

# **MODERN ELECTRONICS FOR AGRICULTURE**

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## **ABSTRACT**

The field of electronics continues to change and evolve rapidly. Electronics are increasingly being used to collect and process all types of data, transfer information, make decisions, and provide automation and control functions. Modern microcontrollers and semiconductor components offer many advantages and ease of use in designing custom measurement and control systems. An array of microcontrollers, sensors, and accessory components are presented and their features, capabilities, and costs are discussed. Several measurement and datalogging circuits were designed for use in irrigation-related research activities. The design, implementation, and performance of these systems are described.

**Keywords:** electronics, automation, microcontrollers, sensors

# MODERN ELECTRONICS FOR AGRICULTURE

The field of electronics continues to change and evolve rapidly. Electronic components and assemblies can be found in a wide variety of industrial and commercial products, and with a wide variety of functions and capabilities. Modern household appliances, toys, and automobiles often contain microprocessors, sensors, displays, and data storage and transfer systems.

Electronics are increasingly being used to collect and process all types of data, transfer information, make decisions, and provide automation and control functions. Electronic components are increasing in their capabilities, while becoming easier to use, smaller in size, and cheaper to buy. Many more specialized components and sensors are available which interface easily and simplify circuit design.

The microcontroller is an important element in modern electronics, and has brought about a change in the way electronic circuits are designed. A microcontroller is a device that interfaces with external components, can input and output information to and from these external components, and can be programmed by the user. It is similar to the central processing unit (CPU) of a personal computer in that it is very flexible and can be programmed to do a wide variety of things.

In the past, significant electronics expertise and experience were required to design a circuit. Now, with a microcontroller, a circuit can be designed much more simply because many of the desired functions can be accomplished in the microcontroller's software. Examples of functions easily accomplished with a microcontroller include; timing (doing something at regular intervals, or measuring elapsed time between events); calibration (converting a raw measurement to a quantity in the desired units); accurate signal measurement (measuring a voltage level or frequency from a sensor); data output (transferring measured data or information to another device, computer, or display).

The number and capabilities of semiconductor sensors and auxiliary components that interface easily with microcontrollers have also increased. Many components, such as sensors, clocks, memory chips, and display units are designed to connect directly to microcontrollers, operate over compatible voltage ranges, and communicate easily with one another. These components usually require minimal external circuitry, have low power requirements, and are controlled in software.

These modern electronic components can be put to use in agriculture as in the many other applications in which they already serve. The availability, compatibility, and ease of use combine to offer many advantages to using microcontrollers and semiconductor components to create measurement and control systems.

The objective of this paper is to present and discuss some of the current, powerful, inexpensive, and easy-to-use electronic components available to and of potential use in agricultural research. The function, operation, and costs of some of these components will be discussed, and a number of examples of their use will be presented.

## MATERIALS

### Microcontrollers

The number of manufacturers, number and variety of products, and capabilities of the products continue to grow each year. Cravotta (2004) lists 45 manufacturers of microcontroller products, and gives an overview of the target applications, users, and capabilities of each manufacturer's product lines. Rather than discussing the many microcontroller options, capabilities, and differences, however, experiences with two microcontrollers from one manufacturer will be presented.

The PIC microcontrollers from Microchip (Microchip Technology Inc.<sup>1</sup>, Chandler, Arizona USA, [www.microchip.com](http://www.microchip.com)) were chosen due to their widespread use and availability, ease of programming, low cost, and advanced features. PIC microcontrollers are among the most popular in use today, and are used in many diverse applications. Much information is available, especially on the Internet, in the form of application notes, project descriptions and documentation, circuit diagrams and schematics, program code, and user forums.

PIC microcontrollers are available in a range of sizes and features. Sizes range from 8 pins to 84 pins. Available features include digital and analog input and output, analog-to-digital (A-D) converters, serial ports, USB capability, varying processor speeds, built-in oscillators, timers, and varying amounts of program memory.

The work presented in this paper was accomplished using two different PIC microcontrollers, the 16F819 and the 16F877. The 16F819 was chosen for its size and features: it has 16 input/output pins, five 10-bit analog-to-digital converters, a built-in oscillator, an adjustable processor speed, serial-port capability, and a large program memory area. The 16F877 has similar capabilities, but with additional input/output pins.

## Programming

An additional reason for selecting the PIC microcontrollers was for their ease in programming. A number of programming environments are available for PIC microcontrollers, including assembly language, C compilers, and BASIC compilers. Programming environments are available free of charge, including an assembly-language programming environment provided by Microchip, while others can be purchased. Many code examples and complete programs

for these and other programming environments can be found on the Internet.

Among the simplest programming environments are PicBasic and PicBasic Pro (MicroEngineering Labs, Inc., Colorado Springs, Colorado USA). These versions of the BASIC programming language include many functions which greatly simplify the programming of the microcontrollers. Functions are included for using the PICs' analog-to-digital converters, communicating with other digital chips via common protocols (such as I2C and SPI), outputting information to serial ports and LCD displays, measuring frequencies and pulsewidths, outputting analog signals, and enabling interrupts and power-saving features. Once a program has been written, the PicBasic compiler converts the BASIC program to the proper format for downloading to a PIC. While the PicBasic programming environments are not free (PicBasic costs about US\$100, PicBasic Pro about US\$240), they are much easier to learn and use than assembly language.

A hardware interface is required to download the compiled program to the microcontroller. One such interface, the EPIC programmer (MicroEngineering Labs, Inc.), connects to a computer's parallel port, includes software for editing and downloading a program, is compatible with most PIC microcontrollers, and costs about US\$60. Other programmers are available for purchase, and many plans and schematics can be found on the Internet for building simple programmers.

## Sensors

Many different sensors are available for measuring a variety of variables. These inexpensive, semiconductor sensors operate in low voltage ranges and interface easily with microcontrollers. Examples of sensors available for measuring parameters of interest in agriculture are discussed in Fisher et al. (2003) and presented herein.

### Temperature

Analog temperature sensors are available which output a voltage that is linearly proportional to

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<sup>1</sup> The mention of trade or manufacturer names is for information only and does not imply an endorsement, recommendation or exclusion by USDA-Agricultural Research Service.

temperature. The LM35 (National Semiconductor), for example, requires an excitation voltage of 5 Vdc, and is calibrated to output a voltage with a 10 mV / °C scale factor. The output voltage is read with an analog-to-digital converter, and the voltage is converted to a temperature reading in the microcontroller's software. The LM35 temperature sensor costs about \$2.

### Infrared thermometer

In some applications, a non-contact or remote temperature measurement is required. The MX90601 (Melexis) infrared thermometer module was designed for automotive and consumer appliance applications, and provides remote and ambient temperature measurements in analog voltage and digital signal form. The module requires an excitation voltage of 5 Vdc, and the analog output voltage can be read with the microcontroller's A-D converter. The voltage is then converted to temperature in the microcontroller's software using the manufacturer's calibration equation. The MX90601 infrared thermometer module costs about \$53.

### Pressure

A family of pressure sensors manufactured by Motorola is particularly well-suited for use with microcontrollers. The MPX5xxx sensors are available in a number of pressure ranges: from 0 – 10 kPa (0 - 1.45 psi) with the MPX5010, to 0 – 700 kPa (0 - 101.5 psi) with the MPX5700. The sensors require a 5 Vdc excitation signal and return a signal in the range of 0.2 to 4.7 Vdc. The PIC microcontroller's internal 10-bit A-D converters provide pressure measurements with a resolution of 0.011 kPa (0.0016 psi) with the MPX5010, and 0.76 kPa (0.11 psi) with the MPX5700. The MPX5xxx series of sensors cost about \$20 each.

### Object detection / distance

Non-contact or remote distance/depth measurements can be made using ultrasonic rangefinders similar to those used in autofocus cameras. The Devontech SRF04 rangefinder is a module that contains an ultrasonic transmitter and a detector, and interfaces easily with a microcontroller. The microcontroller triggers the

transmitter, which sends a pulse, and measures the length of time for the pulse to return. The microcontroller then calculates the distance based on the time interval. The SRF04 can measure distances within a range of 3 cm to 3 m, and costs about \$35.

### Other variables

Additional semiconductor sensors are available for measuring many other variables, and interface easily with microcontrollers. There are sensors for measuring acceleration, humidity, proximity, illumination, location (GPS coordinates), and rotation, for example. Many of the sensors return an analog voltage in the range of 0 to 5 Vdc, a digital signal, or a frequency, and require an excitation voltage of 5 Vdc. Other sensors, such as soil-moisture sensors, strain-gage loadcells, and conductivity sensors, which are often connected to traditional dataloggers, may also be suitable for use with inexpensive microcontrollers.

## Auxiliary Components

Additional components are usually required to provide other, necessary functions and complete the measurement system. While the microcontroller provides many of the control and process functions, additional components may be needed for timekeeping, data storage, peripheral equipment control, and data transmission.

### Timekeeping

Real-time clocks provide time and date functions very simply. Real-time clocks such as the Dallas Semiconductor DS1307 and DS1337 interface easily to a microcontroller and are accessed by the microcontroller's software. A crystal oscillator connects to the clock chip to provide an accurate timing signal, and a backup battery maintains operation when the microcontroller is in low-power sleep mode or is disconnected from its power source. The DS1307 costs \$2, the DS1337 costs \$3, and an oscillator costs \$0.75.

## Storage memory

Most microcontrollers do not normally provide memory for long-term data storage. External memory chips, such as Maxim's 24LCxxx series, are available which can store from 1 kbyte to 512 kbytes of data. The non-volatile memory is accessed via the microcontroller's software, and data can be written and read randomly. The chips cost about \$2 each.

## Analog-to-digital converters

While many microcontrollers have internal analog-to-digital converters, a variety of external A-D converters are available. External A-D converters can provide higher resolutions, faster measurements, differential voltage measurements, and multiple input channels. The MAX340x series from Maxim, for example, can be programmed to provide variable resolutions ranging from 8- to 16-bits. A lower-resolution setting can be used if less accuracy but a higher sampling rate is needed, while a higher-resolution setting allows for greater accuracy but more time required for each measurement. The MAX340x ADCs cost about \$5 each.

## LCD displays

Simple and inexpensive LCD displays can be connected for displaying text, while more expensive displays can be used to display graphics. The microcontroller can be programmed to read pushbuttons or keypads to allow users to select options, use menus, or input information to the microcontroller.

## RF transmitters and receivers

Radio frequency (RF) transmitters and receivers provide remote sensing, control, and data transmission capabilities. RF transmitters and receivers connect directly to the microcontrollers with no external components, other than an antenna, and operate with simple microcontroller programming. Transmission ranges up to about 300 ft are common, and several frequencies are available which require no FCC licenses for use. One example, the TXS-434 (Laipac), costs about \$5.

## EXAMPLE APPLICATIONS

Collecting agricultural field data can be labor-intensive, time-consuming, and costly. By automating sensor measurements, data can be collected much more frequently and reliably with much less effort. A few examples of data-collection equipment constructed using microcontrollers and semiconductor components are presented in the following sections.

### Automated Soil Moisture Monitoring

Moisture sensors (Irrrometer, Model 200SS) had been installed at many locations in a number of cotton, corn, and soybean fields at the USDA ARS research station at Stoneville, Mississippi, for use in scheduling irrigations. There were 4 to 18 sensor locations per field, with three sensors installed at different depths in the soil profile at each location. In previous years, sensor readings had been collected periodically by a technician walking to each sensor site, attaching a hand-held electronic meter to each sensor, taking measurements, and recording the readings on a data sheet. Given the number of measurements to be made, the time involved, and other factors, such as inclement weather, weekends and holidays, and other fieldwork, measurements from each sensor were normally collected only once or twice per week.

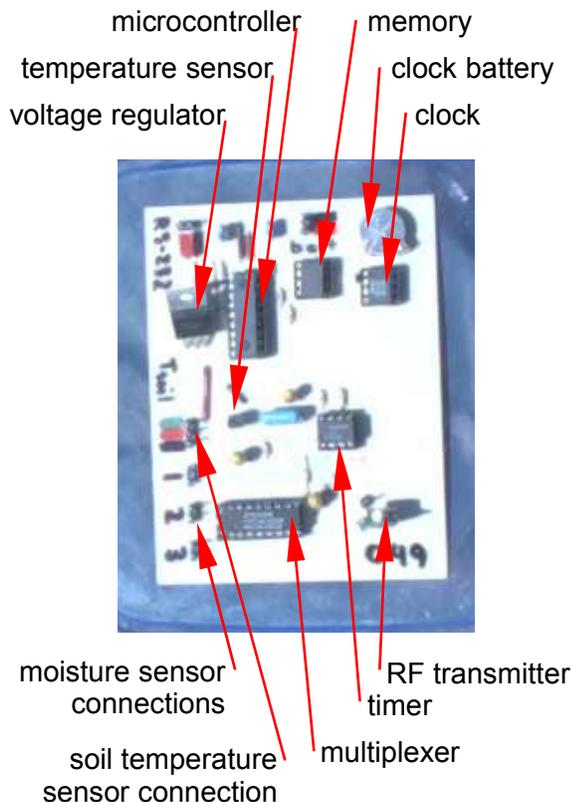
A circuit board was designed prior to the 2004 growing season to automate the moisture-sensor measurements. Circuit design parameters included the ability to power the moisture sensors, make readings at regular intervals, store the readings, and operate on battery power.

An important consideration in powering the sensors was that the moisture sensors required an AC (alternating current) excitation rather than the DC (direct current) energy supplied by a battery. An AC circuit designed by EME Systems (EME Systems, 2002) was modified and used to provide the proper excitation to the sensors.

The output signal from the sensors was in the form of a frequency which was linearly related to the resistance of the sensor, and ultimately to

the water potential of the sensor/soil. A calibration equation was developed to convert frequency to water potential. A series of known resistances was connected to the circuit, and the corresponding frequency from the circuit board was recorded. The known resistances were then connected to the moisture-sensor meter, and the corresponding water potential values were recorded. Correlating these data yielded a calibration equation which provided a water potential value based on output signal frequency.

The main components of the circuit consist of a microcontroller, AC-excitation circuit, multiplexer, real-time clock, memory chip, and batteries. The circuit was etched onto a copper-clad circuit board. Components were then soldered onto the board. Two temperature sensors were added to the circuit, one to measure the temperature of the circuit board, and a second to measure soil temperature. The component-side of the completed circuit board is shown in Figure 1. A list of the main components and their costs is shown in Table 1.



**Figure 1.** Component side of moisture-sensor circuit board.

**Table 1.** Parts list and cost of main components on moisture-sensor circuit board

Description	Cost (US\$)
<u>Part number, Manufacturer</u>	
Microcontroller	
<i>PIC 16F819, Microchip Technologies</i>	3
Clock	
<i>DS1302, Dallas Semiconductor</i>	3
Memory	
<i>24LC512, Microchip Technologies</i>	3
Multiplexer	
<i>74HC4051, Phillips Semiconductors</i>	1
RF transmitter	
<i>TX-434, Laipac</i>	5
Circuit board	1
Batteries	2
Miscellaneous (resistors, capacitors, pins, timer, voltage regulator)	2
<b>total</b>	<b>\$20</b>

The microcontroller was programmed to make and store measurements at 2-hour intervals. The microcontroller continuously monitored the real-time clock, which had a backup battery to maintain the correct time. At the beginning of each measurement interval, the microcontroller activated the AC-excitation circuit and multiplexer chip. The multiplexer selected one sensor at a time, the AC-excitation circuit powered the sensor, and the microcontroller measured the frequency. The microcontroller program applied the calibration routine to convert the frequency to water potential. The program then looped and continued the sensor-measurement process by instructing the multiplexer to select the next sensor, make a measurement, and continue until all sensors had been read. The date, time, and sensor measurements were stored in the memory chip, and the microcontroller then put itself into a low-voltage sleep mode to conserve battery power until the next measurement interval.

The circuit board was also designed to transmit the data out of the field automatically via an on-board RF transmitter. An RF receiver circuit located on one edge of the field would receive the data from all circuit boards within that field, making it quicker and easier to access the data without having to download the data manually from each individual circuit board. The receiver

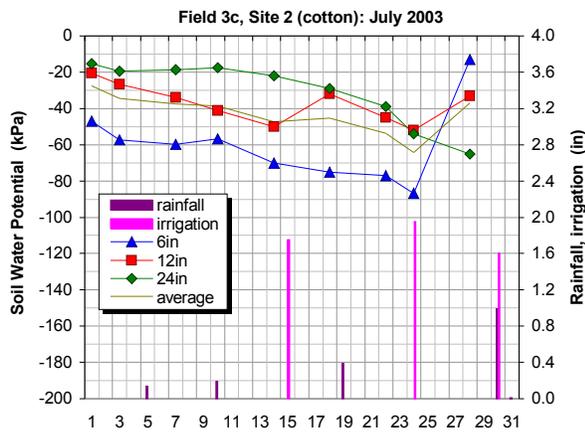
circuit design was not completed by the time the circuit boards needed to be deployed, however, and this feature was not enabled.

Circuit boards were deployed in the 2004 growing season to monitor moisture sensors installed in corn, soybean, and cotton fields. Measurements were made at 3 depths at each sensor location in the field. The three measurements were also averaged.

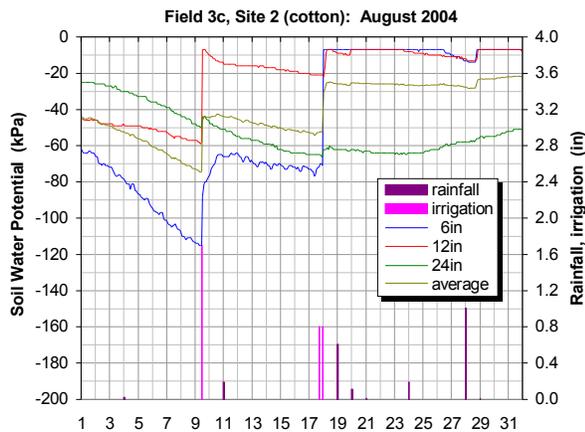
Sensor readings for two one-month periods are shown in Figures 2 and 3. In Figure 2, measurements collected manually during the 2003 growing season are shown. Nine visits to

the field were made during this time period to collect data. Long-term trends are apparent, but conditions immediately after a rainfall or irrigation event are not detected.

Measurements collected automatically during the 2004 growing season are shown in Figure 3. The field was visited normally once per week, to visually inspect crop conditions, collect other data, and download moisture-sensor data. Much less time and labor were required to collect moisture data, and a much more complete picture of the moisture conditions was obtained by automating the measurements.



**Figure 2.** Moisture-sensor measurements collected manually, July 2003.



**Figure 3.** Moisture-sensor measurements collected automatically, August 2004.

### Automated Evaporation Pan and Atmometer Measurements

Recent efforts to automate evaporation pan and atmometer readings have been described. Bruton et al. (2000) used a float mechanism to automate evaporation pan readings, but malfunctions in the mechanism and differences between manual and automated readings were noted. Dukes et al. (2004) described a low-cost (US\$200) float and pulley datalogger system designed to automate atmometer readings.

An evaporation pan and atmometer were installed at the USDA ARS research station at Stoneville, Mississippi, for use in irrigation scheduling of cotton. Previously, pan and atmometer measurements were made manually, requiring frequent site visits, and recorded on a data sheet.

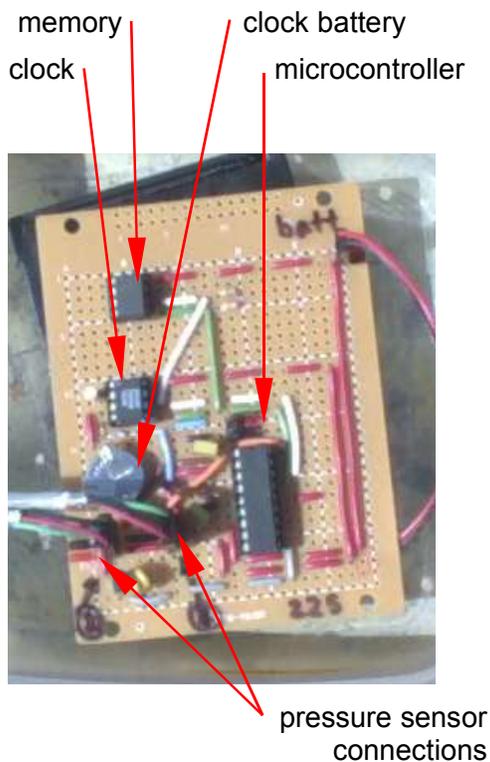
A circuit board was designed to automate the data-collection process. The metal evaporation pan was first modified by drilling a hole in the side of the pan. A barbed hose fitting was installed in the hole, and a differential pressure sensor was connected to the hose fitting with a short length of plastic tubing. The atmometer was modified in the same way: a hole was drilled in the side and a pressure sensor was attached.

The pressure sensors were used to measure the hydrostatic pressure of the water. The hydrostatic pressure is the pressure caused by the weight of the water, which is a function of its depth. The depth of water, then, could easily be

determined by measuring the hydrostatic pressure and calculating the depth based on the pressure vs depth relationship for water.

The main components of the circuit board consist of a microcontroller, connectors for the two pressure sensors, real-time clock, memory chip, and batteries. The circuit was built on a prototype board, shown in Figure 4. The main components of the circuit and their costs are shown in Table 2.

The microcontroller was programmed to make and store measurements at 2-hour intervals. The microcontroller continuously monitored the real-time clock, and when time came to make measurements, provided an excitation voltage to the pressure sensors. The pressure sensors were factory calibrated to provide a voltage signal linearly related to pressure. The microcontroller measured the signal voltages with its built-in analog-to-digital converters. The microcontroller program contained a calibration routine to convert the voltage signals to pressures and then to the depths of water. The



**Figure 4.** Evaporation-pan and atmometer measurement prototype circuit board.

**Table 2.** Parts list and cost of main components for evaporation pan/atmometer circuit

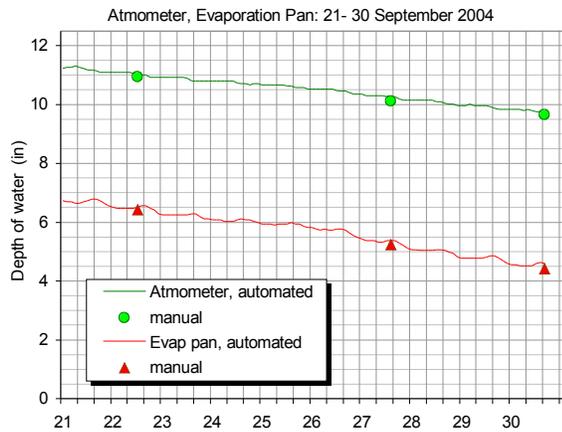
Description	Cost (US\$)
<u>Part number, Manufacturer</u>	
Microcontroller <i>PIC 16F819, Microchip Technologies</i>	3
Clock <i>DS1302, Dallas Semiconductor</i>	3
Memory <i>24LC512, Microchip Technologies</i>	3
Pressure sensors <i>MPX5010D, Motorola</i>	20 ea
Circuit board	1
Batteries	2
Miscellaneous (resistors, capacitors, connector pins, voltage regulator)	2
<b>total</b>	<b>\$54</b>

date, time, and water depth data were then stored in the memory chip, and the microcontroller put itself into a low-voltage sleep mode to conserve battery power until the next measurement interval.

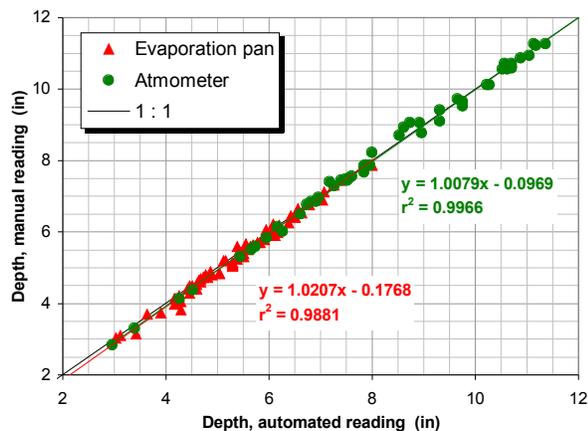
To test the accuracy of the automated measurements, manual depth measurements were collected periodically and compared to those made with the circuit board. Manual evaporation-pan measurements were made by reading the metal scale in the evaporation pan. Manual atmometer measurements were made by reading the height of the water column in the clear plastic standpipe on the side of the atmometer. Data from the circuit board were downloaded periodically, and the automated and manual data were input to a spreadsheet for analysis and graphing.

Depth measurements from a 10-day period in September 2004 are shown in Figure 5. Manual measurements were made three times during this period, and compare well with the automated measurements.

Between April and September 2004, 55 manual measurements were made during visits to the site. Measurements were not made at any regular time, rather occurred at various times of the day between 0800 and 1600. The manual measurements were compared to concurrent automated measurements, shown in Figure 6. The automated measurements compared well



**Figure 5.** Automated and manual evaporation pan and atmometer measurements during a 10-day period in September 2004.



**Figure 6.** Comparison of automated and manual measurements.

with the manually collected measurements. Standard errors of the automated readings compared to the manual readings were 0.13 in for the evaporation pan and 0.12 in for the atmometer.

### Pressure Chamber Controller

An important hydraulic property of a soil is its soil-water retention curve. The soil-water retention curve is the relationship between the soil's water content and water potential. A common laboratory procedure for developing

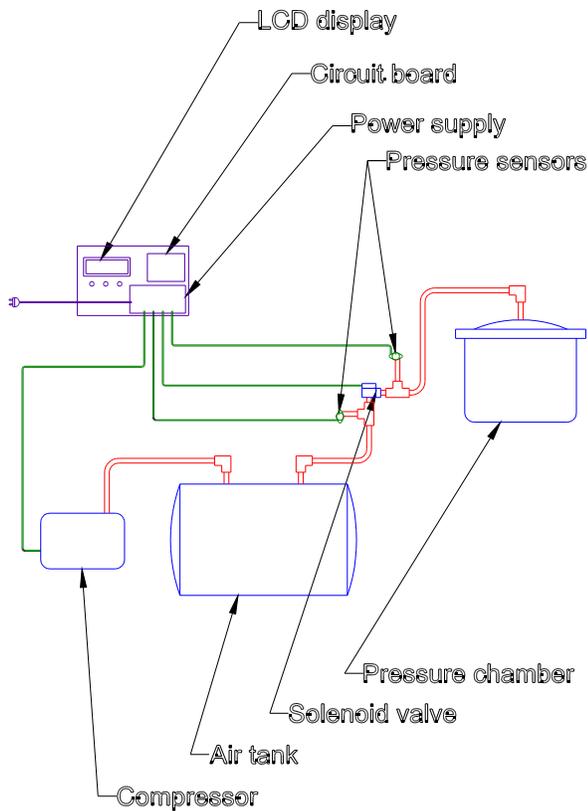
the retention curve is described by Klute (1986), and involves determining the water content of a soil sample over a range of known water potentials.

The equipment used to develop a water retention curve normally consists of a pressure chamber and porous ceramic plate, a source of compressed air, and an air-pressure regulating system. The compressed-air source, usually an electric air compressor, supplies pressurized air to the pressure chamber. The pressure-regulating system maintains the pressure in the pressure chamber at the desired level.

One pressure-chamber system is commercially available (Soilmoisture Equipment Corp., Santa Barbara, California USA). The system consists of mechanical regulator valves, large pressure gages, metal piping, and an industrial-size air compressor. The system has a few potential drawbacks, however. The industrial, high-pressure compressor is noisy, and the equipment takes up considerable space. It is also expensive, and its purchase could be hard to justify for a small project or with a limited budget.

A system was designed to provide an inexpensive, well-regulated source of pressurized air to a pressure chamber for developing water retention curves. The system consisted mainly of an electric air compressor, an air storage tank, an electric solenoid valve, pressure sensors, and a PIC microcontroller circuit board. A sketch of the pressure chamber system is shown in Figure 7. A list of the components and their costs are shown in Table 3.

The system is controlled by a microcontroller which continuously monitors two pressure sensors. One sensor measures the pressure inside the pressure chamber. If this pressure decreases below the desired level, the microcontroller opens the solenoid valve for a fraction of a second. Higher-pressure air upstream of the solenoid valve enters the chamber, increasing the pressure inside the chamber. The second sensor measures the pressure inside the air storage tank, which is maintained at a pressure higher than that desired inside the pressure chamber. If the



**Figure 7.** Sketch of components

**Table 3.** Parts list and cost of main components on pressure chamber controller

Description	Cost (US\$)
<i>Part number, Manufacturer</i>	
Microcontroller	
<i>PIC 16F877, Microchip Technologies</i>	7
Pressure sensor	
<i>MPX5010D, Motorola</i>	20
LCD display	10
Circuit board	1
Batteries	2
Miscellaneous (resistors, capacitors, pushbuttons, LEDs, voltage regulator)	3
Power supply	
<i>MKS150-12, Astrodyne</i>	73
Solenoid valve	
<i>6011, Burkert</i>	27
Air compressor	
<i>12V Ultra, NuTech</i>	20
Air storage tank	
<i>41712, Central Pneumatics</i>	20
Plastic tubing, fittings	5
<b>total</b>	<b>\$188</b>

storage-tank pressure decreases below a set level, the microcontroller turns on the air compressor. The compressor remains on until the pressure inside the storage tank is recharged. The microcontroller program loops continuously, monitoring the pressure sensors and adjusting the pressures at 1-second intervals.

The control circuitry consists essentially of a power supply, circuit board, and LCD display. The power supply converts the 120 Vac main electrical source to a 12 Vdc supply needed to run the air compressor and the solenoid valve. The 12 Vdc supply provides power to the microcontroller circuit, pressure sensors, and LCD display through a 5-Vdc voltage regulator.

The circuit board consists of a microcontroller, relays, three pushbuttons, and a few resistors, capacitors, and LED lights. Since the compressor and solenoid valve draw more electrical current than the microcontroller can tolerate, each is controlled by the microcontroller via a relay. Pushbuttons enable the user to increase or decrease the desired chamber pressure, and to temporarily pause the system to allow the pressure chamber to be opened and the soil samples accessed. LED lights indicate when the system is operating and when it is paused.

The system has performed well in initial testing. A range of chamber pressures from 10 kPa to 150 kPa have been tested, and the pressure inside the pressure chamber has remained within  $\pm 1$  kPa of its set pressure.

### Non-Contact Water Level Measurements

While pressure sensors are being used to measure water levels (see above), there may be occasions where non-contact measurements are desired. The use of a sensor which does not come into contact with the substance being measured would then be needed.

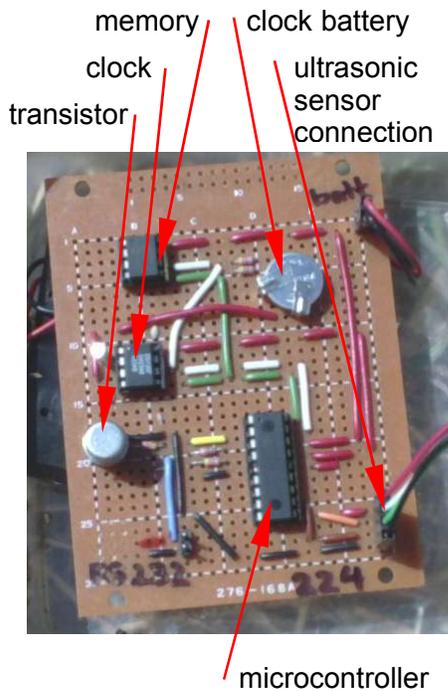
A circuit was designed for making non-contact depth measurements using an ultrasonic rangefinder. The rangefinder transmits a high-frequency acoustic pulse, which is reflected if it comes into contact with an object. A receiver is

activated to detect the reflected signal. The distance of the object from the sensor can be calculated based on the time it takes for the pulse to be reflected and return to the sensor and the speed of sound in air.

The rangefinder was installed above the evaporation pan described previously, and used to measure the depth of water in the pan. Depth measurements were then compared to those made manually and with the pressure-sensor circuit described above.

The main components of the circuit board consist of a microcontroller, real-time clock, memory chip, transistor, connector for the ultrasonic rangefinder, and batteries. The circuit was built on a prototype board, shown in Figure 8. The main components of the circuit and their costs are shown in Table 4.

The microcontroller was programmed to make and store measurements at 2-hour intervals. When time came to make measurements, the microcontroller first energized the transistor, which acted as a switch to turn on power to the ultrasonic rangefinder. The microcontroller



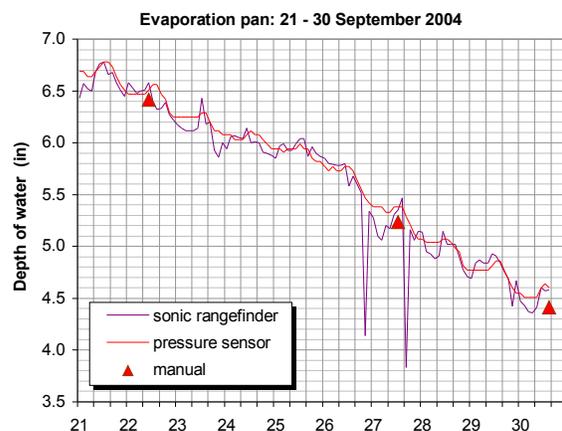
**Figure 8.** Ultrasonic rangefinder prototype board.

**Table 4.** Parts list and cost of main components on ultrasonic rangefinder circuit board

Description	Cost (US\$)
<u>Part number, Manufacturer</u>	
Microcontroller	
<i>PIC 16F819, Microchip Technologies</i>	3
Clock	
<i>DS1302, Dallas Semiconductor</i>	3
Memory	
<i>24LC512, Microchip Technologies</i>	3
Ultrasonic rangefinder	
<i>SRF04, Devontech</i>	35
Circuit board	1
Batteries	2
Miscellaneous (resistors, capacitors, connector pins, transistor)	2
<b>total</b>	<b>\$49</b>

triggered the sensor, which transmitted an acoustic pulse, and initiated a timer. When the sensor's receiver detected the reflected pulse, the timer stopped. The microcontroller program contained a routine to convert the time of travel of the pulse to a distance, and then to a depth of water. The date, time, and water depth data were then stored in the memory chip, and the microcontroller put itself into a low-voltage sleep mode to conserve battery power.

A series of water depth measurements made manually, with the rangefinder, and with the pressure-sensor circuit is shown in Figure 9. In general, the rangefinder showed more variation



**Figure 9.** Ultrasonic rangefinder measurements.

in depth than did the pressure sensor. This may have been due in part to the mounting of the rangefinder: the rangefinder was attached to the chicken-wire screen covering the evaporation pan which may have flexed throughout the day. On a few occasions, unrealistic depths were recorded. The cause of these significant random errors is unknown and must be investigated.

## CONCLUSIONS

The capabilities, prevalence, and ease of use of modern electronic components are increasing rapidly. Electronics are increasingly being used to collect and process all types of data, transfer information, and provide automation and control functions. Many more specialized components and sensors are available which interface easily and simplify circuit design.

These modern electronic components can be put to use in agriculture as in the many other applications in which they already serve. A number of useful, inexpensive, and easy-to-use electronic components were described. Several examples of circuits used in irrigation research were presented and discussed.

## ACKNOWLEDGEMENTS

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