Low Cost Autonomous Field-Deployable Environment Sensors

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Abstract. An Autonomous Environmental Sensor (AES) is a miniature electronic package combining position location capability (using the Global Positioning System (GPS)), communications (packet or voice-synthesized radio), and environmental detection capability (thermal, gas, radiation, optical emissions) into a small, inexpensive, deployable package. AESs can now be made with commercial off-the-shelf components. The AES package can be deployed at a study site by airdrop or by workers on the ground, and operates as a data logger (recording data locally) or as a sentry (transmitting data real-time). Using current low-power electronics technology, an AES can operate for a number of weeks using a simple dry battery pack, and can be designed to have a transmitting range of several kilometers with current low power radio communication technology. A receiver to capture the data stream from the AES can be made as light, inexpensive and portable as the AES itself. In addition, inexpensive portable repeaters can be used to extend the range of the AES and to coordinate many probes into an autonomous network.

We will discuss the design goals and engineering restrictions of an AES, and show a design in a particular application as a wildland fire sentry.

INTRODUCTION AND CONCEPT

Studies in ecology, biology, geology and other fields often require collection of data in widely dispersed remote locations. The recent attack on the United States by extremist groups has created new requirements for remote and sometimes clandestine monitoring of radiation, airborne chemicals and microbes. Current data collection methods are cumbersome, expensive and manpower intensive and do not usually provide measurements over an extended period of time. For example, monitoring the surface temperature of a body of water to study its hydrodynamic and biologic properties is commonly done by field biologists, most often by crews collecting data manually from boats. A system that could automatically measure and process a number of physical parameters in a remote setting would thus be embraced by workers in a large number of fields. A tremendous advantage is obtained if such a system could be built inexpensively and adapted for a variety of applications without extensive redevelopment. We call such a low cost environmental re-configurable data collection system an autonomous environmental sensor (AES).

Recently, advances in positioning capability (using the global positioning system), electronics design, component packaging, networking and radio communication technology have made it possible to construct the AES in lightweight, compact inexpensive packages. The AES has the ability to record and analyze data and report the data and the position of the device by radio to a collection station. These devices can be deployed using a variety of means, and could collect data continuously, periodically or on command. The collected data can be reported immediately, stored and forwarded at a known time, or stored and retrieved later if the AES is recovered. Technology is available for recording a wide variety of physical parameters using inexpensive, compact sensors. Some of the environmental parameters and the corresponding sensors suitable for monitoring by AES are shown in Table 1.

An AES can be constructed using commercially available off-the-shelf components and software, speeding development time and minimizing the cost of the devices. Many of the devices and software developed over the last ten years for the cellular telephone and Internet computer infrastructure can be applied directly to the AES concept. The savings in development time and cost are substantial allowing simple AES systems to be deployed for as little as $100 each. (US$2002)

AN EXAMPLE APPLICATION: WILDLAND FIRE SENTRY

One of the major problems in combating wildland fires is monitoring the time history of the fire [1]. Understanding the size, location, and progression of the fire front is critical to optimal allocation of fire fighting resources and maintaining safety of the fire crew. Investigation of major wildland fire accidents involving loss of life indicates that the crews became imperiled because of insufficient or untimely information about the location and progression of the fire [2].

An AES can be used as a field deployed fire alarm that has the ability to report its location and whether a fire is in the vicinity. A fire can be detected by one or more inexpensive sensors in the AES that detect smoke, carbon monoxide, methyl chloride or temperature. These devices may also be equipped to record and transmit other data affecting fire spread like humidity and wind speed. The data gathered by the AES can be recorded locally to get a post-fire time history and is also transmitted by radio to individual firefighters equipped with appropriate receivers or to a central control receiver.

At present, once firefighters are on the ground near the fire site, they are effectively blind to the activity of the fire. Spotter planes and other aircraft may periodically over

Table 1. Environmental measurements suitable for monitoring with inexpensive sensor systems.

Environmental Parameter	Sensor	Cost (US$2002)
Temperature	Thermistor and signal conditioning (+/- 0.2K)	3 - 40
Humidity	Capacitive humidity sensor	10
Solar Flux	Cosine-corrected photodiode and signal conditioning	30
Radioactivity (a,b,g)	Large area PIN photodiode and signal conditioning	50
Wind Speed	Thermistor cooling-rate monitoring	30
Water Turbidity, Particulate Smoke	IR 90^{o} scattering cell	5
Gas Detection	Catalytic or electrochemical sensor and signal conditioning	5 - 30

fly the area and report the movement and location of the fire to the incident commander, but often even this rudimentary data is lacking. In its simplest use model, AESs provide direct real time voice data to firefighters on the ground. The time history of the fire can be kept manually by the incident commander by recording the position and time of AES fire alarms on paper maps.

Much effort has been expended in modeling the movement of fires in wildland settings [3,4] but these models are only as good as the detailed weather, terrain and fuel load information. Lacking precise information of the fire site, these complex fire models can predict fire behavior for short time periods, but must then be 'tuned' with actual data to obtain long-term accuracy. These fire models are similar to modern weather simulations that are similarly adjusted periodically with weather data to provide long-term modeling.

Using AESs, and armed with handheld computers running these fire models, firefighters will have accurate real-time data for model 'tuning', and may be able to more accurately predict the behavior based on past fire movement even when only very imprecise weather, fuel and terrain information is initially available. The ability to predict the movement of the fire is a powerful advantage to fire logistics and firefighter safety.

The use of satellites to obtain fire data for model tuning is feasible, but complications are imposed by limited satellite spatial resolution, complicated ground link equipment, and short satellite loiter time (for low Earth orbit satellites) over the target area. Real time data can be obtained using unmanned or remotely controlled unmanned flying vehicles (UFVs) flying over the fire site, but this solution is both

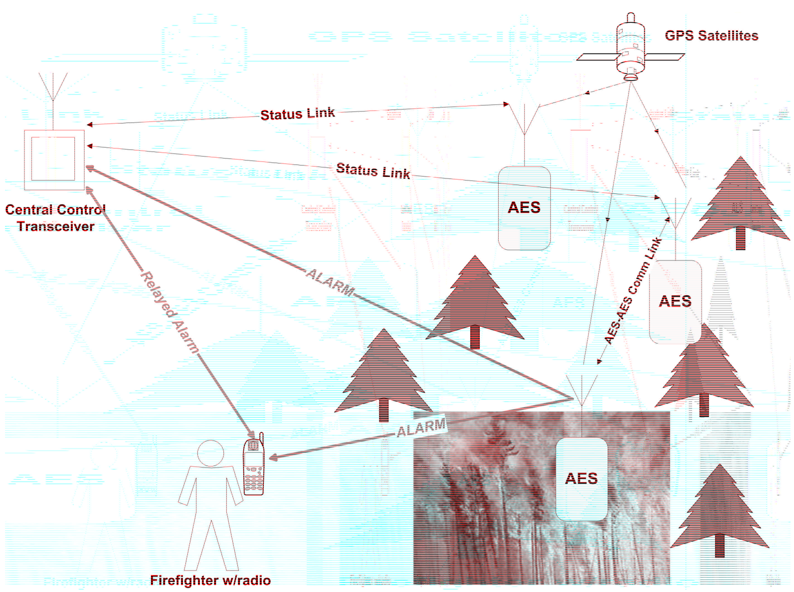

FIGURE 1. Deployment and communication between AESs and base units, other AESs and firefighters in a fully networked system.

complex and difficult to support in the field, and would require additional worker training to operate and maintain the UFV. A small number of AESs that are located in the forest could provide this data at low cost and with little additional effort in training or support. We present both advanced and simple AES communication concepts and show the initial design of a prototype.

OPERATIONAL CONSIDERATIONS

In use, AESs can be dropped from an aircraft or unmanned airborne vehicle (UAV) or placed manually by crews in a study area. The mechanical package of the AES can be designed for any of a number of applications, including urban environmental monitoring, wildland monitoring, or as drifters on bodies of water. The devices periodically report their position and status to each other, to a central receiver, or to radio receiving equipment carried by individuals.

After they are deposited in the fire area, AESs will find their location (via their internal GPS receiver) and report their initial position and fire alarm status via a radio link.

Networked Operation

One option for communication is a digital link with a network protocol. In this application, the radio link allows AES-to-AES as well as AES-to-base unit communication. A diagram of the communication links between the various units is shown in Figure 1. The AESs will periodically report their status to each other and a central control transceiver unit. Upon detection of a fire, the reporting AES or AESs will transmit an alarm to other AESs in the area and to the central transceiver. Crews in the area can be alerted either directly from the reporting AES, or through alarm messages that are relayed from the control transceiver. The control transceiver has the capability of overlaying geographical information system (GIS) maps with the location and alarm state of the AES, and presenting this data to the incident commander or other personnel at the fire site. This system represents a relatively complex configuration of the AES system.

Non-Networked Operation (Point-to-Point)

There are many simpler modes of operation of the AES system, one of which is depicted in Figure 2. In this mode, the AESs operate independently of each other, without a central control transceiver, instead reporting synthesized voice messages to firefighters on the ground. This message might contain the ID number of the AES, its GPS position and the alarm state of the device. Since the AESs have highly accurate synchronized clocks via their GPS receivers, each can be programmed to transmit at a slightly different time in order to avoid AES message collisions and interference, even when operating on a single radio frequency. The firefighter, equipped with nothing more than the present VHF/UHF FM radio transceiver ('handi-talki'), and with no

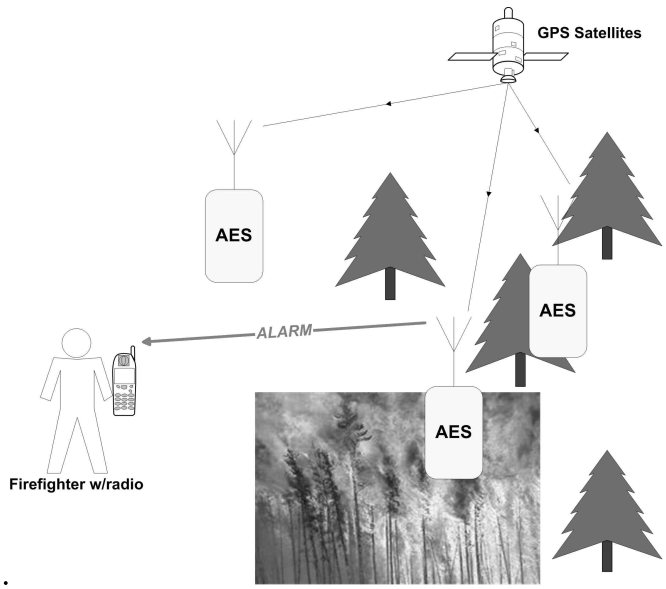

FIGURE 2. Simple point-to-point AES operation. The AES units report via synthesized voice messages directly to radio receivers at the fire site.

additional infrastructure, would be able to receive voice AES status on one of the normal radio communication channels. This mode of operation is most suitable when a few (~10) AESs are used on geographically small fires.

A block diagram of the AES is shown in Figure 3. A microprocessor coordinates inputs from the global positioning system receiver and the fire sensors, and generates the communication and modulation stream for the radio transceiver system. This communication stream can be digital, can employ packet or radio-teletype encoding technology or can be a synthesized voice, as discussed above. Several fire sensors may be used in an AES. These sensors can be smoke detectors (photoelectric or ionization), gas detectors (combustion precursor gases, carbon monoxide, etc.), thermal (temperature), passive microwave or optical radiation detectors. The AES internally measures the strength of signals from the sensors and makes decisions as to whether or not to issue an alarm. The use of more than one inexpensive detector can greatly reduce the probability of false alarms while not significantly increasing the cost. We are currently planning a test program to evaluate and optimize several fire sensor configurations during controlled wildland fires. The AES will be programmed to observe and report sensor input periodically and to 'sleep' in the interim to conserve battery energy.

PROTOTYPE DESIGN

We have constructed a prototype AES that conforms to the basic design discussed above. Key prerequisites of the design are cost effectiveness, durability, low power consumption and adequate transmitting range. Any design must be sensitive to the multiple design constraints of low cost, ruggedness, low power consumption, and

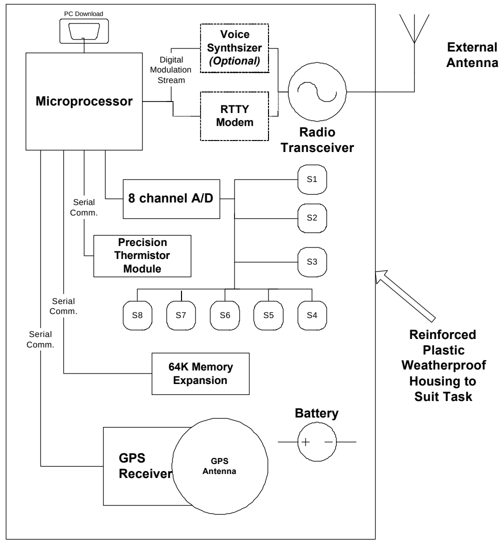

FIGURE 3. Block diagram of the AES, showing the logical and signal interconnections between the fire sensors, global positioning system receiver, radio transceiver and power system.

adequate transmitting range. The prototype uses commercially available components and systems where possible. The prototype device is currently transmit-only and uses a simple voice messaging system to report the unit ID number, position and time (as determined by the GPS) and alarm status or sensor level for up to eight sensors. The alarm information is transmitted at a predetermined time that is unique for each unit to avoid data collisions. The units use VHF (145 MHz) frequency modulated (FM) radio transceivers employing audio frequency shift keying (AFSK) to transmit digital information at 9600 bits per second. The entire transmission lasts under a second, conserving battery power. A radio receiver-demodulator attached by a serial link to a laptop computer receives the data stream and displays the messages. All of the components, including the radio transmitter, were obtained commercially. A photograph of the circuit boards of the prototype is shown in Figure 4, and a detailed block diagram is shown in Figure 5.

In order to speed development, a Parallax, Inc. Basic Stamp 2 microcomputer module (BS2) was used for the central processing unit. The BS2 has 16 digital input/output lines that can be programmed individually to perform a number of functions. This microcomputer module has been optimized for control applications and has several programmable 'sleep' modes that reduce power consumption to a very low level during idle periods (e.g. when no alarm or status information is being transmitted). The BS2 has a programming port and comes with development software using the powerful PBASIC programming language. Programs are developed on a PC-compatible computer and downloaded to the BS2, where they reside on an electrically erasable programmable memory (EEPROM). The combination of powerful input/output based programming language and self-contained development system

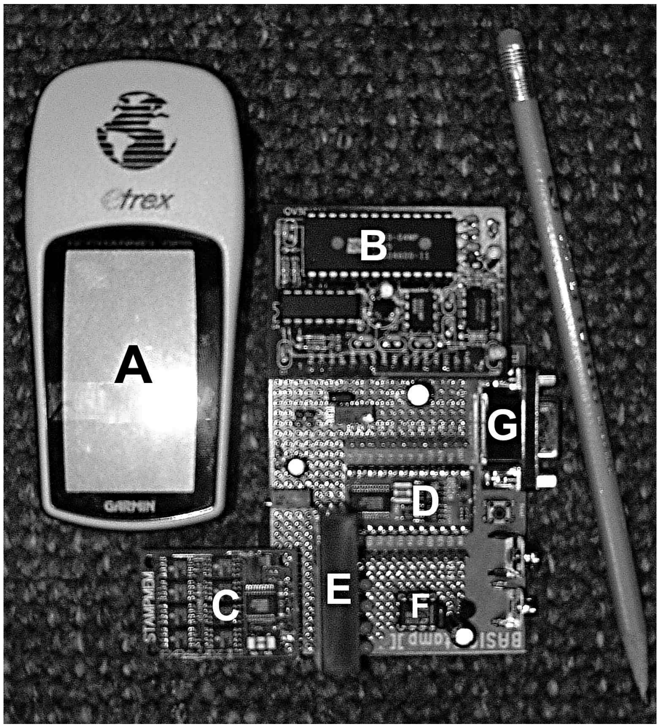

FIGURE 4. Photograph of the prototype AES. A - Packaged GPS unit; B - Voice synthesizer board; C - 64 kbyte non-volatile memory expansion unit; D - Parallax BS2 microcomputer module; E - Precision thermistor interface module; F - LTC1298 2 channel 12 bit analog to digital converter; G - Programming/ data downloading RS232 port.

makes the BS2 very easy to use for rapid development of simple applications. Detailed information about this processor can be found at the company's web site [5].

The prototype AES has two 12-bit analog input channels to accept input from fire sensors. A Linear Technology, Inc. LTC1298 ADC communicates with the microprocessor through a 3-wire synchronous serial link. We are currently evaluating several sensor types for suitability in this application. We have successfully detected test fires using commercial ionization chamber smoke and carbon monoxide detector modules. In addition to the analog inputs, several switch inputs provide access to test routines, enable the device after deployment, and halt the device for storage. Four status LEDs provide visual indication of unit ID number, self-test results and AES state information (alarm, transmitting, idle, etc.). An audio alert is also included to provide local indication of an alarm condition.

Asynchronous serial communication in RS-232 format is used to communicate with the transmitter and GPS unit. A commercial Garmin Model 12 GPS unit sends ASCII information indicating time, latitude and longitude over one serial link to the microprocessor. The messages transmitted by the GPS unit conform to the National Marine Electronics Association NMEA-0183 standard. The actual AES will use one of the readily available unpackaged GPS 'decks' that do not have displays or keyboard input and are smaller and consume less power. Another RS-232 link is used to communicate ASCII information to the radio modulator/transmitter. One of two modulators may be used, depending on the demands of the application. One modulator employs an AMD AM7910 audio frequency shift keying modulator/demodulator that allows transmission of an ASCII digital data stream. The other modulator we have tested is a voice synthesizer manufactured by Quradravox, Inc. Serial commands to this synthesizer allow direct voice communication. Both of these modulators drive a commercial VHF-FM transceiver unit which, in our application, operates at an output power of 5 watts in the 2-meter (145 MHz) amateur radio portion of the VHF spectrum. With a moderate antenna, this transmitter has a worst case range of more than 5 miles over water and about 5 miles on land, depending on the terrain.

A flow diagram of the software written for the prototype AES is shown in Figure 6. The powerful control-oriented PBASIC language simplified programming and reduced the initial effort to just a few days. There are other branch points in the software flow (not shown in Figure 6) that provide test functions (such as sensor and battery test) and readiness verification. Another Basic Stamp BS2 has been programmed as an input test set. This device produces simulated signals for the input switches and two analog voltages to represent sensor outputs, and allows us to test the AES without directly stimulating the sensors.

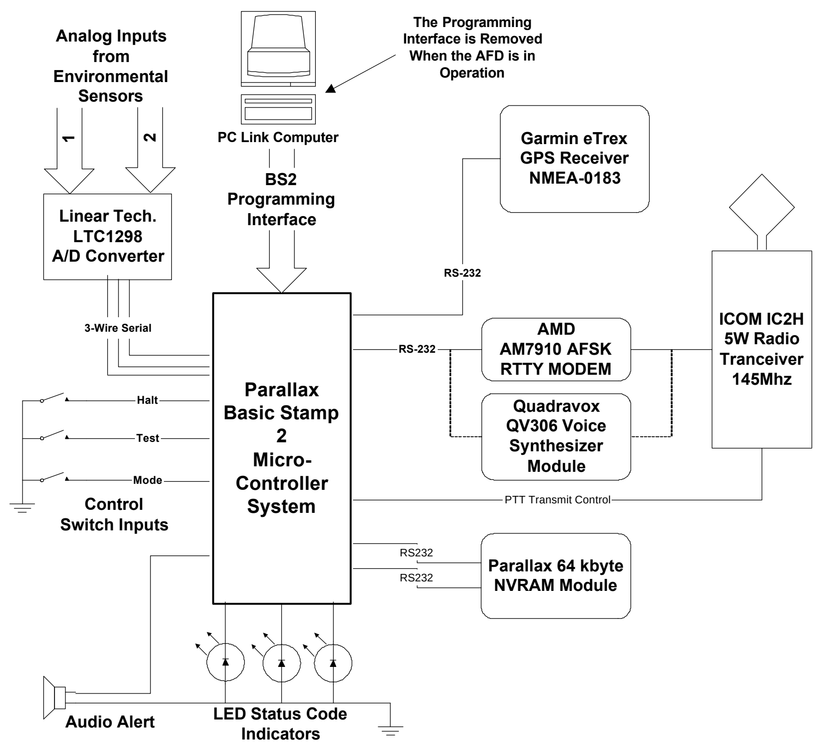

FIGURE 5. Detailed block diagram of the prototype AES. Fourteen of the sixteen available input/output pins of the BS2 are used in this application.

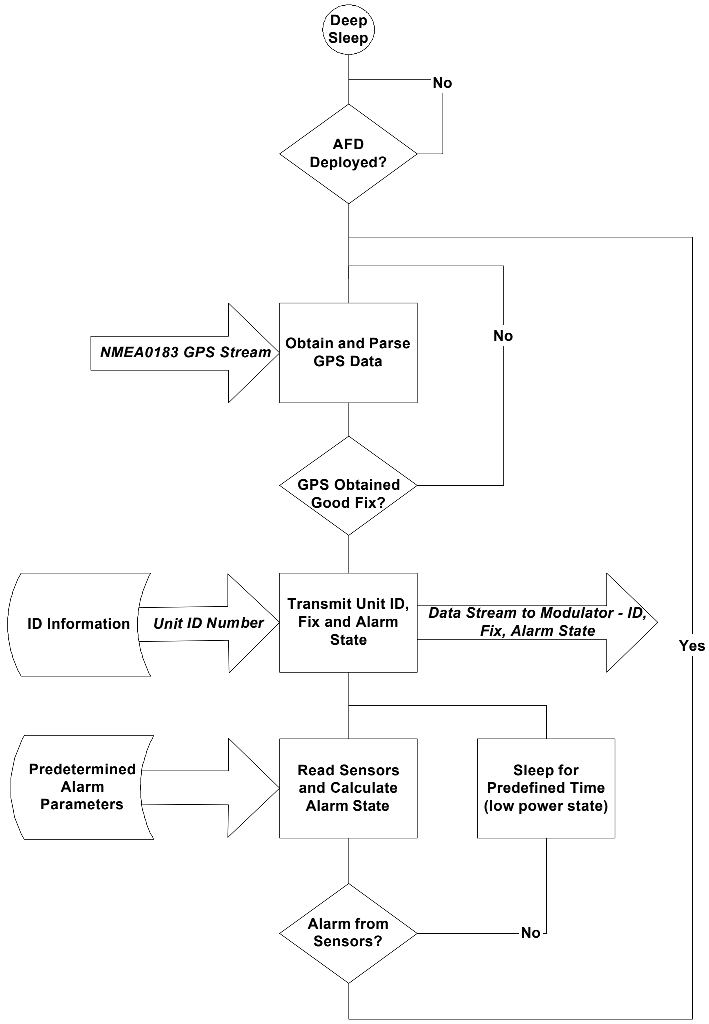

FIGURE 6. Software flow diagram for the AES prototype. The software makes use of the powerful instructions in the Parallax, Inc. PBASIC programming language.

CONCLUSION AND FUTURE DEVELOPMENT

We have demonstrated the concept and electronics for an autonomous environmental sensor, with a particular application as a wildland fire sentry. By maintaining the simplicity of both the physical hardware and operational principles, the device has been prototyped rapidly. We are currently evaluating 1 and 2-sensor wildland fire detector packages using small test fires, and will further test a completed mechanical and electrical package during controlled wildland burns planned with the United States Forest Service for the Spring of 2002.

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