 3rd. row of keypad.
400 A1=PEEK(&D001)             ;Read keypad buffer.
410 AW1=A1 AND 240             ;Maintain 4 MSB of reading.
420 IF AW1=208 THEN 3330       ;AVG key is depressed.
                               ;Go to L#1.AVG subroutine.
430 IF C1=300 THEN 2240        ;Delay time is over. Go to
                               ;error subroutine.
440 GOTO 340                   ;Wait for MAX.or AVG key is
                               ;depressed.
-------------------------------------------------------------
  ;After L#2 key is depressed, either MAX or AVG key
  ;should be depressed in a certain time period. Otherwise
  ;it is treated as a wrong operation.
  ;C2 = time delay counter.
-------------------------------------------------------------
450 C2=0                       ;Clear C2
460 C2=C2+1                    ;Time delay counter plus 1.
470 POKE &D000,101             ;Activate 2nd.row of keypad.
480 M2=PEEK(&D001)             ;Read keypad buffer.
490 MW2=M2 AND 240             ;Maintain 4 MSB of reading.
500 IF MW2=208 THEN 3180       ;MAX key is depressed.  Go to
                               ;L#2.MAX subroutine.
510 POKE &D000,102             ;Activate 3rd.row of keypad.
520 A2=PEEK(&D001)             ;Read keypad buffer.
530 AW2=A2 AND 240             ;Maintain 4 MSB of reading.
540 IF AW2=208 THEN 2950       ;AVG key is depressed.  Go to
                               ;L#2.AVG subroutine.
550 IF C2=300 THEN 2240        ;Delay time is over.
560 GOTO 460                   ;Wait for MAX.or AVG key is
                               ;depressed.
-------------------------------------------------------------
  ;After L#3 key is depressed, either MAX or AVG key
  ;should be depressed in a certain time period.
  ;Otherwise, it is treated as a wrong operation.
```

```
  ;C3 = time delay counter.
-------------------------------------------------------------
570 C3=0                          ;Clear C3
580 C3=C3+1                       ;Time delay counter plus 1.
590 POKE &D000,101                ;Activate 2nd.row of keypad.
600 M3=PEEK(&D001)                ;Read keypad buffer.
610 MW3=M3 AND 240                ;Maintain 4 MSB of reading.
620 IF MW3=208 THEN 2800          ;MAX key is depressed.
                                  ;Go to L#3.MAX subroutine.
630 POKE &D000,102                ;Activate 3rd row of keypad.
640 A3=PEEK(&D001)                ;Read keypad buffer.
650 AW3=A3 AND 240                ;Maintain 4 MSB of reading.
660 IF AW3=208 THEN 2570          ;AVG key is depressed.
                                  ;Go to L#3.AVG subroutine.
670 IF C3=300 THEN 2240           ;Delay time is over.
680 GOTO 580                      ;Wait for MAX.or AVG key is
                                  ;depressed.
-------------------------------------------------------------
  ;After HGT key is depressed, either MAX or AVG key
  ;should be depressed in a certain time period.  Otherwise
  ;it is treated as a wrong operation.
  ;CH = time delay counter.
-------------------------------------------------------------
690 CH=0                          ;Clear CH
700 CH=CH+1                       ;Time delay counter plus 1.
710 POKE &D000,101                ;Activate 2nd.row of keypad.
720 MH=PEEK(&D001)                ;Read keypad buffer.
730 MAXH=MH AND 240               ;Maintain 4 MSB of reading.
740 IF MAXH=208 THEN 2280         ;MAX key is depressed.
                                  ;Go to HGT.MAX subroutine.
750 POKE &D000,102                ;Activate 3rd. row of keypad.
760 AH=PEEK(&D001)                ;Read keypad buffer.
770 AEH=AH AND 240                ;Maintain 4 MSB of reading.
780 IF AEH=208 THEN 2280          ;AVG key is depressed.
                                  ;Go to HGT.AVG subroutine.
790 IF CH=300 THEN 2240           ;Delay time is over.
800 GOTO 700                      ;Wait for MAX.or AVG key is
                                  ;depressed.
```

# APPENDIX C

# TEST SUBROUTINE

```
****************************************************************
                        TEST SUBROUTINE
       Acquisite data from the seven ultrasonic sensors and
store the data into the SBC memory. The first memory
location for data storage is 17980.  The maximum data
storage capacity is 7000 data values.
****************************************************************
----------------------------------------------------------------
  ;Initialize I/O ports for data acquisition.  Set
  ;constants, "Warm up" the ultrasonic ranging module.
----------------------------------------------------------------
1370 POKE &D003,130              ;Initialize I/O ports.  Port A
                                 ;and port C for output.  Port
                                 ;B for input.
1380 POKE &D000,8                ;Clear encoder counter.
1390 M=17980                     ;M = 1st. address for data
                                 ;storage.
1395 MR=0                        ;Reset loop counter.
1400 POKE &D000,16               ;Switch sensor No. a1 to
                                 ;ultrasonic ranging module.
1410 POKE &D000,72               ;Output INIT signal.
1420 POKE &D000,88               ;Enable encoder buffer.
1430 S(0)=PEEK(&D001)            ;Read encoder buffer to check
                                 ;if ECHO is back.
1440 Y(0)=S(0) AND 8             ;
1450 IF Y(0)=0 THEN 1470         ;ECHO comes back.
1460 GOTO 1430                   ;Check ECHO again.
1470 POKE &D000,80               ;Enable sensor data buffer.
1480 A=PEEK(&D001)               ;Read sensor data.
----------------------------------------------------------------
1490 FOR Z=1 TO 7                ;Set-up a sensor for fire.
1500 C=0                         ;Reset time counter.
1510 X(0)=8                      ;
1520 J=Z-1                       ;
1530 X(Z)=X(J)+8                 ;
1540 POKE &D000,X(Z)             ;Switch a sensor to the
                                 ;ultrasonic module.
1550 POKE &D000,72               ;Output INIT signal.
1560 POKE &D000,88               ;Enable encoder buffer.
1570 S(Z)=PEEK(&D001)            ;Read encoder buffer and check
                                 ;if ECHO comes back.
1580 Y(Z)=S(Z) AND 8             ;
1590 IF Y(Z)=0 THEN 1630         ;ECHO is back.
1600 C=C+1                       ;Time counter plus 1.
1610 IF C=2 THEN 1670            ;C=2, ECHO signal missed
1620 GOTO 1570                   ;Chech ECHO again.
1630 POKE &D000,80               ;Enable sensor data buffer.
1640 A=PEEK(&D001)               ;Read sensor data.
1650 POKE M,A                    ;Store data.
1660 GOTO 1720                   ;
----------------------------------------------------------------
```

```
;Process the invalid data.
------------------------------------------------------------
1670 POKE &D000,104             ;Simulate ECHO.
1680 POKE &D000,80              ;Enable sensor data buffer.
1690 A=PEEK(&D001)              ;Read sensor data.
1700 A=250                      ;Invalid data.
1710 POKE M,A                   ;Store data.
------------------------------------------------------------
1720 M=M+1                      ;Increase address.
1730 NEXT Z                     ;Loop to fire another sensor.
1740 MR=MR+1                    ;Loop counter for cycle.
------------------------------------------------------------
;Check forward distance (sample interval).  If the forward
;movement of the instrument is 31 mm or greater, then
;start next scan loop.
------------------------------------------------------------
1750 POKE &D000,0               ;Enable encoder buffer.
1760 G=PEEK(&D001)              ;read data from encoder
                                ;counter.
1770 IF G=160 THEN 1840         ;Check forward distance.
1780 IF G>160 THEN 1840         ; ,,     ,,      ,,
------------------------------------------------------------
;Check if STOP key is depressed. if it is depressed, go to
;MONITOR subroutine.
------------------------------------------------------------
1790 POKE &D000,101             ;Check if STOP key
1800 P2=PEEK(&D001)             ;is depressed.
1810 K2=P2 AND 240              ;
1820 IF K2=112 THEN 1870        ;STOP key is depressed.
------------------------------------------------------------
1830 GOTO 1750                  ;Check forward distance again.
1840 POKE &D000,8               ;Reset encoder counter.
1850 IF MR=1000 THEN 1870       ;Is 1000 cycles completed?
1860 GOTO 1490                  ;Start next scan loop.
1870 MR=MR-3                    ;Remove first 3 loops,  Those
                                ;3 loops are for "warming up"
                                ;the sensors.
1875 GOTO 80                    ;Go to monitor program.
```

# APPENDIX D

# COMPUTATION SUBROUTINES

```
************************************************************
                    H(1-9) SUBROUTINE
         This subroutine is used for operator to input the
height setting through the keypad.  The maximum height
setting is 70 inches.  H(1) is the height setting.
************************************************************
1880 DD=0                        ;DD is the value for display.
1890 GOSUB 3710                  ;Go to display subroutine.
1900 POKE &D000,102              ;Check if H(0-9) is
1910 P3=PEEK(&D001)              ;depressed.
1920 K3=P3 AND 240               ;
1930 IF K3=176 THEN 1950         ;H(0-9) key is depressed.
1940 GOTO 80                     ;Go to monitor subrountine.
------------------------------------------------------------
  ;Time counter
------------------------------------------------------------
1950 FOR TDH=1 TO 100            ;Time counter.
1960 IF TDH=50 THEN 1980         ;
1970 NEXT                        ;
------------------------------------------------------------
1980 H1=H1+1                     ;H1 is increased by one.
1990 H(1)=H1/10                  ;Icrement is 0.1.
2000 IF H(1)>70 THEN 2030        ;Max. H(1) is 70.
2010 DD=H(1)                     ;Display H(1).
2020 GOTO 1890                   ;Keep increasing.
------------------------------------------------------------
  ;If the operator attempts to set H(1) greater than 70,
  ;then it starts from zero again.
------------------------------------------------------------
2030 DD=0                        ;Start from zero again.
2040 H1=0                        ;
2050 GOTO 1890                   ;Keep increasing.
```

```
*************************************************************
                    W(0-9) SUBROUTINE
       This subroutine is used for the operator to input the
width setting.  The maximum width W(1) is 70 inches.
*************************************************************
2060 DD=0                          ;Reset display; DD = display
                                   ;value.
2070 GOSUB 3710                    ;Display zero.
2080 POKE &D000,102                ;Check if W(0-1) key
2090 P3=PEEK(&D001)                ;is depressed.
2100 K3=P3 AND 240                 ;
2110 IF K3=112 THEN 2130           ;W(0-9) key is depressed
2120 GOTO 80                       ;Go to monitor subroutine.
-------------------------------------------------------------
  ;Time counter
-------------------------------------------------------------
2130 FOR TDW=1 TO 100              ;Time counter.
2140 IF TDW=40 THEN 2160           ;
2150 NEXT                          ;
-------------------------------------------------------------
2160 W1=W1+1                       ;W1 increases one
2170 W(1)=W1/10                    ;Increment is 0.1
2180 IF W(1)>70 THEN 2210          ;Max. setup width is 70 inch.
2190 DD=W(1)                       ;Display W(1)
2200 GOTO 2070                     ;
-------------------------------------------------------------
  ;The operator attemps to set W(1) greater than 70, then it
  ;starts from zero again.
-------------------------------------------------------------
2210 DD=0                          ;Start from zero again
2220 W1=0                          ;
2230 GOTO 2070                     ;Keep increasing
```

```
************************************************************
                    ERROR SUBROUTINE
      This subroutine is used to display a error sign "-".
************************************************************
2240 DD=300                    ;Set data for display
2250 GOSUB 3710                ;display error sign "-".
2260 GOSUB 3890                ;
2270 GOTO 80                   ;Go to monitor subroutine.
```

```
*************************************************************
                    VOLUME SUBROUTINE
       This subroutine computes the volume of the measured
plant row or row segment.
       S = cross section area of the plant row.
       TS = total cross section area of the row.
       DIS = sample interval (1.22 inches).
       COE = coefficient (7.5 counts per inch).
*************************************************************
1070 S=0                        ;Clear variable for volume
1080 TS=0                       ;calculation.
1090 DIS=1.22                   ;
1100 COE=7.5                    ;7.5 counts per inch.
1110 AH1=0                      ;Clear temporary variable.
1120 LADD=7*(MR-1)+7+18000      ;Calculate the address of
                                ;last memory location in which
                                ;datum from sensor No.7 is
                                ;stored.
-------------------------------------------------------------
  ;The first address in which datum from sensor No.7 is
  ;stored is 18007.  The following loop computes the
  ;average distance from the sensor No.7 to the plant row
  ;(AVH).
-------------------------------------------------------------
1130 FOR M=18007 TO LADD STEP 7 ;Begin at address 18007.
1140 A7=PEEK(M)                 ;Read data from sensor No.7.
1150 IF A7>240 THEN 1180        ;Chech if data is valid.
1160 DH=A7                      ;Get ready for calculation.
1170 GOTO 1190
1180 DH=H(1)*COE                ;Processing invalid data.
1190 AH1=DH+AH1                 ;Sum counts from sensor No. 7.
1200 NEXT M                     ;Loop.
1210 AVH=AH1/(COE*MR)           ;Calculate the distance from
                                ;the sensor No.7 to the plant
                                ;row surface.
-------------------------------------------------------------
  ;Calculate the total cross section area of the plant row.
  ;H(1) is the height setting.  W(1) is the width setting.
-------------------------------------------------------------
1220 FOR M=18007 TO LADD STEP 7 ;Begin at address 18007.
1230 A1=PEEK(M-6)               ;Read data from sen.No. a1.
1240 A2=PEEK(M-5)               ;Read data from sen.No. b1.
1250 A3=PEEK(M-4)               ;Read data from sen.No. a2.
1260 A4=PEEK(M-3)               ;Read data from sen.No. b2.
1270 A5=PEEK(M-2)               ;Read data from sen.No. a3.
1280 A6=PEEK(M-1)               ;Read data from sen.No. b3.
1290 S=(H(1)-AVH)*(3*W(1)-((A1+A2+A3+A4+A5+A6)/COE))/4
1300 TS=S+TS                    ;Calculate total cross section
                                ;area.
1310 NEXT M                     ;Loop.
-------------------------------------------------------------
```

```
1320 VOL=(TS*DIS)/1728          ;Calculate volume in cu. ft.
1330 DD=VOL                     ;DD is volume value for
                                ;display.
1340 GOSUB 3710                 ;Go to display subrountine.
1350 GOSUB 3890                 ;Time delay.
1360 GOTO 80                    ;Go to monitor subroutine.
```

```
*************************************************************
                    HGT. AVG. SUBROUTINE
         This subroutine is used to calculate the average
height of the plant row.  AVH is the distance from the
sensor No. 7 to the plant row surface.
*************************************************************
2280 AH1=0                     ;AH1=temporary variable.
2290 LADD=7*(MR-1)+7+18000     ;Calculate the address of the
                               ;last memory location in which
                               ;the datum from sensor No.7 is
                               ;stored.
2300 COE=7.5                   ;7.5 pulses per inch.
2310 FOR M=18007 TO LADD STEP 7 ;Starting addr.is 18007
2320 A7=PEEK(M)                ;Read data from sen. No. 7
2330 IF A7>240 THEN 2360       ;Check invalid data.
2340 DH=A7                     ;
2350 GOTO 2370                 ;
2360 DH=H(1)*COE               ;Process invalid data.
2370 AH1=DH+AH1                ;Sum data values.
2380 NEXT M                    ;loop
-------------------------------------------------------------
  ;Calculate average height (H(1)-AVH).
-------------------------------------------------------------
2390 AVH=AH1/(COE*MR)          ;Calculate average height.
2400 DD=H(1)-AVH               ;
2410 GOSUB 3710                ;Go to display subroutine.
2420 GOSUB 3890                ;
2430 GOTO 80                   ;Go to monitor subroutine.
```

************************************************************

HGT. MAX. SUBROUTINE

This subroutine is used to calculate the Maximum height of the plant row. QH= the minimum distance between the sensor No. 7 to the row surface. The maximum height = H(1) - (QH/COE).

************************************************************

```
2440 QH=1000                      ;Set up value for comparison.
2450 LADD=7*(MR-1)+7+18000        ;Calculate the address of
                                  ;last memory location in which
                                  ;datum from sensor No. 7 is
                                  ;stored.
2460 FOR M=18007 TO LADD STEP 7 ;Starting addr.is 18007
2470 A7=PEEK(M)                   ;Read data from sensor No. 7
2480 IF A7<QH THEN 2500           ;Compare.
2490 GOTO 2510                    ;
2500 QH=A7                        ;Find the minimum datum from
                                  ;sensor No. 7.
2510 NEXT                         ;Loop.
2520 COE=7.5                      ;Coefficient=7.5 counts/inch.
2530 DD=H(1)-(QH/COE)             ;Calculate and display
2540 GOSUB 3710                   ;maximum height.
2550 GOSUB 3890                   ;
2560 GOTO 80                      ;Go to monitor subroutine.
```

************************************************************

L#3. AVG. SUBROUTINE

This subroutine is used to calculate the average width of the row at level 3.

FI=average distance between sensor No. a3 and the row surface.

SI=average distance between sensor No. b3 and the row surface.

The average $W_3$ = W(1) - TL.

************************************************************

```
2570 FI=0                        ;Reset variables
2580 SI=0                        ;
2590 COE=7.5                     ;
2600 LADD=7*(MR-1)+5+18000       ;Calculate the address of the
                                 ;last memory location in which
                                 ;the datum from sensor No. a3
                                 ;is stored.
2610 FOR M=18005 TO LADD STEP 7 ;Starting addr. is 18005
2620 A5=PEEK(M)                  ;Read data from sensor No. a3.
2630 IF A5>240 THEN 2660         ;Check invalid data.
2640 IV=A5                       ;
2650 GOTO 2670                   ;
2660 IV=W(1)*COE/2               ;Process invalid data
2670 FI=IV+FI                    ;Sum data values.
2680 A6=PEEK(M+1)                ;Read data from sensor No. b3.
2690 IF A6>240 THEN 2720         ;Check invalid data.
2700 VI=A6                       ;
2710 GOTO 2730                   ;
2720 VI=W(1)*COE/2               ;Process invalid data.
2730 SI=VI+SI                    ;Sum data values.
2740 NEXT M                      ;Loop
2750 TL=(FI+SI)/(MR*COE)         ;Compute average width
2760 DD=W(1)-TL                  ;at level #3 and display.
2770 GOSUB 3710                  ;
2780 GOSUB 3890                  ;
2790 GOTO 80                     ;Go to monitor subroutine.
```

```
****************************************************************
                 L#3. MAX. SUBROUTINE
         This subroutine is used to calculate the maximum
width of the plant row at level 3.
       QW=the minimum distance between sensors and the plant
row.
       The maximum W3 = W(1) - (QW/COE).
****************************************************************
2800 QW=1000                     ;Set a number for comparison.
2810 LADD=7*(MR-1)+5+18000       ;Calculate the address of the
                                 ;last memory location in which
                                 ;the datum from sensor No. a3
                                 ;is stored.
2820 FOR M=18005 TO LADD STEP 7 ;Starting addr. is 18005.
2830 A5=PEEK(M)                  ;Read data from sensor No. a3
2840 A6=PEEK(M+1)                ;and b3.
2850 WT=A5+A6                    ;Compute minimum space between
                                 ;sensors and the row surface.
2860 IF WT<QW THEN 2880          ;
2870 GOTO 2890                   ;
2880 QW=WT                       ;
2890 NEXT                        ;Loop
2900 COE=7.5                     ;
2910 DD=W(1)-(QW/COE)            ;Calculate the maximum
2920 GOSUB 3710                  ;width at level #3 and go
2930 GOSUB 3890                  ;to display subroutine.
2940 GOTO 80                     ;Go to monitor subroutine.
```

```
************************************************************
                 L#2. AVG. SUBROUTINE
          This subroutine is used to calculate the average
width of the plant row at level 2.
       TR=average distance between sensor No. a2 and the row
surface.
       FO=average distance between sensor No. b2 and the row
surface.
       The average W2 = W(1) - SL.
************************************************************
2950 TR=0                         ;Reset variable
2960 FO=0                         ;Reset variable
2970 COE=7.5                      ;Set coefficient
2980 LADD=7*(MR-1)+3+18000        ;Calculate the address of
                                  ;the last memory location
                                  ;in which the datum from
                                  ;sensor No. a2 is stored.
2990 FOR M=18003 TO LADD STEP 7 ;Starting addr. is 18003
3000 A3=PEEK(M)                   ;Read data from sen.No. a2.
3010 IF A3>240 THEN 3040          ;Check invalid data.
3020 TW=A3                        ;
3030 GOTO 3050                    ;
3040 TW=W(1)*COE/2                ;Process invalid data.
3050 TR=TW+TR                     ;Sum data values.
3060 A4=PEEK(M+1)                 ;Read data from sen.No. b2.
3070 IF A4>240 THEN 3100          ;Check invalid data.
3080 WF=A4                        ;
3090 GOTO 3110                    ;
3100 WF=W(1)*COE/2                ;Process invalid data.
3110 FO=WF+FO                     ;Sum data values.
3120 NEXT M                       ;Loop
3130 SL=(TR+FO)/(MR*COE)          ;Compute average W2.
3140 DD=W(1)-SL                   ;
3150 GOSUB 3710                   ;Go to display subroutine.
3160 GOSUB 3890                   ;
3170 GOTO 80                      ;Go to monitor Subroutine.
```

```
*************************************************************
                  L#2. MAX. SUBROUTINE
         This subroutine is used to calculate the maximum
width of the plant row at level 2.
       QW=the minimum distance between sensors and the plant
row.
       The maximum W2=W(1) - (QW/COE).
*************************************************************
3180 QW=1000                     ;Set a number for comparison.
3190 LADD=7*(MR-1)+3+18000       ;Calculate the address of
                                 ;the last memory location in
                                 ;which the datum from sensor
                                 ;No. a2 is stored.
3200 FOR M=18003 TO LADD STEP 7 ;Starting addr. is 18003
3210 A3=PEEK(M)                  ;Read data from sen.No. a2.
3220 A4=PEEK(M+1)                ;Read data from sen.No. b2.
3230 WS=A3+A4                    ;Calculate the minimum space
3240 IF WS<QW THEN 3260          ;between sensors and the row.
3250 GOTO 3270                   ;
3260 QW=WS                       ;
3270 NEXT M                      ;Loop
3280 COE=7.5                     ;Set coefficient
3290 DD=W(1)-(QW/COE)            ;Calculate the maximum W2.
3300 GOSUB 3710                  ;Display maximum W2.
3310 GOSUB 3890                  ;
3320 GOTO 80                     ;Go to monitor subroutine.
```

```
*************************************************************
                  L#1. AVG. SUBROUTINE
          This subroutine is used to calculate the average
width of the plant row at level 1.
       FS=average distance between sensor No. a1 and the row
surface.
       SS=average distance between sensor No. b1 and the row
surface.
       The average W1 = W(1) - FL.
*************************************************************
3330 FS=0                         ;Clear variable.
3340 SS=0                         ;
3350 COE=7.5                      ;Set up coefficient.
3360 LADD=7*(MR-1)+1+18000        ;Calculate the address of
                                  ;the last memory location
                                  ;in which the datum from
                                  ;sensor No. a1 is stored.
3370 FOR M=18001 TO LADD STEP 7 ;Starting addr. is 18001.
3380 A1=PEEK(M)                   ;Read data from sensor No. a1.
3390 IF A1>240 THEN 3420          ;Check invalid data.
3400 FW=A1                        ;
3410 GOTO 3430                    ;
3420 FW=W(1)*COE/2                ;Process invalid data.
3430 FS=FW+FS                     ;Sum data values.
3440 A2=PEEK(M+1)                 ;Read data from sensor No. b1.
3450 IF A2>240 THEN 3480          ;Check invalid data.
3460 SW=A2                        ;
3470 GOTO 3490                    ;
3480 SW=W(1)*COE/2                ;Process invalid data.
3490 SS=SW+SS                     ;Sum data values.
3500 NEXT M                       ;Loop.
3510 FL=(FS+SS)/(MR*COE)          ;Compute average width at
3520 DD=W(1)-FL                   ;level 1, and go to display
                                  ;subroutine.
3530 GOSUB 3710                   ;
3540 GOSUB 3890                   ;
3550 GOTO 80                      ;Go to monitor program.
```

```
*************************************************************
                 L#1. MAX. SUBROUTINE
         This subroutine is used to calculate the maximum
width of the plant row at level 1.
         QW1=the minimum distance between sensors and the
plant row.
       The maximum W1=W(1)-(QW1/COE).
*************************************************************
3560 QW1=1000                     ;Set a number for comparison.
3570 LADD=7*(MR-1)+1+18000        ;Calculate the address of
                                  ;the last memory location in
                                  ;which the datum from sensor
                                  ;No. a1 is stored.
3580 FOR M=18001 TO LADD STEP 7 ;Starting addr. is 18001.
3590 A1=PEEK(M)                   ;Read data from sen.No. a1.
3600 A2=PEEK(M+1)                 ;Read data from sen.No. b1.
3610 W12=A1+A2                    ;Compute the minimum space
3620 IF W12<QW1 THEN 3640         ;between sensors and the row.
3630 GOTO 3650                    ;
3640 QW1=W12                      ;
3650 NEXT M                       ;Loop
3660 COE=7.5                      ;Set up coefficient.
3670 DD=W(1)-(QW1/COE)            ;calculate the maximum W1.
3680 GOSUB 3710                   ;Go to display subroutine.
3690 GOSUB 3890                   ;
3700 GOTO 80                      ;Go to monitor program.
```

# APPENDIX E
# DISPLAY SUBROUTINE

```
*************************************************************
                    DISPLAY SUBROUTINE
       This subroutine is used display the results.  DD= the
value to display.  The maximum value to display is 199.9.
*************************************************************
3710 DB=CINT(DD/100-0.5)         ;Calculate hundreds.
  ;calculate tens.
3720 DC=CINT((DD-DB*100)/10-0.5)
  ;calculate units.
3730 DX=CINT(DD-(DB*100)-(DC*10)-0.5)
  ;calculate tenths.
3740 DE=CINT((DD-(DB*100)-(DC*10)-(DX*1))/0.1-0.5)
3750 IF DB=1 THEN 3790          ;Check if the hundreds is
3760 IF DB=0 THEN 3790          ;greater than 1.
3770 DF=4                       ;Greater than 1, display
3780 GOTO 3800                  ;error sign `-`
3790 DF=DB+1                    ;
3800 DB1=DF AND 128             ;Display hundreds.
3810 POKE &D002,DB1             ;
3820 DC1=DC OR 64               ;Display tens.
3830 POKE &D002,DC1             ;
3840 DX1=DX OR 32               ;Display units.
3850 POKE &D002,DX1             ;
3860 DE1=DE OR 16               ;Display tenths.
3870 POKE &D002,DE1             ;
3880 RETURN                     ;Return
3890 FOR TD=1 TO 1000           ;Time delay procedure.
3900 IF TD=800 THEN 3920        ;
3910 NEXT TD                    ;Loop
3920 RETURN                     ;Return
```

## VITA

Ruixiu Sui was born in Qiansuilou, Xiayi, Henan, People's Republic of China on 11 December 1956. He attended Jiguolou Elementary School, and graduated from Huiting High School, Xiayi, Henan, China in February 1974.

In August of 1976, the author entered the Lanzhou University, Lanzhou, China, and graduated in August of 1979 with a major in Radiophysics. As a Visiting Scholar, he was sent by Chinese Government to the United States for furthering his study in March of 1986. In January of 1987, he entered the Graduate School at The University of Tennessee, Knoxville, Tennessee, and accepted a graduate research assistantship in the Agricultural Engineering Department. He completed his graduate studies in December of 1987 and received a Master of Science degree with a major in Agricultural Engineering.

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