TEMPERATURE CONTROL
USING A K-TYPE THERMOCOUPLE

by

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ABSTRACT

TEMPERATURE CONTROL USING A K-TYPE THERMOCOUPLE

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A temperature data acquisition and control system applicable for process control was designed, built, and tested. A K-type thermocouple was used to sense the temperature and a MMD-1 mini microcomputer was used to process the data and generate the control signals. Three types of interfaces were required -- sensory, user-interaction, and control. Both hardware and software implementations were evaluated as means of compensating for the K-type thermocouple's nonlinearity and the reference junction temperature and to provide the set-point control signal. The system was calibrated by two independent techniques -- fixed point and direct comparison. Noise rejection techniques and ways of improving the performance of the data acquisition and control system were explored.

ACKNOWLEDGEMENTS

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LIST OF SYMBOLS

SYMBOL	DEFINITION	REFERENCE
1N961	A Zener diode	
2N2222	A transistor	
3904	A NPN transistor complementary with 3906	
3906	A PNP transistor complementary with 3906	
4066	An analog switch	
7402	A Quadruple 2-input Positive NOR Gate	
7404	A Hex Inverter	
7407	A Hex Buffer/Driver	
7442	A BCD-to-decimal decoder	
7447	A BCD-to-seven segment decoder/driver	
7475	A Quadruple Bistable Latch	
a	Ra'/Ra	Fig. 17
AC	Alternating current	
AD7570	An analog to digital converter	
ANSI	American National Standards Institute	
AWG	American Wire Guage	
A/D	Analog to digital	
BCD	Binary-coded Decimal	
BI	The Blanking Input bit of 7447	
$\overline{\text{BUSY}}$	The conversion status pin of LR-36	
CLK	An enable input of 7475	
CMOS	Complementary Metal Oxide Semiconductor	
CMRR	Common mode rejection ratio	

SYMBOL	DEFINITION	REFERENCE
CPU	Central Processing Unit	
d.p.	Decimal point	
DC	Direct current	
DDSPLY	A subroutine	Appendix F
e	Charges carried by an electron	
E	Energy of electrons	Eq. (3)
ECG3049	An isolator	Fig. 15
ECG5677	A TRIAC	
Ef	Fermi level energy	Eq. (2)
EX	An electric field	Eq. (2)
f0	Unperturbed density distribution of electrons	Eq. (3)
Hi	High input terminal of the precision amplifier	
I1, I2	Defined in Eq. (3)	
IPTS-68	International Practical Temperature Scale set up in 1968	
I/O	Input and output	
J1(2,3)	Metallic junction	Fig. 10
LED	Light-emitting diode	
Lo	The low input of the precision amplifier	
LM113	A temperature compensated low voltage reference diode	
LM121A	A precision pre-amplifier	
LM308A	A precision amplifier	
LM311	A comparator	
LR8321R	A seven-segment common-anode dispay	
LR-36	An A/D converter outboard	

SYMBOL	DEFINITION	REFERENCE
LSB	Least significant bit	
LT	The Lamp Test pin of 7447	
m*	Effective mass of electrons	Eq. (3)
MMD-1	A mini microcomputer	
MOS	Metal Oxide Semiconductor	
MSB	Most significant bit	
M/I	Memory and Interface	
NBS	National Bureau of Standards	
ONESEC	A subroutine for a time delay of 1 sec	
OP	Operational	
PROM	Programmable Read Only Memory	
PT	Platinum	
R5	Defined in Fig. 20	
R9	Defined in Fig. 20	
Ra	Defined in Fig. 17	
Ra'	Defined in Fig. 17	
RBI	The Ripple Blanking Input pin of 7447	
Rds(on)	The ON resistance of the analog switch in Fig. 24	
Ro	The output resistance of the input voltage follower in Fig. 24	
Rs	The shunted resistance with a thermistor to improve its linearity	Fig. 18
Rth	Thevenin's equivalent resistance	Fig. 19
R	A temperature-sensitive resistance	
RTD	Resistance Temperature Detector	
Rx	Defined in Fig. 17	
Ry	Defined in Fig. 17	

SYMBOL	DEFINITION	REFERENCE
SCR	Silicon-controlled Rectifier	
SSR	Solid State Relay	
STRT	The start input of AD7570	
Tad	The output of LR-36 for the detected temperature	
TC	Thermocouple	
Tm	The modification number used in the software modification	
Toc	The over-counted temperature used in the software modification	
Tr	Reference temperature	
TRIAC	A bidirectional triode thyristor	
TTL	Transistor-transistor Logic	
uA741	A general-purpose OP amplifier	
Va	Accumulated voltage used in the software modification	
Vam	The K-type thermocouple voltage at ambient temperature	
Vb	The DC source for the cold junction compensation bridge	Fig. 17
VFET	A MOS device employing a V-shaped semiconductor channel	
Vm	Defined in Fig. 23	
Vn	Defined in Fig. 23	
Vol	The output of the precision amplifier due to thermocouple	Fig. 22
Vr	The K-type thermocouple voltage at the detected temperature	
Vrt	The emf of the reference thermocouple	
Vs	Seebeck voltage	Eq. (4)
Vth	Thevenin's equivalent voltage	Fig. 19

SYMBOL	DEFINITION	REFERENCE
W	Work function	
X1	The hot end in Fig. 6	
X2	The cold end in Fig. 6	
ZVS	Zero voltage switch	
α	Seebeck coefficient	
τ	Mean free path of electrons with energy E	
Δr	Resistance change of a thermistor due to a temperature change ΔT	
ΔR	Resistance change per °C of the arm including the R_T in Fig. 17	

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CHAPTER I

INTRODUCTION

Sensors

Sensing transducers, or sensors, as they are often called, are the sensory components of measuring systems, which are part of a broad field of technology called instrumentation. They, like human beings, are sensitive to the environmental inputs: pressure, force, motion, strain, temperature, sound, radiation, electric fields, magnetic fields, etc. They enable machines to recognize environments in order to make appropriate responses. They are to machines what the four senses are to human beings. Sensors play the vital roles in our modern technological world. The flight of the first space shuttle, viewed remotely by millions, is a prime example of an experimental project involving a multitude of sensors and computers.

To reduce pollution, many chemical sensors are employed in the gas-refining processes. The operation of a modern fuel-efficient car needs the onboard sensors and computer for optimum performance and fuel economy. The operation of robots needs the coordination of an assembly system of sensors. Sensors are also intimately involved in improving health. Doctors use an electrocardiograph to check your heart. It is not uncommon to hear a doctor say that when you are forced or pressured to do something, you experience stress and the strain shows.

Temperature Sensors

Temperature has an effect on almost all the properties, both physical and chemical, of materials. Chemical reactions, the melting of solids, the boiling of fluids, the conductivity of conductors, the insulation capability of dielectrics, etc., are all greatly affected by temperature. The surprising explosion of the space shuttle Challenger was caused by the effect of low temperature on the safety seal for fuel.

Heat is dissipated when energy is being converted from one form to another or when work is being done. In some cases, such as conversion of coal to steam to electricity, large losses are caused by heat dissipation. In other cases, such as air conditioning, it is indeed desirable for heat to be removed. As all industries place new emphasis on energy efficiency, the fundamental measurement of temperature assumes new importance.

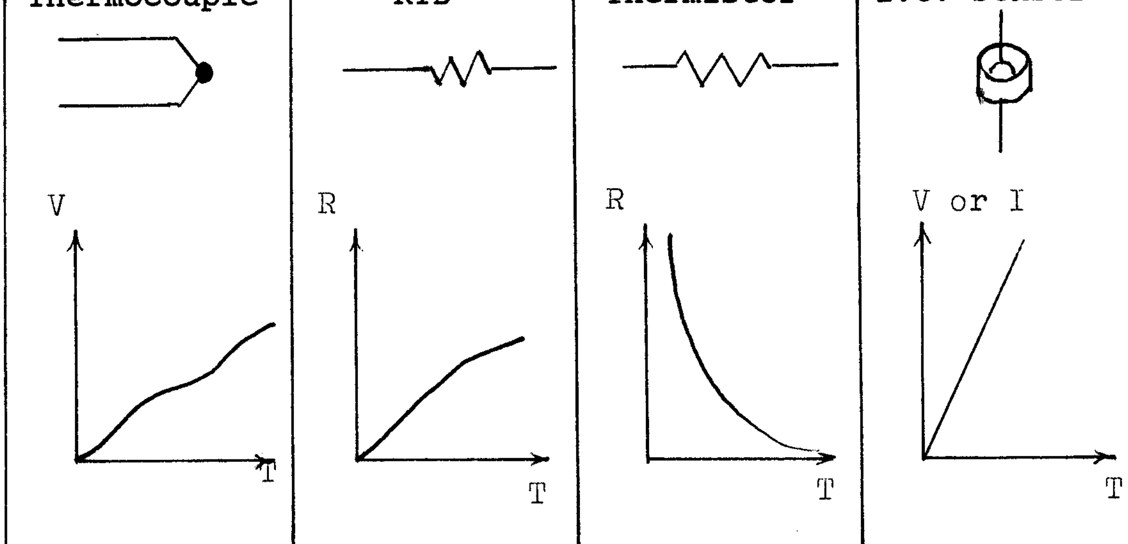
There are four common temperature sensors: the thermocouple, the RTD, the thermistor and the integrated circuit sensor. A thermocouple is made of two dissimilar metals with one end of them joined together. When the junction is heated, some voltage output will be detected at the two unjoined ends. The voltage is a function of the junction temperature and the composition of the two metals. A RTD (Resistance Temperature Detector) is a metal which produces a positive change in resistance for a positive change in temperature. Thermistors are generally composed of semiconductor materials. Most thermistors have a negative temperature coefficient; that is, their resistance decreases with increasing temperature. An integrated circuit temperature transducer is a semiconductor device with an output, either voltage or current, that is linearly proportional to absolute temperature. Fig. 1 lists the advantages and disadvantages of these sensors.

Background of the Thesis

Once we have a sensor, the problem then is how to use it. Some sensors transform the environmental inputs directly into electric signals, and some sensors accomplish it indirectly. The outputs of some sensors are linear, and those of the others are nonlinear. The outputs of some sensors are high, and the others are low. The responses of some sensors are fast, and the others are slow. Therefore most sensor systems include a data conditioner. For some nonlinear sensors, such as thermocouples, the relation of the outputs to the inputs is very complex. A computer can be used to improve the performance of such sensors.

Traditionally the conditioned output of a sensor is compared to a set-point in order to control the system. Some computer-based systems that use this approach locate

Thermocouple	RTD	Thermistor	I.C. Sensor



Thermocouple	RTD	Thermistor	I.C. Sensor
Advantages			
_Self-powered _Simple _Rugged _Inexpensive _Wide variety _Wide temperature range	_Most stable _Most accurate _More linear than thermocouple	_High output _Fast _Two-wire ohms measurement	_Most linear _Highest output _Inexpensive
Disadvantages			
_Nonlinear _Low voltage _Reference required _Least stable _Least sensitive	_Expensive _Current source required _Small ΔR _Low absolute resistance _Self-heating	_Nonlinear _Limited temp. range _Fragile _Current source required _Self-heating	_$T < 200^{\circ}C$ _Power supply required _Slow _Self-heating _Limited configurations

Fig. 1.--Common Temperature Transducers

the comparator with the set-point before an A/D converter as shown in Fig. 2. But if the output of the pre-amplifier is matched with the resolution of the A/D converter, the comparison can be put inside the computer(see Fig. 3). In this way the set-point potentiometer, usually an expensive multiturn one is needed for an accurate control, and the differential amplifier can be saved. In addition, the A/D converter can be used in a unipolar operation in stead of a bipolar operation. As the result, the resolution can be more precise. The costs are increased software and response time. For a thermocouple, the response time is about 5 secs. The time delay because of executing the increased software, a few milliseconds, is of little importance. Table 1 lists the comparion of these two approaches.

The goals of this thesis are to investigate:

1. a data acquisition system that uses a thermocouple as the sensor,

2. the application of a microcomputer to improve the performance of a nonlinear sensor, and

3. the software approach to implement the set-point.

Overview

Chapter II reviews the fundamental theory and characteristics of thermocouples. This includes the quantum theory basis for the Seebeck effect, a description of the material designations and operating ranges of thermo-

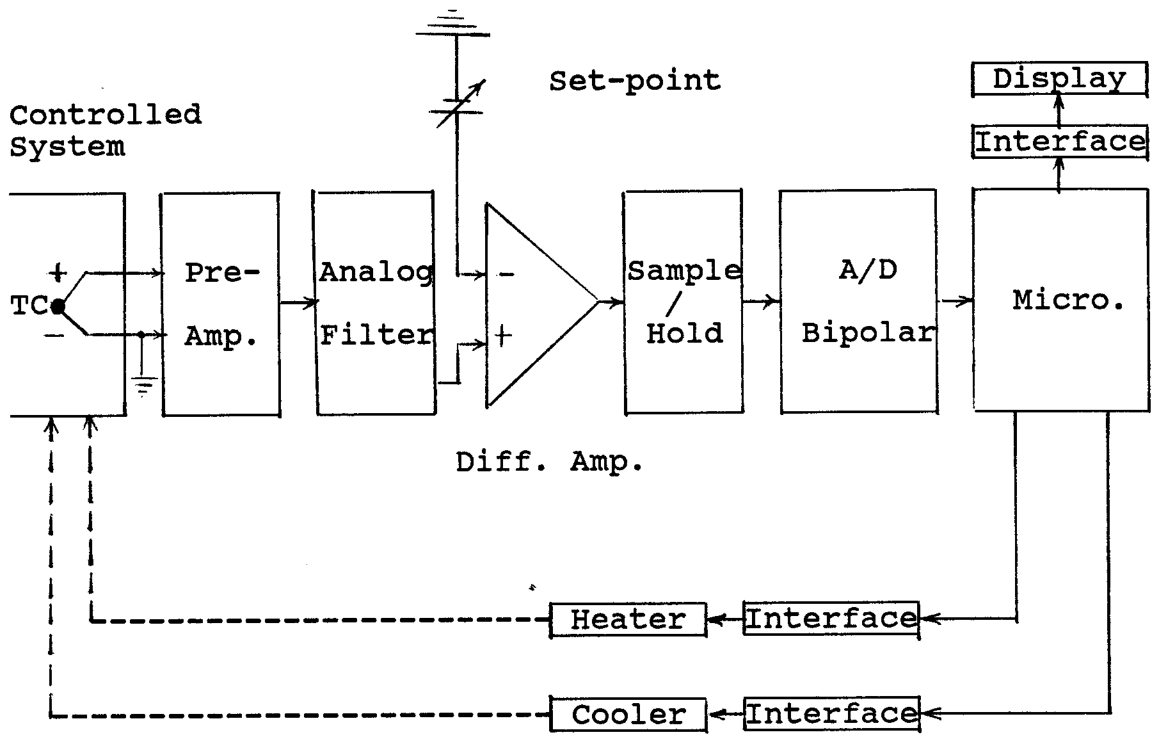


Fig. 2.--Hardware Implemented Set-point

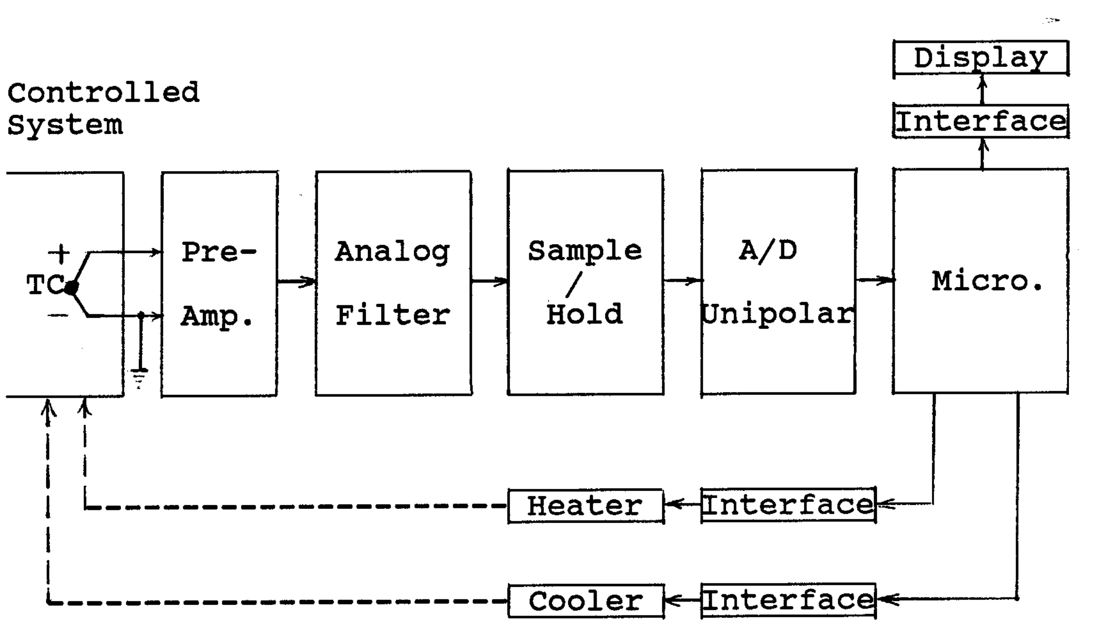


Fig. 3.--Software Implemented Set-point

TABLE 1

COMPARISON OF TWO APPROACHES TO IMPLEMENT THE SET-POINT

Software Approach	Hardware Approach
Advantages	
1. Save the set-point potentiometer and a differential amplifier.	1. Control software is simpler.
2. Use a unipolar A/D converter in stead of a bipolar A/D converter.	2. A faster response.
3. Resolution is smaller.	3. Smaller memory.
4. More set points.	
5. Software cold junction compensation can be used.	
Disadvantages	
1. Need a software modification for the output of the nonlinear sensor.	1. Need a set-point potentiometer and a differential amplifier.
2. Response time is longer because of executing the the modifying software. (2ms for my case)	2. Need a bipolar A/D converter.
3. Need a larger memory.	3. Resolution is larger.
	4. Fewer set points.

couples, and a discussion of the construction and the extension wires of thermocouples.

Chapter III introduces various kinds of interfaces. The interfaces to a 4-digit decimal display and the interfaces to the cooling system (an electric fan) and the heating system (a high-power electric furnace and a water heater) are discussed and presented.

Chapter IV deals with the sensory interfaces (data acquisition system) that use a K-type thermocouple as the sensor. Although the circuit design is for the K-type thermocouple, the principles described are also applicable to any type of thermocouples. Cold junction compensation is discussed. A precision amplifier with cold junction compensation is designed. An analog filter is introduced. The Sample/Hold circuit design, sampling time and holding techniques are discussed. Finally the LR-36 A/D converter is introduced and its interconnection with the MMD-1 mini microcomputer presented.

Chapter V deals with the control software. A software-modifying technique for K-type thermocouple is introduced. The control flow chart including displaying the set-point for five seconds, clearing the display for one second, controlling the Sample/Hold, handshaking between the A/D converter and the microprocessor, modifying data, displaying the detected temperature and controlling the system temperature within $\pm 3\,^{\circ}C$ from the set-point is presented and interpreted.

Chapter VI deals with the calibration techniques for the temperature controller and lists some test results.

In Chapter VII, the noise rejection techniques for thermocouple measurements are discussed. Some suggestions for improving the performance of a microprocessor-based temperature controller are presented. The flexibility of the microprocessor-based temperature controller, including the adjustments for other types of thermocouples and a controller for various types of thermocouples, is discussed. Finally, the multi-sensor control technique is evaluated.

CHAPTER II

THEORY AND CHARACTERISTICS OF THERMOCOUPLES

Introduction

When two wires composed of dissimilar metals are joined at both ends and one of the ends is heated, there is a continuous current flowing in the thermoelectric circuit (see Fig. 4). This effect, called Seebeck Effect, was discovered by Thomas J. Seebeck in 1821. The heated junction is called the hot junction, while the other is called the cold junction. In Fig. 4, the current flows from the copper wire to the iron wire at the hot junction. If the circuit is broken at the cold junction, we will find that some voltage exists across the cold junction. The voltage is called the thermocouple potential. Its polarity and magnitude are dependent upon the hot junction temperature and the composition of the two metals. All dissimilar metals exhibit this effect.

Theory

The energy-band models of two dissimilar metals at absolute zero are shown in Fig. 5. The work that must be done to remove an electron which is inside the crystal to a distance far from the crystal is called the work function W of that crystal. At absolute zero, this can be

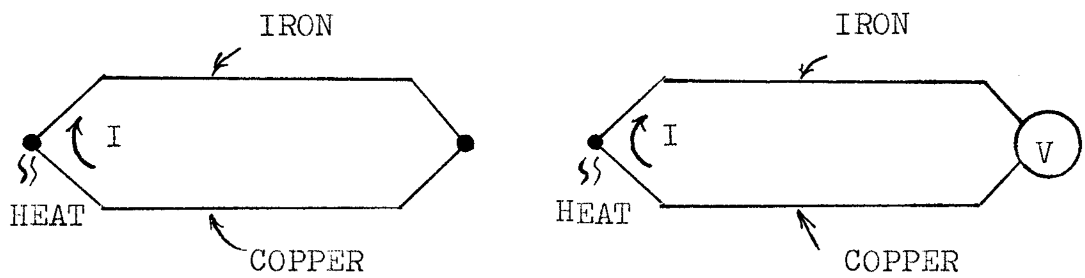


Fig. 4.--Seebeck Effect for Two Dissimilar Metals

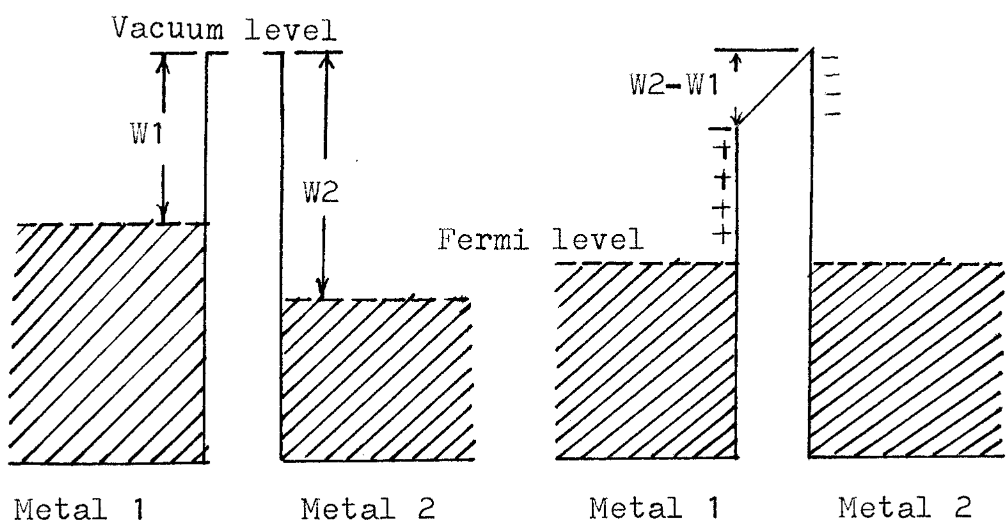


Fig. 5.--Contact Potential of Two Dissimilar Metals

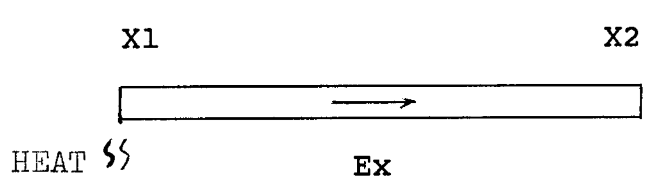


Fig. 6.--Seebeck Effect for Single Conductor

represented in the band model by the energy required to raise an electron from the Fermi energy to the so-called Vacuum level. When the two metals are brought in intimate contact with each other, some of the electrons in metal 1, shown to the left in Fig. 5, occupy quantum states that have larger energies than those of unoccupied states in metal 2. The electrons near the Fermi level in metal 1, therefore, flow into metal 2 until at equilibrium the Fermi energy in both metals is at the same energy level. In the process, the surface of metal 2 becomes negatively charged while the surface of metal 1 becomes positively charged as indicated in Fig. 5. This produces a potential difference between the two metals called the contact potential V determined by

$$eV = W2 - W1. \qquad (1)$$

Since a local electric field cannot exist inside a metal because of its high conductivity, the change in the free-electron distribution in the two metals that produced the potential in (1) takes place on the contact surface between them.

Considering a conductor ending at both X1 and X2 (see Fig. 6), if we heat at the end X1, then an internal electric field

$$\mathbb{E}X = -\frac{1}{e}\left(\frac{I2}{I1 \cdot T} - \frac{Ef}{T}\right)\frac{dT}{dx} \qquad (2)$$ [1]

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[1] W. R. Beam, Electronics of Solids (McGRAW HILL, 1965), p.141.

exists at any point between X1 and X2. Here

Ef = Fermi level energy,

e = charges carried by an electron,

T = temperature at point X,

and

$$Ij = \frac{4\pi 2^{3/2} m^{*1/2}}{3} \int_0^\infty \tau E^{j+1/2} \frac{\partial f0}{\partial E} dE \qquad j = 1, 2, 3 \ldots \qquad (3)$$ [2]

where

E = energy of electrons,

m^* = effective mass of electrons,

τ = mean free path of electrons with energy E,

and

$f0$ = unperturbed density distribution of electrons.

This is the electrothermal (or Seebeck) field. It is produced because electrons from one end are carried towards the other end of the conductor by a difference in temperature. While the effect is subtly dependent on $\tau(E)$, it is convenient to imagine that more high-energy electrons from the hotter end migrate to the colder end.

If there is no closed current path, across the two ends (X1, X2) of a conductor having temperature distribution T(X) will appear a Seebeck voltage Vs, the integral of the field:

$$Vs = -\frac{1}{e}\int_{X1}^{X2}\left(\frac{I2}{T \cdot I1} - \frac{Ef}{T}\right)\left(\frac{dT}{dx}\right)dx$$

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[2]W. R. Beam, Electronics of Solids, p. 139.

$$= -\frac{1}{e}\int_{T1}^{T2}\left(\frac{I2}{T\cdot I1}-\frac{Ef}{T}\right)dT. \tag{4}$$

The voltage depends only on the two particular temperatures at the ends of the conductor; the conductor length is unimportant. This is not to say, however, that the Seebeck voltage need be linear in temperature difference, since the Seebeck coefficient (or thermoelectric power), which is the integrand of Eq.(4),

$$\alpha = \frac{1}{e}\left(\frac{I2}{T\cdot I1}-\frac{Ef}{T}\right), \tag{5}$$

is a function of T. Room-temperature values of α for simple metals lie scattered over the range of +10 to -10 uV/°C.

The coefficient α in metals is strongly dependent on the energy dependence of the mean free path. Fig. 7 shows that in the upper conductor, the mobility of high-energy electrons is greater than that of low-energy electrons, and accordingly the negative charges accumulate at the cold end. In the lower situation the low-energy electrons have greater mobility.

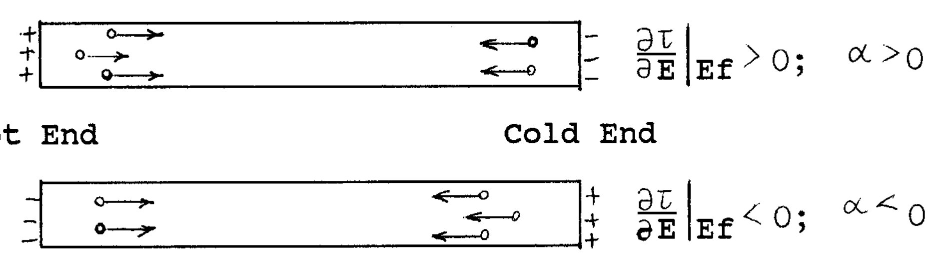


Fig. 7.--Dependence of the Seebeck Coefficient on the Mobility of Electrons

Typical measurement techniques do not measure the absolute Seebeck voltage Vs, because the electrodes connecting the meter with the conductor in question are also under the influence of the same thermal gradient. Their own electrothermal voltage may oppose that of the conductor. The usual tabulated voltages (thermocouple voltages) are differences between Vs values in two different metals. Although in metals these voltage differences are small, the voltage difference is a reliable measure of temperature difference. To be assured of a reliable calibration, most thermocouples are made from pairs of specially formulated alloy wires, or a metal vs. an alloy.

Material Designations

The standards of thermocouples have been developed by industry and the National Bureau of Standards. Thermocouples are designated by letter types. The common metals (called base materials) are ANSI (American National Standards Institute) types T, E, J, and K. The more exotic metals used are called noble alloys. These are more expensive but are able to operate at higher temperature and highly resistant to oxidation and corrosion. These are ANSI types R and S. Table 2 lists the ANSI type and its thermocouple alloys. After the material there are (+) and (-) signs. The (+) polarity establishes the metal with the higher energy state.

TABLE 2

ANSI SYMBOL AND ITS THERMOCOUPLE ALLOYS

ANSI Symbol	Thermocouple Alloy
T	Copper(+)versus constantan(-)
E	Chromel(+)versus constantan(-)
J	Iron(+)versus constantan(-)
K	Chromel(+)versus Alumel(-)
R	Platinum(+)versus platinum 13% rhodium(-)
S	Platinum(+)versus platinum 10% rhodium(-)
B	Platinum 6% rhodium(+)versus platinum 30% rhodium

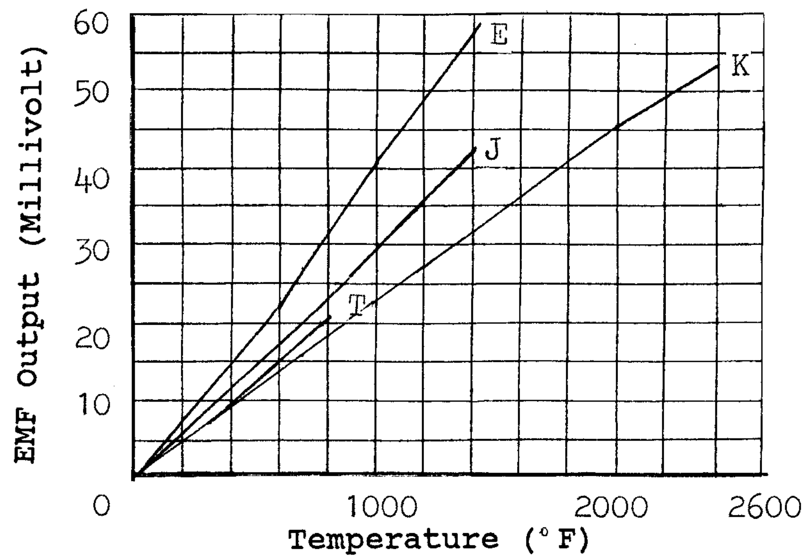
Operating Ranges

The thermocouple does not generate an enormous amount of voltage. Fig. 8 is a plot of millivolt versus temperature curves for the ANSI-standard thermocouples. We can find that the base alloys (T, E, J, K) have larger outputs but operate in comparatively low temperature ranges. The noble alloys (R, S), however, operate in relatively high temperature ranges but have low voltage outputs. The tungsten-rhenium alloys (3, 4) operate at extremely high temperatures at an output voltage range between the base and the noble alloys.

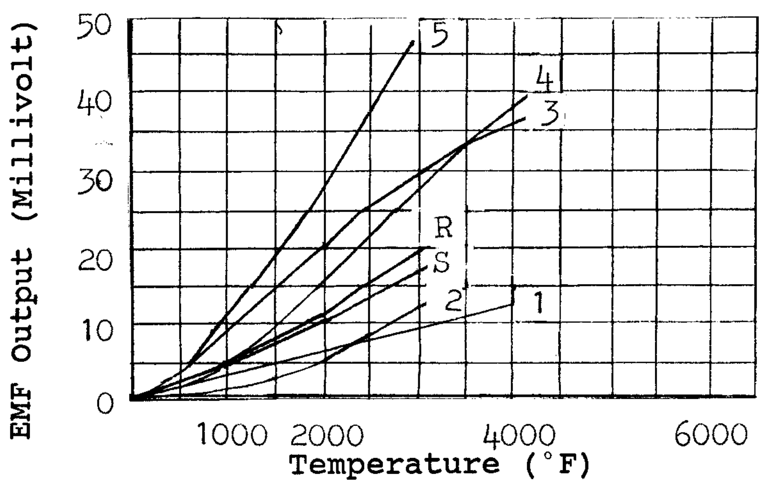
Each thermocouple has specific capabilities. These are as follows:

Type J - This type is recommended for reducing atmospheres. The operating range for it is 1382°F for the largest wire size (AWG #1). Smaller size wires can be used at correspondingly lower temperatures.

Type T - This type is recommended for use in mildly oxidizing and reducing atmospheres up to 662°F. They



* Low Temperature Thermocouple Materials



* High Temperature Thermocouple Materials

Type	Typical Thermocouple Material
1	60% Iridium 40% Rhodium/Iridium
2	Platinum 30% Rhodium/Platinum 6% Rhodium
3	Tungsten 5% Rhenium/Tungsten 26% Rhenium
4	Tungsten/Tungsten 26% Rhenium
5	PT 5% Molybdenum/PT 0.1% Molybdenum

Fig. 8.--Thermocouple Output Voltages[a]

[a]Robert G. Seippel, Transducers, Sensors, and Detectors (Reston Publishing Company, 1983), p. 264.

are suitable for applications where moisture is present. This alloy is recommended for low-temperature work since the homogeneity of the component wires can be maintained better than other base-metal wires. Therefore, errors due to lack of homogeneity of wires in zones of temperature gradients are greatly reduced.

Type K - This type is recommended for use in clean oxidizing atmospheres. The operating range is 2282°F for the largest wire size (AWG #1).

Type E - This type may be used for temperature up to 1652°F in a vacuum or inert, mildly oxidizing, or reducing atmospheres. At subzero temperatures, it is not subject to corrosion. It has the highest output of any standard metallic thermocouples.

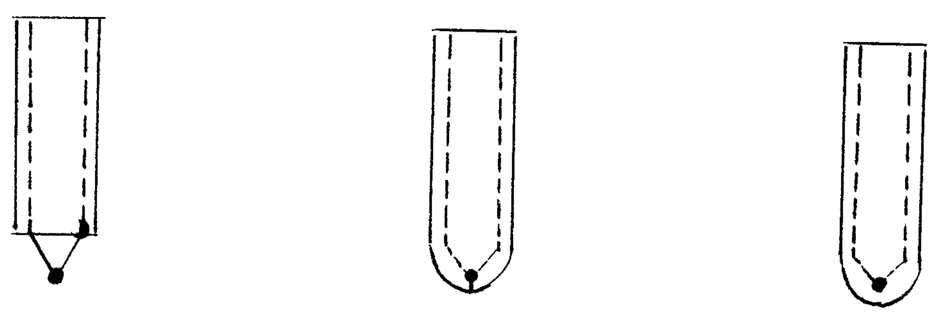
Type S, R - These types have a high resistance to oxidation and corrosion. However, hydrogen, carbon, and many metal vapors can contaminate them. The recommended operating range is 2642°F.

Type 3, 4 - These types are in common use for measuring temperatures up to 4000°F. They have inherently poor oxidation resistance and should be used in vacuum, hydrogen, or inert atmospheres.

Construction

The measuring junctions of some thermocouples are constructed in a tube to provide the junction with support while still achieving uninhibited sensing of the environment to be measured. The supporting material is called a sheath and is made from metal such as inconel or stainless steel. The sheath is insulated from the junction with ceramic or magnesium oxide. There are three basic junction models as shown in Fig. 9.

The exposed junction extends beyond the protective sheath to give fast response. It is recommended for the measurement of static or flowing noncorrosive gas temperatures in cases where the response time must be minimal.



Exposed Junction Grounded Junction Ungrounded Junction

Fig. 9.--Construction of a Thermocouple

The ungrounded junction is physically insulated from the sheath by a hard, high-purity ceramic. It is recommended for the measurement of static or flowing corrosive gas and liquid temperatures in critical electrolytic applications.

The grounded junction is welded to the sheath, giving faster response than ungrounded junction type. It is recommended for the measurement of static or flowing corrosive gas and liquid temperatures in high-pressure applications.

The Reference Junction

Let's connect a voltmeter across a chromel-alumel thermocouple and look at the voltage output (see Fig. 10). We would like the voltmeter to read only V1, but two more metallic junctions, J2 and J3, has been created. If J2 and J3 are kept isothermal, the resulting voltmeter reading will be proportional to the temperature difference between J1 and J2. This says that we can't find the temperature at J1 unless the temperature of J2 is found.

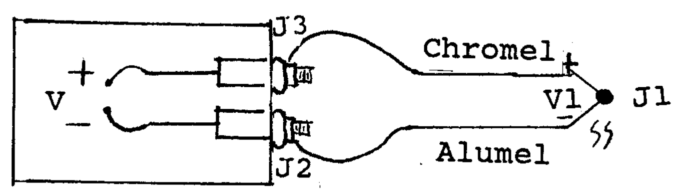


Fig. 10.--Measuring a Junction Temperature with a Voltmeter

Usually the junction J2 is put into an ice bath to force its temperature to be 0°C and establish J2 as the Reference Junction. Now the voltmeter reading is

$$V = f(T1 - T2) = f(T1) \tag{6}$$

The ice point is used by the National Bureau of Standards (NBS) as the fundamental reference point for their thermocouple tables, so we can now look at the NBS tables and directly convert from voltage V to temperature T1. The OMEGA INC. use the same method to establish their thermocouple tables (see Appendix A).

Extension Wires

In a large number of applications, the measuring junctions of a thermocouple system are located at a considerable distance away from the indicating instrument. If the copper wires are used to connect them, the temperature of the cold junction will change widely because of its proximity to the hot junction. In addition a steep temperature gradient will be created at the sensor. Thus it would be very difficult to measure the temperature of the hot junction accurately. If thermocouple wires are used to cover this distance, it will be very expensive, especially for those made of platinum. The way to solve the problems is to use thermocouple extension wires to cover the long distance instead of copper wires or thermocouple wires.

The material of the extension wire is matched to the corresponding thermocouple wire so that no junction voltage exists at the junction of these two wires. When the extension wires are used to connect thermocouple to the measuring instrument, the cold junction will be kept at the ambient temperature. By using the cold junction compensation techniques described in the next chapter, the temperature of the hot junction can accurately be measured. Table 3 lists the material designations of various types of thermocouple extension wires.

TABLE 3

MATERIAL DESIGNATIONS OF THERMOCOUPLE EXTENSION WIRES

Symbol	Alloy Combination	TC Used With	Temp. Range (°C)
JX	Iron/Constantan	J	0 to 200
KX	Chromel/Alumel	K	0 to 200
TX	Copper/Constantan	T	-60 to 100
EX	Chromel/Constantan	E	0 to 200
SX, RX	Cu/Alloy 11	R, S	0 to 150

CHAPTER III

INTERFACE

Introduction

Interfacing is defined as the mating of one component in a system to another to form a totally operational unit. Since a microprocessor standing alone is essentially useless, extensive interfacing is required to build a usable product.

The interfaces can be divided into four basic categories: operational overhead, user-interaction, sensory, and control. Operational overhead interfaces are those interface componenets necessary to make a processor function on the most basic level. This class includes data and address bus drivers, bus receivers, and the clock circuit surrounding the microprocessor. User-interaction interfaces are those circuits required to send and receive user-specified data to and from a processing system. This class includes terminal interfaces, keyboard interfaces, graphic-device interfaces, and voice recognition and synthesis interfaces. Sensory interfaces are those circuits required to monitor events in the real world and send the results to a microprocessor system. This class includes various kinds of data acquisition systems. Control interfaces take the microcomputer's milliampere-level data signals and convert them to the proper voltage and current levels to control the real-world devices. The circuitry needed to drive a stepping motor, to activate a solenoid-controlled valve, or to illuminate a bank of stoplights falls into this category.

By using a MMD-1 mini microcomputer to detect and control the system temperature, three categories of interfaces: sensory, user-interaction (4-digit decimal display), and control, are needed (see Fig. 11). The first one will be described in the next chapter. The other two are discussed in this chapter.

Interfaces to the 4-digit Decimal Display

The LED's on the ports of MMD-1 correspond to the binary codes. For ease of reading, a decimal display is needed. To be compatible with the 10-bit operation of LR-36, the display must have 4 digits.

The display LR8321R is a seven-segment common-anode display. Fig. 12 shows its pin assignments. To protect the LED's of the display, a resistor of 15 ohms must be used between the common pin and +5 V. When any of the other pins is at low voltage, the LED of the corresponding segment will light up. When the pin goes high, the corresponding LED will be off. For example, when the pins: a, b, c, d, e, f, and g, receive 0010010 respectively (the pin d.p. floating), a digit "2" will be displayed.

7447 is a BCD-to-Seven Segment Decoder which is designed to match a common-anode digit display. Appendix C

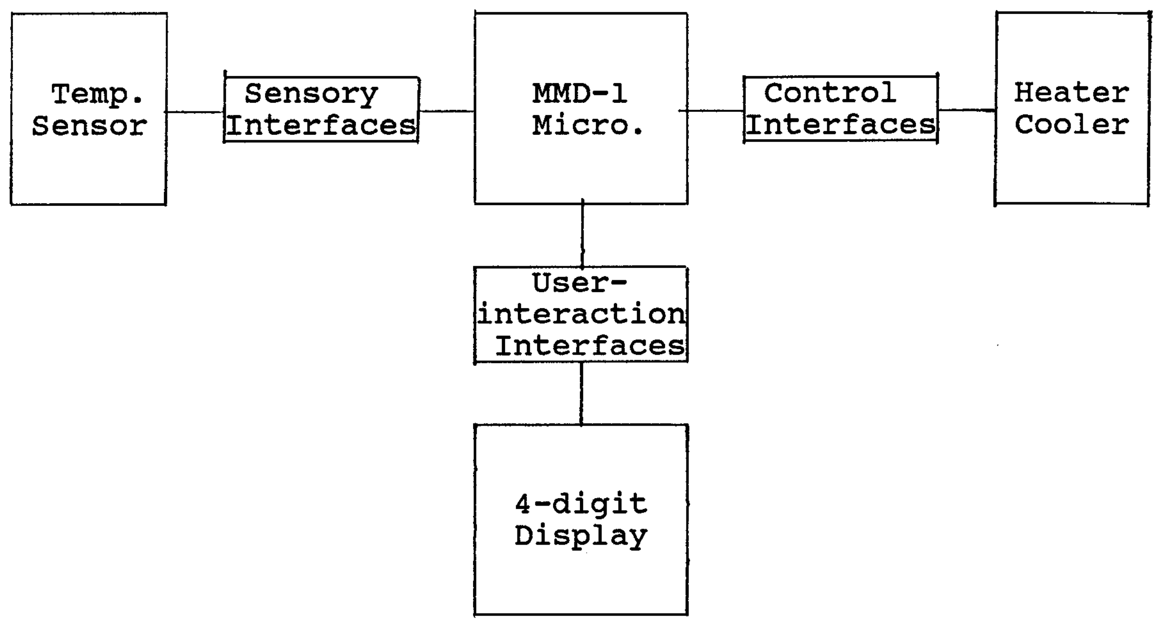


Fig. 11.--Block Diagram of Interfaces

shows the pin configuration, the segment identification and the truth table of 7447. Since output functions 0 through 15 are desired, the blanking input BI/RBO, the ripple-blanking input RBI, and the light test LT must be connected to high.

To use four 7447's to drive the 4-digit LR8321R dispay, the 10-bit binary code of the detected temperature must transform to a 2-byte BCD code before being output to the display. When a microprocessor outputs data to the external devices, the data must be latched from the data bus. To transfer a 16-bit BCD code, four 7475's (Quadruple Bistable Latch) are needed. A latch has a data input (D), a data output (Q), an inverted output ($\overline{Q}$), and an enable input (CLK). A latch allows data to freely pass from the D input to the Q output when the enable is high. When the enable is low, Q will maintain its value.

Fig. 12 shows the interfaces to the 4-digit display. The 4 CLK's of the two 7475's for the High Byte are connected together to the output (pin 10) of one NOR gate with its inputs connected to the $\overline{\text{OUT}}$ and the port 4. The 4 CLK's of the two 7475's for the Low Byte are connected together to the output (pin 13) of another NOR gate with its inputs connected to the $\overline{\text{OUT}}$ and the port 3. Therefore when the instruction codes

323 004

are executed, the data in the accumulator will be output, latched by the High Byte latches, and displayed on the High

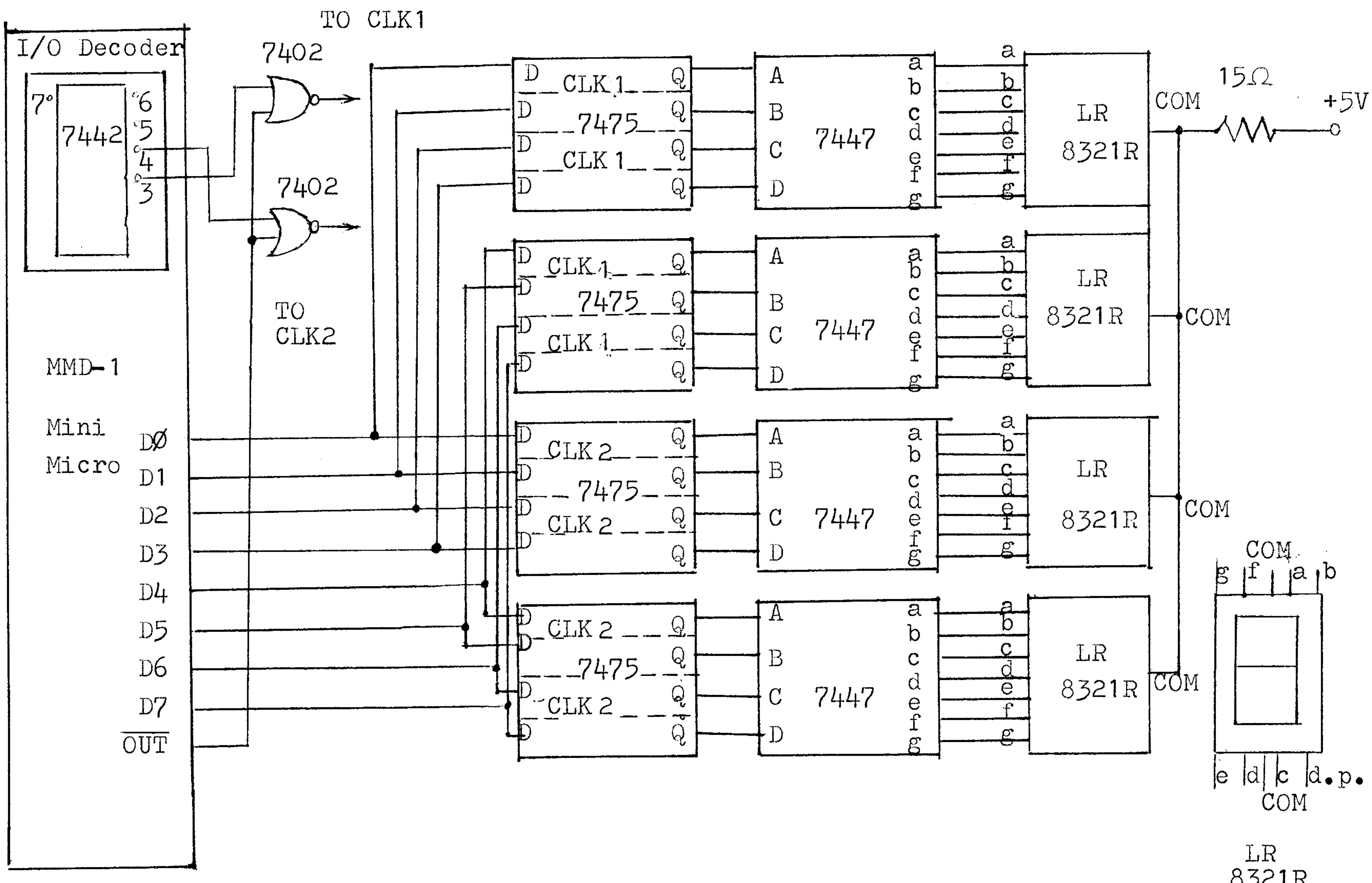


Fig. 12.--Interfaces to the 4-digit Display

Byte display. When the instruction codes

323 003

are executed, the data in the accumulator will be output, latched by the Low Byte latches, and displayed on the Low Byte display.

Interfaces to the Heating/Cooling System

The TTL logic gates can only sink about 16 mA. To turn on the high-power devices, additional amplifying or high power switching circuits are needed. There are many devices that may be used for power switching: buffers, power transistors, Darlington power devices, Thyristors, mechanical relays, solid-state relays, VFET devices, and servoamplifiers. A brief description of each of these devices follows:

1. Buffers are useful in applications requiring high logic fan-outs or low-current peripheral drive currents (such as LED drive current). For example, 7407 can be used as the buffer for LED.

2. Power transistors are designed to handle high current levels. It is important that the drive current to a switching transistor must be high enough. If this current is insufficient, the transistor will limit the load current by dropping voltage across the transistor, thereby destroying it. For example, the maximum power dissipation of 2N2222 is 240 mW, but during the switching transition the transistor goes through a dangerous "burn-

out" zone. When the transistor is sinking only half the current while in the middle of its turn-on transition, it drops half the load voltage across the collector-emitter junction. The worst case for the 2N2222 is 40 V at 400 mA, or 16 W. It is acceptable to swing switching transistors quickly through dangerous zones; but if too low a current is used to drive the transistor, the transistor could get stuck on one of these zones and burn up.

3. The Darlington transistor is a two cascaded transistor with a very high gain and a very high input impedance. For example, the General Electric D40K1 is an NPN Darlington transistor with a minimum gain of 10000. With a gain this high, even a CMOS circuit can control the high-power switching.

4. Thyristor is a generic term for any semiconductor device that exhibits the regenerative switching characteristic of a four layer or p-n-p-n arrangement. The most important member of the thyristor family is the silicon controlled rectifier (SCR). The SCR is a three-terminal, three-junction, four-layer (p-n-p-n) semiconductor device with two power terminals and one control terminal. Essentially the device is a switch, and presents a high forward impedance if no positive signal is applied to the gate. But when a positive signal is applied to the gate, it will go into a low impedance state. Once it is on, it will not turn off even the gate signal is removed. It will turn off, however, when the

anode-cathod current is reduced below a level called the holding current. The ratio of load current to drive current is rarely less than 1000. A gate current of 50 mA can switch 50 A or more. Because of this characteristic, SCR has found wide use in heavy-load ac switch circuits. When used with an ac signal, the SCR permits only the positive half-cycle current to pass from anode to cathod.

The TRIAC is an extensively used device in ac line control. It can be thought of as a pair of SCR connected in reverse parallel with the gates tightened together. When the gate is triggered, it will permit anode-cathod conduction with either polarity. Most TRIAC's are available in ratings of less than 40 A and at voltage up to 600 V.

5. Mechanical relays are used in conventional controls in which low current toggle switches must control large loads. Its biggest problem is contact arcing. This may cause the reeds to be welded together. Another problem comes from the back-emf voltage spike generated when the relay is turned off. Because of the mechanical contact operation, it can not be applied for high-frequency switching.

6. Solid-state relays (SSR's) are designed to be nearly direct, one-package replacements for conventional mechanical relays. In ac applications the most commonly used device is the TRIAC, and in dc applications the transistor is used. Most SSR's are electrically isolated

between the control circuit and the ac load circuit; this is commonly achieved by optocouplers. In addition, its input is usually compatible with digital logic devices. Another feature that is common to ac application is the provision of zero voltage switching. The OMEGA SSR is rated with 25 A. Fig. 13 shows the block diagram of an SSR.

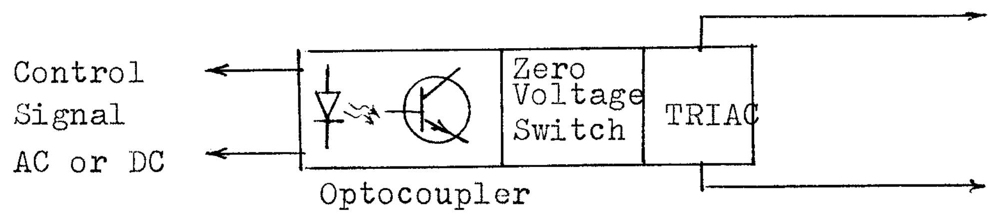


Fig. 13.--Diagram of an SSR

7. VFET[3] is a MOS device employing a V-shaped semi-conductor channel. It can switch moderate and even high power loads. Some of the VFET important characteristics include high-frequency operation, low input current and the ability to be turned off at will.

8. Servoamplifiers are simply linear dc amplifiers that accurately amplify an input voltage to drive a variable-voltage peripheral.

Fig. 14 shows the interfaces to the Heating/Cooling system. The control signal for heating is from bit 6 of the port 0. The control signal for cooling is from bit 7 of the port 0. The heating system for the low-temperature

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[3]Bruce A. Artwick, Microcomputer Interfacing, Prentice-Hall Inc., 1980, P. 233

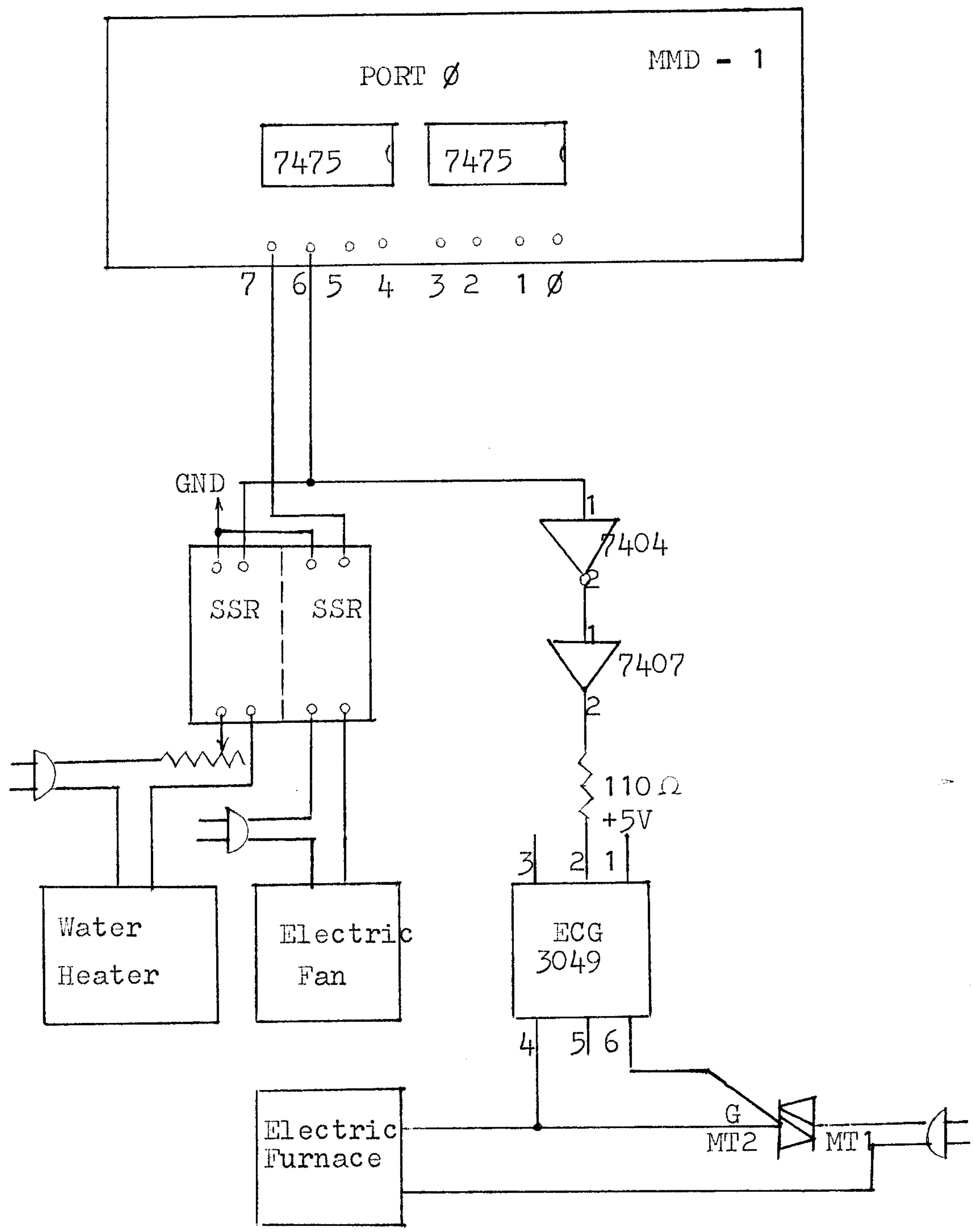

Fig. 14.--Interfaces to the Heating/Cooling System

test is a water heater with a rated power of 250 W. The cooling system is an electric fan with a rated power of 14 W. The SSR's available can switch a 1.5 A load. Therefore bit 6 is directly connected to the input of one SSR to control the water heater and bit 7 is directly connected to the input of the other SSR to control the electric fan. The heating system for the high-temperature test is a furnace with a rated voltage of 120 V and a rated current of 8.8 A. Therefore building a high-power SSR is necessary.

ECG5677 is a TRIAC with the forward current of 15 A, the peak reverse voltage of 600 V, the gate trigger current of 50 mA and the gate trigger voltage of 2.5 V. ECG3049 is an isolator with the internal circuit as shown in Fig. 15.

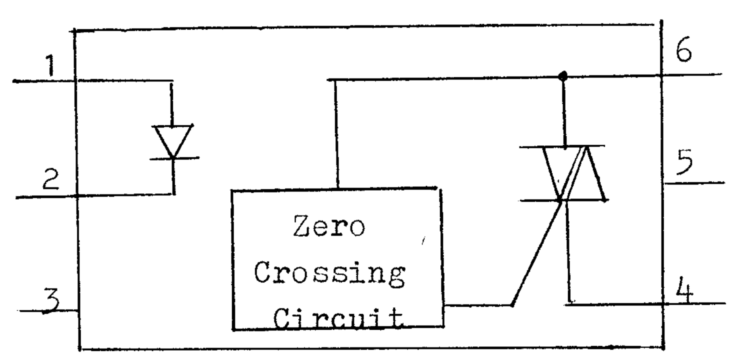

Fig. 15.--Internal Circuit of an ECG 3049

Zero Crossing Circuit detects when the ac voltage crosses the zero axis and produces an output pulse of approximately 100-usec duration to trigger the thyristor.

This circuit is necessary because experience has shown that thyristors will develop the least amount of electromagnetic interference, if in ac applications the thyristor is turned on at the earliest possible instant after the applied voltage crosses the zero axis.

Because SCR's and TRIAC's usually control large loads with large voltage swings, it is difficult and dangerous to connect an SCR or TRIAC switching circuit directly to digital logic circuitry. Therefore an optocoupler is needed. The 110 ohm resistor is needed to protect the LED inside the ECG3049. The buffer 7407 is used to drive the LED. When bit 6 of the port 0 is high, the LED is lit up, causing the TRIAC inside the ECG3049 triggered. As the TRIAC inside the ECG3049 is triggered, the ECG5677 is also triggered and the furnace is actuated.

CHAPTER IV

DATA ACQUISITION SYSTEM

Introduction

A thermocouple is an example of nonlinear sensor. The relation of its output voltage to the measured temperature is very complex (see Fig. 16). In Chapter V, a software-modification technique is used to compensate for the nonlinearity. Therefore only the data acquisition systems that are computer controlled are discussed in this chapter.

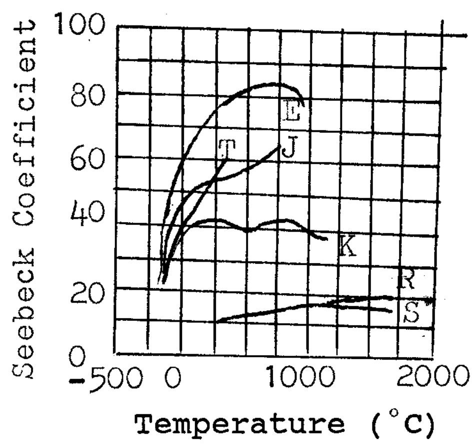

Fig. 16.--Seebeck Coefficient Versus Temperature

Cold Junction Compensation

To measure the temperature of the hot junction accurately, the cold junction (refernce junction) should be kept at constant temperature. Usually it is put into an ice-water bath to keep it at a constant 0°C. Because ice baths are often inconvenient to maintain and are not always practical, several other methods are employed. A chamber cooled by thermoelectric cooling elements can be used to maintain a 0°C environment. Two temperature-controlled ovens[4] can be used to simulate the ice-point reference temperature. Microprocessor-operated devices can use software compensation techniques to adjust for the reference junction temperature.

In the following section, the offset technique is used to accomplish the compensation when the cold junction is at 25°C. In this section, an electrical bridge is employed to accomplish the compensation near 25°C.

Consider the circuit shown in Fig. 17. When the ambient temperature rises (or goes down) by 1°C, the output

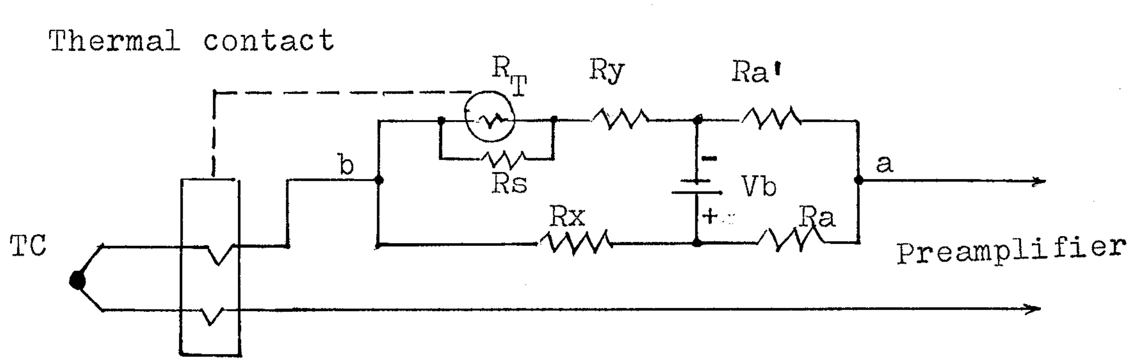

Fig. 17.--Cold Junction Compensation Bridge

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[4] Robert G. Seippel, Transducers, Sensors, and Detectors, p. 271.

voltage of the K-type thermocouple will decrease (or increase) by 41 uV. If the voltage Vab increases (or decreases) by 41 uV correspondingly, the effect because of change of ambient temperature will be compensated.

Vb is a mercury battery giving a constant output voltage of 1.35 V. R_T is a thermistor with a resistance of 392 ohms at 25°C. It's a temperature-sensive resistance which is electrically isolated but thermally contacted with the cold junction of the thermocouple. The resistor Rs shunted with R_T has a resistance of 392 ohms which is the same as that the thermistor has at 25°C. This resistor Rs is used to make the performance of the thermistor more linear relative to the temperature change. To realize this, consider Fig. 18.

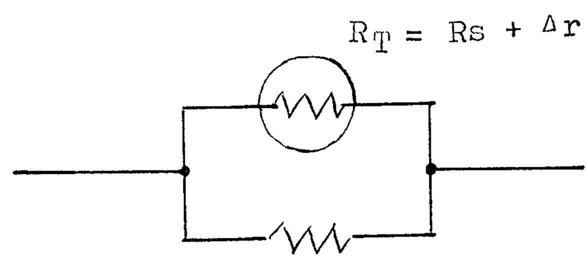


Fig. 18.--Linearity-improving Circuit for a Thermistor

Suppose the thermistor has a resistance change Δr due to a temperature change ΔT, the overall resistance

$$Rs//R_T = \frac{Rs(Rs+\Delta r)}{Rs+Rs+\Delta r} = \frac{Rs}{2}\left(1+\frac{\Delta r}{Rs}\right)\left(1+\frac{\Delta r}{2Rs}\right)^{-1}$$

$$= \frac{Rs}{2}\left(1+\frac{\Delta r}{Rs}\right)\left(1-\frac{\Delta r}{2Rs}+\frac{(-1)(-2)}{2!}\left(\frac{\Delta r}{2Rs}\right)^2-\cdots\right)$$

$$\doteqdot \frac{Rs}{2}\left(1+\frac{\Delta r}{2Rs}\right) \qquad \left(\because \frac{\Delta r}{Rs} \ll 1\right) \tag{7}$$

We find that the overall resistance has become Rs/2 and the overall temperature coefficient has decreased to half the original one. Therefore the overall temperature effect is more linear.

Let's design the other parts of the electrical bridge. First we assume the bridge is in balance at 25 °C and Ra'= a·Ra. The bridge near 25°C is transformed to the Thevenin's equivalent circuit as shown in Fig. 19.

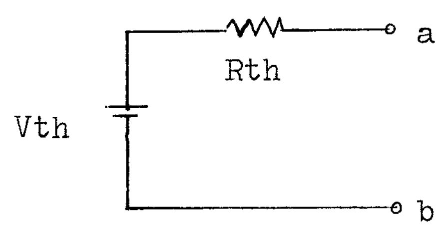


Fig. 19.--Thevenin's Equivalent Circuit of a Cold Junction Compensation Bridge

Here $Rth = 2(Ra /\!/ Ra') = (2a \cdot Ra)/(a+1)$ (8)

$$Vth = \frac{a}{1+a}Vb - \frac{aRx + \Delta R}{(1+a)Rx + \Delta R} Vb$$

$$= \frac{a}{1+a}Vb - \frac{a}{1+a}Vb\left(1+\frac{\Delta R}{aRx}\right)\left(1+\frac{\Delta R}{(1+a)Rx}\right)^{-1}$$

$$\doteqdot \frac{-Vb}{(1+a)^2}\,\frac{\Delta R}{Rx} \qquad \left(\because \frac{\Delta R}{Rx} \ll 1\right) \tag{9}$$

By experimental measurement, we find that the thermistor changes resistance from 405 ohms at 22.8°C to 376 ohms at 28.2°C. On the average, when the ambient temperature rises, the thermistor decreases resistance in 5.37 ohms/°C. Under this condition the ΔR in Eq. (9) equals to -5.37/4 ohms. On the other hand, Vth should be +41 uV/°C in order to accomplish the cold junction compensation for the K-type thermocouple. If a = 9,

$$Rx = (5.37/4)(1.35/100)(1/0.000041) = 442 \text{ ohms} \quad (10)$$

$$Ry = (442)(9)-196 = 3782 \text{ ohms} \quad (11)$$

$$Ra = Rx = 442 \text{ ohms} \quad (12)$$

$$Ra' = 9Ra = 3978 \text{ ohms.} \quad (13)$$

If a = 1, we get Rx = 11050 ohms, and Rth = 11050 ohms. In this way, loading will occur when the bridge is connected to the preamplifier in next section. If a = 99, Rx = 4.42 ohms. The loading is small but very accurate resistors must be employed.

Amplification of the Thermocouple Output Voltage

The output voltage of a K-type thermocouple is near 40 uV/°C. The resolution of the LR-36 A/D converter is

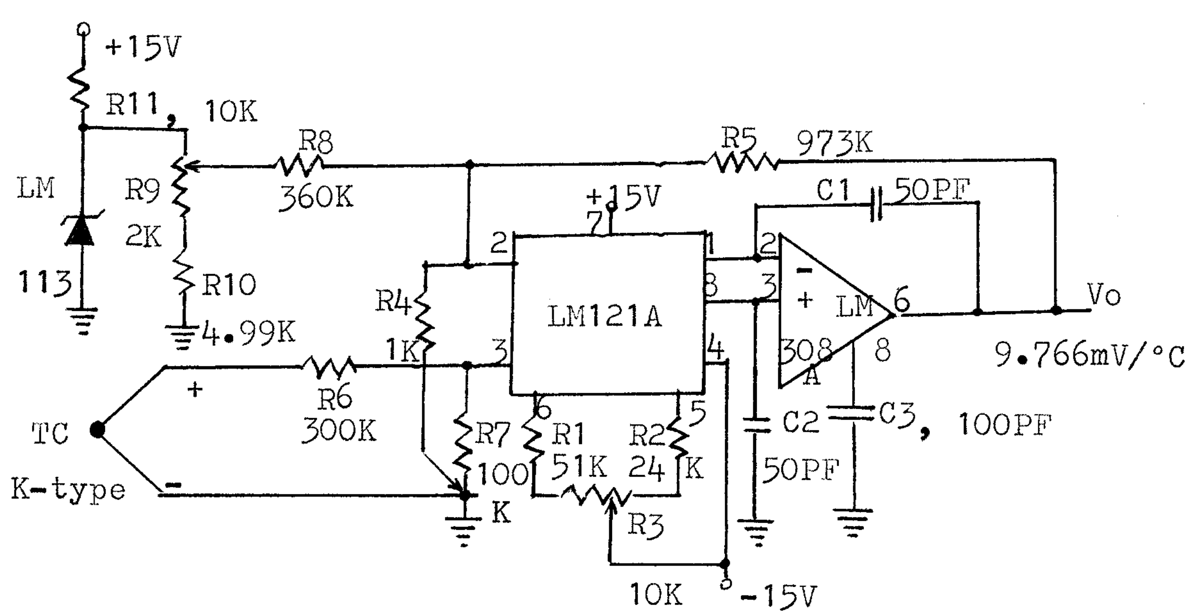


Fig. 20.--Precision Amplifier for the K-type Thermocouple

9.765625 mV when 10 V is used as the reference voltage. The amplifier in Fig. 20 was designed to have the output of 9.767 mV/°C. Thus the least significant bit corresponds to 1°C. The LM121A is a precision preamplifier with extremely low drift, low bias current, and high CMRR. These characteristics qualify it for use with almost any precision dc circuit. The LM308A is a precision amplifier with low input current. Its offset voltage is extremly low, making it possible to eliminate offset adjustments in most cases, and obtain a performance approaching that of chopper stablized amplifiers. The LM113 is a temperature compensated, low voltage reference diode with 1.220 V as the breakdown voltage.

The LM308A together with LM121A functions as an OP amplifier. Pin 2 of LM121A would be the inverting input of this amplifier because its corresponding output Pin 1 is connected to the inverting input of the LM308A. Similarly, Pin 3 of the LM121A could be regarded as the noninverting input of the overall amplifier. Pin 6 of the LM308A is still the output of the overall amplifier. R1, R2, and R3 provide the offset adjustments for the overall amplifier. C1 and C2 are for freqency compensation. C3 is for rejection of power supply noise. R6 and R7 form a voltage divider to let only 1/4 of the output voltage of a K-type thermocouple be amplified. The output voltage of a K-type thermocouple is counted as 40 uV/°C. Therefore 10 uV/°C is input to the noninverting input of the amplifier.

Fig. 21 is the simplified circuit of Fig. 20. There are two voltage sources in this circuit. Using the Superposition Theorem we can separate the output Vo into two parts. One is due to the thermocouple output (see Fig. 22). The other is due to the breakdown voltage of the LM113.

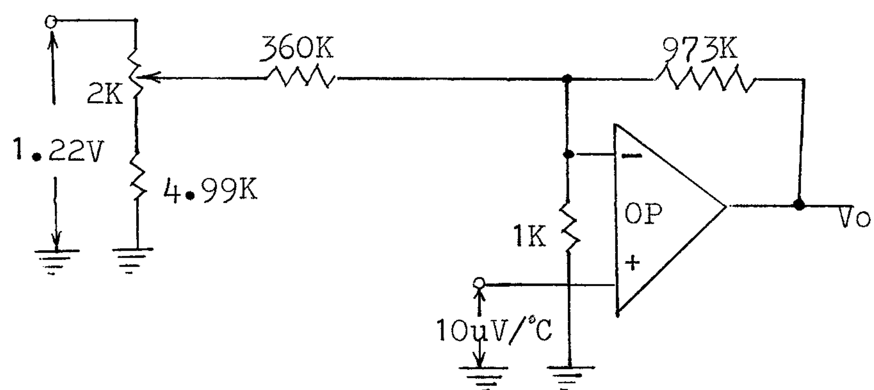


Fig. 21.--Simplified Circuit of Fig. 20

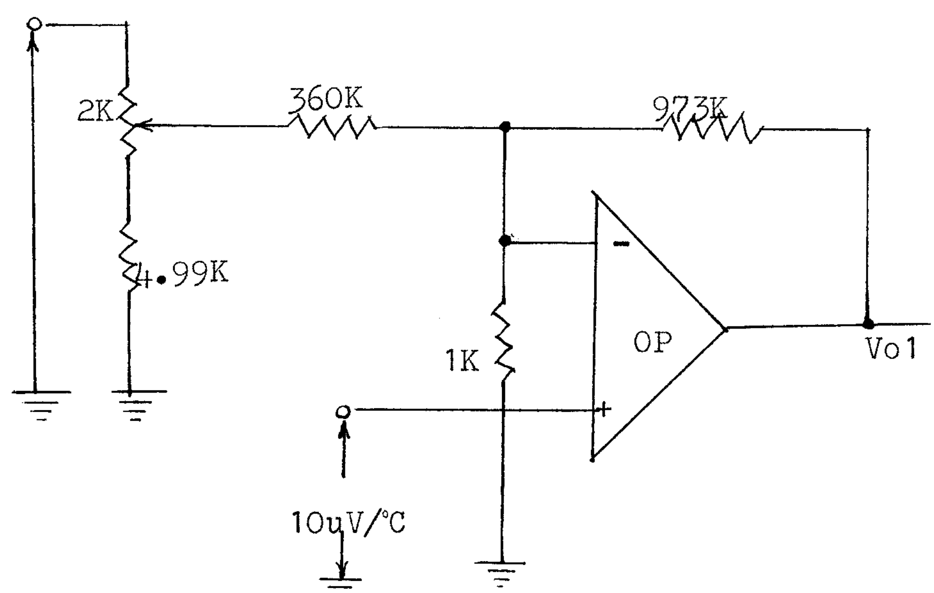


Fig. 22.--The Amplifier Output Due to the Thermocouple

Vol is calculated as following:

$$Vo1 = 10\times10^{-6}((1+(973/1/\!/360)) = 9.767\times10^{-3} V/^{\circ}C = 9.767\ mV/^{\circ}C \quad (14)$$

The output due to the breakdown voltage of the LM113 has two functions. One is to cancel the offset effect of R1, R2, and R3. The other is for cold junction compensation at 25°C.

To make the output of this amplifier matched with an LR-36 A/D converter, that is to say, Vo = 9.767 mV/°C, and to do the cold junction compensation at 25°C, we need the following procedures:

1. Adjust R3 to obtain an output of 2.97 V with both the LM113 and the thermocouple short-circuited. Then the output would be 9.767 mV/°K with the LM113 short-circuited and the thermocouple in normal operation.

2. With the thermocouple short-circuited and the LM113 in normal operation, adjust R9 to obtain an output of 244 mV (= 25×9.767 mV). Now the cold junction compensation at 25 °C has been done and the output will correspond to the temperature of the hot junction in 9.767 mV/°C during normal operation.

Analog Filter

Fig. 23 shows an analog filter. The output Vm of the first OP amplifier equals to Vi. The high-frequency components of Vm go through C4 and enter ground by C5. Therefore the high-frequency components of Vn are very small. This causes the high-frequency noise of Vi to by-pass by C6. As a result, the high-frequency noises that appear in Vout have been dramatically reduced.

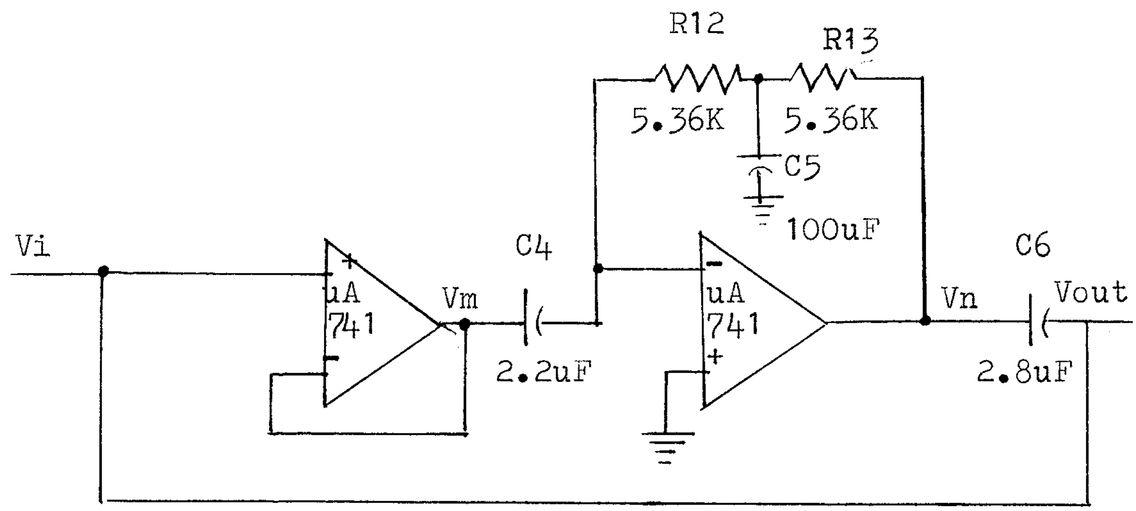


Fig. 23.--Analog Filter

The filter shown in Fig. 23 is an active filter. The advantages of active filters over passive filters are:

1. They use resistors and capacitors that behave more ideally than do inductors.

2. They are relatively inexpensive.

3. They can provide gain in the passband and seldom have any severe loss (as do passive filters).

4. The use of OP amplifiers provides isolation from input to output. This allows active filters to be easily cascaded to obtain higher performance.

5. Very low frequency filters can be constructed using modest value components.

6. Active filters are small and light.

Active filters do have some disadvantages. They require a power supply and are limited in maximum frequency to a few MHz.

Position of the Set-point

The amplified signal of a temperature sensor must be compared with the set-point signal in order to control the system temperature. Traditionally this is accomplished by hardware. For example, a millivolt potentiometer is used as the set-point for thermocouples. If an accurate control is needed, the potentiometer must be very accurately calibrated. That would be very costly. After comparison with the set-point, a differential amplifier is also needed to match the A/D converter, which should be in bipolar operation. Fig. 2 shows this traditional control system.

In my experiment, I tried a software approach. Fig. 3 shows this type of control system. The comparison with the set-point is done inside the computer. The amplified signal of sensor goes straight through the Sample/Hold, the A/D converter, then enters the computer. Some software has been prepared to modify the 10-bit binary code output from the A/D converter. After modification, a 2-byte, 16-bit binary code of the hot junction temperature in $^{\circ}C$ is obtained. Then it will be compared with the set-point to accomplish the temperature control.

Note that with the software approach, we are able to accomplish an accurate temperature control without the precision potentiometer, the differential amplifier, and the bipolar A/D converter. The costs are the execution time and the software preparation time. The response time of a thermocouple is 4-5 second. Usually the time delay due to software modification and comparison is a few milliseconds. Therefore it has little effect on the response time. The details about software modification will be described in Chapter V.

Sample/Hold

Suppose that it is desired to covert an analog signal into its correspondent digital form through an A/D converter. If the signal varies quite fast with respect to time, the value of the analog signal might be changed during the A/D conversion process. But it is highly desirable

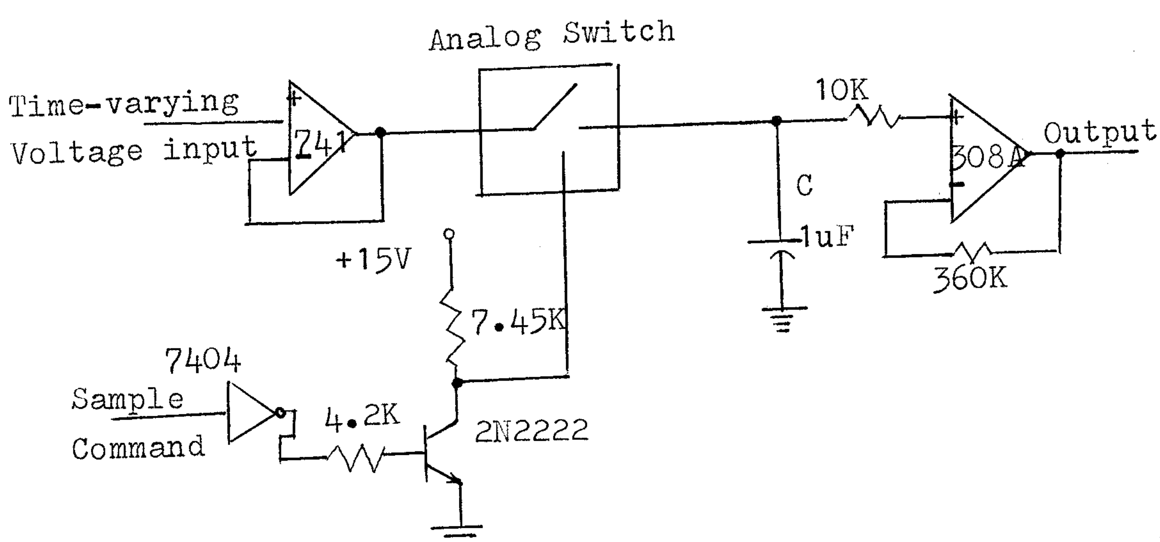


Fig. 24.--A Typical Sample/Hold Circuit

for the analog signal to remain constant during the conversion process. Otherwise the digital output will get mixed up. To solve this problem, a Sample/Hold circuit is needed before the A/D converter.

Usually a circuit like Fig. 24 is employed. When the sample command is received, the analog switch is turned on. The analog signal enters and is stored in the capacitor. When the sample command is removed, the capacitor holds the last instantaneous voltage value sampled from the input. The output will follow this value during the holding period.

In the sampling period, the holding capacitor is charged with a time constant (Ro + Rds(on))C, where Ro is the very small output resistance of the input voltage follower and Rds(on) is the ON resistance of the analog switch. The acquisition time is defined as the time it takes for the capacitor to charge from one level of holding voltage to the new value of input voltage after the switch has been closed. Usually the acquisition time is set to be equal to 10(Ro+Rds(on))C. In an ideal case, the acquisition time should be zero in order to avoid any effect due to variation of the analog signal. For this reason the analog switch 4066 with very low Rds(on) is employed.

In the absence of the sample command, the switch is turned off and the capacitor is isolated from any load through the output OP AMP. Thus it will hold the voltage impressed on it. It is recommended that a capacitor with polycarbonate, polyethylene, polystyrene, Mylar, or Teflon dielectric be used. Most other capacitors do not retain the stored voltage, due to a polarization phenomenon which causes the stored voltage to decay with a time constant of several seconds. Even if the polarization effects do not occur, the off current of the switch and the bias current of the OP AMP will flow through the capacitor. As a result, the voltage of the capacitor will drift during the holding period. To elimate the drift rate, the 4066 analog switch (with the typical off current 0.01 nA) and the LM-308A OP AMP (with the bias current 3.0 nA) are used.

The larger the value of the capacitance, the smaller is the drift in the hold voltage. However, the larger the capacitance, the longer is the acquisition time. Therefore the value of the capacitance must be chosen as a compromise between the two conflicting requirements. When the capacitor is larger than 0.05 uF, an isolation resistor of approximately 10 KΩ should be included between the capacitor and the (+) input of the output OP AMP to protect the OP AMP in case the output is short-circuited or the power supplies are abruptly shut down while the capacitor is charged.

Fig. 25 shows an improved Sample/Hold circuit. Note that an external complementary emitter follower is used to charge (or discharge) the capacitor extremely rapidly. When the switch is on, if Vo < Vi, a positive high voltage will appear at the output of the uA741. This

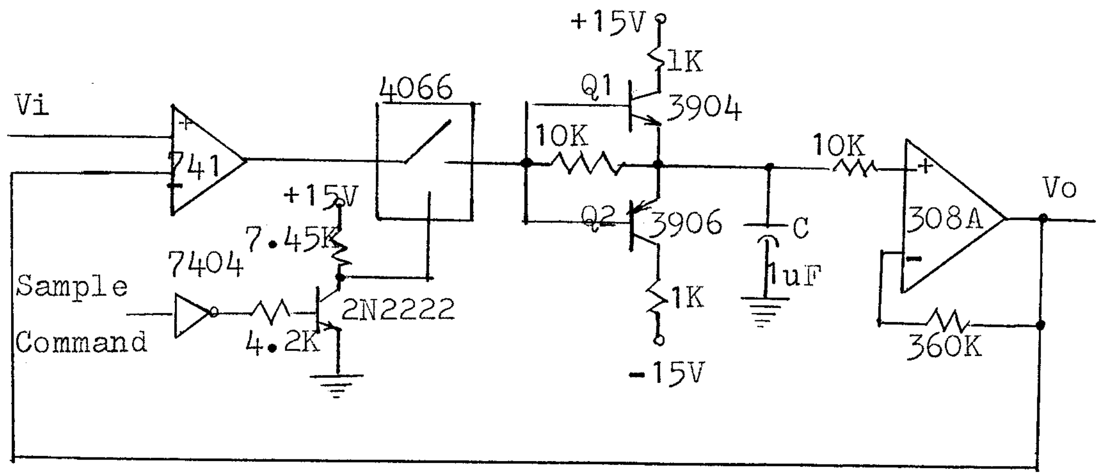


Fig. 25.--Improved Sample/Hold Circuit

causes Q1 to be on and charge the capacitor with large current. As a result, the capacitor is charged to the value of Vi in a very short time. If Vo > Vi, a negative voltage appears at the output of the uA741. This causes Q2 to be on and discharge the capacitor with a large current. As a result, the capacitor is discharged to the value of Vi in a very short time. This circuit ensures that Vo = Vi during the sampling interval. Since the sample command is from the bit 7 of the port 1 of the MMD-1 microcomputer, the operation of the Sample/Hold circuit is controlled by the computer.

A/D Conversion

Most sensors converting physical phenomena to electrical signals develop an analog voltage. In digital computers, the data format for computation or transmission is often digital, usually because of requirements regarding accuracy or data-handling speed. Processing data or computations with analog equipments degrades the accuracy of the data somewhat each time an operation is performed. Also, in general, the greater the required operating speed, the lower is the analog equipment accuracy. With digital techniques, however, the data accuracy is not degraded during each operation. To accomplish an accurate temperature control, a digital microcomputer is used. Therefore an A/D converter is needed to convert the analog signals into its digital forms so that they could be input into the microcomputer.

The LR-36 A/D converter outboard uses the AD7570 as the A/D converter. Its internal circuits are shown in Appendix D. The AD7570 is a monolithic CMOS A/D converter which uses the successive approximations technique to provide up to 10 bits of digital data in a serial and parallel format. The successive approximations technique has the advantage to perform a fast and accurate conversion. The details about this technique are also described in Appendix D. The LR-36 can be used in either unipolar or bipolar operation. Table 4 is the conversion table in unipolar operation. FS is full scale, i.e., -VREF. For 10-bit operation, 1 LSB equals (-VREF)(2^{-10}). Table 5 is the conversion table in bipolar operation. For 10-bit operation, 1 LSB equals (-VREF)(2^{-9}).

Fig. 26 shows the interconnection between the LR-36 A/D converter and the MMD-1 mini microcomputer. The 10-bit

TABLE 4

UNIPOLAR OPERATION OF THE LR-36

Analog Input (AIN)	Digital Output Code MSB LSB
FS - 1 LSB	1 1 1 1 1 1 1 1 1 1
FS - 2 LSB	1 1 1 1 1 1 1 1 1 0
3/4 LSB	1 1 0 0 0 0 0 0 0 0
1/2 FS + 1 LSB	1 0 0 0 0 0 0 0 0 1
1/2 FS	1 0 0 0 0 0 0 0 0 0
1/2 FS - 1 LSB	0 1 1 1 1 1 1 1 1 1
1/4 FS	0 1 0 0 0 0 0 0 0 0
1 LSB	0 0 0 0 0 0 0 0 0 1
0	0 0 0 0 0 0 0 0 0 0

TABLE 5

BIPOLAR OPERATION OF THE LR-36

Analog Input (AIN)	Digital Output Code MSB LSB
+(FS - 1 LSB)	1 1 1 1 1 1 1 1 1 1
+(FS - 2 LSB)	1 1 1 1 1 1 1 1 1 0
+(1/2 FS)	1 1 0 0 0 0 0 0 0 0
+(1 LSB)	1 0 0 0 0 0 0 0 0 1
0	1 0 0 0 0 0 0 0 0 0
-(1 LSB)	0 1 1 1 1 1 1 1 1 1
-(1/2 FS)	0 1 0 0 0 0 0 0 0 0
-(FS - 1LSB)	0 0 0 0 0 0 0 0 0 1
-FS	0 0 0 0 0 0 0 0 0 0

operation is needed because the controlled temperature range is from 0 to 900 °C. Therefore $\overline{SC8}$ is kept at high. Otherwise the conversion would stop after 8 bits. Unipolar operation is used because the comparison with the set-point occurs inside the computer. The reference voltage is 10 V because the breakdown voltage for the 1N961 is 10 V. As the result, the LSB corresponds to 9.765625 mV.

The handshaking software between the LR-36 and the MMD-1 is listed below:

ADDRESS	OP CODE	MNEMONIC	COMMENT
030 121	323	OUT	/START A/D CONVERSION
030 122	005	005	
030 123	333	IN	/CHECK CONVERSION STATUS
030 124	005	005	
030 125	346	ANI	/BIT 5 FOR $\overline{BUSY}$
030 126	040	040	
030 127	312	JZ	/IF IN CONVERSION, CHECK
030 130	123	123	/AGAIN
030 131	030	030	
030 132	333	IN	/IF COMPLETE, READ HIGH
030 133	006	006	/BYTE TO ACCUMULATOR
030 134	346	ANI	/MASK OUT THE OTHER BITS
030 135	003	003	/EXCEPT DB9 AND DB8
030 136	127	MOV D,A	/STORE DB9 AND DB8 IN D
030 137	333	IN	/READ LOW BYTE
030 140	007	007	
030 141	137	MOV E,A	/STORE LOW BYTE IN E

After execution of this program, DB9 and DB8 are stored in the D register and DB7 through DB0 are stored in E register.

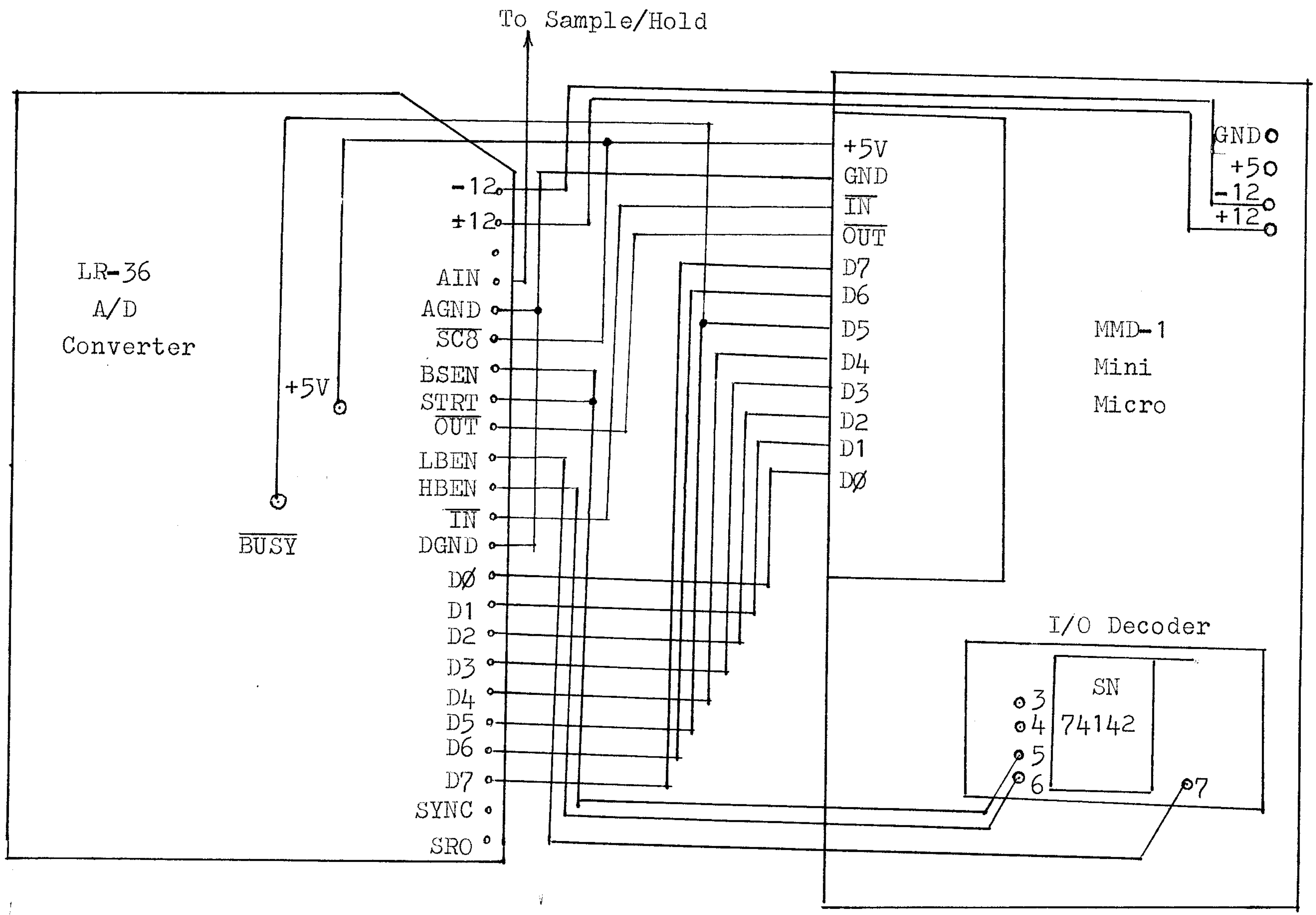


Fig. 26.--Interconnection Between the LR-36 and the MMD-1

CHAPTER V

CONTROL SOFTWARE

Introduction

This chapter deals with the software required to control the temperature to within ± 3°C of the set-point. It includes displaying the set-point, controlling the Sample/Hold, handshaking between an A/D converter and a microprocessor, warning for dangerous temperatures, modifying data for the K-type thermocouple, displaying the detected temperature, and controlling the Heating/Cooling System.

MMD-1 Mini Microcomputer

The MMD-1 is a complete educational and engineering microcomputer using an 8080A microprocessor. It features direct keyboard entry of data and instructions, status and data indication via LED's, immediate access to buffered input/output busses and a convenient breadboarding socket. Its specifications are listed in Appendix E. The M/I board expands the MMD-1 by providing additional memory, 1K PROM and 2K RAM, a teletype interface and mass storage of data via the audio recorder interface. The details about using the MMD-1 mini microcomputer together with the M/I board are available from their manuals in the Micro. Lab..

Data Modification for a K-type Thermocouple

The precision amplifier described in Chapter IV is designed to have the output of 9.766 mV/°C in response to the input of 40 uV/°C. Because of the 10-bit operation of the LR-36 A/D converter, its LSB corresponds to a thermocouple voltage of 40 uV. If a thermocouple has a contant increment of 40 uV/°C, the output of the LR-36 will exactly be the binary code of the detected temperature. However, the K-type thermocouple is a nonlinear sensor with an output swing around the value of 40 uV/°C. That is to say it has an output of 40 uV/°C at some temperature range, 41 uV/°C at another range, and 42 uV/°C at still another range. Therefore the output of the LR-36 must be modified in order to represent exactly the detected temperature. A software modification technique is described below.

First determine the increment of the K-type thermocouple voltage per °C rise from 0°C through 900°C (see Appendix B). Then select the modifying points in the following way:

1. Using 40 uV as reference, count the accumulated excessive voltage Va beginning from 0°C through 900°C. The original value of Va is set to be 0.

2. If the increment Vic of some interval differs from 40 uV, add to Va the number which is equal to Vic minus 40 uV.

3. When Va = 19 uV, select the end temperature of the last interval as the first modifying point.

4. Select the end temperature of the last interval as the successive modifying point every time when Va increases by another more 40 uV.

Table 6 lists the selected modifying points, its accumulated excessive voltage Va, the over-counted temperature Toc, the corresponding output Tad of the LR-36 (both Decimal and Octal), and the corresponding modification number Tm. Using this table, we can modify the output of the LR-36 to represent exactly the detected temperature. For example, if the output of the LR-36 is between two continuous modifying points, namely Tad1 < Tad < Tad2, then the detected temperature is obtained by subtracting Tm2 from Tad.

Flow Chart of the Control Software

Fig. 27 shows the flow chart of the control software. At first, the set-point saved at the addresses 003 001 and 003 000 is displayed for 5 secs. Then the display is cleared for 1 sec. After that, the amplified thermocouple voltage is sampled for .25 ms. Because of the large charging (or discharging) current of the complementary transistors, the holding capacitor will be charged (or discharged) to the amplified thermocouple voltage in this period. Then the sample command is removed and the capacitor holds the voltage for A/D conversion.

To start A/D conversion, the microprocessor outputs a pulse to the STRT of the AD7570 by executing the instruc-

TABLE 6

DATA-MODIFYING POINTS FOR A K-TYPE THERMOCOUPLE

Selected Point (°C)	Va (uV)	Tm(= Toc) (°C)	Tad(Decimal) (°C)	Tad(Octal) (°C)
047	0019	00	047	000 057
076	0059	01	077	000 115
103	0099	02	105	000 151
226	0139	03	229	000 345
279	0179	04	283	001 033
308	0219	05	313	001 071
332	0259	06	338	001 122
354	0299	07	361	001 151
374	0339	08	382	001 176
393	0379	09	402	001 222
411	0419	10	421	001 245
428	0459	11	439	001 267
444	0499	12	456	001 310
461	0539	13	474	001 332
476	0579	14	490	001 352
492	0619	15	507	001 373
507	0659	16	523	002 013
522	0699	17	539	002 033
537	0739	18	555	002 053
553	0779	19	572	002 074
568	0819	20	588	002 114
583	0859	21	604	002 134
599	0899	22	621	002 155
615	0939	23	638	002 176
632	0979	24	656	002 220
649	1019	25	674	002 242
667	1059	26	693	002 265
686	1099	27	713	002 311
706	1139	28	734	002 336
728	1179	29	757	002 365
753	1219	30	783	003 017
784	1259	31	815	003 057
826	1299	32	858	003 132
900	1325	33	933	003 245

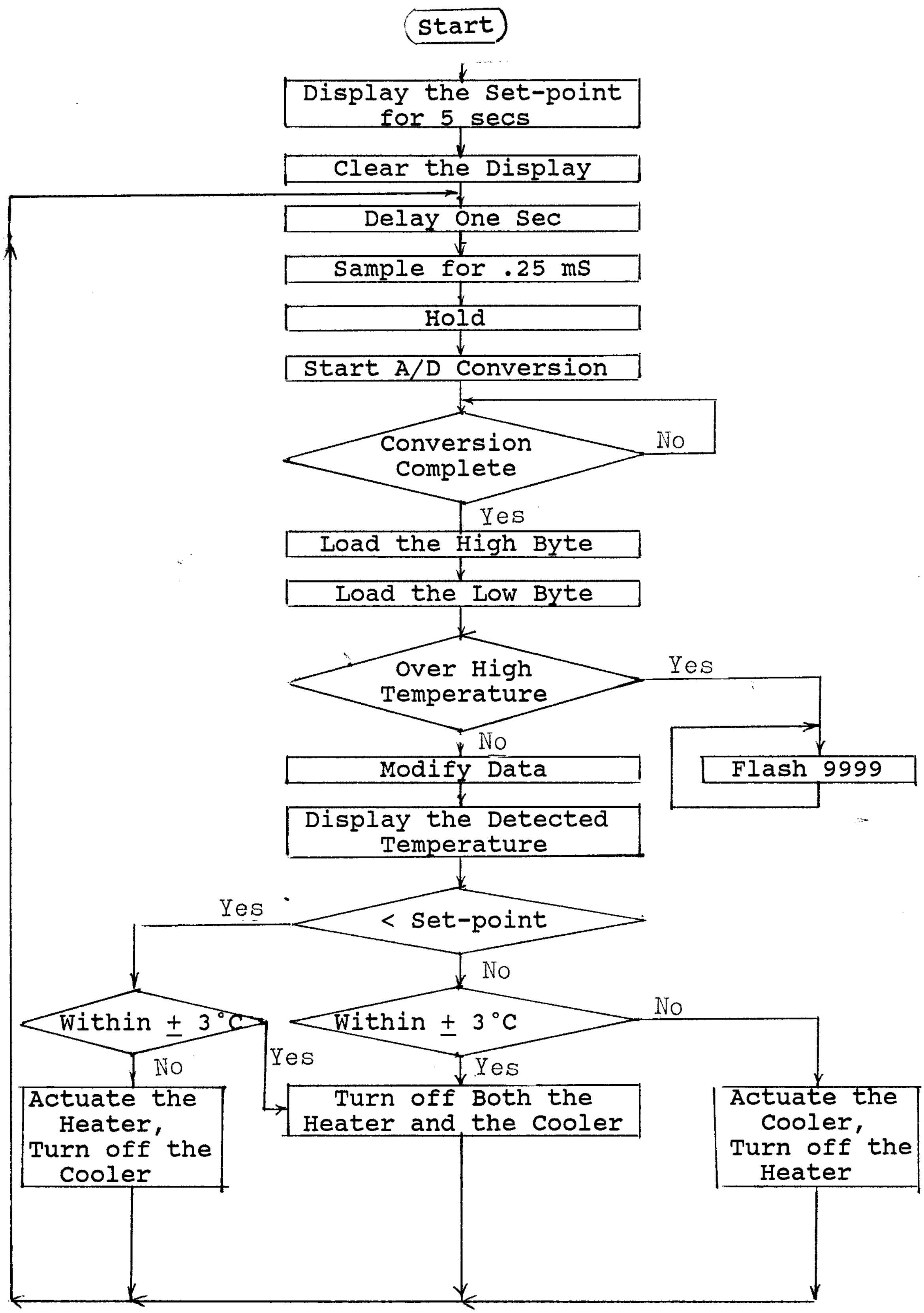


Fig. 27.--Flow Chart of the Control Software

tion codes "OUT 005". Note that the output port 005 is connected to the STRT of the LR-36 board. Then the microprocessor checks the status of conversion by checking the $\overline{\text{BUSY}}$ of the LR-36, which is connected to Bit 5 of the input port 005. If $\overline{\text{BUSY}}$ is in the low state, that means the conversion is in progress, the microprocessor will then continue checking the status. If $\overline{\text{BUSY}}$ is in the high state, that means the conversion is complete, the digital outputs, first the High Byte then the Low Byte, will be input to the accumulator then saved in the D and E register respectively. This process is called the Handshaking between the A/D and the Micro. For the High Byte, the remaining bits except the two least significant bits, those are DB9 and DB8, must be masked before being saved in the D and E register.

As explained before, the digital output of the A/D converter has to be modified in order to represent the exact detected temperature. This is accomplished by the software-modifying technique which was described in the preceding section. The modified data are saved at the addresses 003 201 and 003 200. Then they are transformed into the corresponding 2-byte BCD codes and displayed on the 4-digit display by a subroutine named DDSPLY. If the detected temperature is over 900°C, the display will flash "9999".

The detected temperature, that is the modified code, must be compared to the set-point temperature in order to control the system temperature. The tolerance is set to be

$\pm$ 3°C of the set-point. This tolerance is selected because of the response time of the thermocouple (about 5 secs), the error due to the A/D converter, and the error due to the other circuits. The response time of a thermocouple makes the detected temperature different from the present temperature. I assume a difference of 1°C. The A/D converter has an error of 1 LSB after calibration. The error due to the other circuits is also taken to be 1 LSB. Therefore a tolerance of $\pm$ 3°C is selected. When the detected temperature is lower than the set-point by more than 3°C, the bit 6 of the port 0 will be set to high and the bit 7 of the port 0 be set to low. This will turn on both the furnace and the water heater and turn off the electric fan. As a result, the system temperature will rise. When the detected temperature is higher than the set-point by more than 3°C, the bit 7 of the port 0 will be set to high and the bit 6 of the port 0 will be set to low. This will turn off both the furnace and the water heater and turn on the electric fan. As a result, the system temperature will drop. When the detected temperature is within $\pm$ 3°C from the set-point, both bit 6 and bit 7 of the port 0 will be set to low. As a result, both the heating and the cooling systems are turned off and the system temperature will be maintained.

All the processes described above except displaying the set-point and clearing the display will be repeated until the computer is reset. As the result, the system temperature will be kept within $\pm$ 3°C from the set-point.

Control Software

The necessary control software can be divided into four parts:

1. The main program: including displaying the set-point for 5 secs, clearing the display for 1 sec, controlling the Sample/Hold, handshaking between the A/D converter and the Micro., modifying the output of the A/D converter to the detected temperature, detecting dangerous temperature conditions, displaying the detected temperature, and controlling the system temperature, the starting address of which is 030 000,

2. The set-point saved at the addresses 003 001(High Byte) and 003 000 (Low Byte),

3. The data-modifying points which are saved at the addresses 037 000 through 037 105, with two addresses for each point, and

4. A subroutine named DDSPLY to transform a 10-bit binary code into a 2-byte BCD code and display it on the 4-digit display.

These are all listed in Appendix F.

CHAPTER VI

CALIBRATION AND TEST FOR THE CONTROLLER

Introduction

Once the microprocessor-operated thermometer has been designed and implemented, it must be calibrated. Calibration of a device involves applying a known input, measuring the output and relating the output to the input. We can then easily determine the input only by observing the output. After calibration, the controller must be tested to see whether it works well or not. Should it not work well, some adjustment, change, or analysis will be needed.

Principles of Calibration

Basically there are two types of temperature calibration. The first is that of Fixed Point Temperature Calibration. The second is that of Comparison Temperature Calibration. Both of the two types of calibration will be used.

Fixed point calibration is performed by placing the temperature sensors of the devices to be calibrated into a single temperature-fixed bath. Typical fixed point temperatures are listed in TABLE 7. Generally speaking, fixed point calibration has the advantage of higher accuracy.

TABLE 7

FIXED POINT TEMPERATURES

Physic State	Temperature (°C)
Triple Point of Hydrogen	-259.34
Liquid/Vapor Phase of Hydrogen at 25/76 Standard Atmosphere	-256.108
Boiling Point of Hydrogen	-252.87
Boiling Point of Neon	-246.048
Triple Point of Oxygen	-218.789
Boiling Point of Oxygen	-182.962
Ice Bath	0
Triple Point of Water	0.01
Boiling Point of Water	100
Freezing Point of Zinc	419.58
Freezing Point of Silver	961.93
Freezing Point of Gold	1064.43

This is especially true at higher temperatures (400°C or higher). However, with the exception of the ice bath, it has two disadvantages: 1. long calibration time; and 2. relatively high cost of the bath itself.

Comparison calibration is performed by direct comparison of the unknown thermometer with the reference thermometer. If it is used for the temperature calibration between -150°C and 400°C, the advantages are: 1. a single bath is needed for any temperature within the operation range of the sensor; and 2. speed of calibration. Two major elements necessary for comparison calibration are:

1. a constant temperature environment and
2. a standard thermometer.

At temperatures near ambient, water can be used as a stable constant temperature environment if it is suitably agitated or temperature controlled. Using a large amount of water will help keep the temperature constant. When calibration temperature requirements increase above 85°C, various oils are available to about 260°C, and molten salts to 1092°C. The standard thermometer used for reference thermometer depends on the operation range and the required accuracy. It may be a standard platinum resistance thermometer that has been calibrated at the National Bureau of Standards in accordance with the IPTS-68, or it can be a working standard that has been calibrated by the manufacturer.

Calibration Procedures

The operation range of the microprocessor-operated thermometer is from 0°C to 900°C. Calibration of this thermometer is separated into two ranges. For the temperature range of 0°C through 100°C, temperature-controlled water is used for the constant temperature environment and a finely calibrated mercury thermometer is used for the reference thermometer. For the temperature range of 100°C through 900°C, a temperature-controlled furnace is used for the constant temperature environment. The reason is that it is available from the Department of Chemical and Metallurgical Engineering. A K-type thermocouple from OMEGA together with its data sheet and an accurately calibrated millivoltmeter are used for the reference thermometer. To assure a stable temperature inside the furnace, its temperature must have been controlled for a long time. To maintain the temperature, significant thermal loading can not be accepted. Therefore all the holes, gaps, and slots should be stuffed with paper.

The calibration points are chosen as: (1) 0°C, (2) 50°C, (3) 100°C, (4) 150°C, (5) 300°C, (4) 500°C, (5) 700°C, and (6) 890°C. The calibration procedures are as follows:

1. Prepare an ice bath and place the temperature sensor of the thermometer to be calibrated into the ice bath. Measure the output of the thermometer.

2. Run the microprocessor-operated temperature controller with 50°C as the set-point. When the water has been heated around the set-point, read the water temperature by the mercury thermometer and read the display as the output.

3. Run the thermometer with its sensor placed into boiled water. Read the display.

4. For the calibration points above 100°C, place two sensors, one for the controller and the other for a reference, close together into the furnace. Run the controller with the set-point in the order listed above. When the display reading has been around the set-point for a long time, read the display and measure the emf V_{rt}

of the reference thermocouple. Also take the ambient temperature with the mercury thermometer. Find out the emf Vam of K-type thermocouple at ambient temperature from the OMEGA data sheet. Add Vam to Vrt to obtain the emf Vr. Then find out the corresponding temperature of Vr from the same data sheet. This temperature will be used as the reference temperature. For example, if the ambient temperature is 24°C and the potentiometer reading is 5.25 mV, then

Vrt = 5.25 mV;

Vam = 0.96 mV (from the data sheet);

Vr = 5.25 mV + 0.96 mV = 6.21 mV.

From the data sheet, we find Tr is near 152°C.

5. Compare overall the display reading with its corresponding reference temperature and make some adjustments if necessary. Repeat the above procedures until a satisfactory relationship between the display reading and the reference temperature is obtained.

TABLE 8

THERMOMETER CALIBRATION RESULTS

Display	Vrt (mV)	Ambient (°C)	Vam (mV)	Vr (mV)	Tr (°C)
179	6.40	23	.919	7.319	180
207	7.56	23	.919	8.479	209
238	8.81	23	.919	9.729	240
258	9.60	23	.919	10.519	259
307	11.60	23	.919	12.519	308
347	13.29	23	.919	14.209	348
404	15.70	23	.919	16.619	405
444	17.36	23	.919	18.279	445
497	19.56	23	.919	20.479	496
546	21.65	23	.919	22.569	545
593	23.71	23	.919	24.629	594
649	26.02	23	.919	26.939	648
702	28.20	23	.919	29.119	700
753	30.35	23	.919	31.269	751
801	32.40	23	.919	33.319	801
855	34.53	23	.919	35.449	853
893	36.10	23	.919	37.019	892

Test of the Controller

After the thermometer has been calibrated, the controller should be tested to see whether it works well or not. The objective of the controller is to control the system temperature within $\pm 3^\circ C$ from the set-point. For the following tests, the reference temperature is taken only after the displayed number has around the set-point for a long time. That means the system temperature has been stable before it is measured by the reference thermometer.

TABLE 9

CONTROLLER TEST RESULTS

Set-point (°C)	Vrt (mV)	Ambient (°C)	Vam (mV)	Vr (mV)	Tr (°C)
50					48
80					79
150	5.17	24.0	.960	6.130	150
300	11.02	24.0	.960	11.980	295
500	19.44	26.2	1.049	20.489	496
700	27.85	26.2	1.049	28.899	695
850	34.19	26.2	1.049	35.239	848
(Flash 9999)	36.53	27.0	1.081	37.611	907

CHAPTER VII

CONCLUSION

Introduction

This chapter discusses the noise rejection for thermocouple measurements, the performance improvements for a microprocessor-based temperature controller, the flexibility of a microprocessor-based temperature controller, and multi-sensor control.

Noise Rejection

Analog signals are easily corrupted by noises. For thermocouples, the voltage outputs are very small. A K-type thermocouple, for example, outputs 40 uV/°C. Therefore its measurement accuracy will be greatly influenced by noises. To reduce the noise effects, the following techniques are important.

1. Guard the thermocouple leads and the extension wires with conductors and guard the electronic circuits with a metal box. Connect the wire guard to the metal box, which is also connected to the ground. This will shunt the interfering current as shown in Fig. 28. Without the wire guard, the interfering current will flow through the resistance of the thermocouple lead, including the extension wire, to the Lo input of the pre-

amplifier, which is connected to the ground. This will cause a noise voltage drop. With the wire guard connected to the metal box, the interfering current will flow in the guard lead in stead of the thermocouple lead and the extension wire (see Fig. 28). This will not cause a noise voltage drop across the input terminals of the pre-amplifier.

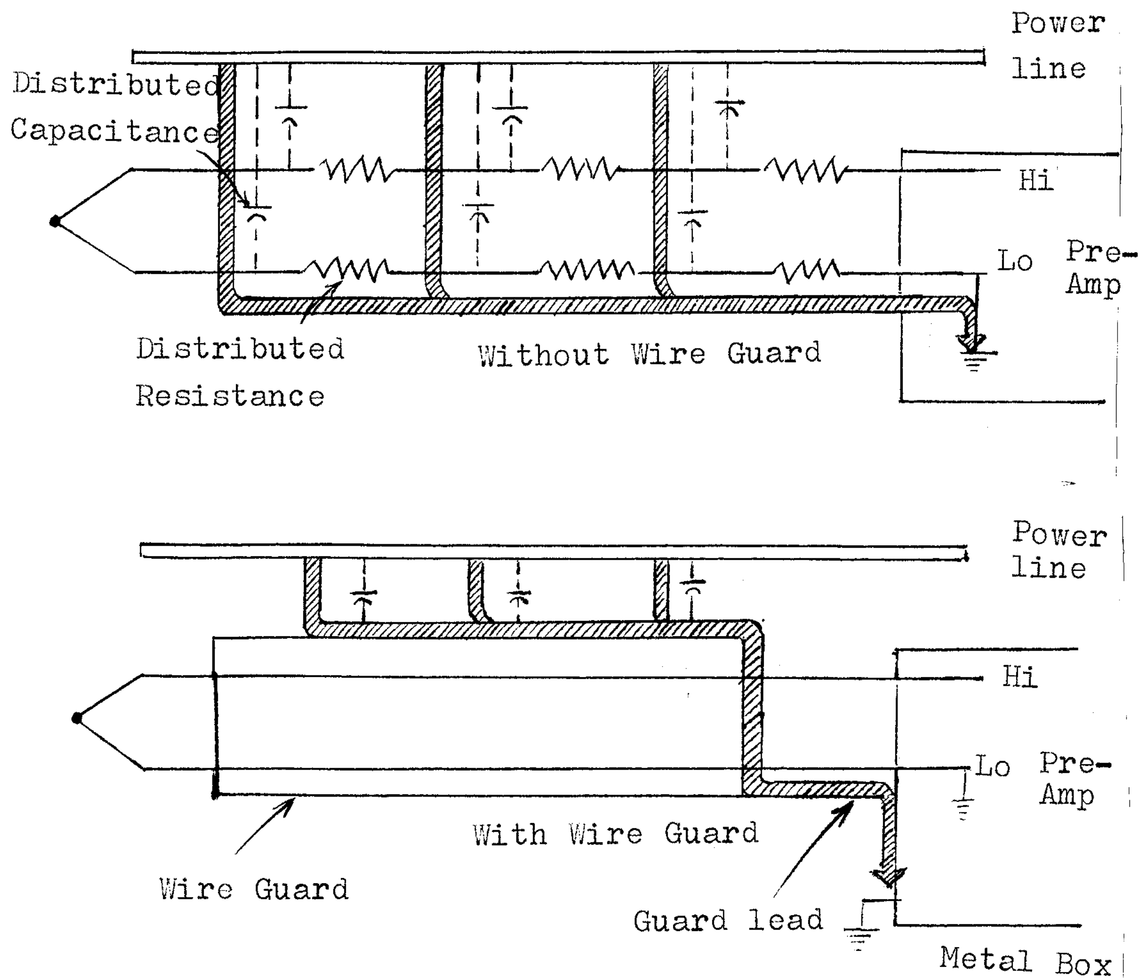


Fig. 28.--Guard Shunts the Interfering Current

2. Use larger thermocouple wires to minimize the noise by minimizing the thermocouple resistance.

3. Twist the extension wires in a uniform manner to reduce the magnetically induced noises.

4. Reduce the travelling distance of the analog signals or convert them to digital forms if possible.

5. Put an analog filter, as described in Chapter IV, just in front of the Sample/Hold circuit.

6. Use the integrating A/D converter which will average the noise over one full line cycle.

Performance Improvements

To further improve the performance of a microprocessor-based temperature controller, the following considerations for the sensor, the data acquisition system, and the control system must be taken into account.

Sensor

1. Thermocouple wires should be carefully manufactured to conform with the NBS standards.

2. Avoid mechanical stress and vibration which may strain thermocouple wires.

3. Avoid creating a steep temperature gradient on sensor by using metallic sleeving or careful placement of sensor.

4. Use thermocouple only in the region of detection and extension wire to travel the long distance between

the detection region and the measuring machine.

5. Use the sensor well within its operating range.

6. Use the proper sheath material to protect the sensor from damage.

7. Take a continuous record of thermocouple resistance to see if it is good for use.

Data Acquisition System

1. The voltage source used in the electrical bridge for cold junction compensation should have constant output voltage through its operation period. A mercury battery is recommended.

2. The resistors in the cold junction compensation bridge should be very accurate.

3. The cold junction compensation voltage should be well designed to match the output voltage of the thermocouple used.

4. The resistors related to the gain of the preamplifier should be very accurate.

5. The pre-amplifier should be a precision amplifier with low drift, low input offset voltage, low bias current, and high CMRR.

6. The gain for the thermocouple outputs should be well designed to match the resolution of the A/D converter.

7. The best capacitors for the analog filter are polystyrene, NPO ceramic, and mica because they have low

dissipation factor and low temperature coefficients. For noncritical uses, such as laboratories in school, metallized mylar or polycarbonate capacitors may be used. The physically small disk ceramic capacitors should be avoided for active filter use since their capacitance changes up to several percent with voltage, temperature, time, and frequency.

8. The acquisition time for the Sample/Hold circuit should be as short as possible to prevent changes in the sampled voltage. The addition of an external complementary emitter follower can reduce the acquisition time. This is especially required by the fast time-varying systems.

9. To reduce the acquisition time of the Sample/Hold circuit, the output resistance of the input voltage follower and the ON resistance of the analog switch must be very small.

10. The larger the holding capacitance, the smaller is the drift in voltage during the hold mode. However, the smaller the capacitance, the shorter is the acquisition time. Hence the value of the holding capacitance must be chosen as a compromise between the two conflicting requirements, depending on the application.

11. It is recommended that the holding capacitor has polycarbonate, polyethylene, polystyrene, Mylar, or Teflon as its dielectric. Most other capacitors do not retain the stored voltage due to a polarization

phenomenon and a phenomenon called dielectric absorption.

12. To reduce the drift rate during the Hold period, the bias current of the output voltage follower and the leakage current of the analog switch must be very small.

13. The holding time between Sampling and A/D conversion should be as short as posssible.

14. The A/D converter should be well calibrated.

15. Handshaking between the A/D converter and the microprocessor should be employed.

Control System

1. On/Off Control is simple, but the performance of Proportional Control is more accurate. Fig. 29 shows the approach of Proportional Control. If the system temperature is higher than the set-point, when the temperature is outside the proportional range, the cooling system is

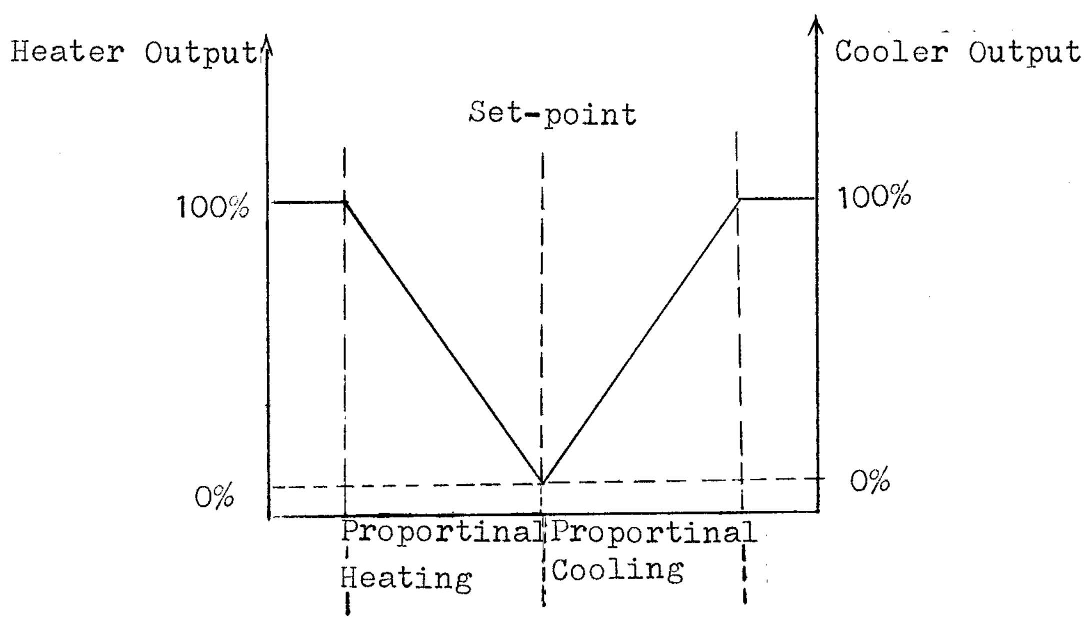


Fig. 29.--Proportional Control

fully actuated. When the temperature drops to within the proportional range, the cooling system is actuated in a way proportional to the difference between the detected temperature and the set-point. If the system temperature is lower than the set-point, when the detected temperature is outside the proportional range, the heating system is fully actuated. When the temperature rises to within the proportional range, the heating system is actuated in a way proportional to the difference between the detected temperature and the set-point. With this control, the system temperature can more steadily approach to the set-point.

2. The heating system and the cooling system should be isolated from the microcomputer to avoid interfering with the computer. Therefore photocoupling is usually employed in their interfaces.

3. For the temperature below the ambient temperature, another cooling system other than the electric fan is needed.

4. For high temperature control, the system had better be enclosed.

Flexibility of the Controller

Flexibility is an advantage of the computer-based devices. The temperature controller described so far uses a K-type thermocouple as sensor. If a controller using other types of thermocouples is needed, the following changes are necessary if software cold junction compensation is used:

1) Tear down the cold junction compensation bridge and connect the thermocouple output directly to the preamplifier input.

2) With the thermocouple short-circuited, adjust R9 to have zero output at Pin 6 of the LM308A (see Fig. 20).

3) Use another value of R5 so that the amplified output per °C of the used thermocouple can match the resolution of the A/D converter.

4) Select the data-modifying points for the thermocouple to be used, as described in Chapter V, and save them in memory.

5) Take the ambient temperature and save it at some addresses in memory.

6) Modify the control software as shown in the flow chart of next page.

Suppose we save all the control software for various types of thermocouples in PROM, and install a multirange switch which connects the inverting input of the LM121A to a different R5, designed for each type of thermocouple, in each range. When a K-type thermocouple is used, we can turn the switch to the K range, save the ambient temperature in memory, set the starting address to the beginning of the K-type control software, and run the the controller. When an E-type thermocouple is used, we turn the switch to the E range, save the ambient tempera-

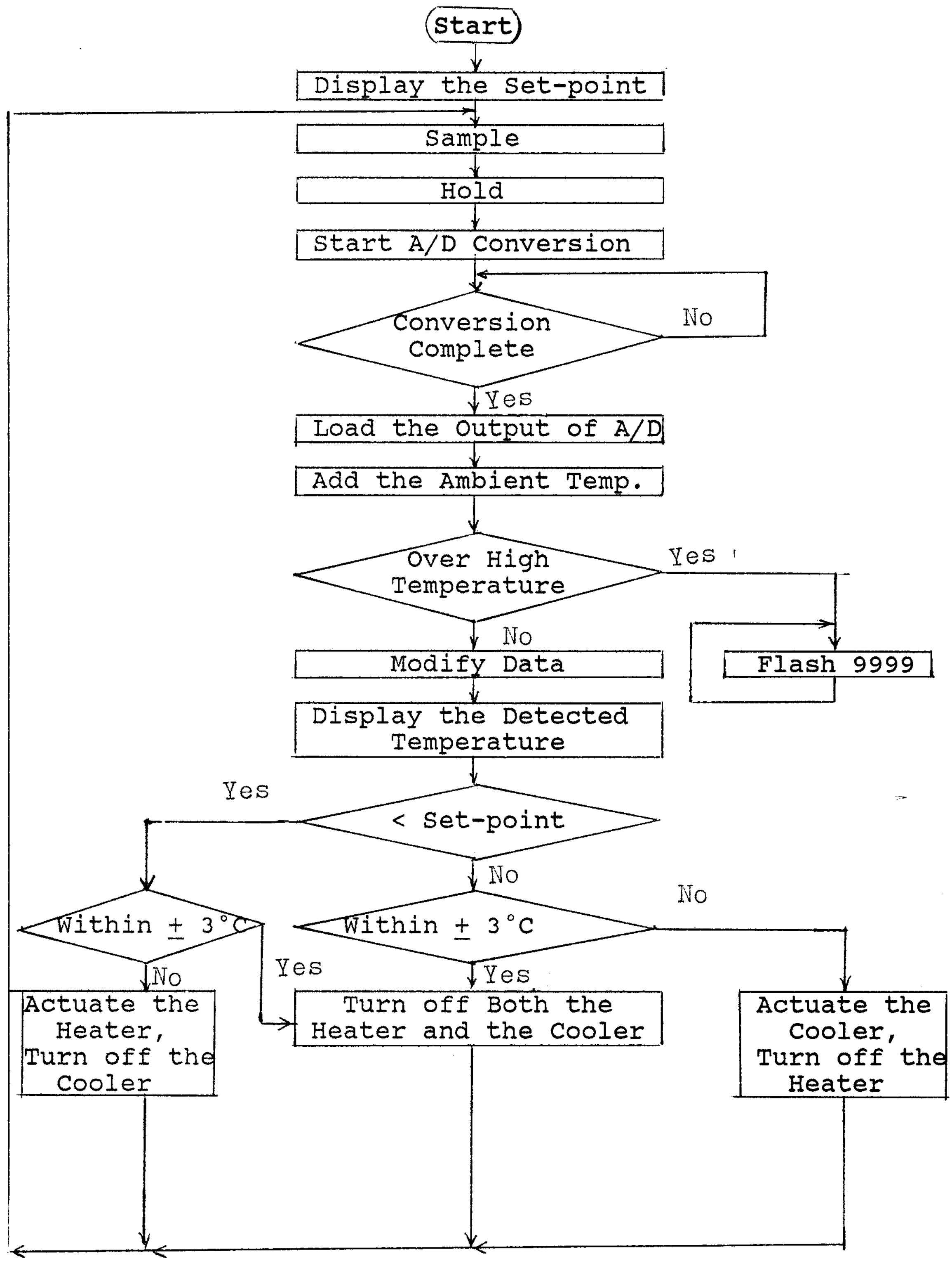


Fig. 30.--Flow Chart of the Control Software, Using Software Cold Junction Compensation

ture, set the starting address to the beginning of the E-type control software, and run the controller. In this way a controller for various types of thermocouples can be carried out.

Multi-sensor Control

If a multi-sensor control is required, for example, the temperature inside a furnace is required to be homogenous, we can go through the following approach.

1. Set one channel, including a cold junction compensation bridge, a precision amplifier, and an analog filter, for each sensor.

2. All channels are connected to the common holding capacitor by a multiplexer as shown in Fig. 31.

3. By varying the control input of the multiplexer, we can sample from various channels, detect the temperature of various points, and accomplish a multi-sensor control.

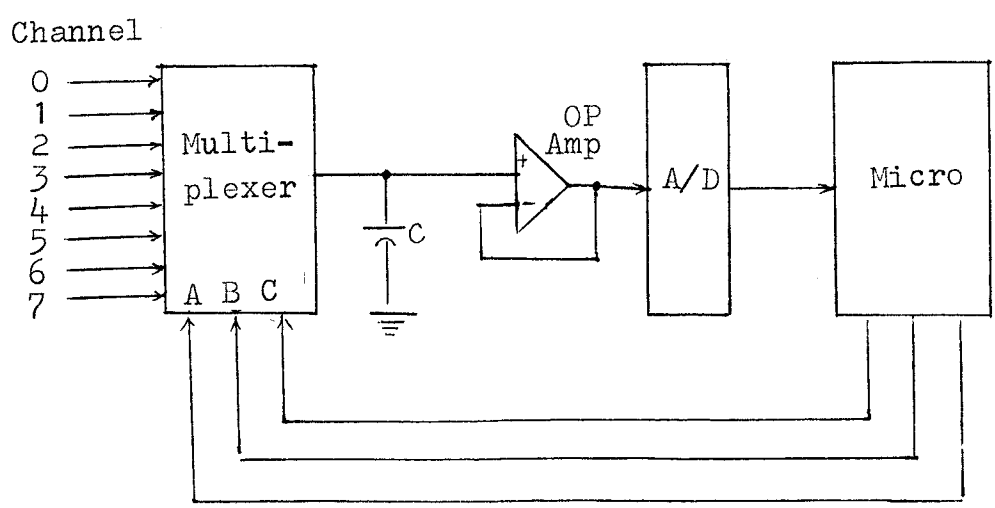


Fig. 31.--Multi-sensor Control

APPENDIX A

K-type Thermocouple Voltage Table from OMEGA

K-TYPE THERMOCOUPLE VOLTAGE TABLE FROM OMEGA

°C	mV	°C	mV	°C	mV
000	00.000	045	01.817	090	03.681
001	00.039	046	01.858	091	03.722
002	00.079	047	01.899	092	03.764
003	00.119	048	01.940	093	03.805
004	00.158	049	01.981	094	03.847
005	00.198	050	02.022	095	03.888
006	00.238	051	02.064	096	03.930
007	00.277	052	02.105	097	03.971
008	00.317	053	02.146	098	04.012
009	00.357	054	02.188	099	04.054
010	00.397	055	02.229	100	04.095
011	00.437	056	02.270	101	04.137
012	00.477	057	02.312	102	04.178
013	00.517	058	02.353	103	04.219
014	00.557	059	02.394	104	04.261
015	00.597	060	02.436	105	04.302
016	00.637	061	02.477	106	04.343
017	00.677	062	02.519	107	04.384
018	00.718	063	02.560	108	04.426
019	00.758	064	02.601	109	04.467
020	00.798	065	02.643	110	04.508
021	00.838	066	02.684	111	04.549
022	00.879	067	02.726	112	04.590
023	00.919	068	02.767	113	04.632
024	00.960	069	02.809	114	04.673
025	01.000	070	02.850	115	04.714
026	01.041	071	02.892	116	04.755
027	01.081	072	02.933	117	04.796
028	01.122	073	02.975	118	04.837
029	01.162	074	03.016	119	04.878
030	01.203	075	03.058	120	04.919
031	01.244	076	03.100	121	04.960
032	01.285	077	03.141	122	05.001
033	01.325	078	03.183	123	05.042
034	01.366	079	03.224	124	05.083
035	01.407	080	03.266	125	05.124
036	01.448	081	03.307	126	05.164
037	01.489	082	03.349	127	05.205
038	01.529	083	03.390	128	05.246
039	01.570	084	03.432	129	05.287
040	01.611	085	03,473	130	05.327
041	01.652	086	03.515	131	05.368
042	01.693	087	03.556	132	05.409
043	01.734	088	03.598	133	05.450
044	01.776	089	03.639	134	05.490

°C	mV	°C	mV	°C	mV
135	05.531	185	07.538	235	09.543
136	05.571	186	07.578	236	09.583
137	05.612	187	07.618	237	09.624
138	05.652	188	07.658	238	09.664
139	05.693	189	07.697	239	09.705
140	05.733	190	07.737	240	09.745
141	05.774	191	07.777	241	09.786
142	05.814	192	07.817	242	09.826
143	05.855	193	07.857	243	09.867
144	05.895	194	07.897	244	09.907
145	05.936	195	07.937	245	09.948
146	05.976	196	07.977	246	09.989
147	06.016	197	08.017	247	10.029
148	06.057	198	08.057	248	10.070
149	06.097	199	08.097	249	10.111
150	06.137	200	08.137	250	10.151
151	06.177	201	08.177	251	10.192
152	06.218	202	08.216	252	10.233
153	06.258	203	08.256	253	10.274
154	06.298	204	08.296	254	10.315
155	06.338	205	08.336	255	10.355
156	06.378	206	08.376	256	10.396
157	06.419	207	08.416	257	10.437
158	06.459	208	08.456	258	10.478
159	06.499	209	08.497	259	10.519
160	06.539	210	08.537	260	10.560
161	06.579	211	08.577	261	10.600
162	06.619	212	08.617	262	10.641
163	06.659	213	08.657	263	10.682
164	06.699	214	08.697	264	10.723
165	06.739	215	08.737	265	10.764
166	06.779	216	08.777	266	10.805
167	06.819	217	08.817	267	10.846
168	06.859	218	08.857	268	10.887
169	06.899	219	08.898	269	10.928
170	06.939	220	08.938	270	10.969
171	06.979	221	08.978	271	11.010
172	07.019	222	09.018	272	11.051
173	07.059	223	09.058	273	11.093
174	07.099	224	09.099	274	11.134
175	07.139	225	09.139	275	11.175
176	07.179	226	09.178	276	11.216
177	07.219	227	09.220	277	11.257
178	07.259	228	09.260	278	11.298
179	07.299	229	09.300	279	11.339
180	07.338	230	09.341	280	11.381
181	07.378	231	09.381	281	11.422
182	07.418	232	09.421	282	11.463
183	07.458	233	09.462	283	11.504
184	07.498	234	09.502	284	11.546

°C	mV	°C	mV	°C	mV
285	11.587	335	13.665	385	15.763
286	11.628	336	13.706	386	15.805
287	11.669	337	13.748	387	15.847
288	11.711	338	13.790	388	15.889
289	11.752	339	13.832	389	15.931
290	11.793	340	13.874	390	15.974
291	11.835	341	13.915	391	16.016
292	11.876	342	13.957	392	16.058
293	11.918	343	13.999	393	16.100
294	11.959	344	14.041	394	16.142
295	12.000	345	14.083	395	16.184
296	12.042	346	14.125	396	16.227
297	12.083	347	14.167	397	16.269
298	12.125	348	14.208	398	16.311
299	12.166	349	14.250	399	16.353
300	12.207	350	14.292	400	16.395
301	12.249	351	14.334	401	16.438
302	12.290	352	14.376	402	16.480
303	12.332	353	14.418	403	16.522
304	12.373	354	14.460	404	16.564
305	12.415	355	14.502	405	16.607
306	12.456	356	14.544	406	16.649
307	12.498	357	14.586	407	16.691
308	12.539	358	14.628	408	16.733
309	12.581	359	14.670	409	16.776
310	12.623	360	14.712	410	16.818
311	12.664	361	14.754	411	16.860
312	12.706	362	14.796	412	16.902
313	12.747	363	14.838	413	16.945
314	12.789	364	14.880	414	16.987
315	12.831	365	14.922	415	17.029
316	12.872	366	14.964	416	17.072
317	12.914	367	15.006	417	17.114
318	12.955	368	15.048	418	17.156
319	12.997	369	15.090	419	17.199
320	13.039	370	15.132	420	17.241
321	13.080	371	15.174	421	17.283
322	13.122	372	15.216	422	17.326
323	13.164	373	15.258	423	17.368
324	13.205	374	15.300	424	17.410
325	13.247	375	15.342	425	17.453
326	13.289	376	15.384	426	17.495
327	13.331	377	15.426	427	17.537
328	13.372	378	15.468	428	17.580
329	13.414	379	15.510	429	17.622
330	13.456	380	15.552	430	17.664
331	13.497	381	15.594	431	17.707
332	13.539	382	15.636	432	17.749
333	13.581	383	15.679	433	17.792
334	13.623	384	15.721	434	17.834

°C	mV	°C	mV	°C	mV
435	17.876	485	20.001	535	22.132
436	17.919	486	20.044	536	22.175
437	17.961	487	20.086	537	22.218
438	18.004	488	20.129	538	22.260
439	18.046	489	20.172	539	22.303
440	18.088	490	20.214	540	22.346
441	18.131	491	20.257	541	22.388
442	18.173	492	20.299	542	22.431
443	18.216	493	20.342	543	22.473
444	18.258	494	20.385	544	22.516
445	18.301	495	20.427	545	22.559
446	18.343	496	20.470	546	22.601
447	18.385	497	20.512	547	22.644
448	18.428	498	20.555	548	22.687
449	18.470	499	20.598	549	22.729
450	18.513	500	20.640	550	22.772
451	18.555	501	20.683	551	22.815
452	18.598	502	20.725	552	22.857
453	18.640	503	20.768	553	22.900
454	18.683	504	20.811	554	22.942
455	18.725	505	20.853	555	22.985
456	18.768	506	20.896	556	23.028
457	18.810	507	20.938	557	23.070
458	18.853	508	20.981	558	23.113
459	18.895	509	21.024	559	23.156
460	18.938	510	21.066	560	23.198
461	18.980	511	21.109	561	23.241
462	19.023	512	21.152	562	23.284
463	19.065	513	21.194	563	23.326
464	19.108	514	21.237	564	23.369
465	19.150	515	21.280	565	23.411
466	19.193	516	21.322	566	23.454
467	19.235	517	21.365	567	23.497
468	19.278	518	21.407	568	23.539
469	19.320	519	21.450	569	23.582
470	19.363	520	21.493	570	23.624
471	19.405	521	21.535	571	23.667
472	19.448	522	21.578	572	23.710
473	19.490	523	21.621	573	23.752
474	19.533	524	21.663	574	23.795
475	19.576	525	21.706	575	23.837
476	19.618	526	21.749	576	23.880
477	19.661	527	21.791	577	23.923
478	19.703	528	21.834	578	23.965
479	19.746	529	21.876	579	24.008
480	19.788	530	21.919	580	24.050
481	19.831	531	21.962	581	24.093
482	19.873	532	22.004	582	24.136
483	19.916	533	22.047	583	24.178
484	19.959	534	22.090	584	24.221

°C	mV	°C	mV	°C	mV
585	24.263	635	26.387	685	28.498
586	24.306	636	26.430	686	28.540
587	24.348	637	26.472	687	28.583
588	24.391	638	26.515	688	28.625
589	24.434	639	26.557	689	28.667
590	24.476	640	26.599	690	28.709
591	24.519	641	26.642	691	28.751
592	24.561	642	26.684	692	28.793
593	24.604	643	26.726	693	28.835
594	24.646	644	26.769	694	28.877
595	24.689	645	26.811	695	28.919
596	24.731	646	26.853	696	28.961
597	24.774	647	26.896	697	29.002
598	24.817	648	26.938	698	29.044
599	24.859	649	26.980	699	29.086
600	24.902	650	27.022	700	29.128
601	24.944	651	27.065	701	29.170
602	24.987	652	27.107	702	29.212
603	25.029	653	27.149	703	29.254
604	25.072	654	27.192	704	29.296
605	25.114	655	27.234	705	29.338
606	25.157	656	27.276	706	29.380
607	25.199	657	27.318	707	29.422
608	25.242	658	27.361	708	29.464
609	25.284	659	27.403	709	29.505
610	25.327	660	27.445	710	29.547
611	25.369	661	27.487	711	29.589
612	25.412	662	27.529	712	29.631
613	25.454	663	27.572	713	29.673
614	25.497	664	27.614	714	29.715
615	25.539	665	27.656	715	29.756
616	25.582	666	27.698	716	29.798
617	25.624	667	27.740	717	29.840
618	25.666	668	27.783	718	29.882
619	25.709	669	27.825	719	29.924
620	25.751	670	27.867	720	29.965
621	25.794	671	27.909	721	30.007
622	25.836	672	27.951	722	30.049
623	25.879	673	27.993	723	30.091
624	25.921	674	28.035	724	30.132
625	25.964	675	28.078	725	30.174
626	26.006	676	28.120	726	30.216
627	26.048	677	28.162	727	30.257
628	26.091	678	28.204	728	30.299
629	26.133	679	28.246	729	30.341
630	26.176	680	28.288	730	30.383
631	26.218	681	28.330	731	30.424
632	26.260	682	28.372	732	30.466
633	26.303	683	28.414	733	30.508
634	26.345	684	28.456	734	30.549

°C	mV	°C	mV	°C	mV
735	30.591	785	32.661	835	34.705
736	30.632	786	32.702	836	34.746
737	30.674	787	32.743	837	34.787
738	30.716	788	32.784	838	34.827
739	30.757	789	32.825	839	34.868
740	30.799	790	32.866	840	34.909
741	30.840	791	32.907	841	34.949
742	30.882	792	32.948	842	34.990
743	30.924	793	32.990	843	35.030
744	30.965	794	33.031	844	35.071
745	31.007	795	33.072	845	35.111
746	31.048	796	33.113	846	35.152
747	31.090	797	33.154	847	35.192
748	31.131	798	33.195	848	35.233
749	31.173	799	33.236	849	35.273
750	31.214	800	33.277	850	35.314
751	31.256	801	33.318	851	35.354
752	31.297	802	33.359	852	35.395
753	31.339	803	33.400	853	35.435
754	31.380	804	33.441	854	35.476
755	31.422	805	33.482	855	35.516
756	31.463	806	33.523	856	35.557
757	31.504	807	33.564	857	35.597
758	31.546	808	33.604	858	35.637
759	31.587	809	33.645	859	35.678
760	31.629	810	33.686	860	35.718
761	31.670	811	33.727	861	35.758
762	31.712	812	33.768	862	35.799
763	31.753	813	33.809	863	35.839
764	31.794	814	33.850	864	35.880
765	31.836	815	33.891	865	35.920
766	31.877	816	33.931	866	35.960
767	31.918	817	33.972	867	36.000
768	31.960	818	34.013	868	36.041
769	32.001	819	34.054	869	36.081
770	32.042	820	34.095	870	36.121
771	32.084	821	34.136	871	36.162
772	32.125	822	34.176	872	36.202
773	32.166	823	34.217	873	36.242
774	32.207	824	34.258	874	36.282
775	32.249	825	34.299	875	36.323
776	32.290	826	34.339	876	36.363
777	32.331	827	34.380	877	36.403
778	32.372	828	34.421	878	36.443
779	32.414	829	34.461	879	36.483
780	32.455	830	34.502	880	36.524
781	32.496	831	34.543	881	36,564
782	32.537	832	34.583	882	36.604
783	32.578	833	34.624	883	36.644
784	32.619	834	34.665	884	36.684

°C	mV	°C	mV	°C	mV
885	36.724	890	36.925	895	37.125
886	36.764	891	36.965	896	37.165
887	36.804	892	37.005	897	37.205
888	36.844	893	37.045	898	37.245
889	36.885	894	37.085	899	37.285
				900	37.325

APPENDIX B

Increments of the K-type Thermocouple Voltage Per °C Rise

INCREMENTS OF THE K-TYPE THERMOCOUPLE VOLTAGE PER °C RISE

Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)
001	39	046	41	091	41
002	40	047	41	092	42
003	40	048	41	093	41
004	39	049	41	094	42
005	40	050	41	095	41
006	40	051	42	096	42
007	39	052	41	097	41
008	40	053	41	098	41
009	40	054	42	099	42
010	40	055	41	100	41
011	40	056	41	101	42
012	40	057	42	102	41
013	40	058	41	103	41
014	40	059	41	104	42
015	40	060	42	105	41
016	40	061	41	106	41
017	40	062	42	107	41
018	41	063	41	108	42
019	40	064	41	109	41
020	40	065	42	110	41
021	40	066	41	111	41
022	41	067	42	112	41
023	40	068	41	113	42
024	41	069	42	114	41
025	40	070	41	115	41
026	41	071	42	116	41
027	40	072	41	117	41
028	40	073	42	118	41
029	41	074	41	119	41
030	41	075	42	120	41
031	41	076	42	121	41
032	41	077	41	122	41
033	40	078	42	123	41
034	41	079	41	124	41
035	41	080	42	125	41
036	41	081	41	126	40
037	41	082	42	127	41
038	40	083	41	128	41
039	41	084	42	129	41
040	41	085	41	130	40
041	41	086	42	131	41
942	41	087	41	132	41
043	41	088	42	133	41
044	42	089	41	134	40
045	41	090	42	135	41

Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)
136	40	186	40	236	40
137	41	187	40	237	41
138	40	188	40	238	40
139	41	189	39	239	41
140	40	190	40	340	40
141	41	191	40	241	41
142	40	192	40	242	40
143	41	193	40	243	41
144	40	194	40	244	40
145	41	195	40	245	41
146	40	196	40	246	41
147	40	197	40	247	40
148	41	198	40	248	41
149	40	199	40	249	41
150	40	200	40	250	40
151	40	201	40	251	41
152	41	202	39	252	41
153	40	203	40	253	41
154	40	204	40	254	41
155	40	205	40	255	40
156	40	206	40	256	41
157	41	207	40	257	41
158	40	208	40	258	41
159	40	209	41	259	41
160	40	210	40	260	41
161	40	211	40	261	40
162	40	212	40	262	41
163	40	213	40	263	41
164	40	214	40	264	41
165	40	215	40	265	41
166	40	216	40	266	41
167	40	217	40	267	41
168	40	218	40	268	41
169	40	219	41	269	41
170	40	220	40	270	41
171	40	221	40	271	41
172	40	222	40	272	41
173	40	223	40	273	42
174	40	224	41	274	41
175	40	225	40	275	41
176	40	226	40	276	41
177	40	227	41	277	41
178	40	228	40	278	41
179	40	229	40	279	41
180	39	230	41	280	42
181	40	231	40	281	41
182	40	232	40	282	41
183	40	233	41	283	41
184	40	234	40	284	42
185	40	235	41	285	41

Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)
286	41	336	41	386	42
287	41	337	42	387	42
288	42	338	42	388	42
289	41	339	42	389	42
290	41	340	42	390	43
291	42	341	41	391	42
292	41	342	42	392	42
293	42	343	42	393	42
294	41	344	42	394	42
295	41	345	42	395	42
296	42	346	42	396	43
297	41	347	42	397	42
298	42	348	41	398	42
299	41	349	42	399	42
300	41	350	42	400	42
301	42	351	42	401	43
302	41	352	42	402	42
303	42	353	42	403	42
304	41	354	42	404	42
305	42	355	42	405	43
306	41	356	42	406	42
307	42	357	42	407	42
308	41	358	42	408	42
309	42	359	42	409	43
310	42	360	42	410	42
311	41	361	42	411	42
312	42	362	42	412	42
313	41	363	42	413	43
314	42	364	42	414	42
315	42	365	42	415	42
316	41	366	42	416	43
317	42	367	42	417	42
318	41	368	42	418	42
319	42	369	42	419	43
320	42	370	42	420	42
321	41	371	42	421	42
322	42	372	42	422	43
323	42	373	42	423	42
324	41	374	42	424	42
325	42	375	42	425	43
326	42	376	42	426	42
327	42	377	42	427	42
328	41	378	42	428	43
329	42	379	42	429	42
330	42	380	42	430	42
331	41	381	42	431	43
332	42	382	42	432	42
333	42	383	43	433	43
334	42	384	42	434	42
335	42	385	42	435	42

Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)
436	43	486	43	536	43
437	42	487	42	537	43
438	43	488	43	538	42
439	42	489	43	539	43
440	42	490	42	540	43
441	43	491	43	541	42
442	42	492	42	542	43
443	43	493	43	543	42
444	42	494	43	544	43
445	43	495	42	545	43
446	42	496	43	546	42
447	42	497	42	547	43
448	43	498	43	548	43
449	42	499	43	549	42
450	43	500	42	550	43
451	42	501	43	551	43
452	43	502	42	552	42
453	42	503	43	553	43
454	43	504	43	554	42
455	42	505	42	555	43
456	43	506	43	556	43
457	42	507	42	557	42
458	43	508	43	558	43
459	42	509	43	559	43
460	43	510	42	560	42
461	42	511	43	561	43
462	43	512	43	562	43
463	42	513	42	563	42
464	43	514	43	564	43
465	42	515	43	565	42
466	43	516	42	566	43
467	42	517	43	567	43
468	43	518	42	568	42
469	42	519	43	569	43
470	43	520	43	570	42
471	42	521	42	571	43
472	43	522	43	572	43
473	42	523	43	573	42
474	43	524	42	574	43
475	43	525	43	575	42
476	42	526	43	576	43
477	43	527	42	577	43
478	42	528	43	578	42
479	43	529	42	579	43
480	42	530	43	580	42
481	43	531	43	581	43
482	42	532	42	582	43
483	43	533	43	583	42
484	43	534	43	584	43
485	42	535	42	585	42

Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)
586	43	636	43	686	42
587	42	637	42	687	43
588	43	638	43	688	42
589	43	639	42	689	42
590	42	640	42	690	42
591	43	641	43	691	42
592	42	642	42	692	42
593	43	643	42	693	42
594	42	644	43	694	42
595	43	645	42	695	42
596	42	646	42	696	42
597	43	647	43	697	41
598	43	648	42	698	42
599	42	649	42	699	42
600	43	650	42	700	42
601	42	651	43	701	42
602	43	652	42	702	42
603	42	653	42	703	42
604	43	654	43	704	42
605	42	655	42	705	42
606	43	656	42	706	42
607	42	657	42	707	42
608	43	658	43	708	42
609	42	659	42	709	41
610	43	660	42	710	42
611	42	661	42	711	42
612	43	662	42	712	42
613	42	663	43	713	42
614	43	664	42	714	42
615	42	665	42	715	41
616	43	666	42	716	42
617	42	667	42	717	42
618	42	668	43	718	42
619	43	669	42	719	42
620	42	670	42	720	41
621	43	671	42	721	42
622	42	672	42	722	42
623	43	673	42	723	42
624	42	674	42	724	41
625	43	675	43	725	42
626	42	676	42	726	42
627	42	677	42	727	41
628	43	678	42	728	42
629	42	679	42	729	42
630	43	680	42	730	42
631	42	681	42	731	41
632	42	682	42	732	42
633	43	683	42	733	42
634	42	684	42	734	41
635	42	685	42	735	42

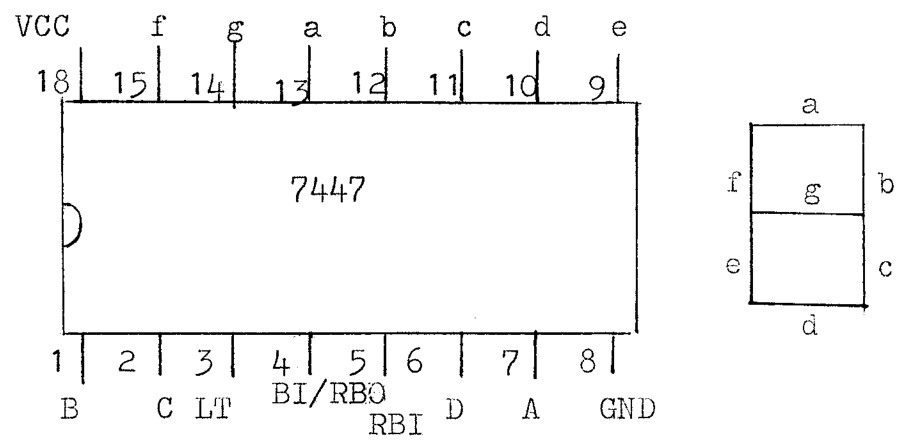
Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)
736	41	786	41	836	41
737	42	787	41	837	41
738	42	788	41	838	40
739	41	789	41	839	41
740	42	790	41	840	41
741	41	791	41	841	40
742	42	792	41	842	41
743	42	793	42	843	40
744	41	794	41	844	41
745	42	795	41	845	40
746	41	796	41	846	41
747	42	797	41	847	40
748	41	798	41	848	41
749	42	799	41	849	40
750	41	800	41	850	41
751	42	801	41	851	40
752	41	802	41	852	41
753	42	803	41	853	40
754	41	804	41	854	41
755	42	805	41	855	40
756	41	806	41	856	41
757	41	807	41	857	40
758	42	808	40	858	40
759	41	809	41	859	41
760	42	810	41	860	40
761	41	811	41	861	40
762	42	812	41	862	41
763	41	813	41	863	40
764	41	814	41	864	41
765	42	815	41	865	40
766	41	816	40	866	40
767	41	817	41	867	40
768	42	818	41	868	41
769	41	819	41	869	40
770	41	820	41	870	40
771	42	821	41	871	41
772	41	822	40	872	40
773	41	823	41	873	40
774	41	824	41	874	40
775	42	825	41	875	41
776	41	826	40	876	40
777	41	827	41	877	40
778	41	828	41	878	40
779	42	829	40	879	40
780	41	830	41	880	41
781	41	831	41	881	40
782	41	832	40	882	40
783	41	833	41	883	40
784	41	834	41	884	40
785	42	835	40	885	40

Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)	Temp. (°C)	Increment (uV)
886	40	891	40	896	40
887	40	892	40	897	40
888	40	893	40	898	40
889	41	894	40	899	40
890	40	895	40	900	40

APPENDIX C

<u>7447</u>

PIN CONFIGURATION AND SEGMENT IDENTIFICATION



TRUTH TABLE

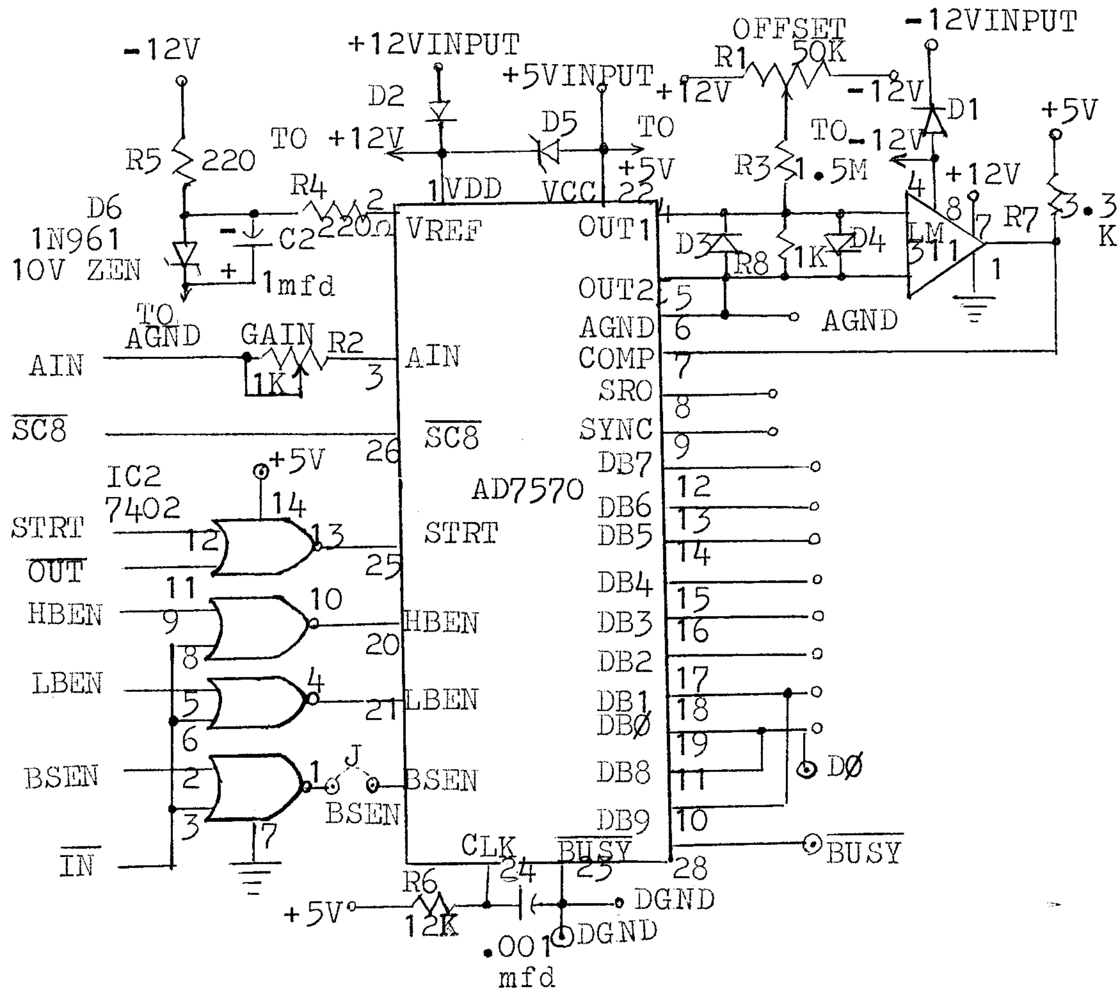
Decimal or Function	LT	RBI	D	C	B	A	BI/RBO	a	b	c	d	e	f	g
0	1	1	0	0	0	0	1	0	0	0	0	0	0	1
1	1	*	0	0	0	1	1	1	0	0	1	1	1	1
2	1	*	0	0	1	0	1	0	0	1	0	0	1	0
3	1	*	0	0	1	1	1	0	0	0	0	1	1	0
4	1	*	0	1	0	0	1	1	0	0	1	1	0	0
5	1	*	0	1	0	1	1	0	1	0	0	1	0	0
6	1	*	0	1	1	0	1	1	1	0	0	0	0	0
7	1	*	0	1	1	1	1	0	0	0	1	1	1	1
8	1	*	1	0	0	0	1	0	0	0	0	0	0	0
9	1	*	1	0	0	1	1	0	0	0	1	1	0	0
10	1	*	1	0	1	0	1	1	1	1	0	0	1	0
11	1	*	1	0	1	1	1	1	1	0	0	1	1	0
12	1	*	1	1	0	0	1	1	0	1	1	1	0	0
13	1	*	1	1	0	1	1	0	1	1	0	1	0	0
14	1	*	1	1	1	0	1	1	1	1	0	0	0	0
15	1	*	1	1	1	1	1	1	1	1	1	1	1	1
BI	*	*	*	*	*	*	0	1	1	1	1	1	1	1
RBI	1	0	0	0	0	0	0	1	1	1	1	1	1	1
LT	0	*	*	*	*	*	1	0	0	0	0	0	0	0

* : Don't care

APPENDIX D

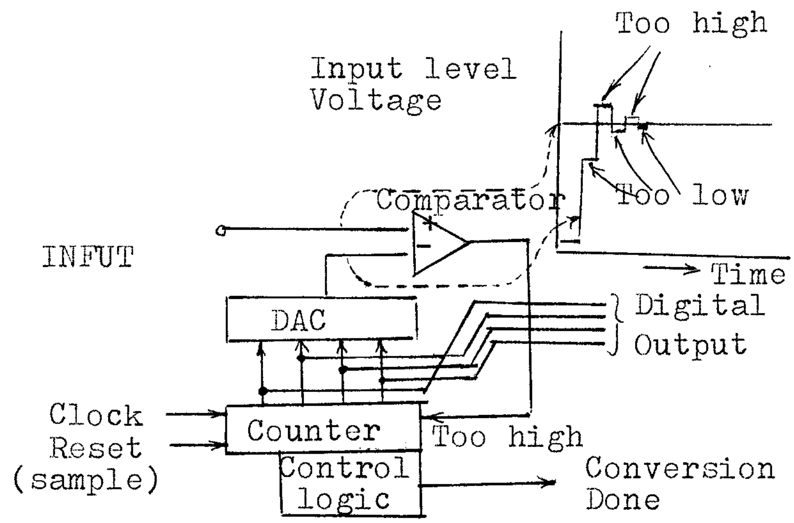
LR-36

INTERNAL CIRCUITS



AD7570

The AD7570 is a monolithic CMOS A/D converter which uses the successive approximations technique to provide up to 10 bits of digital data in a serial and parallel format. The figure on the following page shows the successive approximation A/D conversion system. Successive bits, starting with the most significant bit (DB9) are applied to the input of the D/A converter. The DAC output is then compared to the unknown analog input voltage (AIN) using a comparator LM311. If the DAC output is greater than AIN,



Successive Approximation A/D Conversion System

the data latch for the trial bit is reset to zero, and the next less significant bit is tried. If the DAC output is smaller than AIN, the trial data bit stays in the "1" state and the next less significant bit is tried. Each successive bit is tried until the least significant bit (DB0) decision is made. At this time, the AD7570 output is a valid digital representation of the analog input.

When the start input STRT (pin 25) goes to high, the MSB data latch is set to logic 1 and all the other data latches are set to logic 0. When STRT returns low, the conversion sequence begins. If BSEN (pin 27) is addressed with high, $\overline{\text{BUSY}}$ (pin 28) will indicate a 0 during conversion or a 1 when conversion is complete. When HBEN (pin 20) is high, digital data for the bit 9 (MSB) and bit 8 appear on the data lines. When LBEN (pin 21) is high, digital data for the bits 0 (LSB) through 7 appear on the data lines. SRO (pin 8) provides output data in serial format. Data are available only during conversion. It must be used together with SYNC (pin 9) to avoid misunderstanding data.

Gain Adjustment

1. Apply continuous start commands to the STRT of the AD7570.

2. Apply full scale minus 3/2 LSB to the AIN.

3. Observe the SRO by an oscilloscope, and adjust the gain potentiometer (R2) until the LSB flickers between 0 and 1, and all other data bits equal "1".

APPENDIX E

Specifications of the MMD-1

SPECIFICATIONS OF THE MMD-1

CPU: Intel 8080A

Memory: RAM, 512 bytes (8 bits) on board

PROM, two 256-byte PROM, one of which is programmed to accomodate keyboard entry of data, the other is programmed for Loading and Dumping

Expansion capability: additional memories, 1K PROM and 2K RAM, are provided by installing the M/I board

Display: Three groups of 8 LED's individually latched and addressible under software control. During keyboard program entry, these LED's display Lo address, Hi address and memory data via the KEX PROM

Data Entry: 16 switch keyboard -- numerals 0 through 7, Hi address(H), Lo address(L), go(G), reset(R), examine/deposit(S), and three optional keys(A, B, C)

Breadboarding Socket: Buss signals hardwired to socket:

A0 through A7

GND

+5 V

INT

INTE

$\overline{\text{I ACK}}$

$\overline{\text{MEM R}}$

$\overline{\text{MEM W}}$

$\overline{\text{IN}}$

$\overline{\text{OUT}}$

WAIT

READY

D0 through D7

Internal Power Supply: 115/230 VAC operation outputs:

+5 V at 1.5 A

+12 V at 150 mA

-12 V at 150 mA

APPENDIX F

Control Software

MAIN PROGRAM

ADDRESS	OP CODE	MNEMONIC	COMMENT
030 000	061	LXI SP	/DISPLAYING THE SET-
030 001	000	000	/POINT
030 002	004	004	
030 003	041	LXI H	
030 004	000	000	
030 005	003	003	
030 006	176	MOV A,M	
030 007	062	STA	/THE SET-POINT MUST BE
030 010	200	200	/PUT AT THE ADDRESSES
030 011	003	003	/003 201 AND 003 200
030 012	043	INX H	/BEFORE BEING DISPLAYED
030 013	176	MOV A,M	
030 014	062	STA	
030 015	201	201	
030 016	003	003	
030 017	315	CALL	
030 020	000	DDSPLY	
030 021	035		
030 022	315	CALL	
030 023	130	FIVSEC	
030 024	001		
030 025	076	MVI A	/CLEAR THE DISPLAY FOR
030 026	377	377	/1 SEC
030 027	323	OUT	
030 030	004	004	
030 031	323	OUT	
030 032	003	003	
030 033	315	CALL	
030 034	000	ONESEC	
030 035	034		
030 036	076	MVI A	/SAMPLING FOR 0.25 MS
030 037	200	200	/THE SAMPLE COMMAND IS
030 040	323	OUT	/CONNECTED TO THE BIT 7
030 041	001	001	/OF THE OUTPUT PORT 1
030 042	000	NOP	
030 043	000	NOP	
030 044	000	NOP	
030 045	000	NOP	
030 046	000	NOP	
030 047	000	NOP	
030 050	000	NOP	
030 051	000	NOP	
030 052	000	NOP	
030 053	000	NOP	
030 054	000	NOP	
030 055	000	NOP	
030 056	000	NOP	
030 057	000	NOP	

```
030 060        000        NOP
030 061        000        NOP
030 062        000        NOP
030 063        000        NOP
030 064        000        NOP
030 065        000        NOP
030 066        000        NOP
030 067        000        NOP
030 070        000        NOP
030 071        000        NOP
030 072        000        NOP
030 073        000        NOP
030 074        000        NOP
030 075        000        NOP
030 076        000        NOP
030 077        000        NOP
030 100        000        NOP
030 101        000        NOP
030 102        000        NOP
030 103        000        NOP
030 104        000        NOP
030 105        000        NOP
030 106        000        NOP
030 107        000        NOP
030 110        000        NOP
030 111        000        NOP
030 112        000        NOP
030 113        000        NOP
030 114        000        NOP
030 115        076        MVI A      /HOLDING THE SAMPLED
030 116        000        000        /VOLTAGE
030 117        323        OUT
030 120        001        001
030 121        323        OUT        /START THE A/D CON-
030 122        005        005        /VERSION
030 123        333        IN         /CHECK THE STATUS OF
030 124        005        005        /THE A/D CONVERSION
030 125        346        ANI
030 126        040        040
030 127        312        JZ         /IF THE CONVERSION IS
030 130        123        123        /IN PROCESS, THEN CON-
030 131        030        030        /TINUE CHECKING
030 132        333        IN         /IF THE CONVERSION IS
030 133        006        006        /COMPLETE, THEN INPUT
030 134        346        ANI        /THE DIGITAL OUTPUT OF
030 135        003        003        /THE A/D CONVERTER AND
030 136        127        MOV D,A    /STORE IT IN THE D AND
030 137        333        IN         /E REGISTERS
030 140        007        007
030 141        137        MOV E,A
030 142        001        LXI B      /MODIFY THE DIGITAL
030 143        000        000        /OUTPUT OF A/D CON-
030 144        000        000        /VERTER TO THE EXACT
```

```
030 145    041    LXI H      /DETECTED TEMPERATURE
030 146    000    000
030 147    037    037
030 150    176    MOV A,M
030 151    223    SUB E
030 152    043    INX H
030 153    176    MOV A,M
030 154    232    SBB D
030 155    322    JNC
030 156    220    220
030 157    030    030
030 160    003    INX B
030 161    171    MOV A,C
030 162    376    CPI        /IS THE TEMPERATURE
030 163    042    042        /OVER HIGH?
030 164    322    JNC        /IF THE TEMPERATURE
030 165    173    173        /OVER HIGH, JUMP TO
030 166    030    030        /030 173
030 167    043    INX H      /IF THE TEMPERATURE
030 170    303    JMP        /NORMAL, CONTINUE
030 171    150    150        /MODIFYING DATA
030 172    030    030
030 173    076    MVI A      /FLASHING "9999" ON THE
030 174    231    231        /DISPLAY
030 175    323    OUT
030 176    004    004
030 177    323    OUT
030 200    003    003
030 201    315    CALL
030 202    000    ONESEC
030 203    034
030 204    076    MVI A
030 205    377    377
030 206    323    OUT
030 207    004    004
030 210    323    OUT
030 211    003    003
030 212    315    CALL
030 213    000    ONESEC
030 214    034
030 215    303    JMP
030 216    173    173
030 217    030    030
030 220    173    MOV A,E
030 221    221    SUB C
030 222    062    STA        /SAVE THE MODIFIED DATA
030 223    200    200        /AT THE ADDRESSES 003
030 224    003    003        /201 AND 003 200
030 225    172    MOV A,D
030 226    230    SBB B
030 227    062    STA
030 230    201    201
030 231    003    003
```

```
030 232     315     CALL      /DISPLAY THE DETECTED
030 233     000     DDSPLY    /TEMPERATURE
030 234     035
030 235     001     LXI B     /COMPARE THE DETECTED
030 236     003     003       /TEMPERATURE TO THE
030 237     000     000       /SET-POINT
030 240     041     LXI H
030 241     000     000
030 242     003     003
030 243     072     LDA
030 244     200     200
030 245     003     003
030 246     226     SUB M
030 247     137     MOV E,A
030 250     072     LDA
030 251     201     201
030 252     003     003
030 253     043     INX H
030 254     236     SBB M
030 255     127     MOV D,A
030 256     332     JC        /IF LOWER, JUMP TO 030
030 257     277     277       /277
030 260     030     030
030 261     171     MOV A,C   /IS THE DIFFERENCE
030 262     223     SUB E     /WITHIN 3°C?
030 263     170     MOV A,B
030 264     232     SBB D
030 265     322     JNC       /IF YES, JUMP TO 030
030 266     315     315       /315
030 267     030     030
030 270     076     MVI A     /IF HIGHER BY MORE THAN
030 271     200     200       /3 C, ACTUATE THE COOL-
030 272     323     OUT       /ING SYSTEM AND SAMPLE
030 273     000     000       /THE AMPLIFIED THERMO-
030 274     303     JMP       /COUPLE VOLTAGE AGAIN
030 275     033     033
030 276     030     030
030 277     171     MOV A,C   /IF LOWER, BUT WITHIN 3
030 300     203     ADD E     /°C, JUMP TO 030 315
030 301     170     MOV A,B
030 302     212     ADC D
030 303     332     JC
030 304     315     315
030 305     030     030
030 306     076     MVI A     /IF LOWER BY MORE THAN
030 307     100     100       /3°C, ACTUATE THE HEAT-
030 310     323     OUT       /ING SYSTEM AND SAMPLE
030 311     000     000       /THE AMPLIFIED THERMO-
030 312     303     JMP       /COUPLE VOLTAGE AGAIN
030 313     033     033
030 314     030     030
030 315     076     MVI A     /IF THE DIFFERENCE IS
030 316     000     000       /WITHIN 3°C, TURN OFF
```

```
030 317        323        OUT        /BOTH THE HEATING AND
030 320        000        000        /THE COOLING SYSTEM AND
030 321        303        JMP        /SAMPLE THE AMPLIFIED
030 322        033        033        /THERMOCOUPLE VOLTAGE
030 323        030        030        /AGAIN
```

DDSPLY SUBROUTINE

ADDRESS	OP CODE	MNEMONIC	COMMENT
035 000	365	PUSH PSW	/CONTEXT SWITCHING
035 001	305	PUSH B	
035 002	325	PUSH D	
035 003	345	PUSH H	
035 004	072	LDA	/TRANSFORM THE LOWER
035 005	200	200	/BYTE
035 006	003	003	
035 007	021	LXI D	
035 010	000	000	
035 011	000	000	
035 012	041	LXI H	/DECIMAL 100 (OCTAL 144
035 013	000	000	/)IS SAVED AT 036 000
035 014	036	036	
035 015	006	MVI B	
035 016	002	002	
035 017	276	CMP M	/COMPARED TO 100
035 020	332	JC	/IF < 100, JUMP TO 035
035 021	031	031	/031
035 022	035	035	
035 023	226	SUB M	/IF $\geq$ 100
035 024	024	INR D	
035 025	005	DCR B	
035 026	302	JNZ	
035 027	017	017	
035 030	035	035	
035 031	043	INX H	/DECIMAL 10 (OCTAL 012)
035 032	006	MVI B	/IS SAVED AT 036 001
035 033	011	011	
035 034	276	CMP M	/IS THE REMAIN $\geq$ 10
035 035	332	JC	/IF NO, JUMP TO 035 053
035 036	053	053	
035 037	035	035	
035 040	226	SUB M	/IF YES
035 041	117	MOV C,A	
035 042	173	MOV A,E	
035 043	306	ADI	
035 044	020	020	
035 045	137	MOV E,A	
035 046	171	MOV A,C	
035 047	005	DCR B	
035 050	302	JNZ	
035 051	034	034	
035 052	035	035	
035 053	043	INX H	/DECIMAL 1 (OCTAL 001)
035 054	006	MVI B	/IS SAVED AT 036 002
035 055	011	011	
035 056	276	CMP M	/IS THE REMAIN $\geq$ 1?
035 057	332	JC	/IF NO, JUMP TO 035 070

```
035 060        070        070
035 061        035        035
035 062        226        SUB M      /IF YES
035 063        034        INR E
035 064        005        DCR B
035 065        302        JNZ
035 066        056        056
035 067        035        035
035 070        072        LDA        /TRANSFORM THE HIGH
035 071        201        201        /BYTE
035 072        003        003
035 073        376        CPI
035 074        001        001        />1?
035 075        332        JC         /IF NO, JUMP TO 035 122
035 076        122        122
035 077        035        035
035 100        117        MOV C,A    /IF YES
035 101        024        INR D
035 102        024        INR D
035 103        173        MOV A,E
035 104        306        ADI
035 105        126        126
035 106        267        ORA A
035 107        047        DAA
035 110        137        MOV E,A
035 111        076        MVI A
035 112        000        000
035 113        212        ADC D
035 114        127        MOV D,A
035 115        171        MOV A,C
035 116        075        DCR A
035 117        302        JNZ
035 120        073        073
035 121        035        035
035 122        172        MOV A,D
035 123        267        ORA A
035 124        047        DAA
035 125        323        OUT        /DISPAYING THE 2-BYTE
035 126        004        004        /BCD AFTER TRANSFORMA-
035 127        127        MOV D,A    /TION
035 130        173        MOV A,E
035 131        323        OUT
035 132        003        003
035 133        341        POP H      /CONTEXT SWITCHING
035 134        321        POP D
035 135        301        POP B
035 136        361        POP PSW
035 137        311        RET
```

ONESEC SUBROUTINE

ADDRESS	OP CODE	MNEMONIC	COMMENT
034 000	365	PUSH PSW	/CONTEXT SWITCHING
034 001	305	PUSH B	
034 002	001	LXI B	/LOAD COUNT
034 003	144	144	
034 004	000	000	
034 005	315	CALL	/DELAY 10 mS FOR EACH
034 006	277	TIMEOUT	/COUNT
034 007	000		
034 010	013	DCX B	
034 011	170	MOV A,B	
034 012	261	ORA C	
034 013	302	JNZ	
034 014	005	005	
034 015	034	034	
034 016	301	POP B	/CONTEXT SWITCHING
034 017	361	POP PSW	
034 020	311	RET	

DATA MODIFYING POINTS FOR A K-TYPE THERMOCOUPLE

ADDRESS	DATA	ADDRESS	DATA
037 000	057	037 042	033
037 001	000	037 043	002
037 002	115	037 044	053
037 003	000	037 045	002
037 004	151	037 046	074
037 005	000	037 047	002
037 006	345	037 050	114
037 007	000	037 051	002
037 010	033	037 052	134
037 011	001	037 053	002
037 012	071	037 054	155
037 013	001	037 055	002
037 014	122	037 056	176
037 015	001	037 057	002
037 016	151	037 060	220
037 017	001	037 061	002
037 020	176	037 062	242
037 021	001	037 063	002
037 022	222	037 064	265
037 023	001	037 065	002
037 024	.245	037 066	311
037 025	001	037 067	002
037 026	267	037 070	336
037 027	001	037 071	002
037 030	310	037 072	365
037 031	001	037 073	002
037 032	332	037 074	017
037 033	001	037 075	003
037 034	352	037 076	057
037 035	001	037 077	003
037 036	373	037 100	132
037 037	001	037 101	003
037 040	013	037 102	245
037 041	002	037 103	003
		037 104	000
		037 105	000

STORED DATA FOR DDSPLY

ADDRESS	DATA
036 000	144
036 001	012
036 002	001

BIBLIOGRAPHY

Artwick, Bruce A. Microcomputer Interfacing. Prentice-Hall Inc., 1980

Azaroff, Leonid V. Introduction to Solids. Robert E. Krieger Publishing Company, 1965

Beam, W. R. Electronics of Solids. McGraw Hill, 1965

Blasewitz, Robert M. and Stern, Frank. Microcomputer Systems. Hayden Book Company, Inc., 1982

Faukenberry, Luces M. An Introduction to Operational Amplifiers. John Wiley & Sons, 1982

Millman, Jacob. Micro Electronics. McGraw-Hill Book Company, 1979

OMEGA. Complete Temperature Measurement Handbook and Encyclopedia, OMEGA Engineering Inc., 1986

Pearman, Richard A. Power Electronics, Solid State Motor Control. Reston Publishing Company, 1980

Plumb, Harmon H. Temperature, Its Measurement and Control in Science and Industry. Instrument Society of America, Vol. 4

Seippel, Robert G. Transducers, Sensors, and Detectors. Reston Publishing Company, 1983

REFERENCES

Coughlin, Robert F. and Driscoll, Frederick F. Operational Amplifiers and Linear Integrated Circuits. Prentice Hall Inc., 1982

E & L Instruments Inc. LR-36 Analog To Digital Converter Outboard, Manual. E & L Instruments Inc.

E & L Instruments Inc. MMD-1 Mini Micro Designer, Operating Manual. E & L Instruments Inc., 1976

E & L Instruments Inc. MMD-1/MI, Operating Manual. E & L Instruments Inc., 1976

Frank, Ernest. Electrical Measurement Analysis. McGraw Hill Book Company, 1959

Motorola. CMOS Data Book. Motorola Inc., Series C, 1978

Motorola. The Semiconductor Data Book. Motorola Inc., 1968

National Semiconductor. Linear Data Book. National Semiconductor Inc., 1982

PHilips. ECG Semiconductors Master Replacement Guide. Philips ECG Inc., 1982

Rice, Leslie R. SCR Designers Handbook. Westinghouse Electric Corporation, 1970

Sedra, Adel S. and Bruckett, Peter O. Filter Theory and Design, Active and Passive. Matrix Publishers Inc., 1978

Signetics. Digital, Linear, MOS Data Book. Signetics Corporation, 1982

Texas Instruments Inc. The Transistor and Diode Data Book for Design Engineers. Texas Instruments Inc., 1968

Wolf, Stanley. Guide to Electronic Measurements and Labortory Practice. Prentice-Hall Inc., 1973