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Short Note

An inexpensive, microprocessor-based, data logging system

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1. Introduction

Efforts to understand and model environmental variables require data sets that track both temporal and spatial changes. Networks of recording instruments or instruments connected to commercially available data loggers can gather these data (e.g., Silliman and Booth, 1993), but the cost of such networks is typically several thousands to tens of thousands of dollars and may require the development of software to interface between the data logger and a host computer (e.g., Mukaro and Carelse, 1997). The high cost of these networks together with the risks of vandalism and theft associated with their deployment in remote locations prohibit their general use, even in studies that could clearly benefit from them. This note describes an inexpensive, easy-to-build, microprocessor-based, data logger system that is currently being adapted to a number of field applications (Dedrick, 1998). The low cost of this system coupled with the increasing availability and decreasing cost of a wide variety of compatible sensors should enable more researchers and educators to systematically gather temporal and spatial data without the necessity of a large budget.

Our system is based upon Microchip's PIC 16C73A microcontroller, and: (1) digitizes and records an analog voltage from a sensor at programmable sample periods of a few seconds to many hours; (2) stores over 4000 digital data values; (3) logs data for a number of weeks or more with a power supply of 4 AA alkaline batteries; (4) is readily adaptable for use with a variety of sensors; and (5) is inexpensive. Individual data loggers cost less than \$20 per unit to build and can be assembled in less than an hour on a printed circuit board. In this note we describe the system, identify its unique qualities and provide an example of its use as a recording thermometer.

2. Overview of the data logger system

Our data logging system is composed of two separate units, a "logger" and a "reader" which work with a host computer (Fig. 1). The logger is a 3 × 13 cm circuit board with an 8-bit microcontroller chip (PIC 16C73A, Microchip Technology, Inc.), a non-volatile serial EEPROM memory chip (24LC32A, Microchip Technology, Inc.), and supporting components (Fig. 2). Power is supplied by 4 AA or 4 C batteries. The logger converts an analog voltage signal from an external sensor into a digital value, and stores the digital value in the logger's EEPROM memory at user-supplied sample periods. The "reader" is a separate 5 × 7.5 cm circuit board with an identical microcontroller, a RS-232 transceiver interface chip (MAX232A, Microchip Technology), and supporting components (Fig. 3). Power is supplied by a 9 V battery regulated to 5 V (7805A regulator). The reader enables communication between the logger and a "host" PC-compatible computer using one cable to the logger and another cable to the RS-232 serial port of the host computer. The host computer runs a Windows-based program written by the authors that, through commands sent to the

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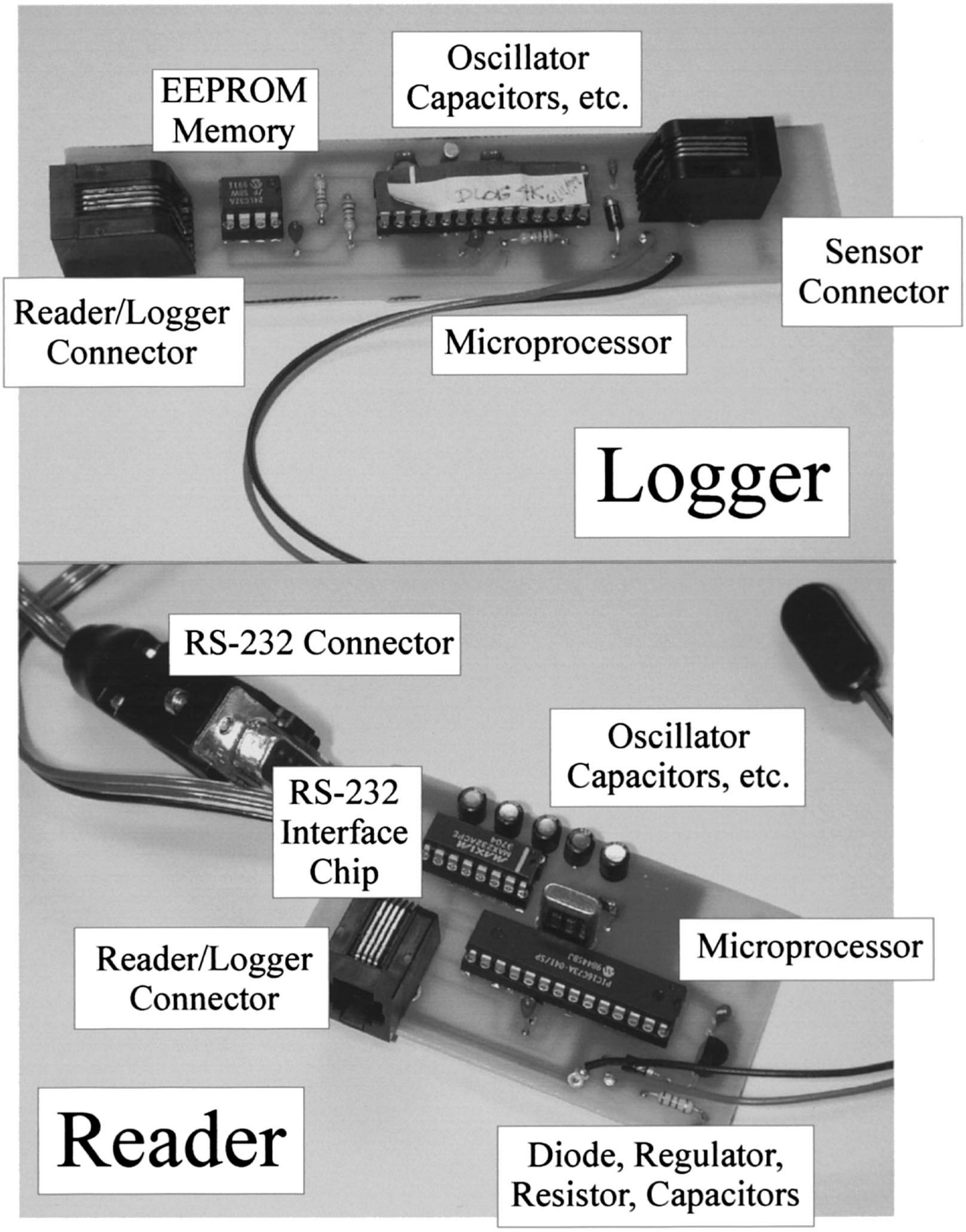


Fig. 1. Photograph of prototype logger and reader circuit boards without protective housing. Standard telephone wire and modular plugs connects reader to logger and logger to sensor. Reader is connected to host computer through standard RS-232, 9-pin, female connector. For scale, logger circuit board is 3 × 13 cm, and reader board is 5 × 7.5 cm. Tallest component extends approximately 2 cm above circuit board.

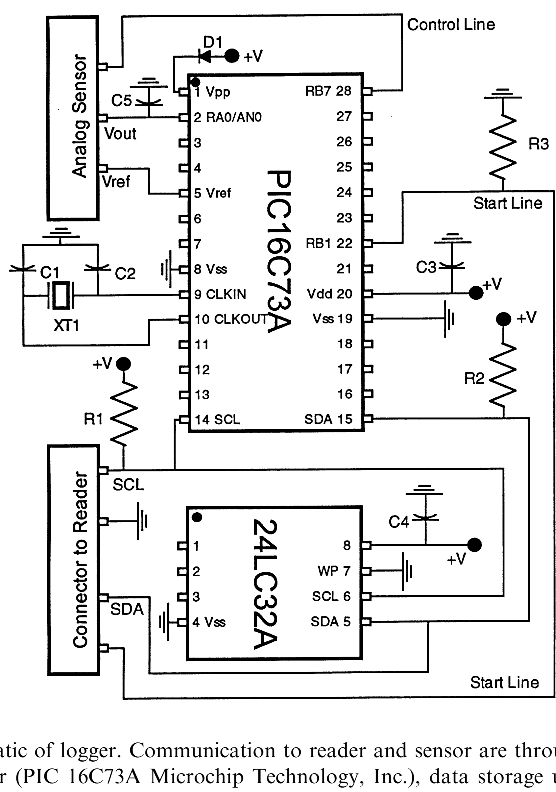
reader and relayed to the logger's memory chip, initializes the logger at the beginning of data collection and retrieves data once sampling is completed. Typically, a logger is connected to the reader for initialization, then disconnected from the reader, connected to the sensor and deployed in the field for data collection, and finally reconnected to the reader to download and store the data on the host computer.

Operation of the system depends upon coordinated software running on the host computer, reader and logger. The flow chart in Fig. 4 shows how the software of the host, reader and logger function (vertical columns), as well as how all three programs are linked by software "handshakes" (links between columns). Ultimately, digitized sensor data are saved on the host computer as a character-delimited ("^"), ASCII text file. The sensor data in this file are uncalibrated numbers ranging between 0 and 255, reflecting the 8-bit resolution of the microcontroller's on-board analog to digital converter. This file also includes user-supplied comments about the deployment (e.g., field location), sensor and logger information (e.g., serial numbers), start time, start date, sample period, memory state, and sample times. This text file is readily imported into a spreadsheet for analysis. For example, most applications will require that the file's digital sensor data be converted to standardized units (temperature, stage height, pressure, etc.) by application of a calibration function. An example data file appears in Appendix A.

3. Features and advantages of the system

Several aspects of the system deserve special note, particularly the use of the PIC 16C73A microcontroller, the use of the serial EEPROM chip for data storage, the separate reader and logger, the low cost of the system, the software design of the data download and initialization functions, and the adaptability of the logger to many different sensor types.

The PIC 16C73A, 8-bit, microcontroller (Microchip Technology, Inc) is well suited for an inexpensive data logger. It has a built-in analog-to-digital converter, hardware and software support for serial communication and EEPROM data storage, an internal programmable timer that can operate in the background but produce time-out interrupts, and very low power consumption. Our system uses two identical microcontrollers, one in the reader, another in the logger. The reader's microcontroller operates at a clock speed of



Logger Schematic
Version 2.2 - June, 1999

Pin #	Name	Description
1	Vpp	Positive Supply (+6 V)
2	RA0/AN0	Sensor Output
5	Vref	Voltage Reference
8	Vss	Ground
9	CLKIN	External Clock In
10	CLKOUT	External Clock Out
14	SCL	Serial Clock Line
15	SDA	Serial Data Line
19	Vss	Ground
20	Vdd	Voltage Supply for I/O
22	RB1	Start Line
28	RB7	Control Line

Electrical Components

PIC16C73A	PIC Microcontroller
24LC32A	EEPROM 4K Memory
C1 & C2	33 pf Capacitor
C3 & C4	1 µf Capacitor
C5	150 pf Capacitor
D1	1 Amp Diode
R1-R3	10,000 Ω Resistor
XT1	32.768 kHz External Crystal
+V	Logger Power Supply, +6V

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Fig. 2. Schematic of logger. Communication to reader and sensor are through standard telephone wires, control of operations is by microprocessor (PIC 16C73A Microchip Technology, Inc.), data storage uses 2-wire serial EEPROM (24LC32A Microchip Technology, Inc), and power (+6 V) is from 4 AA or 4 C batteries.

4 MHz to support 2400-baud serial communication with the host computer. By contrast, the logger's microcontroller operates at a slower clock speed of 32.768 kHz to simplify its timing functions and reduce its power consumption. We have measured the operating current of the logger to be less than 2 mA. Assuming a 4 AA alkaline battery pack and battery capacities of 2140 mAh (Glover, 1997), this provides a theoretical 44 day operating supply (currently, 15 days is our maximum field trial duration). Sample periods are user selected during initialization, and implemented by two internal, cascaded 8-bit counters that provide sample periods of 8 s to any multiple of 8 s up to approximately 6 days ($8\ s \times 2^8 \times 2^8$). The PIC microcontroller costs less than $10, and is available from many different suppliers.

The use of a separate reader and logger is not necessary, but advantageous for several reasons. Segregating host communications functions into the reader: (1) reduces the number of components and complexity of the logger thus reducing the cost of each logger; (2) allows the logger to operate at the lower, power-saving clock frequency discussed above; (3) allows a single reader to service many loggers, significantly reducing the total cost in the typical situation where a project requires multiple measurement sites (many loggers). Excluding the housing, parts for the logger cost under $20, and for the reader cost under $35.

A serial EEPROM chip serves as the logger memory (24LC32A, Microchip Technology, Inc.). It is a low-cost and low-power storage solution designed to interface with the PIC microcontroller. This 4 K EEPROM has 4096 memory locations, each capable of storing an 8-bit integer, i.e., a digital value from 0 to 255. More importantly, it provides non-volatile storage for the data logger. Even if the power source for the logger is removed for extended periods of time, the data remains in the EEPROM and can be retrieved. This chip requires only a "2-wire" interface with the microcontroller, a serial data line (SDA) and a serial clock line (SCL), which greatly simplifies the remaining circuitry and so the cost of the system. It also makes it possible for the reader and the logger to access the EEPROM independently so that when the logger is attached to the reader, the reader is storing and retrieving information directly to or from the logger's EEPROM, rather than relaying the data through the

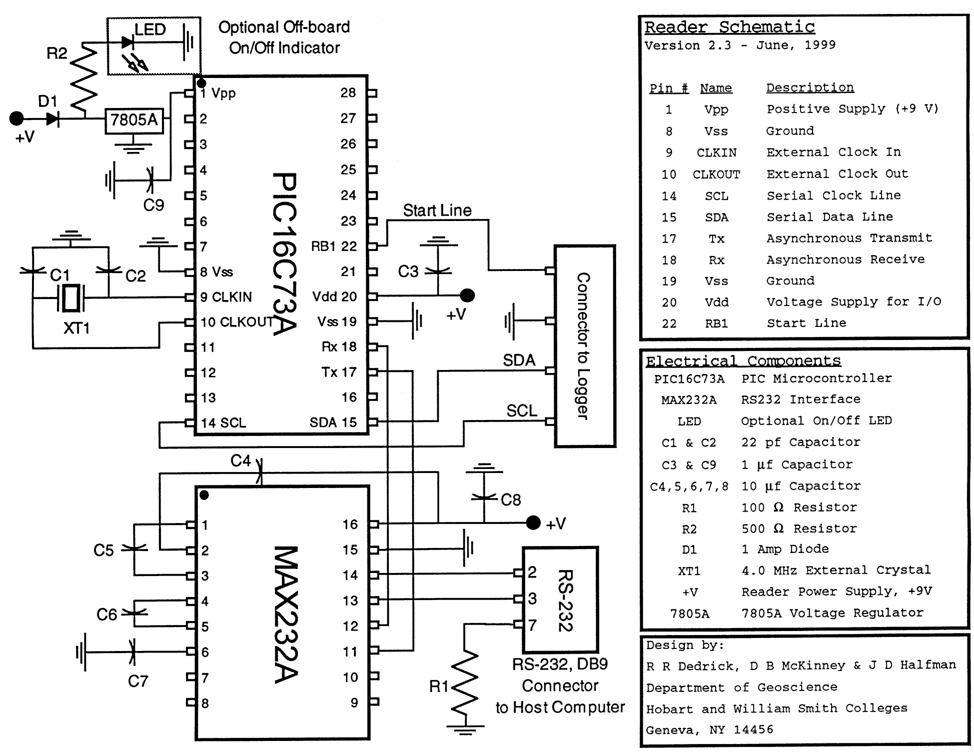

Fig. 3. Schematic of reader. Communication is through RS-232 communication port to host computer and standard telephone wire to logger. Control of operations is by microprocessor (PIC 16C73A, Microchip Technology, Inc.), serial interface to host computer by MAX232 chip (Microchip Technology, Inc.), and power is from 9 V transistor battery. Optional power on/off LED is attached to outside of protective enclosure (neither item is shown).

logger microcontroller. This simplifies the logger circuitry and the associated software.

Our software design combines data transfer and initialization functions so that the host computer always transfers data from the logger before initialization is permitted. This contrasts with the operation of generic data loggers in which data transfer and initialization may be separated. The operation of a generic data logger typically has three stages: (1) initializing the logger with date and sampling information; (2) deployment of the logger and an attached sensor; and (3) retrieval of the logger and transfer of the data to the host computer. In our system, combined download and initialization functions reduce the risk of reinitializing a logger before the data from a previous deployment has been transferred. Thus the operation of our system has two stages: (1) transfer of data; followed by (2) the *option* to reinitialize the logger for a new deployment.

Our system is adaptable to a wide and increasing array of sensors. To date, we have tested it with temperature, pressure and light intensity sensors, and details of the temperature application are described below. Virtually any sensor that produces an analog voltage signal from ground (Vss) to the positive supply (Vpp) can be connected to the logger. In our case, the approximate range is from 0 to 6 V. The microcontroller's on-board analog-to-digital converter produces an 8-bit digital value equal to the ratio between the analog signal and a voltage reference (minimum reference voltage is 3 V). Thus the system can provide a theoretical resolution of approximately 0.5% (1/256) of the reference voltage. Experiments with three different loggers tested at 25 and 3°C over periods of 2 or 3 days indicate that the time-of-sample errors are less than 12 s per day.

To maximize sensor battery life, the microcontroller also provides a sensor "control line" logic output. In the temperature sensor design described below, this output is connected to a solid state relay (Aromot AVQ 210E) that toggles power on and off to the sensor. When the control line output is high (+Vss), power is connected to the sensor so it can warm up, stabilize, and then provide output to the logger microcontroller; when the control line is low (ground), power is disconnected from the sensor. Between samples, all PIC microcontroller connections to the logger are high-impedance inputs that are unaffected by voltage changes in the sensor circuit. An optional sensor LED illuminates when the control line is on.

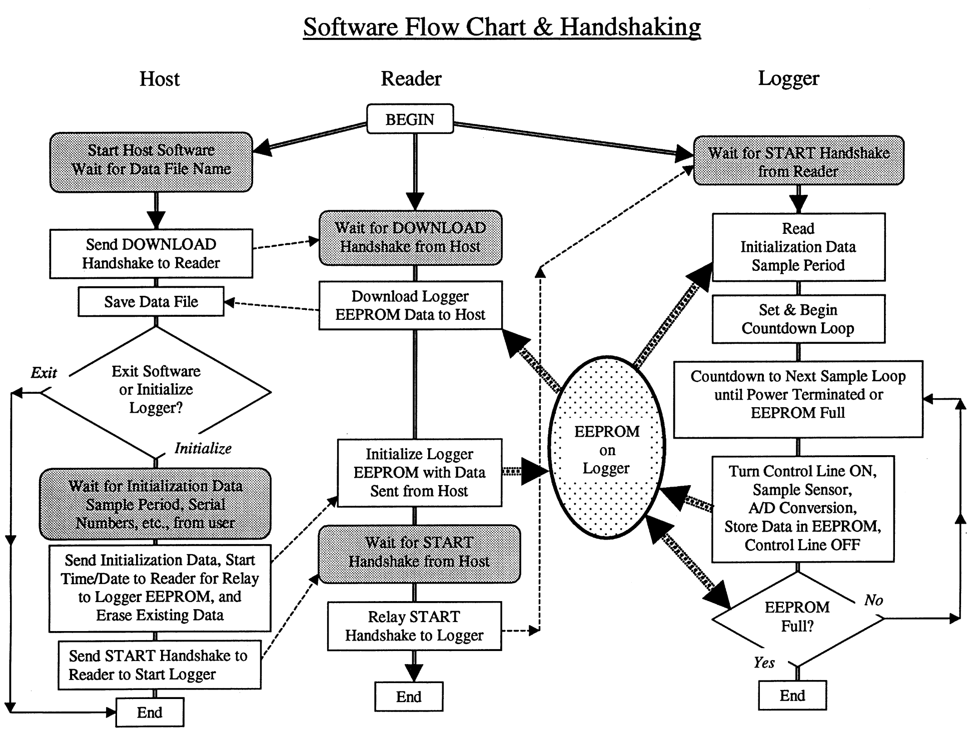

Fig. 4. Software and operation flow chart for data logger system. Host sequence is in left column, reader sequence is in middle column, and logger sequence is in right column. Reader and logger software are power activated, i.e., each program starts when power is applied to microcontroller, and stops when power is disconnected from microcontroller.

The very low-cost of individual loggers allow our system to be adapted to situations that might require multiple input channels or data capacities of more than 4000 samples (4 K) per deployment. Where multiple channels are required, one simply uses more loggers. At less than $20 per logger, this is a cost-effective solution. When more than 4000 samples are required during a deployment, one simply uses two or more loggers. This involves using multiple loggers with the same sample period but staggered start times to independently sample and record sensor output. Each logger records data from its own sensor for the full deployment period; the time-staggered data from each logger are then standardized (based on individual logger/sensor calibration curves), combined and sorted by time within any spreadsheet to produce a single data set with the desired temporal resolution. Again the low cost of individual loggers makes this option cost effective. An additional benefit of multiple loggers is full data coverage over the deployment period even if one logger or sensor malfunctions (though at an increased sample interval).

Though our system has many advantages, its effective use requires additional care and work on the part of the user. First, although the system will work with a wide-array of sensors, users must pay careful attention to the output of these sensors. The microcontroller's on-board analog-to-digital converter produces a number between 0 and 255 that is proportional to the ratio of the analog sensor voltage to a voltage reference. However, the minimum voltage reference is 3.0 V and the maximum is approximately 6 V. Sensors that produce voltages outside this range, or sensors that only produce a narrow range of voltages like pH and conductivity electrodes within this range (for example, 4.0–4.1 V) must be "conditioned" for use with the system. Coupling this type of sensor to the logger would require an amplifier circuit to boost the output of the sensor into the 0–5 V range. Furthermore, the user must establish a calibration between the analog-to-digital converter's digital values and the desired reference units (degree Celsius, pound per square inch, etc.). The calibration directly affects the accuracy and resolution of the final data. The user must also be concerned with changes in calibrations over the range in environmental conditions (temperature, pressure, humidity, etc.) that the sensor/logger may experience. Finally, users must be cautious about measuring rapidly fluctuating signals. The microcontroller's analog-to-digital converter takes an "instantaneous" sample of sensor output presumed to constant over a period of at least several milliseconds. Rapidly fluctuating signals may require an "averaging" or "peak hold" circuit to make reliable measurements appropriate to a particular investigation. Discussion of signal conditioning circuits appropriate to particular sensors and applications is beyond the scope of this short note. An accessible introduction to sensor, analog-to-digital conversion and signal conditioning is Carr (1997).

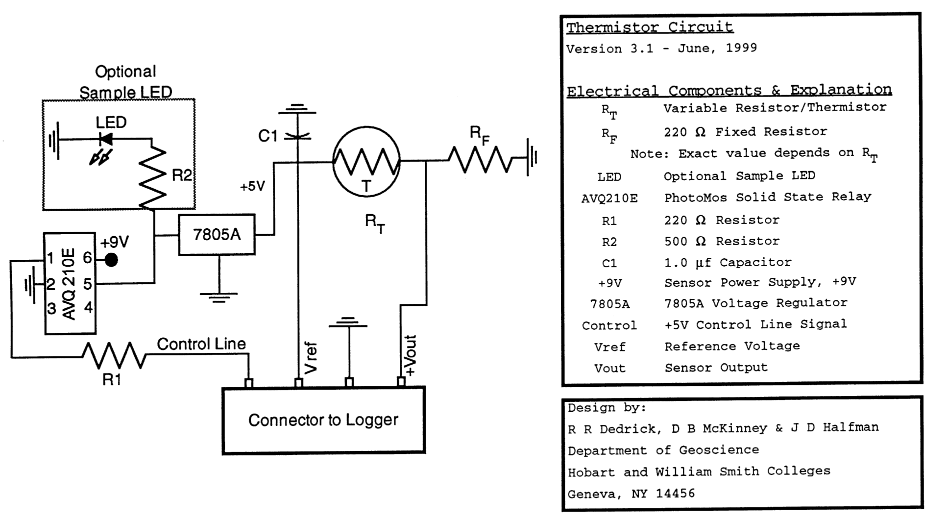

Fig. 5. Schematic for any "variable-resistance/variable-voltage" sensor. This example integrates thermistor to electronically measure temperature. Communication is through telephone wire to logger. Power is from separate 9 V battery, regulated to 5 V. Exact value for fixed resistor (R_F) depends on range of variable resistor (R_T). Sensor's power toggles on and off by solid state relay connected to a "control line" from the logger's microprocessor to save battery life. Control line is turned on (+Vss) before sample time to provide power to sensor circuit. This allows sensor to warm up, stabilize and then provide output to logger. It is turned off (ground) after digitizing and storing sensor output. Optional LED illuminates whenever control line is on.

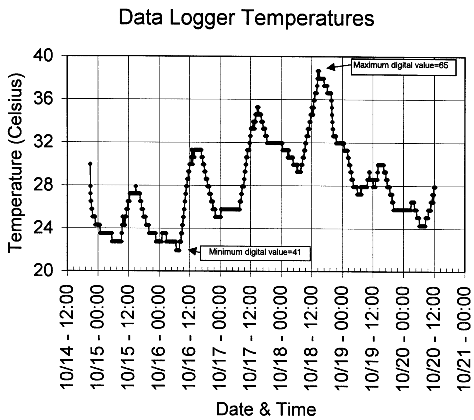

Fig. 6. Temperature data interpolated from logger output using linear calibration curve over 5-day period. Sensor was deployed between window and storm window of lab. Data reveal significant variation over daily and longer-term scales that mimic observed daily and longer-term air temperatures during sensor deployment. Signal is also influenced by heating cycle of lab and direct solar gain through window.

4. Recording thermometer application

Fig. 5 shows a schematic for a temperature sensor that can be connected to the data logger system to create a recording thermometer. In this example, the sensing element is a thermistor used in series with a fixed resistor to create a voltage divider. The resultant voltage output varies with temperature, and Fig. 6 shows the calibrated output of our test run. The sensor circuit is powered by a separate 9 V battery regulated by a 7805A voltage regulator to provide a constant 5 V power supply. A regulated supply eliminates voltage drift that could result from decreasing battery output over the deployment period. Pin one of the solid state relay is connected to the sensor's "control line." This configuration switches current flow on and off through the sensing circuit. The sensor and circuitry as shown cost under $10 to construct.

The sensor was deployed between the inner and storm window of our lab for approximately 5 days in the fall to monitor daily cycles in air temperature (Fig. 6). The daily cycle in temperature detected by the data logger is temporally consistent with observed daily and longer-term changes in outside air temperature over the deployment period. The plot also reveals higher resolution fluctuations that are probably related to the heating cycle of the room and periods of more direct sunlight through the window.

5. Conclusions

The data logger system is an inexpensive and simple solution to the collection of temporal and spatial field data for numerous research and educational endeavors. It can be integrated with a large array of available sensors. The schematics, circuit board layouts, parts list, suppliers, PIC and host software, and other associated items will be published on a Web site so that any educator or researcher can download sufficient information to construct her/his own data logger. In addition to the recording thermometer example described here, this Web site will also contain information on use of the logger as a pressure-based recording stream gauge. We welcome any and all suggestions.

Acknowledgements

John Vaughn and Larry Campbell, Hobart and William Smith Colleges, provided many useful suggestions during the design and development of this data logger system. Initial financial support was provided by the Committee on Research and Honors, Hobart and William Smith Colleges. The project is currently supported by the National Science Foundation, Division of Education, CCLI-EMD 9950544. Hobart and William Smith Colleges reserve the rights to this Data Logger System, and allows at no charge educational and research use of the data logger system. We are grateful for the thoughtful reviews by Kevin Telmer and Quetin Bristow on an earlier draft of the manuscript.

Appendix. Example data file

This data file reveals user-supplied comments, initialization variables, and the first 52 digital values that were subsequently converted to temperature using a linear calibration curve and plotted in Fig. 6. The remaining logger data are omitted for brevity.

User Supplied Comments:

Temperature Sensor in Lansing Hall Window
Start a few days ago
End 17:36 10/20/98
Start from logger data 20:55 10/14/98
Hope to see daily temperature cycle

Initialization Parameters:

EEPROM Address	Value	Description
0	1	Logger Serial Number
1	1	Type of Sensor
2	1	Sensor Serial Number
3	0	Not used — proposed counter for start delay

4	0	Not used — proposed counter for start delay
5	1	Data Read Yet? (no = 0, yes = 1)
6	55	Start Minutes — Seconds Ignored
7	20	Start Hours
8	14	Start Day
9	10	Start Month
10	98	Start Year
11	19	Start Century
12	15	Number of 8 s. Ticks per Interval
13	2	Number of Intervals per Sample
14	8	Last EEPROM Bank
15	255	Last Address in Last Bank

Number of Data = 2033

Logger Data:

EEPROM Address	Date (m,d,y)	Time (h,m,s)	Logger Data
16	10/14/98	20:59:00	52
17	10/14/98	21:03:00	49
18	10/14/98	21:07:00	48
19	10/14/98	21:11:00	47
20	10/14/98	21:15:00	47
21	10/14/98	21:19:00	47
22	10/14/98	21:23:00	47
23	10/14/98	21:27:00	46
24	10/14/98	21:31:00	46
25	10/14/98	21:35:00	46
26	10/14/98	21:39:00	46
27	10/14/98	21:43:00	46
28	10/14/98	21:47:00	46
29	10/14/98	21:51:00	45
30	10/14/98	21:55:00	45
31	10/14/98	21:59:00	45
32	10/14/98	22:03:00	45
33	10/14/98	22:07:00	45
34	10/14/98	22:11:00	45
35	10/14/98	22:15:00	45
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37	10/14/98	22:23:00	45
38	10/14/98	22:27:00	45
39	10/14/98	22:31:00	45
40	10/14/98	22:35:00	45
41	10/14/98	22:39:00	45
42	10/14/98	22:43:00	45
43	10/14/98	22:47:00	45
44	10/14/98	22:51:00	45
45	10/14/98	22:55:00	45
46	10/14/98	22:59:00	44
47	10/14/98	23:03:00	44
48	10/14/98	23:07:00	44
49	10/14/98	23:11:00	44
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52	10/14/98	23:23:00	44
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54	10/14/98	23:31:00	44
55	10/14/98	23:35:00	44
56	10/14/98	23:39:00	44
57	10/14/98	23:43:00	44
58	10/14/98	23:47:00	44
59	10/14/98	23:51:00	44
60	10/14/98	23:55:00	44
61	10/14/98	23:59:00	44
62	10/15/98	0:03:00	44
63	10/15/98	0:07:00	44
64	10/15/98	0:11:00	44
65	10/15/98	0:15:00	44
66	10/15/98	0:19:00	44
67	10/15/98	0:23:00	44
... and continues at 4 min intervals up to ...			
2048	10/20/98	12:23:00	49

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