An inexpensive open-source ultrasonic sensing system for monitoring liquid levels

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Abstract: Liquid levels are measured in a variety of agricultural applications, and are often measured manually, which can be time-consuming and labor-intensive. Rapid advances in electronic technologies have made a variety of inexpensive sensing, monitoring, and control capabilities available. A monitoring system was developed and evaluated for automatic measurement of liquid levels, and demonstrated by monitoring water levels in evaporation pans used in evaporation studies and irrigation scheduling. The system is composed of an ultrasonic sensor, a microcontroller-based data logger, and a temperature sensor. The ultrasonic sensor measures the distance from the sensor to the liquid surface. Air temperature is measured by the temperature sensor, and is used to compensate for changes in the speed of sound due to air-temperature variations to improve accuracy of ultrasonic distance measurements. The datalogger is programmed to take measurements and to store data on a memory card which can be downloaded for processing and analysis. All components of the system were assembled in a PVC housing. The system was tested in the field, and resulted in water levels measured by the system corresponding very closely to those measured manually (R^2 > 0.98). This system is inexpensive, with total cost of US$85, and easy to build, install, and maintain. In addition to monitoring liquid levels, the system could be adapted to a variety of other measurements.

Keywords: Ultrasonic sensor, liquid level, microcontroller, open-source hardware, datalogger, USA

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1 Introduction

Rapid advances in electronic technologies have made a variety of inexpensive sensing, monitoring, and control capabilities available. An open-source project called Arduino (www.arduino.cc) resulted in the creation of a programmable microcontroller development platform, with expansion capability through add-on circuit boards, and a programming environment to create software for the microcontroller. As an open-source device, all circuit-board and electronic component specifications, as well as the programming software, are freely available for anyone to use or modify. Inexpensive sensors and the Arduino development platform have begun to be used to develop sensing and datalogging systems for agricultural, natural-resource related, and other applications (Buechley and Eisenberg, 2008; Zhang et al., 2009; Bergmann et al., 2010; Gordon et al., 2010; Hicks et al., 2011; Fisher and Gould, 2012). These studies demonstrate the usefulness of automated measurements, and offer guidance for others in developing inexpensive sensing and monitoring systems to further their research.

Ultrasonic sensing technology, used to measure distance to an object, has found useful applications in agricultural research and production. With ultrasonic sensing, a distance is determined by transmitting ultrasonic pulses toward an object at the speed of sound, and waiting for an echo to return after impacting the object. The distance from the sensor to the object can then be calculated based on elapsed time between pulse transmission and echo return. Sui et al. (1989) and Sui

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and Thomasson (2006) reported two ultrasonic devices for measuring plant morphological properties. In characterization of con plant canopy, Aziz et al. (2004) determined height of individual leaves of corn canopy using ultrasonic echo signal from the canopy. Jones et al. (2004) estimated plant biomass using ultrasonic distance measurement combined with top view surface area of the plant. Tumbo et al. (2002) employed ultrasonic sensors to map and quantify canopy volumes of citrus trees. Guo et al. (2002) reported a conceptual safety alert system using ultrasonic sensors which detected moving objects in the vicinity of agricultural machinery. Jeon and Zhu (2012) reported their use of ultrasonic sensors to detect canopy of nursery liner trees and trigger sprayer nozzles for variable-rate chemical applications.

Liquid levels are measured in a variety of agricultural applications; fuel tanks, water reservoirs, irrigation canals, and evaporation pans, for example. Measurements are often made manually, which can be time-consuming and labor-intensive, resulting in either extensive efforts being invested to collect data frequently, or less effort expended and data collected at lower frequency.

The objective of this study was to develop and evaluate an ultrasonic sensing system for automatic monitoring of liquid levels in agricultural applications. To demonstrate the application of this technology, water levels were monitored in evaporation pans. Evaporation pans are used extensively throughout the world to estimate the evaporative demands of the atmosphere, determine crop water use, and assist in irrigation scheduling (Stanhill, 2002). While more-sophisticated methods of estimating evaporative demand are available, such as weather-based equations, equipment costs, maintenance, and personnel issues often limit their adoption. Evaporation pans continue to be relied upon due to their simplicity and lower operational costs and requirements.

2 Materials and methods

The measurement system consists primarily of an ultrasonic sensor, a temperature sensor, and a microcontroller-based datalogger. The ultrasonic sensor measures the distance from the sensor to the targeted object, the water surface in this case, and the temperature sensor measures air temperature. The microcontroller circuit handles all sensor measurements, time and date recording, and data-storage functions. A PVC housing provides protection for the electronic components and a stable platform for mounting sensors and deploying the system in the field. A diagram of the measurement system is shown in Figure 1.

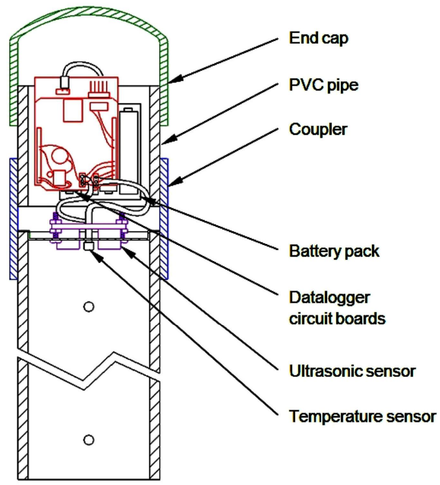

Figure 1 Diagram of ultrasonic water-level measurement system

2.1 Ultrasonic and temperature sensors

The PING ultrasonic module (Parallax Inc., Rocklin, CA USA) consists of two transducers, one which emits a pulse of high-frequency sound waves, and one which detects reflected sound waves that impact a surface. Distance is determined by measuring the time interval between sending the pulse and receiving the reflection, or echo, and converting this to a distance based on the speed of sound. The module is connected to the microcontroller, which is programmed to initiate a pulse, then starts an internal timer and measures the time interval, in microseconds, until an echo signal is detected.

The emitted and reflected sound waves travel through the air, and the measured time interval will, therefore, depend on the speed of sound. While it is normally assumed to be constant, the speed of sound in air is strongly dependent on the air temperature, and slightly affected by humidity (Bohn, 1988). This can be compensated for by calculating the actual speed of sound more accurately using Equation (1)

$$v = 331.4 + 0.6 * T \quad (1)$$

where, v = speed of sound (m s^{-1}), and T = air temperature (C).

To improve the accuracy of distance measurements, the air temperature is measured with an LM35 temperature sensor (National Semiconductor, Santa Clara, CA USA). The temperature sensor is factory-calibrated to output a voltage signal proportional to temperature (10 mV C^{-1}), which is measured using one of the microcontroller's A/D channels.

2.2 Microcontroller-based datalogger

The main components of the datalogger include an Arduino-compatible microcontroller board, voltage regulator, microSD/prototyping board, and real-time clock/calendar. The Diavolino microcontroller board (Evil Mad Science LLC, Sunnyvale, CA USA) was selected based on its low cost, simple design, and ease of modification for battery-powered operation. The microcontroller board consists of a programmable 8-bit microcontroller, model ATmega328 (Atmel Corporation, San Jose, CA USA), installed on a circuit board so that all input/output (IO) pins are easily accessible. The microcontroller contains 32 kilobytes (kb) of non-volatile memory for program storage and 1 kb for data storage. IO lines include 14 digital pins and 6 analog pins, which provide 6 channels of 10-bit analog-to-digital (A/D) conversion capability. Other features include timer/counters, internal and external interrupts, serial and other communications capabilities, and low-power, energy-saving modes. The microcontroller can operate at either a 5-V level and oscillator speed of 16 MHz or a 3.3-V level and 8 MHz, and communicates with a personal computer via a two-wire serial (transmit, Tx, and receive, Rx) connection.

The Diavolino board was modified slightly by adding a two-pin header for connecting an external four-AA battery pack. A 5-V voltage regulator, model LP2950 (National Semiconductor Corp., Santa Clara, CA USA), and two 1-µF capacitors were added to convert the unregulated battery voltage to a stable 5-V source to power the microcontroller circuit and sensors.

A microSD/prototyping board (Sparkfun Electronics, Boulder, CO USA) plugs into the microcontroller board, and was used to provide microSD-card circuitry and a prototyping area for incorporating additional circuit components. The microSD board was also modified for low-power operation: power for the microSD card was rerouted to one of the microcontroller's digital pins so that it could be turned off when not in use to extend battery life. A microSD card (Samsung) with a 2 gigabyte storage capacity was inserted into the microSD card holder for data storage. A real-time clock/calendar chip, model DS1337 (Maxim Integrated Products, Inc., Sunnyvale, CA USA), was installed in the board's prototyping area, and provided date and time information for taking sensor readings at regular time intervals and for date- and time-stamping sensor data stored to the microSD card. A 32.768 kHz crystal oscillator provided a timing signal, and a 3.3-V lithium coin-cell battery provided continuous power to the clock chip.

Two three-pin connector headers were added to provide connections between the ultrasonic and temperature sensors and the microcontroller. Both sensors had the same 3-pin layouts; power, ground, and sensor output. For each sensor, the power pin was wired to one of the microcontroller's digital output pins, the output pin was wired to an input pin, and the ground pin was wired to the microcontroller circuit's common ground. The output signal from the ultrasonic sensor was read with a digital input pin, while the output from the temperature sensor was read with one of the microcontroller's built-in A/D converters. A schematic of the circuit is shown in Figure 2.

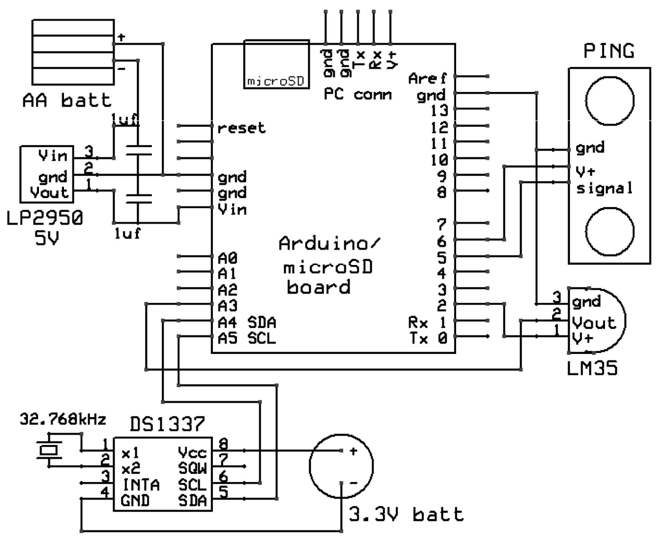

Figure 2 Schematic of datalogging circuit

2.3 System housing

The housing for the measurement system was constructed of commonly available 76 mm (3-in) diameter PVC pipe and fittings. A test cap (a flat piece of plastic which fits into the end of the PVC pipe) was modified by drilling holes for positioning and mounting the ultrasonic and temperature sensors. A length of 76-mm (3 in) diameter pipe was cut, and holes drilled to allow for water and air movement. The test cap and sensors were installed in one end of the pipe, and a pipe coupler fitting was attached over the test cap. A short piece of pipe, approximately 50 mm in length, was inserted into the coupler to provide a location for securing the datalogger boards and battery pack. A PVC end cap was then placed over the short pipe to protect the electronic components. A diagram of the housing and complete system is shown in Figure 1.

2.4 System cost

The cost of the system included costs of the ultrasonic and air-temperature sensors (US$32), microcontroller and microSD/prototyping boards ($30), other electronic components (US$15), and PVC pipe and fittings (US$8). The total cost for each system was approximately US$85. Labor requirements included approximately two hours to construct the electronic circuitry, and one hour to construct the PVC housing.

2.5 Programming and operation

The datalogger program was created using the Arduino Integrated Development Environment (IDE). The IDE provides tools for writing and debugging programs in a language similar to C++, and for downloading programs to the microcontroller. Once the microcontroller is programmed, the battery pack is connected to the microcontroller board, powering the circuit, and the microcontroller program initiates. First, the program checks to ensure that a microSD card is installed and formatted, and creates a data file. The real-time clock is then read to determine if it is time to take measurements, which are programmed to occur at 1 h intervals. If not time, the microcontroller puts the circuit into a low-power sleep mode.

At each measurement interval, the microcontroller first turns on the temperature sensor and reads the sensor's output voltage ten times. The average voltage is calculated, and an air temperature value determined using the factory calibration. The ultrasonic sensor is powered, and ten measurements are made. For each measurement, a trigger signal is sent, an internal timer in the microcontroller is started, and the time for an echo signal to return is measured. The ten readings are then averaged.

Average temperature and echo return time are used to calculate the distance, based on the speed of sound, between the sensor and the surface upon which the ultrasonic pulse impacted. The speed of sound is calculated to compensate for air temperature. The return time is used to calculate the distance from the sensor to the reflecting surface using the speed-time-distance relationship, $d = v \times t$, where d is the distance (m), v is the speed of sound (m s^{-1}), and t is the time interval (s). This distance is then subtracted from the distance of the sensor to the bottom of the evaporation pan, measured when installing the system, to determine the depth of water in the pan.

Following the measurements, the microcontroller turns on the microSD card circuit, and data, including a unique circuit-board identification number, date, time, air temperature, and water depth, are written to the microSD card in ASCII text format. Power to the microSD card and sensors are then turned off, and the circuit is put into a low-power sleep mode.

The length of time the system can operate on a single set of batteries is estimated based on the current consumption of the microcontroller circuit and sensors. During active sensor operation and writing of data to the microSD card, which lasts approximately 3 s, current consumption reaches 40 mA. While in sleep mode, current consumption is approximately 0.39 mA. With a measurement interval of 1 h, the total current consumed is 0.42 mA. With a rated capacity of 2500 mA h for AA batteries, this converts to an estimated battery life of 248 d.

2.6 Field evaluation

Four ultrasonic sensing systems were constructed and tested by monitoring the water level in evaporation pans during the summer of 2012. The systems were installed and operated in the field during a three-month period. Differing lengths of PVC pipe, ranging from 290 to 600 mm, were used for the bottom section of the housings. The systems were installed with the ultrasonic sensor vertically facing down at the water surface in the evaporation pan (Figure 3), which was approximately 760 mm in diameter and 230 mm deep. The microcontroller-based systems recorded water-level measurements to the microSD cards at 1-hour intervals, and the data were downloaded periodically from the cards to a tablet computer. During site visits, manual measurements of the water levels were made by inserting a steel ruler into the evaporation pan and reading the depth of water to the nearest millimeter.

Figure 3 Ultrasonic measurement system installed in evaporation pan

3 Results and discussion

During the three-month time period, the depth of water in the pans varied between 25 and 145 mm, decreasing as water evaporated in response to environmental demand and increasing due to rainfall and periodic manual refilling. Hourly data collected from one ultrasonic sensing system during a six-day period are shown in Figure 4. Data include air temperature, water level measured with the ultrasonic sensor, and water level measured manually. An increase in depth can be seen in response to a manual addition of water to the pan, followed by decreasing depths as water evaporated.

To illustrate the importance of measuring air-temperature and correcting the speed of sound for actual conditions, depth measured with the ultrasonic sensor assuming a constant air-temperature (25 C), and therefore constant speed of sound, are also shown. Large increases in apparent depth of water can be seen in the uncorrected depths as air temperature increased and decreased throughout the day. Correcting for temperature reduced these errors considerably.

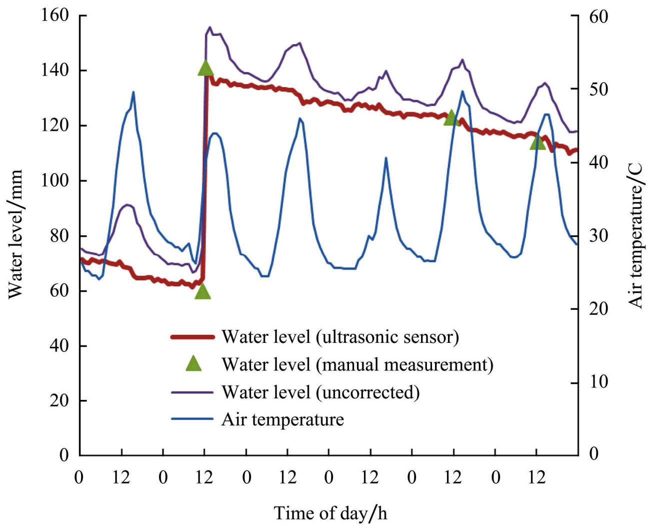

Figure 4 Water-level measurements during a six-day period

Accuracy of ultrasonic measurements was determined by comparing water levels measured with the sensors to those measured manually. Manual depth measurements were recorded at varying times throughout the three-month period and at varying times of day, with from 8 to 25 manual measurements collected for each of the four systems. Manually measured water levels ranged from 24 to 147 mm. Comparison of measurements from the four ultrasonic sensors is shown in Figure 5, and indicates a very good agreement with the manual measurements. Slopes of regression lines between water levels measured with the ultrasonic sensor systems (x) and measured manually (y) were very close to 1.000, with correlation coefficients R^2 > 0.98 for all four systems. Measurement error was determined by calculating the mean absolute error (MAE) as suggested by Willmott and Matsuura (2005), summing the absolute differences between sensor and manual measurements and dividing by the number of measurements. MAE values of 2.1, 2.6, 2.8, and 2.0 mm were determined for the four systems tested.

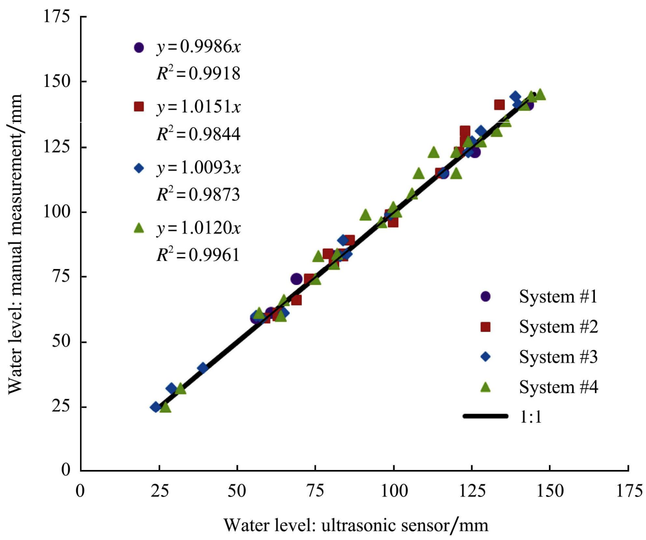

Figure 5 Comparison of ultrasonic and manual water-level measurements for four systems.

4 Conclusions

An ultrasonic sensing system was developed for monitoring water levels in evaporation pans for irrigation scheduling. The system consisted of an ultrasonic sensor, an air-temperature sensor, and a microcontroller-based datalogger. Field tests indicated that the system was capable of automatically monitoring water levels in real time in situ. Results showed that the system-measured water levels agreed well with manual measurements, with correlations of $R^2 > 0.98$ for four systems. The system is inexpensive, with a total cost of approximately $85, and easy to install and maintain in the field. Automation of measurements, such as from an evaporation pan, has significant advantages, including more frequent and regular data collection and less labor involved. This system could be adapted for distance measurements in other circumstances as well.

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