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SECTION 3
DEVICES & SYSTEMS

A low-cost research-oriented biofeedback thermometer with digital readout

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The construction of a research-oriented biofeedback thermometer with digital readout is described. The device uses recently developed low-cost integrated circuits and has a liquid crystal readout with capability of .1° and .01°F display. Internal calibration circuitry enables precision monitoring of overall performance stability. The basic thermometer design has potential application as a general instrument for behavioral and physiological research.

Clinical applications of thermal biofeedback have been reported with increasing frequency in the literature over the past several years.

Peripheral skin temperature training has been applied to cardiovascular disorders such as migraine headaches (Wickramasekera, 1973), Reynaud's disease (Surwit, 1973), and other circulatory dysfunctions. It has been used with relaxation training for treatment of a variety of conditions in which sympathetic activation is implicated, such as asthma and hypertension (Fuller, 1978). Surwit and Shapiro (1975) have reported correlations between digital temperature autoregulation and associated cardiovascular changes.

Temperature feedback may be useful in psychotherapy for giving information during the session about the client's resistance. In general relaxation training, depth of relaxation or resistance to relaxing may be indicated by thermal feedback.

Commercially available thermographs often are not well suited for research of biofeedback-related phenomena. Units having only analog temperature output on a meter scale indicating .1° or .2°F increments may not be adequate for certain research applications. Digital displays of temperature have some advantage by tending to reduce errors in copying of data from the instrument. Most commercially available thermographs do not have available an internally generated calibration signal to determine drift in instrument performance during and across experimental sessions.

DESIGN CONSIDERATIONS

The basic design criteria called for a portable battery-operated thermometer (single sensor) with accuracy and resolution suitable for biofeedback-related research (see Figure 1). A digital display of temperature in .1° and .01°F increments was considered essential for data

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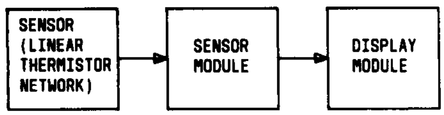

Figure 1. Basic block diagram.

gathering and desirable as a feedback modality to the subject. Calibration techniques using an internal resistance to simulate the sensor network were determined to be a primary requirement. A midrange temperature typically encountered in biofeedback applications (90°F) was selected as the calibration point. Both an absolute and a difference temperature mode initially adjustable to baseline temperature were considered essential for physiological applications.

Low construction cost and low operating cost for battery replacement were considered important. A liquid crystal display (LCD) meets the low battery drain requirement. A less expensive light-emitting diode (LED) display may require two orders of magnitude more current for operation.

A three-terminal linear thermistor network was selected (see Figure 2) as the sensor element because of its excellent interchangeability and accuracy over the typical biofeedback temperature operating range. The resistance bridge in the sensor module was designed to optimize accuracy and linearity over the biofeedback range for the chosen thermistor network. For example, the manufacturer's specified linearity for the sensor used is ±.025°F over the range of 88°-104°F. Self-heating errors due to current flow through the thermistor network were designed to be less than .02°F.

Within the past year, advanced designs have emerged of low-cost high-accuracy analog-to-digital (A/D) converters contained on a single CMOS integrated circuit. The Intersil 7106 kit used as the display module for the thermometer features high input impedance (greater than 10^{12} ohm), differential, and auto zero capability for precise null detection and an LCD

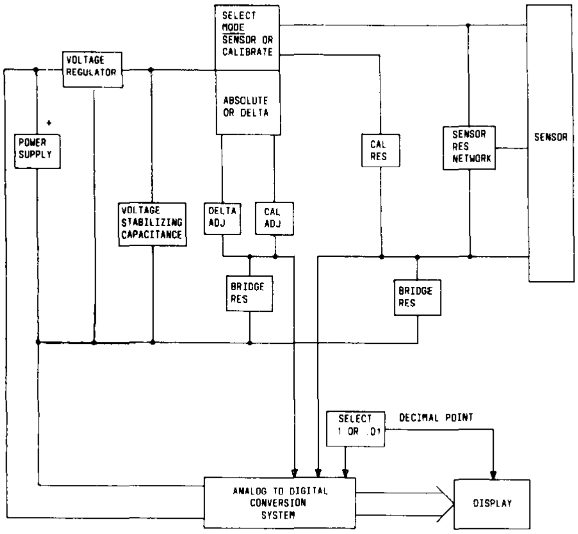

Figure 2. Functional block diagram.

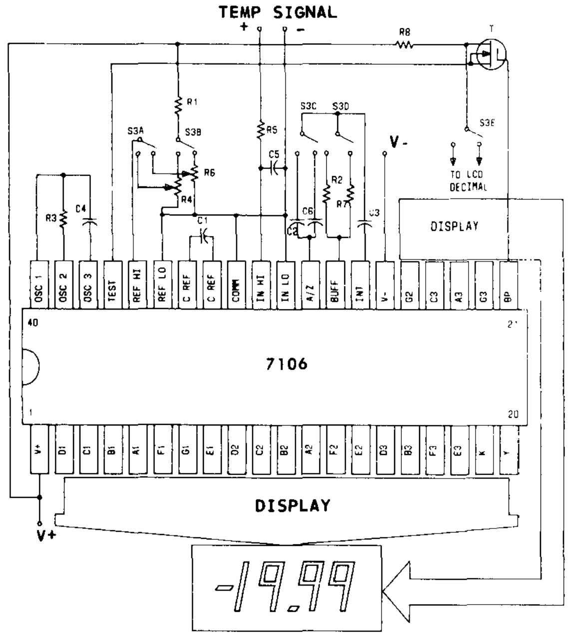

Figure 3. Schematic diagram of display module.

readout. The high input impedance results in completely negligible effects on loading the resistance bridge circuit in the sensor module. Three publications available from Intersil describe construction plans and applications for low-cost digital panel meter kits, including the 7106 (Dufort & Fullager, 1977; Intersil, Inc., 1977a, 1977b).

CIRCUIT CONSTRUCTION

Table 1 lists components required for building the unit. The instructions provided with the 7106 kit should be followed in building the display module. Exceptions to the instructions include the additional components shown in Figure 3 and the deletion of the 9-V battery.

Forty-pin DIP sockets are recommended for the DPM circuit board instead of the molex type provided with the 7106 kit. The 40-pin socket may be adapted for the wider base LCD device by cutting the DIP socket in two halves. When handling and mounting the A/D IC and the LCD display, standard precautions for these type components should be taken to prevent possible damage.

Initial checkout of the digital readout circuitry should be performed before connecting the temperature signal leads. The basic instructions supplied with the LCD kit should be followed.

A digital multimeter (preferably with 4.5-digit capability) is required to set the .100- and 1-V reference

Table 1
Components List

Description	Value	Tolerance	Type or Part Number
LCD Digital Panel Meter Kit*			ICL7106 EV/KIT
Linear Thermistor Network**			LTN-1
Analog-to-Digital Converter			7106
LCD Readout			
Resistors			
R1	24K		
R2	47K		
R3	100K		
R4†	1K		
R5	1M		
R6†	20K		20-turn A/B RT5L203
R7	470K	±10%	
R8	1M	±10%	
R9†	50K		20-turn A/B RT5L503
R10†	500		20-turn A/B RT5L501
R11	100K	1%	Cermet
R12†	20K		20-turn A/B RT5L203
R13	280	1%	Cermet
R14	12.3K	1%	Cermet
R15	35.7K	1%	Cermet
R16	20K	1%	Cermet
R17	10100		
R18	6980		

Table 1 Continued

Description	Value	Tolerance	Type or Part Number
Capacitors			
C1	.1 microF		
C2	.47 microF		
C3	.22 microF		
C4	100 picoF		
C5	.01 microF		
C6	.047 microF	±10%	
C7	25 microF		(15WVDC) (Aluminum Electrolytic)
Voltage Regulator VR			LM317MP
N Channel MOSFET T			3N128 or IT1750
Switch DPST S1			
Switch Rotary S2			5 Position, 2 Pole (Nonshorting)
Switch 6PDT S3			Alcoswitch MSS-6200
Stereo Phone Plug			
Stereo Phone Jack			
Mini Phone Plug (2)			
Mini Phone Jack (2)			
40-Pin Low-Profile DIP Socket (2)			
Metal Cabinet			270-252 (Radio Shack)
12-V Lantern Battery (2) (separate 12-V supplies required for LCD and sensor module)			
Connecting Cables, Miscellaneous Hardware			

*Note–R1-R5 and C1-C5 are included in the ICL7106 EV Kit. R17 and R18 are included in the LTN-1 network. Resistance values for Cermet resistors are standard for Allen Bradley Cermet Film Fixed Resistors Type CC. *Intersil, 10710 N. Tantau Avenue, Cupertino California 95014. **Fenwal Electronics, 63 Fountain Street, Framingham, Massachusetts 01701. †Variable.*

levels for the A/D converter. The best absolute accuracy and linearity will be achieved by setting R10 to yield as close as possible a voltage-regulator output of 3.127 V under load. For best calibration accuracy, trimming of R14 may be necessary to provide 1.935 V at the R14/R16 junction. This may require some adjustment by measuring resistance with a 4.5-digit multimeter and adding resistors in series or parallel to R14. It is important to use the same type resistors, so as not to change the temperature coefficient of the combined resistance.

Figure 4 shows the circuitry for the temperature-sensing signal-conditioning module of the unit. The sensor circuitry may be mounted on a 1.25 x 4 in. circuit board to be installed on the left side of the metal cabinet. Figure 5 shows a completed unit housed in the metal cabinet.

Operating controls are positioned on the right side of the cabinet. Sensor and power supply receptacle jacks (not shown) are on the left side. The unit may be operated in the horizontal or vertical position.

Each of the three connecting wires to the thermistor network head should be insulated through the use of plastic tubing. A sheath of heat-shrinkable tubing may be placed over the three covered wires up to the thermistor head. When soldering the three-conductor connecting cable to the thermistor leads, a heat sink (hold thermistor side of solder joint with pliers) should be used to prevent possible damage to the thermistors. Bulletin L-9A from Fenwal Electronics (1976) provides detailed specifications and applications for the linear thermistor network used. For most operating environ-

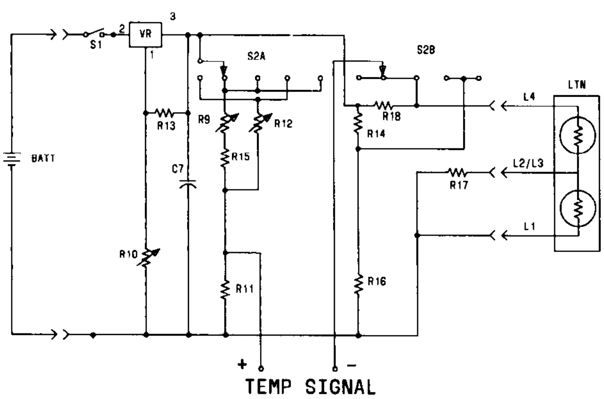

Figure 4. Schematic diagram of sensor module.

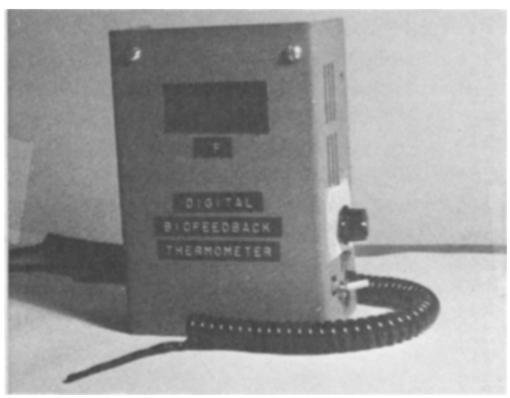

Figure 5. Completed unit housed in metal cabinet.

ments, unshielded three-conductor cable is adequate. The A/D unit has a common-mode rejection ratio (CMRR) of greater than 86 dB, thus minimizing effects of most 60-Hz noise. For high RFI noise areas, a three-conductor cable with foil shield should be used.

OPERATION

Table 2 lists operational modes, readout capabilities, and sensor temperature ranges. Functions of the switches used in operating the unit are shown in Table 3.

If the .01 position is inadvertently left on in an operational mode calling for .1, a "1" is displayed by itself in the most significant digit. This indicates an "overrange" condition on the voltage input of the A/D converter. The digital meter circuitry should not be damaged by the overrange condition. Switching S3 to the specified position of .1° will correct the problem.

For best accuracy at the .1°F level, the .01°F modes should be used. On a 3.5-digit device, the absolute temperature must be displayed in .1°F units for direct readout, thus increasing potential errors in the least significant digit.

At the beginning of an experimental session, the unit should be calibrated at the .01°F level by adjusting R15. Calibration may be checked at any time during the session by briefly switching S2 to the calibrate mode. A properly functioning unit typically shows a stability of within ±.02°F of the initial calibration over 1 h of continuous operation. At typical ambient room temperatures (65°-80°F), only minor adjustment of R15 should be required from day to day.

By using fresh 12-V lantern batteries as the power supplies, 300 h of continuous operation should be realized. For intermittent applications (e.g., 4 h on per day), the battery life should exceed 500 h. Because the IC voltage regulator (VR) requires a minimum of 6-V input to function properly, the battery should be replaced before 6 V is reached. If the battery voltage is permitted to drop below 6 V, errors in absolute accuracy and linearity will be introduced on the display.

APPLICATIONS

In biofeedback-related studies, the thermal unit's display may provide a direct visual feedback to the subject of peripheral vasoconstriction or vasodilation. Very small changes in physiologic state, as indicated by the .01 digit, may be observed in nearly real-time by the subject. Changes in subjects' response patterns may be interpreted much faster and more precisely than with a biofeedback instrument incrementing in .1°F units only.

Table 2
Operational Modes

Mode	Readout	Sensor Temperature Range
Absolute	.1	70-110
Absolute*	.01	70-110
Delta	.01	70-110
Calibrate Absolute	.1	90.0**
Calibrate*	.01	00.0**

*Note—Readout and sensor temperature range are given in degrees Farenheit. *Absolute referenced to 90°F. **Display.*

Table 3
Switch Functions

S1	Power On/Off
S2A	Absolute or Delta Mode
S2B	Sensor or Internal Calibration Mode
S3	.1°F or .01°F Readout (including decimal point)

The basic design, with minor component modifications in some cases, may be used as a general-purpose temperature sensor for both behavioral and physiological research. The least significant digit on the .01 display may be recorded directly or used to indicate a "derivative" function of the acceleration or deceleration rate of response in the physiological system being monitored.

Konecni and Sargent-Pollock (1977) have suggested the assessment of skin conductance changes as an index of the effect of Renaissance and 20th-century paintings on the physiological arousal of the subject. With the rising interest in psychoaesthetic research, it is suggested that skin-surface temperature measurement with thermal units capable of .005°F resolution and .01°F readout may find application such as galvanic skin response in studies of physiological arousal to works of art.

Cost of hardware for the thermal unit is less than $70, including the metal cabinet. Despite low cost, the equipment has performed reliably in a wide range of biofeedback-related experiments.

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