DIGITAL THERMOMETER

Richard Lorenz
J. W. Fogwell

FINAL REPORT - PART II
Contract No. NAS 9-7852
SwRI Project No. 16-2327

Prepared for
National Aeronautics and Space Administration
Manned Spacecraft Center
Houston, Texas

November 1969

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Approved:

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I. INTRODUCTION

Work completed under Contract NAS 9-7852 produced a prototype digital thermometer demonstrating accuracies of better than ± 0.2°F for temperatures measured between 74°F and 115°F. The application of digital techniques allowed the use of integrated circuitry along with minimum power requirements. Direct temperature readout by means of incandescent displays provided precise information without requiring interpolation of scales. The digital technique allowed the use of miniature sensing devices which yielded rapid thermal-response times. Interchangeability of probe devices maintaining the desired accuracy was also accomplished. The digital thermometer was constructed as a prototype unit with primary effort devoted to the establishment of high accuracy. With this success in hand, the miniaturization and refined accuracy through rigorous calibrating techniques could now proceed.

II. GENERAL DESCRIPTION OF OPERATION

The digital thermometer is operated on the intervalometer principle as indicated in Figure 1. A three-stage decade counter stores and displays the number of cycles received during a time interval. The output of an oscillator provides the frequency standard while an AND gate provides the inhibiting and enabling of the oscillator and the counter. An analog to time interval converter is used to control the AND gate output. This in turn controls the number of cycles the counter is allowed to count, this representing the temperature. An important feature of this thermometer is the method used for the early conversion from analog temperature to time Most digital circuits provide a calculatable and fixed error, while analog circuits are subject to drift due to temperature, age, and power supply variations.

Only two analog circuits are used in the system. The first is the oscillator. This oscillator, being crystal controlled, provides the desired accuracy for the system for all conditions. The second analog circuit is the analog to time converter. This converter provides a linear resistance to time relationship and requires minimum "analog state" signal operation.

The time constant involved in the temperature measuring operation is limited only by the sensor or probe. The electronic sampling and time conversion is an insignificant portion of the overall time constant.

Temperature gradients are obvious for oral temperature measurements (under the tongue) as the sensor is moved from a deep portion of the mouth toward the front. These temperature gradients are apparently associated with the proximity of the sensor to major blood vessels in the tongue or in underlying tissue.

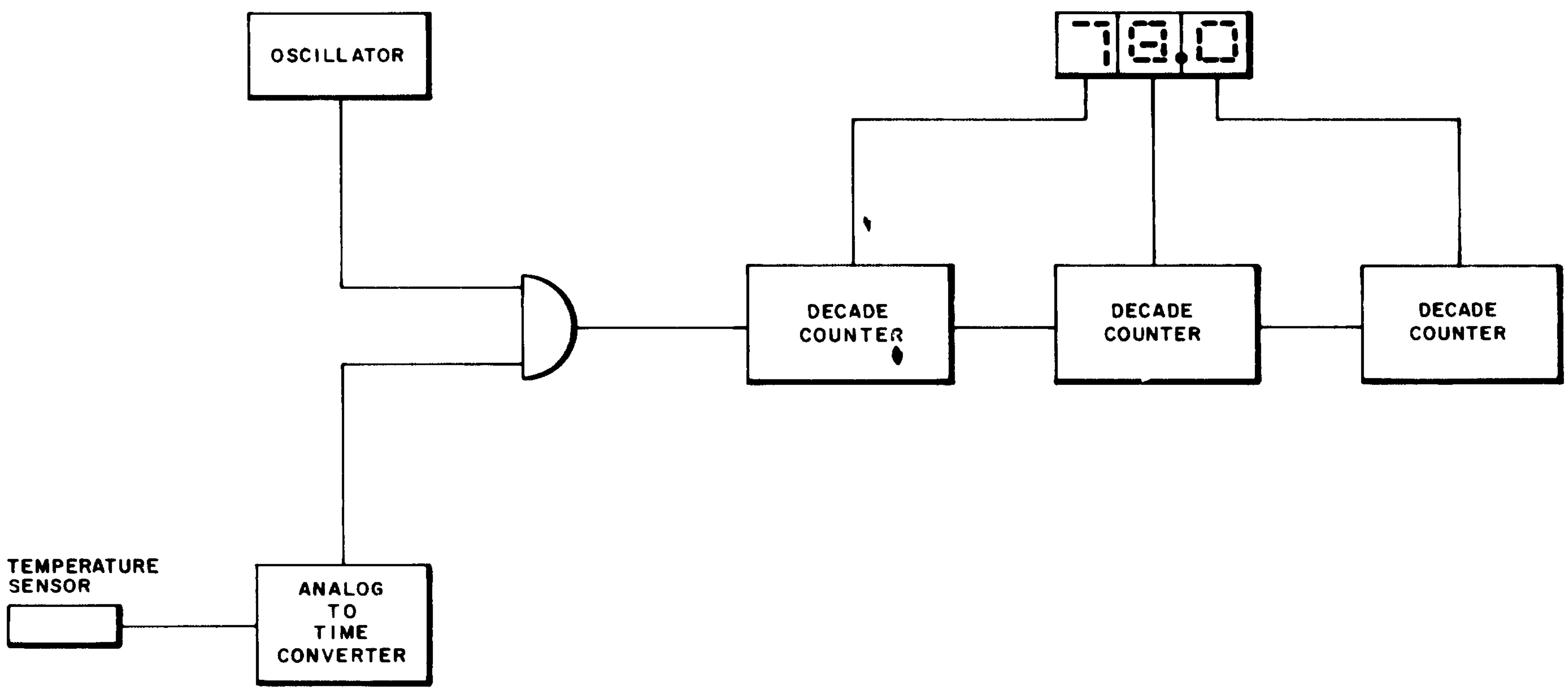

FIGURE 1

BLOCK DIAGRAM

III. TECHNICAL DISCUSSION

A. Probe Design and Construction

In order to insure linearity in temperature measurement for thermistor sensing elements, it is necessary to provide a compensation network which provides a transfer function creating linear thermistor performance. The computer program displayed in Appendix A was developed to evaluate the thermistor performance for various values of resistor variables when connected as a compensation network. As each value of resistance is tested, the deviation in temperature from a calculated best fit linear response is produced. If this deviation is smaller than the preceeding deviation, the new resistor values are recorded. After all variable values have been examined, the best calculated set is printed out. For this best set of values a straight line best fit resistance versus temperature and equivalent resistance (of thermistor with compensation network) versus temperature is calculated and displayed. The maximum temperature deviation from the straight line resistance versus temperature data is also calculated along with the equation for the straight line. With this program, any thermistor or non-linear device can be linearized to a predetermined accuracy. This program was used to insure that all compensated probes provide the proper resistance-temperature characteristics.

When fast thermal response is desired, and accuracy over only a limited range of temperature or limited accuracy over a wider temperature range is tolerable, single thermistor units can be employed. When more accuracy is required for a wide temperature range, multiple thermistors are required. The process of bonding or encapsulating the several thermistors together raises the thermal response time; thus, accuracy and range can be achieved at the cost of size and thermal response time. Two probes have been developed and tested by SwRI, one having a 10-second thermal response time with a ±0.2F° accuracy for a range of 94°F to 104°F. The second probe exhibited a three-minute thermal response time with ±0.3F° accuracy for a range of 74°F to 110°F. Additional calculations are required in order to determine the decline in accuracy for the first probe with increased temperature range.

B. Electronics

The electronics module contains a timing gate which is directly dependent on the resistance value of the thermistor. This gate allows a backward counter to determine the number of cycles of a 10 MHz oscillator occurring during the gated period. The timing gate can be adjusted to provide a difference in gating time $(\tau_2 - \tau_1)$ which allows a count change, as indicated by the digital counter, of temperature 2 - temperature 1. Thus, for a temperature change of 10.2F°, the counter will display a change in the number counted of 102. In order to count the exact and correct number, it is necessary to begin the count at a number other than zero. This number is calculated when the compensation network and probe values have been determined. Readout of the temperature is accomplished by a pinlite 7 bar incandescent display. This, along with the digital system, allows direct reading of the temperature without interpolation of scales or the changing of scale values to obtain the desired accuracy. Appendix B gives the mathematical development.

Construction of the electronics is highly adaptable to medium scale integration because of the use of digital integrated circuits. The system as constructed used integrated circuits but was not built for minimum package density. The prime objective was to design for future dense packaging techniques but construct circuits in the most economical manner sufficient to evaluate the system.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

Testing of the digital thermometer provided results better than the desired accuracy of $\pm 0.2F^\circ$ over the temperature range of 74°F to 115°F. Time constants of approximately 10 seconds were accomplished. The system provided a stable temperature measurement and desired accuracy with interchangeable probes which attached to the measuring unit by a quick-disconnect plug. Probe cost in large quantities would be held to a minimum of approximately $2.00 each.

B. Recommendations

Recommendations are as follows:

1. Evaluation of various probe or sensor temperature ranges vs. accuracy in order to expand the overall measuring capability of the thermometer should be made.

2. Probe configurations would be designed which produce the fastest temperature time constants possible.

3. A miniaturized version of the digital thermometer using medium scale integrated circuits should be constructed

4. The total current requirements should be reduced to not greater than 700 milliamps at 5 volts DC.

5. Rechargeable battery packages should be designed for continuous operation of at least 10 minutes duration before requiring recharging This would provide at least 4 hours normal routine clinical or hospital service life before recharging.

APPENDICES

APPENDIX A

COMPUTER PROGRAM

```
      PROGRAM LIN
      DIMENSION T(100),R(100),REQ(100),RSL(100),XREQ(100),XRSL(100)
      XMINDT=10000
    1  FORMAT(1I2)
      READ 1,N
    2 FORMAT(20F4.0)
      READ 2,(T(I),I=1,N)
    3 FORMAT(7F6.0)
      READ 3,(R(I),I=1,N)
      PRINT3,(R(I),I=1,N)
    4  FORMAT(3I7)
      READ 4,JD,JE,JF,JA,JB,JC,JX,JY,JZ
      PRINT 4,JD,JE,JF,JA,JB,JC,JX,JY,JZ
      PRINT 8
      DO 800 JR=JX,JY,JZ
      DO 300 JRP=JD,JE,JF
      DO 200 JRS=JA,JB,JC
      PDR=0
      XNDR=0
      DO 100 I=1,N
      ZREQ=(1./JR)+(1./(JRS+4.*R(I)))+(1./(JRP+R(I)))
      REQ(I)=1./ZREQ
  100 CONTINUE
      SLS=(REQ(1)-REQ(N))/(T(1)-T(N))
      G=REQ(1)-SLS*T(1)
      DO 400 I=1,N
      RSL(I)=SLS*T(I)+G
  400  CONTINUE
      DO 500 I=1,N
      DR=REQ(I)-RSL(I)
      IF (DR.GT.PDR) 50,51
   51  IF(DR.LT.XNDR)52,500
   50  PDR=DR
      SSLS=SLS
      GO TO 500
   52  XNDR=DR
      SSLS=SLS
  500  CONTINUE
      XMAXDR=ABS(PDR)+ABS(XNDR)
      XMAXDT=ABS(XMAXDR/SLS)
      IF(XMAXDT.LT.XMINDT) 60,700
   60  XMINDT=XMAXDT
      CR=JR
      CRS=JRS
      CRP=JRP
      XSSLS=SSLS
      XG=G
      PRINT 9,CR,CRP,CRS,XMINDT,XSSLS,XG
      DO 600 I=1,N
      XREQ(I)=REQ(I)
      XRSL(I)=RSL(I)
  600  CONTINUE
  700 CONTINUE
  200  CONTINUE
  300  CONTINUE
  800 CONTINUE
```

```
5  FORMAT(1H1,7X,1HT,9X,3HREQ,9X,3HRSL)
   PRINT 5
6  FORMAT(6X,F3.0,5X,F7.0,5X,F7.0)
   PRINT 6,(T(I),XREQ(I),XRSL(I),I=1,N)
7  FORMAT(1H0,6X,27HTHE  REST  RESULTS  FOLLOWS)
   PRINT 7
8  FORMAT(1H0,7X,2HRP,9X,2HRS,9X,3HRSS,9X,2HLT,9X,1HM,12X,1HB)
   PRINT 8
9  FORMAT(1H ,5X,F6.0,5X,F6.0,5X,F6.0,6X,F5.3,5X,F7.0,5X,F9.0)
   PRINT 9,CR,CRP,CRS,XMINDT,XSSLS,XG
   END
```

APPENDIX B

INVENTION DISCLOSURE

DIGITAL THERMOMETER

The purpose of the digital thermometer is to measure temperature with a temperature sensitive resistor and display the actual temperature with an optical readout. The conversion step from the analog temperature sensing element to digital logic circuits can be accomplished by two obvious methods:

(1) Count the number of cycles from an oscillator for a fixed sample time, allowing the temperature sensitive resistor to control the oscillator frequency.

(2) Count the number of cycles from a fixed oscillator, allowing the temperature sensing resistor to vary the sample time.

The second method is most easily employed, using fewer components and providing more stable operation. A one-shot multivibrator is used to vary the sample time of an oscillator as shown in Figure 1. The number of cycles occurring during the sample time is counted by a binary counter, converted to decimal quantities and displayed by an optical readout.

The uniqueness of this system is the method of acquiring direct temperature to count ratio. The "on" or sample time of a one-shot multivibrator is given by the "RC" time constant. The RC components are shown in Figure 2. It is anticipated that this system will operate with a linear resistance vs temperature element. If this temperature sensitive element is allowed to replace the R in the RC equation, then the sample time is directly proportional to R.

Thus

$T = RC$ where T = sample time

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if R varies according to

$$R_x = R_o + R_o N \Delta t$$

where the subscripts denote the temperature and Δt = change in temperature from t_o

$$T_x = R_x C$$

For some change in temperature

$$T_x - T_o = C\ [(R_s + R_x) - (R_s + R_o)]$$ where R_s might be some series resistance

$$R_x = R_o + R_o(N)\ (t_x - t_o)$$

$$T_x - T_o = C\ [R_o N (t_x - t_o)]$$

Then

$$C = \frac{T_x - T_o}{R_o N (t_x - t_o)} \qquad (1.1)$$

We also know

$$T_x = (C)\ [R_s + R_o + R_o N\ (t_x - t_o)] \qquad (1.2)$$

Substitute for (C)

$$T_x = \frac{(T_x - T_o)\ [R_s + R_o(1 + N\ (t_x - t_o))]}{R_o N\ (t_x - t_o)}$$

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An ideal situation would exist where $R_s = 0$.

For this condition:

$$T_x = \frac{T_xR_s + T_xR_o(1 + Nt_x - Nt_o) - T_oR_s - T_oR_o(1 + Nt_x - Nt_o)}{R_oNt_x - R_oNt_o}$$

$$T_x = \frac{T_oR_s + T_xR_o + T_xR_oNt_x - T_xR_oNt_o - T_oR_s - T_oR_o - T_oR_oNt_x + T_oR_oNt_o}{R_oNt_x - R_oNt_o}$$

$$0 = T_xR_o - T_oR_o - T_oR_oNt_x + T_oR_oNt_o$$

$$0 = T_x - T_o - T_oNt_x + T_oNt_o$$

$$0 = T_x - T_o + T_oN(t_o - t_x)$$

$$T_oN(t_o - t_x) = T_o - T_x$$

$$N = \frac{T_o - T_x}{T_o(t_o - t_x)}$$

$$N = \frac{T_x - T_o}{T_o(t_x - t_o)} \quad \text{where } N = \text{change}/°F$$

$$(T_x - T_o) = K(t_x - t_o)\ ;\ T_o = Kt_o$$

We want to force the linear relationship such that

$K = 10^{\pm n}$ where n = 1, 2, 3, etc.

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For a 10 MHz oscillator, the sample time for a four place readout would correspond to $K = 10^{-6}$.

$$\text{Thus } N = \frac{K}{T_o}, \quad N = \frac{10^{-6}}{T_o}; \quad N = \frac{K}{Kt_o} \text{ so that } N = \frac{1}{t_o}$$

This is the value of N which will allow a zero series resistance. A value of N less than that valued would require a $-R_s$ which would be undesirable. In fact, it would be desirable to work with any value of N independent of any series resistance. A silicon resistor is presently marketed produced an $N = .00389/°F$. This N does not meet the minimum value requirement for zero R_s, thus the system must be adjusted in some manner to obtain the desired direct readout.

The value of C must first be calculated to produce a desired change in sample time $(T_x - T_o)$ for a desired change in temperature $(t_x - t_o)$ and a given N and R_o.

Next, evaluating T_x for the calculated C and using $R_s = 0$, it can be shown that the count produced by sampling a fixed oscillator for T_x differs from the actual temperature t_x by an additive constant. This amount of reading is offset by pre-setting the counter to a starting number less than zero, thus producing an accurate readout of the temperature between the limits t_x and t_o.

An example follows:

Temperature values: $t_{min} = 90°F$; $t_{max} = 110°F$
Frequency of oscillation: 10 MHz
Desired to read: 5 places
$R_{90} = 10^4 \Omega$ $N = .00389/°F$

The numbers to be read are:

09000 to 11000

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For the 09000 representing 90.00°F

$$T_{90} = .9 \times 10^{-3}$$

For the 11000 representing 110.00°F

$$T_{110} = 1.1 \times 10^{-3}$$

$t_{min} = 90°F$ $\qquad$ $t_{max} = 110°F$

$$\frac{T_{110} - T_{90}}{t_{max} - t_{min}} = \frac{.15 \times 10^{-3}}{15} = 1 \times 10^{-5} = K$$

$$C = \frac{K}{R_{90}N} = \frac{10^{-5}}{(10^4)(.00389)} = \frac{10^{-5}}{38.9}$$

$$C = .0257 \times 10^{-5} = 0.257\ \mu f$$

$$T_{90} = (C)(R_{90}) = (.0257 \times 10^{-5})(10^4) = 25.7 \times 10^{-4}$$

$$T_{100} = (C)(R_{90} + R_{90}N\Delta t) = (.0257 \times 10^{-5})(10^4 + 10^4 \times .00389 \times 10) =$$

$$T_{100} = 26.6997 \times 10^{-4}$$

$$T_{110} = (C)(R_{90} + R_{90}N\Delta t) = (.0257 \times 10^{-5})(10^4 + (10^4))(.00389)(20)\ 1.0778 \times 10^4$$

$$T_{110} = 27.699 \times 10^{-4}$$

Count for $T_{90} = (T)(f) = 25.7 \times 10^{-4} \times 10^7 = 25700$

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Count for T_{100} = 26699.7 = 26700

Count for T_{110} = 27699.5 = 27700

For a temperature of 90° we read	25700
We want to read	9000
The difference is	16700
For a temperature of 100° we read	26700
We want to read	10000
The difference is	16700
For a temperature of 110° we read	27700
We want to read	11000
The difference is	16700

Note that in each case the decimal reading differs from the actual reading by 16700 counts. Thus, by setting the counter to 83300, the counter will read the correct values of temperature after the proper sample time occurs.

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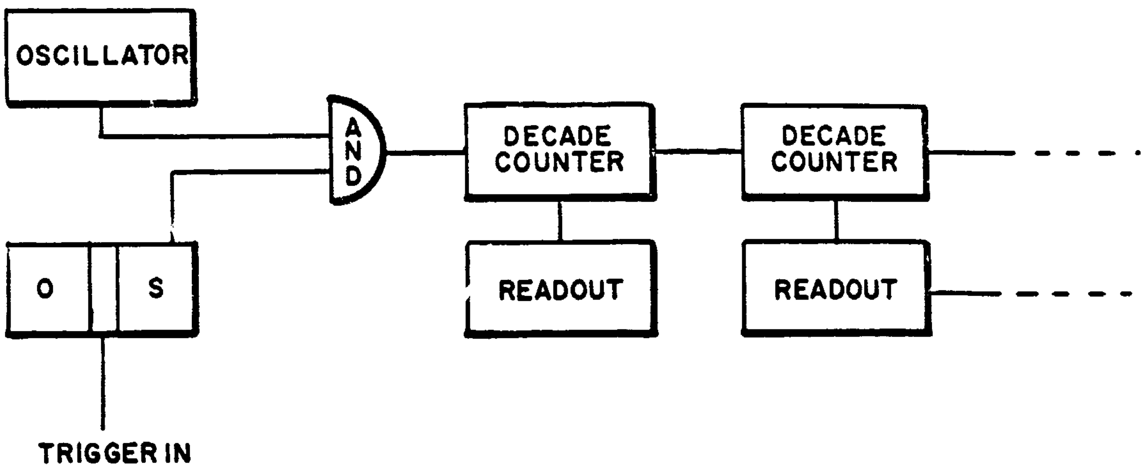

FIGURE 1

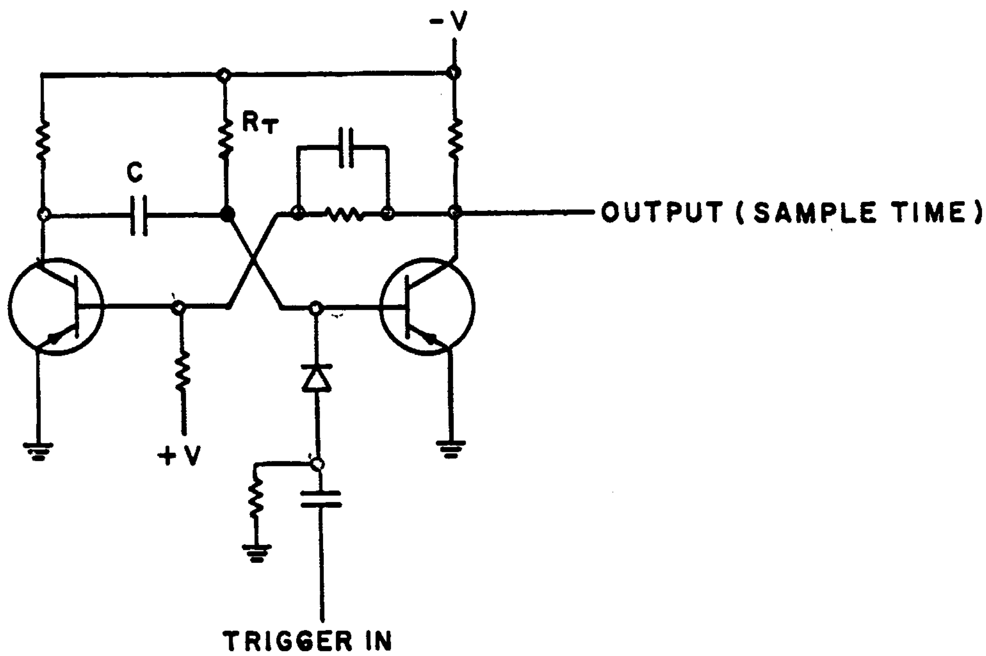

FIGURE 2

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