Open-source Hardware & Software for Irrigation

Daniel K. Fisher

USDA Agricultural Research Service, Crop Production Systems Research Unit, 141 Experiment Station Rd., Stoneville, MS 38701 USA. daniel.fisher@ars.usda.gov

Abstract. *Information is needed in order to study, monitor, or understand a process or event. Data collection efforts often involve compromises related to frequency of measurements, labor requirements, costs, and data access. Advances in electronic technologies, software, and communications infrastructure have resulted in a variety of new and inexpensive monitoring capabilities for agricultural, irrigation, and water-management applications. Programmable microcontrollers and solid-state sensors enable rapid development of unique automated sensing, monitoring, and control systems. Wireless, cellular, and internet infrastructures allow rapid data transfer, and enable transfer of data from remote locations and real-time access to and sharing of data. These emerging technologies are enabled by application of open-source hardware and software, which offer advanced tools and capabilities and are freely available for anyone to use, develop, and modify. Open-source hardware and software resources are discussed, and were used to develop sensing and monitoring systems. Examples of products that have been developed, including a soil-moisture monitor and a mobile plant-canopy monitoring system, are presented to demonstrate the accessibility and usefulness of these development tools.*

Keywords. Arduino, sensors, cellular, internet

Introduction

In order to monitor, study, or understand a process or event, information is needed. Data collection efforts often involve compromises related to frequency of measurements, labor requirements, costs, and data access. Advances in electronic technologies, software, and communications infrastructures have resulted in a variety of new and inexpensive monitoring capabilities for agricultural, irrigation, and water-management applications. Manual measurements can often be automated, reducing time- and labor-intensive activities while increasing the frequency of measurements. Driven by mass-market consumption of electronic devices, costs of electronic sensing and monitoring components have been greatly reduced in recent years, allowing for increased availability and access. As the reach of communications infrastructures, such as wireless, cellular, and internet networks, expands, data transfer options are becoming more accessible for new and unique applications.

While many recent technological advances have been aimed at consumer markets (smartphones, tablet computers, home automation, entertainment systems), the same technologies are available to developers for other markets. Hardware, such as programmable microcontrollers, solid-state sensors, and wireless communications, and the software tools to enable the hardware to function are accessible via the concept of "open-source." Open-source refers to the free and open development of hardware and software, wherein the developer makes all source code, blueprints, and documentation available to all to use, modify, or replicate without limitation. This openness is intended to improve quality, access, and understanding of ideas and products through collaboration rather than competition. Open-source software (Open Source Initiative, http://www.opensource.org) and hardware (Open Source Hardware Association, http://www.oshwa.org) communities have actively advanced software (Linux and Android computer operating systems) and hardware (Arduino) projects, among many others.

The Arduino project (http://arduino.cc) offers options to the agricultural research community, which, due to its small market size, is often underserved and lags in technological progress. The Arduino project consists of hardware and software tools, as well as a large community of collaborators, that can be used to develop unique sensing, monitoring, and interactive devices. Hardware consists of a microcontroller-based development platform, and accompanying software consists of an Integrated Development Environment (IDE) for programming and interacting with the microcontroller. The collaborative community provides programming expertise and assistance, additional hardware and software features to gain increased functionality, and technical support if needed to advance individual projects. Researchers have begun investigating the use of open-source technologies in studies related to irrigation (Bitella et al., 2014; Masseroni et al., 2016; Fisher et al., 2017; Payero et al., 2017), agriculture (Fisher and Sui, 2013; Di Prima, 2015; Thalheimer, 2016; Fisher and Huang, 2017), and the environment (Fisher and Gould, 2012; Mesas-Carrascosa et al., 2015).

The objective of the work presented is to describe and discuss some of the open-source hardware and software options available to the agricultural and irrigation research community. Hardware and software tools for sensing and monitoring, and for data-transmission and access, are presented, followed by examples of open-source monitoring systems that have been developed and deployed under agricultural conditions.

Open-source hardware

Development of sensing and monitoring systems involves the integration of several main hardware components, including a microcontroller, electrical power supply, sensors, and data communications. Other components can be incorporated to offer additional features if desired, such as timekeeping, data storage, and information display.

Microcontroller

The microcontroller serves as the basis for sensing and monitoring instruments. A microcontroller is a programmable device that is configured and programmed to accomplish specific tasks. When the Arduino Uno (http://arduino.cc) open-source development platform was first introduced, Arduino-branded and compatible development boards were built around an 8-bit microcontroller which operated at either a 5 V level and a processing speed of 16 MHz or a 3.3 V level and 8 MHz speed. Programming memory was somewhat limited at approximately 32 Kbytes, but the many built-in features, such as 10-bit analog-to-digital converter, multiple communications ports, and multiple digital input/output pins, resulted in a development board with great flexibility that could be adapted to many and varied applications.

A unique feature of the original Arduino development board was its standardized size and arrangement of electrical power and input/output pins. This standardized layout allowed for the development of peripheral devices, called shields, which could be plugged into the microcontroller board to increase functionality. Microcontroller boards and shields offered by third-party developers that were produced in the standardized form were then also compatible, allowing different microcontroller boards and shields to be interconnected.

As the popularity of the Arduino platform increased, the open-source nature of the Arduino project allowed for the development and availability of a variety of compatible devices. The devices use the same 8-bit microcontroller, allowing the use of the Arduino IDE and existing programming libraries, and for the uploading of existing programs. The form factor of newer development boards is often different, however, and additional features are increasingly being built in. Examples of newer devices include the Pro Mini (Sparkfun Electronics, http://sparkfun.com), a smaller, less expensive board with the same features as the original Arduino Uno. The Moteino (LowPowerLab, http://lowpowerlab.com) offers the same features, plus an optional memory chip with approximately 500 Kbytes of data storage capacity, and several low-power, license-free radio options. The Feather series (Adafruit Industries, http://adafruit.com) offer a microcontroller development board with a variety of optional features including built-in micro SD card, Bluetooth and wi-fi radios, and cellular modem. The original Arduino Uno and several newer development boards are shown in Figure 1.

Rapid advances in electronics technologies continue to make more powerful and less expensive microcontrollers available, and the Arduino project continues to add support for many of these microcontrollers. A new generation of Arduino and compatible development boards features a 32-bit microcontroller, which offers an increased processing speed of 48 MHz, increased program memory of 256 Kbytes, 12-bit resolution analog-to-digital converter, and additional communications features. The Arduino Zero and M0 development boards feature the same form factor as the original Arduino Uno, enabling the connection of existing peripheral shields. Other boards maintain the form factors of their respective manufacturer's earlier products, such as the Pro Mini (Sparkfun Electronics) and the Feather (Adafruit Industries), while updating the boards' processing power with 32-bit microcontrollers.

Electrical power

Sensing and monitoring activities for agricultural, irrigation, and water-management applications often occur in remote areas where access to electrical power is limited. Unattended operation of electronic instrumentation, therefore, requires the use of a self-contained power source, usually in the form of batteries. To enable long-term monitoring, power consumption must be minimized to prolong battery life and extend time intervals between site visits.

To minimize power consumption, software and hardware solutions can be used or combined. Microcontrollers usually have multiple low-power sleep modes that can be programmed to reduce current consumption during periods of inactivity. If peripheral components in the sensing circuit, such as sensors or data-storage devices, remain powered, however, they remain in an

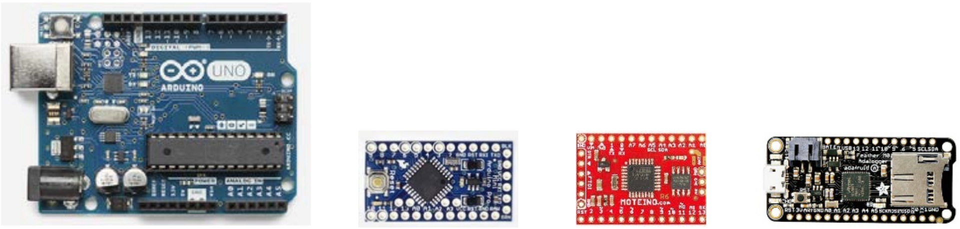


Figure 1. Microcontroller development boards, from left to right; Arduino Uno, Pro Mini, Moteino, and Feather.

active state and their current consumption is not reduced. The circuit can often be redesigned so that power to the peripheral devices is controlled by the microcontroller, enabling the microcontroller to turn the peripherals on during measurement periods and off during low-power sleep periods, greatly reducing drain on the batteries.

Various hardware solutions exist in the form of electronic components designed specifically for enabling low-power circuits. One such component is the TPL5110 Low Power Timer (Adafruit Industries, LowPowerLab), which serves as an interface between an electronic circuit and the battery. The low power timer switches battery power on to the microcontroller-based circuit at a regular time interval, which is set by a resistance value. When power is turned on, the circuit is activated and the microcontroller program executes. After completing the measurement functions, the microcontroller sends a signal to the low power timer instructing the timer to turn power off to the circuit. Battery power is completely disconnected from the microcontroller and circuit, resulting in essentially no current consumption from the battery.

In some applications, the complete shutdown of a monitoring circuit may not be desirable. To maintain long-term operation, a solar-powered circuit can be installed to continuously recharge the battery. The USB/Solar Lithium Ion Battery Charger (Adafruit Industries) and a small Monocrystalline Solar Cell (Newark element14, http://www.newark.com) can be added to almost any circuit to ensure long-term operation.

Sensors and peripheral devices

Analog and digital sensors have been in use in irrigation and agricultural applications for decades. Soil-moisture sensors such as the Watermark (Irrometer Company, Inc., http://www.irrometer.com) and EC-5 (Decagon Devices, http://www.decagon.com) and meteorological sensors (Campbell Scientific, http://www.campbellsci.com) are well-known to the agricultural and irrigation communities.

Rapid proliferation of sensing and monitoring systems for automotive, consumer devices, and home automation and surveillance purposes has made new generations of sensors available which are designed for integration into microcontroller-based circuits. The often small and inexpensive sensors offer opportunities to expand monitoring efforts for a variety of sensed parameters. Sensors to detect and measure motion (presence, movement, acceleration), location (GPS), temperature (ambient, noncontact/infrared), light/radiation (intensity, RGB/color, multispectral, UV), air quality (CO_2, VOC), weather (air temperature, humidity, pressure), and distance (ultrasonic, infrared, lidar) are readily available. In many cases, however, the sensors have been miniaturized to the point where they are difficult to work with other than with specialized surface-mount instrumentation. A number of suppliers, such as Adafruit Industries and Sparkfun Electronics, have recognized this constraint and offer many of these sensors on breakout boards. The breakout boards contain the sensors and other auxiliary electronic components on a circuit board, and make available the connections necessary for interacting with the sensors. Breakout boards provide convenient access to the sensors for prototyping or for inclusion in sensing and monitoring systems.

Sensors are designed to interact with microcontrollers via several standardized communications protocols. Standard two-wire serial ports are common with some components, such as telephone modems and GPS receivers. Newer digital sensors often communicate via Inter Integrated Circuit (I2C) or Serial Peripheral Interface (SPI) protocols, designed specifically for communications between microcontrollers and digital devices. The two-wire I2C interface allows multiple components to connect via the same two microcontroller pins, with each component identified by a unique address. The three-wire SPI interface is similar, allowing multiple devices to share the same communications pins, but each component requires an additional pin for use in identifying that component.

Sensors are often incorporated into a microcontroller-based circuit very simply by connection of appropriate power and logic connections to the microcontroller. Sensor measurements are obtained through the programming of the microcontroller, with the program written to send appropriate addresses or signals to the sensor, wait for the sensor to make a measurement, then read data digitally from internal registers. The microcontroller applies calibration algorithms supplied by the sensor manufacturer to convert the register values to physical measurements. Many programming routines and libraries have been written and are available from the Arduino community, or can be developed from detailed information provided by sensor manufacturers.

Sensors and other peripheral devices are available that can be used with almost any microcontroller. Real-time clocks provide date- and time-keeping functions, allowing events to occur at regular intervals or specific time periods, and as timestamps for data storage. Data can be stored to memory chips or SD cards, which can offer almost unlimited amounts of data to be collected. A number of these sensing and peripheral options have also been developed for specific microcontroller development boards. Shields developed for the original Arduino Uno form factor connect easily to those and other compatible boards. The Feather series (Adafruit Industries) also maintain a standardized form, which while different from that of the Arduino Uno, supports other mating peripheral boards to add increased functionality, such as a GPS receiver, real-time clock, data storage, various radios, and switching relays.

Communications

An important part of a sensing and monitoring system involves the display or transmission of the data collected. While many commercial dataloggers and monitoring systems contain a display for local viewing of information, in many agricultural and environmental-monitoring applications, monitoring sites are in remote or inconveniently accessible locations. Advancements in communications infrastructures have resulted in several options for access to data from remote locations.

Industrial, Scientific and Medical (ISM) radio bands have been designated internationally for low-power, license-free transmission of periodic data. Due to transmission-power limitations, radios operating in these bands are capable of transmitting data to nearby (usually less than one mile) receivers. Many radios, such as the Xbee (Digi International, http://digi.com), interface with a microcontroller using a standard serial port and are simple to incorporate into a monitoring circuit and microcontroller program. Development boards such as the Moteino (LowPowerLab) and Feather (Adafruit Industries) can be configured with built-in radios, further simplifying development of a wireless monitoring system.

As the popularity of Bluetooth-enabled and wi-fi-connected devices and networks has increased, circuits are increasingly being developed with these capabilities. Bluetooth and wi-fi radios are available for adding on to existing circuits, and available built-in on development boards such as the Feather and Huzzah (Adafruit Industries) and ESP8266 Thing (Sparkfun Electronics), among many others. Bluetooth-enabled devices can be controlled by or interact with portable electronic devices such as tablet computers and smartphones, which can take the place of dedicated data displays or radio controllers, reducing cost and complexity of the monitoring system. Wi-fi-connected devices can use existing wi-fi networks to connect sensing systems and upload data to computers and internet-connected devices.

The rapid expansion of the cellular communications network has resulted in the ability to be connected from almost any place in the country. Cellular modems interface easily with microcontrollers via serial communications, and inexpensive modems and machine-to-machine cellular-data plans make cellular connection an affordable option. Stand-alone modems such as the Fona (Adafruit Industries) can be used to add cellular connection to a new or existing circuit, while other development boards, such as the Feather (Adafruit Industries) and Electron (Particle, http://particle.io), offer built-in cellular capability.

Open-source software

In addition to the open-source hardware, the microcontroller development board, a key component of the Arduino project is the open-source software used to program the microcontroller. The Arduino Integrated Development Environment provides a programming environment in which programs are written, in a language based on C/C++, to instruct the microcontroller and manage its operation. The IDE is downloaded from the Arduino project website (http://Arduino.cc) and installed on a computer. The IDE allows for external programming libraries to be included in a program. Many libraries have been written to manage specific peripheral devices, such as real-time clocks, sensors, and cellular modems, and allow a user to rapidly and conveniently incorporate advanced devices and features into a program without the need for the user to understand the often complex programming of the peripheral. After a program is written, the IDE compiles the program and checks for programming errors. The program is then converted into the format required by the microcontroller and uploaded. The IDE also includes a serial monitor that can be used to interact with the microcontroller and view output from the microcontroller program.

An increasingly desirable and attainable option for remote monitoring systems is the transfer and access of remote sensor data via the internet. Many "Internet of Things" and "cloud computing" services are available that allow a user to configure a webpage for posting and viewing of sensor data anywhere using a web browser. Services such as Thingspeak (http://thingspeak.com), Adafruit IO (http://io.adafruit.com), and Thinger.io (http://thinger.io), among others, offer data-hosting and viewing at no cost for low-volume use, and are fairly simple to set up and use. Some services, including Thingspeak and Sparkfun IO, are open-source, allowing the cloud-computing software to be downloaded and installed by anyone to implement a similar service on a local or internet-facing computer.

Example projects

Several projects have been undertaken using some of the components described previously to develop sensing and monitoring systems for irrigation and agricultural applications. Two such systems are described in the following sections. Further details are available in cited publications, and microcontroller programs are available by contacting the author.

Soil-moisture monitor

A soil-moisture monitoring system was developed to continuously measure soil-moisture status for use in scheduling irrigations. The monitoring system consisted of hardware components to measure moisture status and transmit data, and software components to control the hardware and post data via cellular network to an internet website.

The system was based on a Feather 32u4 Fona microcontroller development board (Adafruit Industries) with a built-in cellular modem. Electrical power was supplied to the microcontroller-based circuit by a rechargeable 3.7 V lithium polymer battery through a TPL5110 low power timer (Adafruit Industries). The low power timer was configured via on-board potentiometer to supply power periodically to the circuit at its maximum time interval of approximately 2.5 h. Female headers were soldered to a prototyping board which mated with male headers soldered to the microcontroller board and low power timer. Spring terminal blocks were soldered to the prototyping board to allow connection of four Watermark model 200SS granular matrix sensors (Irrometer Company, Inc.). Each sensor interfaced with the microcontroller via a half-bridge (voltage divider) circuit, consisting of a fixed resistor on one side of the divider and the variable-resistance Watermark sensor on the other side. The center of the divider was connected to an analog input pin, and the divider's excitation and ground connections to two digital output pins. The completed hardware circuit is shown in Figure 2, and further hardware information and electrical schematic are detailed by Fisher et al. (2017).

A microcontroller program was written and uploaded to manage all sensor measurement and data transmission functions. When the low power timer turned on power to the circuit, the microcontroller program began execution. Each moisture sensor was read sequentially by applying an alternating voltage source to prevent polarization of the sensor. An excitation was first applied to the sensor's voltage divider circuit and the center voltage was measured. The polarity of the excitation was then reversed and the center voltage measured again. The basic voltage-divider equation was used to calculate the electrical resistance of the sensor, and a calibration equation was applied to convert resistance to water potential in units of kPa.

The cellular modem was then initialized and registered on the cellular network, and data-transfer and internet services were established. A unique internet address (URL) was created to post the data to the Thingspeak (http://thingspeak.com) website based on the website and channel credentials and four moisture-sensor data values. The cellular modem transmitted the URL, sending sensor data to the Thingspeak website. Data were then accessible via a web browser on a computer or mobile device, as shown in Figure 3.

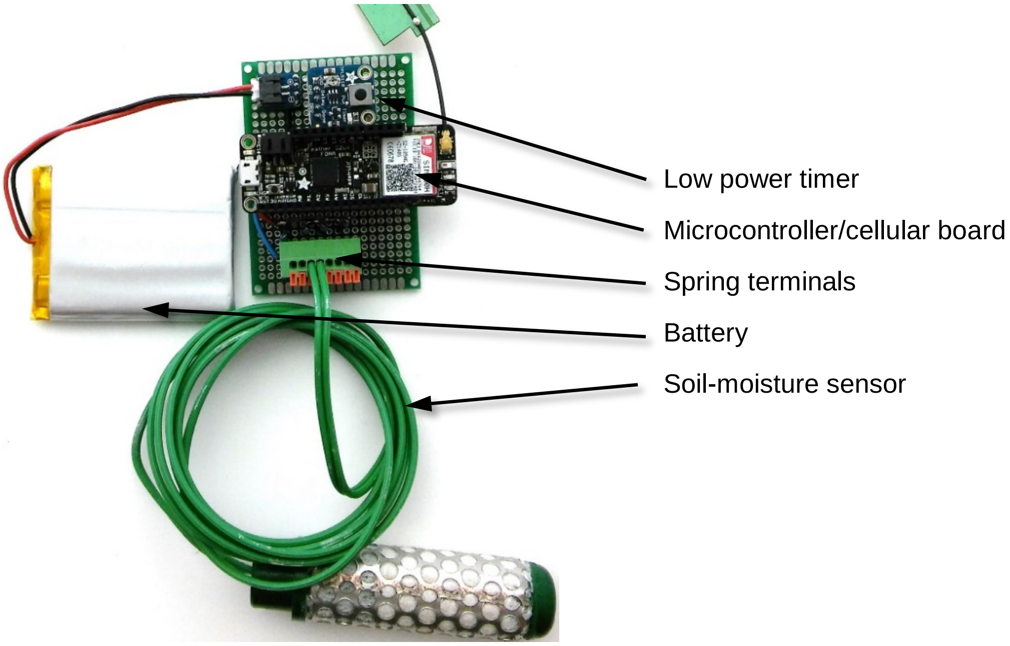
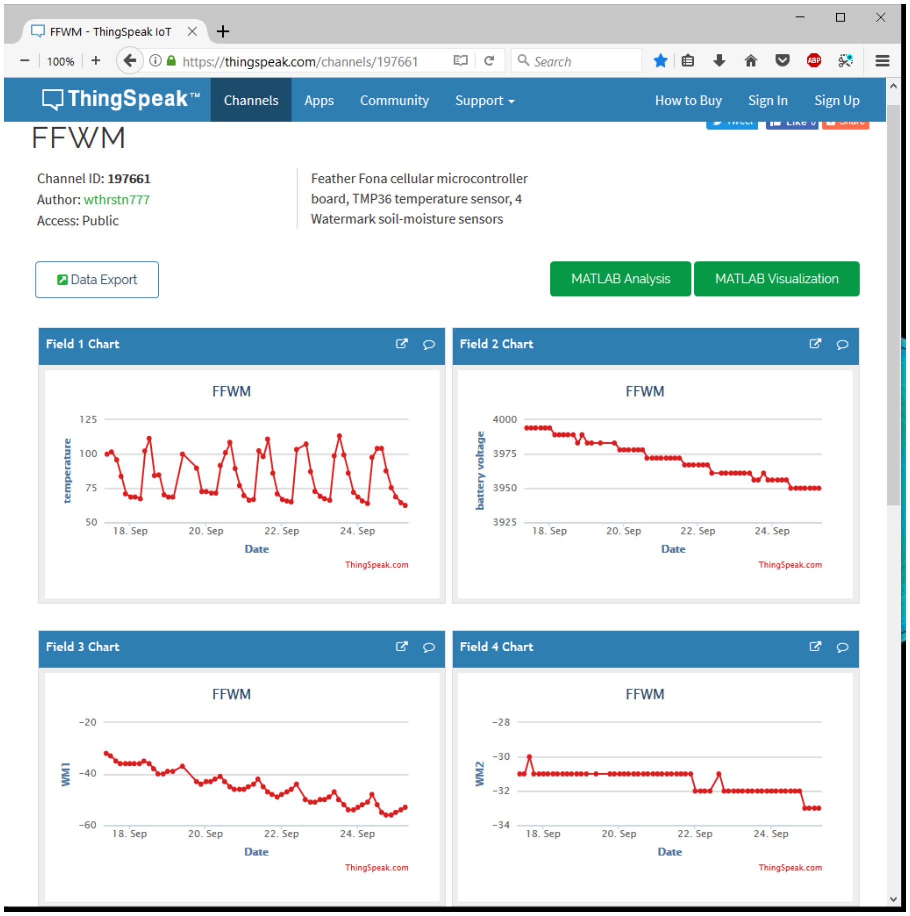


Figure 2. Soil-moisture monitoring system hardware components.



FFWM

Channel ID: **197661**
Author: wthrstn777
Access: Public

Feather Fona cellular microcontroller board, TMP36 temperature sensor, 4 Watermark soil-moisture sensors

Figure 3. Soil-moisture monitor data posted on Thingspeak website.

Fabrication of the monitoring system circuit board was accomplished in approximately one hour using only basic soldering materials. The final cost of the system was approximately US$85 for the monitoring system circuit, US$30 each for the soil-moisture sensors, and US$30 per year for the cellular SIM card and 1 Mbyte per month data plan (Embedded Works, http://embeddedworks.net).

Monitoring systems were deployed in several fields at the USDA Agricultural Research Service's Jamie Whitten Delta States Research Center at Stoneville, MS, and operated throughout the 2017 crop growing season. Soil-moisture sensors were installed at four depths below the soil surface at each site to monitor water use and determine irrigation requirements. The systems continued to operate the entire season with no maintenance requirements or need to change or recharge batteries, and successfully transmitted approximately 98% of the data via cellular network to the internet website.

Mobile plant canopy monitor

A project was undertaken to develop a mobile monitoring system for collecting plant-canopy data, including plant height and canopy temperature measurements. The monitoring system was mounted on an agricultural vehicle, and collected and stored sensor measurements, along with concurrent geographic coordinates, as the vehicle travelled across agricultural fields.

Plant-canopy data were collected from four crop rows concurrently and stored to a micro SD card for download to a computer for viewing and analysis.

The system was based on a Feather M0 microcontroller development board with an onboard Bluetooth LE (Low Energy) radio (Adafruit Industries). Additional features, including GPS receiver and micro SD card data storage, were incorporated via FeatherWing peripheral boards (Adafruit Industries) which plugged in to the microcontroller board. The Feather microcontroller and FeatherWing boards were designed to interconnect, and featured similar board dimensions and identical pin configurations, allowing boards to be staked together and simplifying the electrical circuit. Plant height was determined using HC-SR04 ultrasonic sensors (LowPowerLab), each of which interfaced with the microcontroller using two digital input/output pins. Canopy temperature was measured using Melexis model MLX90614ESF-ACF (Mouser Electronics, http://www.mouser.com) infrared temperature (IRT) sensors. The IRT sensors communicate using the I2C two-wire protocol, and the four sensors were connected over the same I2C port's two digital pins. Electrical power was supplied via a 3.7 V lithium polymer rechargeable battery, which was converted to 3.3 V via a built-in voltage regulator on the microcontroller board to power the Feather microcontroller and peripheral boards. The ultrasonic and IRT sensors, however, operated at a 5 V level, requiring a voltage converter (Miniboost 5V Boost Regulator, LowPowerLab) to supply the required voltage. An additional component, a Bi-directional Logic Level Converter (Adafruit Industries), was needed to interface the 3.3 V microcontroller and the 5 V IRT sensors to convert the different voltage levels and ensure that each component was exposed to the proper voltage level. Female headers for mounting the stacked Feather boards and the two voltage-regulating components were soldered to a prototyping board. Male headers were soldered to the prototyping boards to connect the sensors via custom-made cables. The completed prototyping board and electronic components are shown in Figure 4, with detailed information including electrical schematic provided by Fisher and Huang (2017).

The four-row monitoring system was assembled by first housing pairs of ultrasonic and IRT sensors in protective plastic enclosures, with the sensors installed into holes bored through the

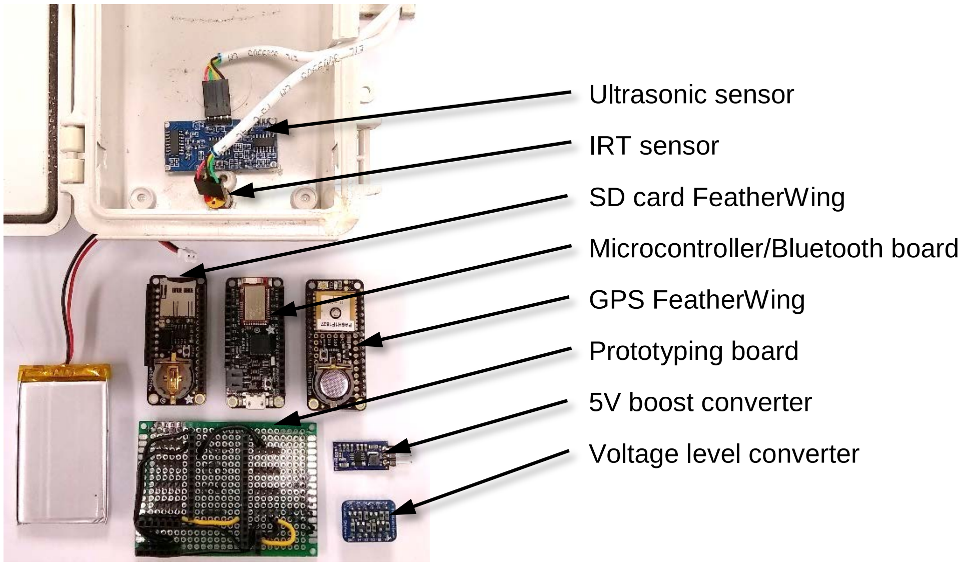


Figure 4. Plant canopy monitoring system components.

Figure 5. Complete plant canopy monitoring system mounted on an agricultural vehicle.

bottoms of the enclosures. Cables were fabricated to connect each sensor to the microcontroller circuit board, which was installed in a separate protective enclosure. The enclosures were attached to a length of aluminum angle stock, with the four sensor enclosures mounted at intervals matching the crop row spacing and the microcontroller enclosure at the center of the aluminum angle. The complete monitoring system mounted on the front of an agricultural spray vehicle is shown in Figure 5.

Construction of the mobile monitoring system, including fabrication of the circuit board and cables, modification of the protective enclosures, and mounting of the completed system on the agricultural vehicle, took approximately four hours. The cost of the hardware components and sensors totaled approximately US$292.

The monitoring system was tested in a field planted to soybean. The monitoring system was powered on and allowed time for the GPS receiver to obtain valid location information. A smartphone was paired to the Bluetooth radio, which was programmed to output GPS information and sensor measurements at 2-sec intervals. Viewing GPS and sensor output in real-time in the field allowed the user to ensure that all components were installed and operating properly prior to field data collection. With the agricultural vehicle stationary on a flat surface prior to entering the field, the heights of each ultrasonic sensor were recorded. Sensor heights were used later to post-process ultrasonic readings and determine plant heights by subtracting the ultrasonic distance measurements (from the sensor to the plant canopy) from the sensor heights.

Samples of plants heights and canopy temperatures collected during one trip across the field are shown in Figure 6. Slight variations in measurements among rows can be observed across the length of the field. Variations in crop characteristics can also be seen down the length of the field. As the vehicle travelled (in the direction from left to right in the graphs), an area of shorter and warmer plants was detected approximately two-thirds down the field. While the monitoring system cannot explain the cause of these differences, the data provide an indication to the user that crop or growing conditions were different in this area. The user could then visit the area to try to determine the cause of the differences.

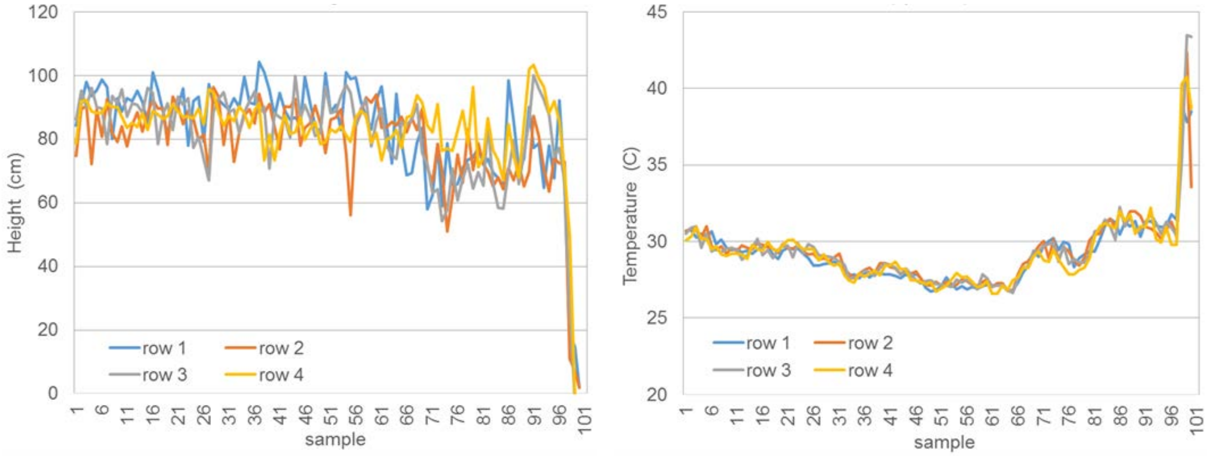


Figure 6. Plant height and canopy temperature data collected during one trip across the field.

Conclusions

Rapid advances in electronics and communications technologies have resulted in a variety of options for development of sensing and monitoring systems. The open-source concept of free and open collaboration offers additional resources and tools for irrigation and agricultural applications, often underserved and lagging in technological progress. Open-source hardware and software can be used to develop new and unique monitoring systems to collect and transmit data from remote locations. Cellular and internet communications networks and open-source cloud computer services enable remote data to be viewed and shared conveniently in real-time, reducing site visits and time and labor expenses.

Disclaimer

Mention of a trade name, proprietary product, or specific equipment does not constitute a guarantee or warranty by the United States Department of Agriculture, and does not imply approval of the product to the exclusion of others that may be available.

References

Bitella, G., R. Rossi, R. Bochicchio, M. Perniola, and M. Amato. 2014. A novel low-cost open-hardware platform for monitoring soil water content and multiple soil-air-vegetation parameters. Sensors 14(10):19639-19659. http://dx.doi.org/10.3390/s141019639.

Di Prima, S. 2015. Automated single ring infiltrometer with a low-cost microcontroller circuit. Computers and Electronics in Agriculture 118:390–395. http://dx.doi.org/10.1016/j.compag.2015.09.022.

Fisher, D.K. and P.J. Gould. 2012. Open-source hardware is a low-cost alternative for scientific instrumentation and research. Modern Instrumentation 1(2): 8-20. http://dx.doi.org/10.4236/mi.2012.12002.

Fisher, D.K. and R. Sui. 2013. An inexpensive open-source ultrasonic sensing system for monitoring liquid levels. Agricultural Engineering International: CIGR Journal 15(4):328-334.

Fisher, D.K., and Y. Huang. 2017. Mobile open-source plant-canopy monitoring system. Modern Instrumentation (in press).

Fisher, D.K., R.S. Fletcher, S.S. Anapalli, and H.C. Pringle III. 2017. Development of an open-source cloud-connected sensor-monitoring platform. Advances in Internet of Things (in press).

Masseroni, D., A. Facchi, E. Vannutelli Depoli, F.M. Renga, and C. Gandolfi. 2016. Irrig-OH: An open-hardware device for soil water potential monitoring and irrigation management. Irrigation and Drainage 65(5):750-761. http://dx.doi.org/10.1002/ird.1989.

Mesas-Carrascosa, F.J., D. Verdú Santano, J.E. Meroño, M. Sánchez de la Orden, and A. García-Ferrer. 2015. Open source hardware to monitor environmental parameters in precision agriculture. Biosystems Engineering 137:73-83. http://dx.doi.org/10.1016/j.biosystemseng.2015.07.005.

Payero, J.O., A. Mirzakhani-Nafchi, A. Khalilian, X. Qiao, and R. Davis. 2017. Development of a low-cost Internet-of-Things (IoT) system for monitoring soil water potential using Watermark 200SS sensors. Advances in Internet of Things 7:71-86. http://doi.org/10.4236/ait.2017.73005.

Thalheimer, M. 2016. A new optoelectronic sensor for monitoring fruit or stem radial growth. Computers and Electronics in Agriculture 123:149-153. http://dx.doi.org/10.1016/j.compag.2016.02.028.