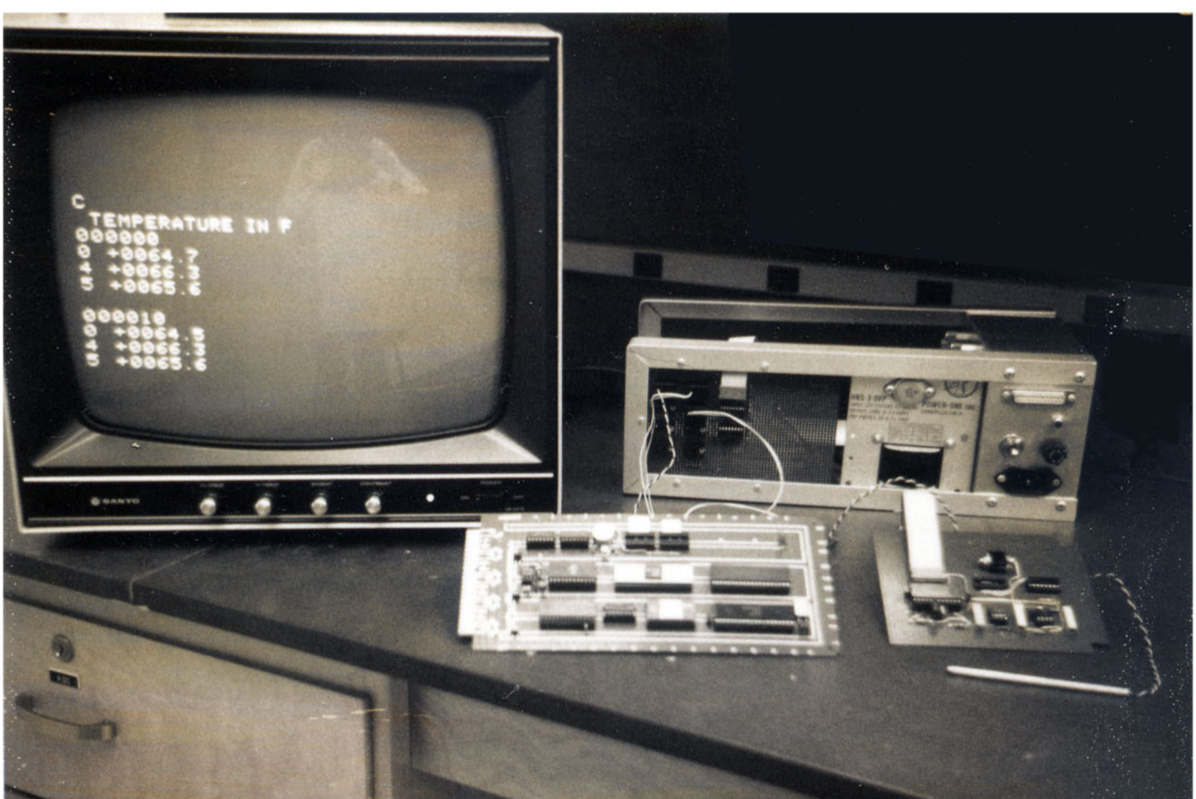
Microprocessor-Based Digital Thermometer
Michael Holley - Seattle University 1981



A Microprocessor-Based Digital Thermometer

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This project was conducted without any outside assistance.

ABSTRACT

This independent study project was to build a temperature measurement system that incorporated a microprocessor for enhanced performance. Before the project was approved, a list of performance specifications and a completion schedule were defined. Design and construction required 80 hours with an additional 160 hours to complete the software. The time schedule was met and the project completed in December 1980.

The temperature measurement system is an 8 channel digital thermometer that may run unattended, making readings at a selected rate. It might be used to monitor the temperatures at various points on a piece of equipment or in laboratory process. The system could send the measured temperatures once an hour to a printer or remote computer.

A Motorola MC6802 microprocessor was used because a development system was available. The writing of the operating software (30 pages of assembly language) without a development system would have taken much more than 160 hours. Hardware - software debug is also faster with a development system.

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I. INTRODUCTION

One of the major oversights in new product design is thermal dissipation. A package the size of a shoe box may hold ten large scale integrated circuits, a battery with charger, a printer, and a display; and consume 40 watts of power. Without proper design, the internal package temperature may rise 40°C over ambient temperature. An often omitted design check is thermal analysis of the product over the specified temperature range.

Testing the product's operation is a time consuming task. In the past, a technician would manually record the temperature and other parameters; today, costs prohibit this practice. Without some automated method of testing, the new product testing is abbreviated, and the product is sent into the field with a hope and a prayer.

To accomplish this testing, a microprocessor-controlled digital thermometer was developed. The new product testing may be done, unattended, using this digital thermometer and other recording instruments. The number of testing hours in a week increases from 40 to 168.

II. SYSTEM REQUIREMENTS

OVERVIEW: The device proposed is a 8 channel temperature monitor. The device must be able to read selected channels with selected delays between readings and shall be controlled by a remote computer or a remote terminal. The device shall make readings upon demand or run unattended, making readings at the selected rate.

OPERATION: The Temperature Monitoring System shall be programmed with the following commands.

1. Read a single channel upon demand.

2. Set period of delay for use in continuous read mode.

3. Select channels to be read in the continuous read mode.

4. Select Fahrenheit or Celsius scale.

5. Enter the continuous read mode.

6. Reset or exit continuous read mode.

The communication with the remote computer or terminal shall be with serial ASCII using a RS-232 interface. The bit rate shall include 110, 300, and 1200 baud. The operator shall be able to install the temperature transducers and the transducers shall be interchangeable between channels without recalibration.

III. DESIGN OVERVIEW

A controller is required to meet the operational specifications. This could be done with a small desk-top computer or with a small microprocessor system. The microprocessor has a lower hardware cost, but a higher software cost than the desk-top computer. The software development is a one time cost, so if the thermometer were to be put into production the microprocessor would be the choice.

There are three types of low cost temperature transducers; thermocouples, thermistors, and semiconductor junctions. The thermocouples are the only transducer that will operate at high temperatures (2000°C), but this thermometer doesn't require that range. All three are nonlinear, but the semiconductor can be linearized with circuitry on the same piece of silicon. With the signal conditioning performed at the transducer high quality relays are not required for multiplexing the transducers.

The block diagram of the digital thermometer is shown in Figure 1. A microprocessor is interfaced to the operator's terminal, an analog to digital converter (A/D), and the probe selector. Each block gives a description, a part number, and the address on the microprocessor bus.

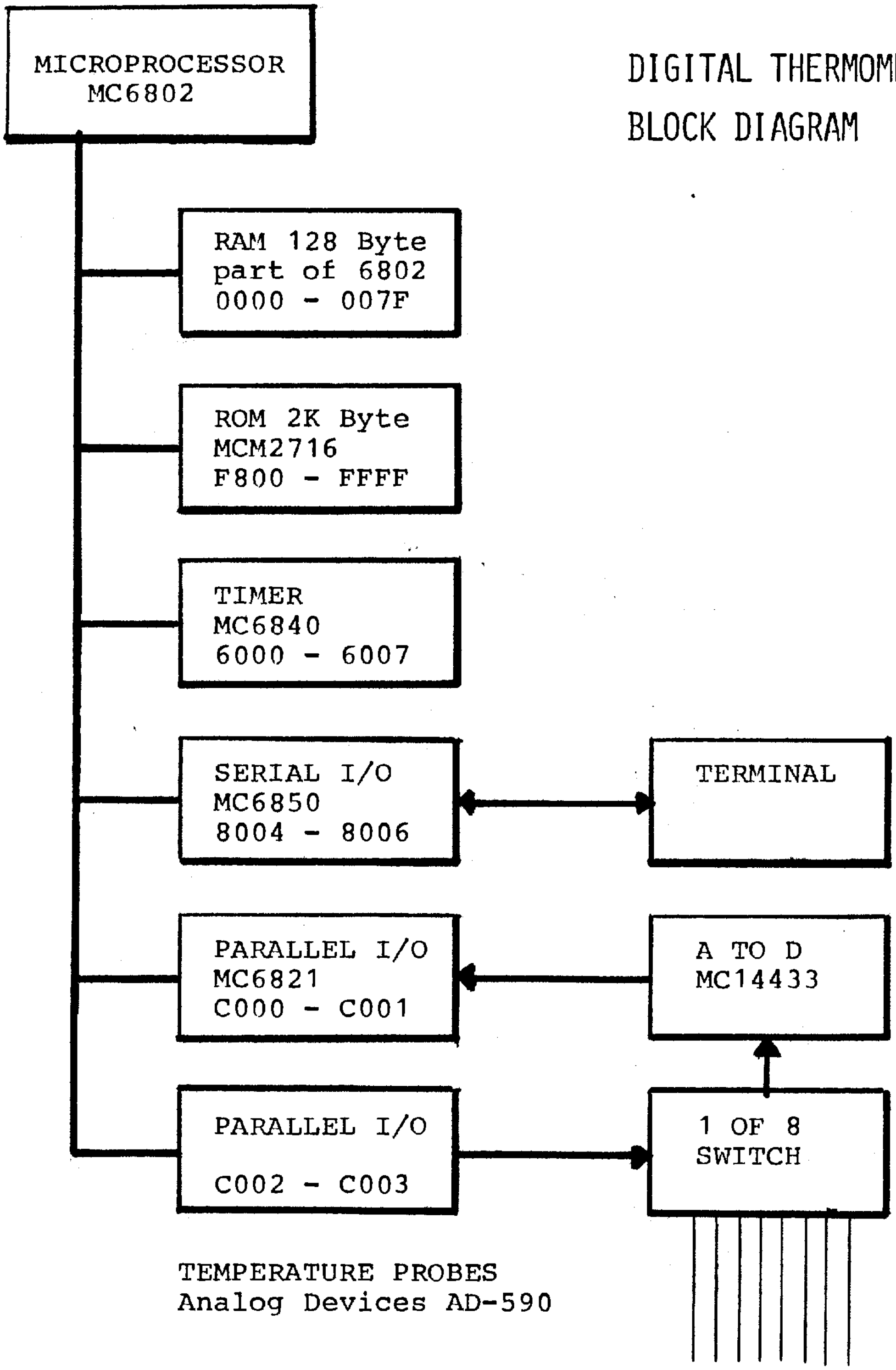

Figure 1 Digital Thermometer

IV. TEMPERATURE TRANSDUCER

A two-terminal integrated circuit (AD-590) that acts as a temperature-dependent current source was chosen for the system temperature transducer [1]. This transducer passes 1µA/°K over a range of 218°K to 423°K (-55°C to 150°C) with a supply voltage of 4 to 30 volts. The fact that the output is a current, and the transducer is insensitive to the terminal voltage, makes the transducer easy to use, even over hundreds of feet of wire.

The transducer uses a fundamental property of the silicon transistor to produce a voltage proportional to temperature. That is, the difference between the base-emitter voltage of two transistors operating at a constant ratio of collector current densities will be directly proportional to absolute temperature. The voltage is equal to $(kT/q)(\ln r)$; where k, Boltzman's constant, q, the charge of an electron, and r, the ratio of current densities, are constants [2].

The temperature dependent voltage is converted to a current by low temperature coefficient thin film resistors. The transducer's output current is a multiple of this current. The scale factor of 1 µA/°K and the offset at 25°C are adjusted by a laser trim process of the resistors while the IC is still in wafer form. After final assembly, 100 percent of the devices are tested at -55°C, 25°C, and 125°C;

over one-half of the units have calibration errors of less the 1°C [3].

The voltage compliance (+4V to +30V) and the reverse blocking charactertic (-20V) of the transducer allows it to be powered from +5V CMOS logic. This eliminates the need for expensive low-thermal relays; low cost CMOS analog multiplexers may be used to switch the transducer's output.

The transducer is available in unpackaged chip form, in two transistor style packages, or in a stainless steel tubular probe. A transducer in a TO-52 transistor case with an accuracy of 2.0°C, a repeatability of 0.1°C, and a nonlinearity of 0.8°C costs about $5. The accuracy specification is after the user corrects the error at a single temperature (25°C).

V. ANALOG TO DIGITAL SYSTEM

The analog to digital system consist of a probe selector, a current to voltage converter, and an analog to digital converter. Figure 2 is a block diagram of the analog to digital system

The temperature transducers have a reverse blocking characteristic (similiar to a diode) that permits easy multiplexing. All of the positive terminals are connected to the voltage-to-current converter while the negative terminals are connected to a -5V source through a CMOS 1-of-8 analog switch. Only one transducer has power applied, and the other seven are effectively out of the circuit.

Selection of the transducer is controlled by three data lines from the system controller interface.

Each temperature transducer has an unique calibration offset that must be corrected. Using diode encoding, the offset error is stored in the probe's connector. A probe may be connected to any channel and the system controller will read that probe's correct offset error. The range of errors that may be coded is +/- 8.5 degrees with 0.5 degree resolution.

The "Kelvin" current is changed to a "Celsius" current by summing a 273.2 microamp current of opposite polarity.

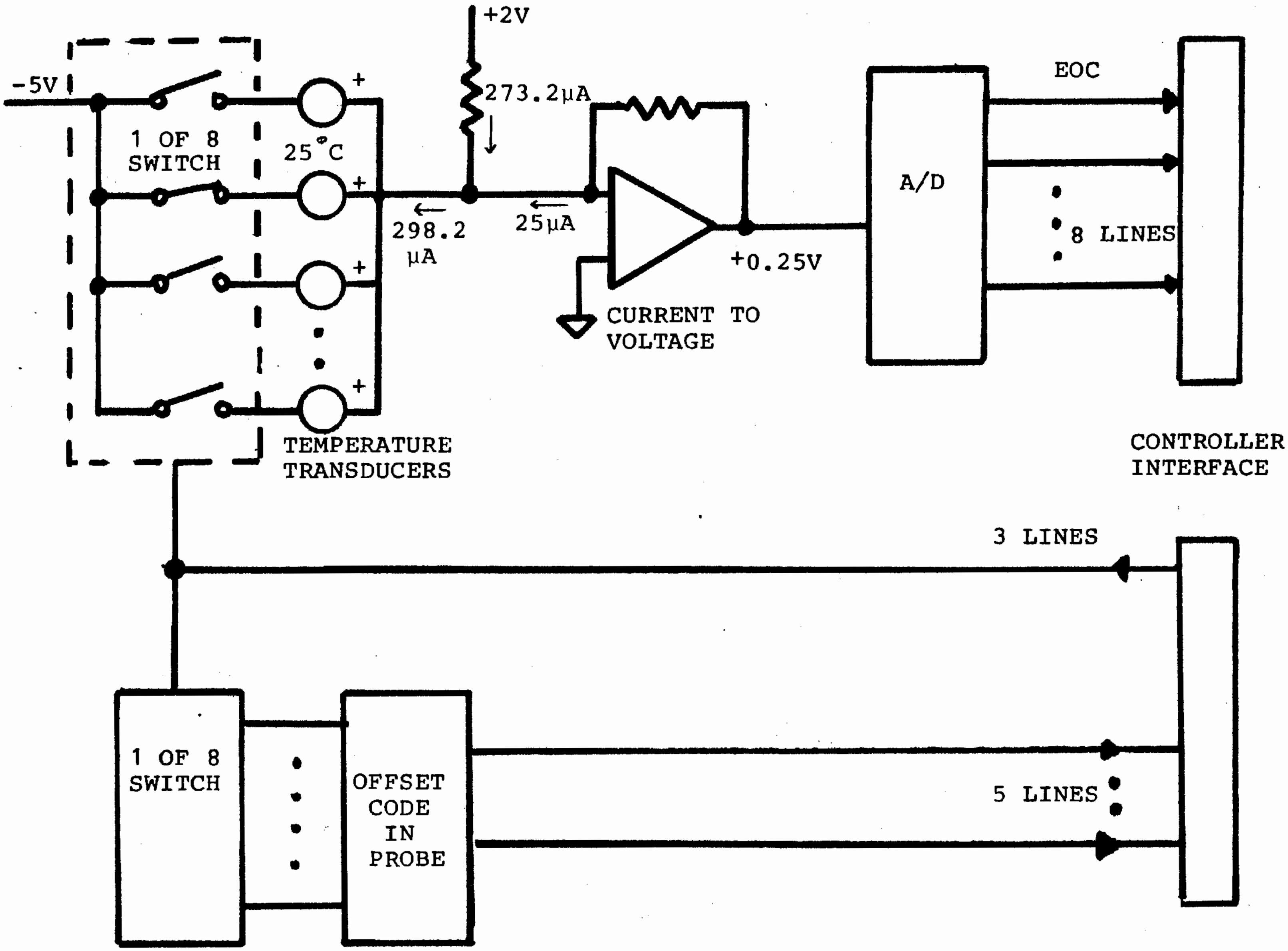

FIGURE 2 ANALOG TO DIGITAL SYSTEM

This reduces the magnitude of the analog signal that must be digitized. (ie 298.4 degrees Kelvin equals 25.2 degrees Celsius.) An operational amplifier (op-amp) is used to convert the output current of the temperature transducer to a voltage. The output of the op-amp is 10 mV per degree Celsius so the -55 to +150 degree input yields a -0.55 to +1.50 volt output.

The system performance specifications require an A/D with 10 or more bits resolution. Either successive approximation or dual-slope integrating A/D converters would provide this 10 bit resolution. The dual-slope converter is inherently noise-immune because the input signal is conditioned by an integrator. The integration period slows the converter but speed isn't important in a temperature measurement.

A 3 1/2 digit (12 bit) dual-slope converter was selected (MC14433) [4]. A +/- 2.000 volt full scale input range and a 4 conversions per second rate was chosen. The converter's output consist of 4 BCD data lines, 4 digit select lines and a end of conversion strobe.

VI. MICROPROCESSOR

The heart of the system controller is a 8-bit microprocessor, a MC6802 [5]. Upon command, the microprocessor will select the desired transducer, read the analog to digital converter, process the digitized reading, and send the temperature reading to the operator's terminal. A block diagram of the entire system is shown in Figure 1.

The controller was designed for low volume production, with the option of using a single chip microcomputer, MC6801, if high volume production was desired [6]. At present, the controller requires five major IC's that could be replaced by a single custom programmed microcomputer IC. Although the MC6800 series microprocessor was used, any of the popular 8-bit microprocessors would meet the system requirements.

For data storage, the microprocessor has 128 bytes of read/write Random Access Memory (RAM). The control program is stored in a 2K byte Erasable Programmable Read Only Memory (EPROM) that allows easy program modification. If the future program requirements exceed the 2K byte EPROM (MCM2716), a 4K byte EPROM (MCM2732) may be used [7] [8].

The programmable timer (MC6840) has three 16-bit binary counters, that may be used for interval measuring, event counting, or generating output signals [9]. Counter 1 generates a 4800 Hertz square wave for the 300 baud serial interface. To use a 110 baud or 1200 baud terminal, the counter may be reprogrammed by a simple software command. Counter 3 utilizes a selectable divide by eight prescaler to produce a 1 Hertz output by counting the 1 MHz system clock. The 1 Hertz signal is used by the system for timekeeping. The delay, in seconds, between temperature readings is controlled by counter 2.

An Asynchronous Communications Interface Adaptor (ACIA), MC6850, provides the data formatting and control for the serial interface [10]. The 8-bit parallel data of the microprocessor system bus is serially transmitted and received by the ACIA with proper formatting and error checking. The TTL levels of the ACIA are translated to RS-232 levels by external buffers.

A Peripheral Interface Adapter (PIA), MC6821, is used to interface the analog to digital converter (A/D) and the probe selector to the microprocessor [11]. The PIA has two 8-bit bidirectional data ports (A and B) and four control lines. Each line of the data port may be programmed as an input or an output. The A/D converter's "end of conversion" strobe is connected to a PIA control input, while all 8 lines of port A are used to input the A/D's readings. Three output lines of Port B select the temperature probe while the other 5 lines input the probe offset code.

VII. SOFTWARE

The key to a successful microprocessor system is the operating software. The interchangeability of the temperature probes, the transducer error correction and other system enhancements are due to software, not additional hardware. The entire operating system was written in assembly language, and requires only 1.5K bytes of ROM and 100 bytes of RAM. The program consists of three modules; a monitor, the thermometer program, and a math library.

The monitor module handles system initialization, the input-output routines, and system debug. On a power-up or system reset, the peripheral interface IC's must be initialized. For example, one section of the timer needs to be programmed to produce the correct baud rate for the serial interface. The other software modules route all input and output through the monitor routines. This way the input could be changed from the terminal to a local keypad with one software change to the monitor. If each sub-routine handled input-output, many software changes would be required. The monitor also has memory examine and change functions that aid in hardware and software troubleshooting.

The digital thermometer module contains all the command functions and a routine to call the functions. When the "T" command is entered, the "Read Single Temperature" sub-routine is executed, then the program waits for the next command. The commands are explained in the System Operation Appendix.

The math routines simulate a simple 5-digit calculator. The calculator has a 3 register stack, addition and subtraction, multiplication and division by 10, and binary-decimal conversions. The math operations use 6-byte Binary Coded Decimal (BCD) registers, but storage is done with a 3-byte packed BCD form. Negative decimal numbers are represented in the ten's complement form [12]. The 16-bit binary conversions are needed to communicate with some peripheral interfaces, such as the programmable timer.

The reading from the analog to digital converter is the "Celsius" voltage without the offset correction. This reading is entered on the stack along with the probe offset. An addition operation yields the corrected Celsius temperature. Conversion to Fahrenheit requires a multiplication and an addition, equation 1. To reduce the program length, full multiplication was omitted; only decimal shifting is used, equation 2.

$$F = C \times 1.8 + 32 \qquad (1)$$

$$F = (\ (C+C) \times 10 - (C+C) + 320)\ /\ 10 \qquad (2)$$

If future applications require full multiplication, the routines can be added; presently this limited form meets all requirements.

VIII. RESULTS AND SUMMARY

All the design goals and specifications given in section II were met. The conversion rate of the A/D was adjusted to 4 readings per second. With a 18 readings per second rate, the system didn't meet the repeatability specification. Since the slower rate met all requirements, no futher rates were tried. As a performance check, four probes were compared with a laboratory grade glass thermometer (ASTM 63-C) in a water bath. Over a range of $0^{\circ}C$ to $30^{\circ}C$ the probes tracked each other and the thermometer to within $1^{\circ}C$. In still air the probe's self-heating caused about a 1 degree temperature rise.

This digital thermometer demonstrates the improvements in temperature logging that are possible with solid state temperature transducers and microprocessor controllers. With automated measurement equipment, testing may be conducted unattended; greatly reducing the test cost.

The next project for this thermometer will be the monitoring of the room temperatures in a house. A real-time clock with calender is being added to the system along with an input to monitor the furnace activity. The information collected will be used to design a microprocessor-controlled thermostat for the house.

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APPENDIX

SUMMARY OF PROGRAMS

DIGITAL THERMOMETER PROGRAM

F800 to FAAD   685 Bytes

COMMAND LOOP
Select Fahrenheit or Celsius
Read single channel
Set delay between readings
Select channels to be read
Start continuous reading

MATH ROUTINES

FC00 to FDB4   436 Bytes

BINARY CODED DECIMAL ROUTINES

Clear Registers
Push number on stack   (ENTER)
Add two numbers
Multiply register by 10
Divide register by 10
Complement register (negative numbers)

Convert binary to BCD
Convert BCD to binary

MONITOR ROUTINES

FE00 TO FF61   353 Bytes

Initialize system
Input characters
Output characters
Print messages
Examine and change Memory
Jump to another program

RESTART VECTORS

Digital Thermometer Commands

A - Enter the thermometer program

T N - N=0-7. Read a single channel.

D N - N=10-9999. Set delay in seconds.

S xxxxxxxx - x=1 or 0. Select channels to be read in continuous read mode. ie. S 11100001 will turn on channels 0,1,2,7, the other will be skipped.

M x - x=C or F. Select Fahrenhiet or Celsius mode

C - Enter continuous read mode

Control C - Exit continuous read mode

X - Exit thermometer program

Monitor Commands

hhhh - a four digit hex address the user enters.
HHHH - a four digit hex address the monitor prints.
dd - a two digit hex data byte the user enters.
DD - a two digit hex data byte the monitor prints.

M hhhh DD dd - Examine the data at location hhhh, If the data is to be changed enter two hex digits. If the data is correct just enter a space or any non hex character (ie 0-9 A-F).

N HHHH DD dd - This will examine the next memory location.

B HHHH DD dd - This will back up the memory pointer and examine the memory location before.

V HHHH DD dd - This examines the same memory location.

J hhhh - Jump to the address given.

The following section describes the operation of the digital thermometer. The temperature transducers may be clamped or epoxied in position on the unit under test. The probes are then connected to the rear panel of the controller. Any probe may be connected to any channel; the calibration correction is encoded in the probe's connector. The operator controls the digital thermometer from the keyboard of a video or printing terminal.

DIGITAL THERMOMETER OPERATION EXAMPLE

TERMINAL DISPLAY	COMMENTS
M F	Fahrenheit Mode
T 1 +073.7	Read channel 1
M C	Celsius Mode
T 1 +023.2	Read channel 1
D 30	30 second delay between readings
S 11001000	Select channels 0,1, and 5
C	Enter continuous reading
TEMPERATURE IN C	
000000	Total time elapsed
0 +023.6	
1 +023.3	
5 +037.4	
000030	Next set of readings
0 +023.5	
1 +023.2	
5 +038.1	
000060	60 Seconds elapsed
0 +023.5	
1 +023.3	
5 +038.9	
(Control C)	Break reading cycle
T 0 +023.6	Read single channel

PERFORMANCE:

1. Temperature measurement range -25 to +135 degrees C.

2. Temperature accuracy of +/- 3 degrees C.

3. Temperature repeatability of +/- 0.3 degrees C.

4. Calibration cycle of 6 months or greater.

5. Measurement time for 8 channels 10 seconds or less.

6. Delay range of 10 seconds to 1 hour.

7. Delay accuracy of +/- 0.025% per day.

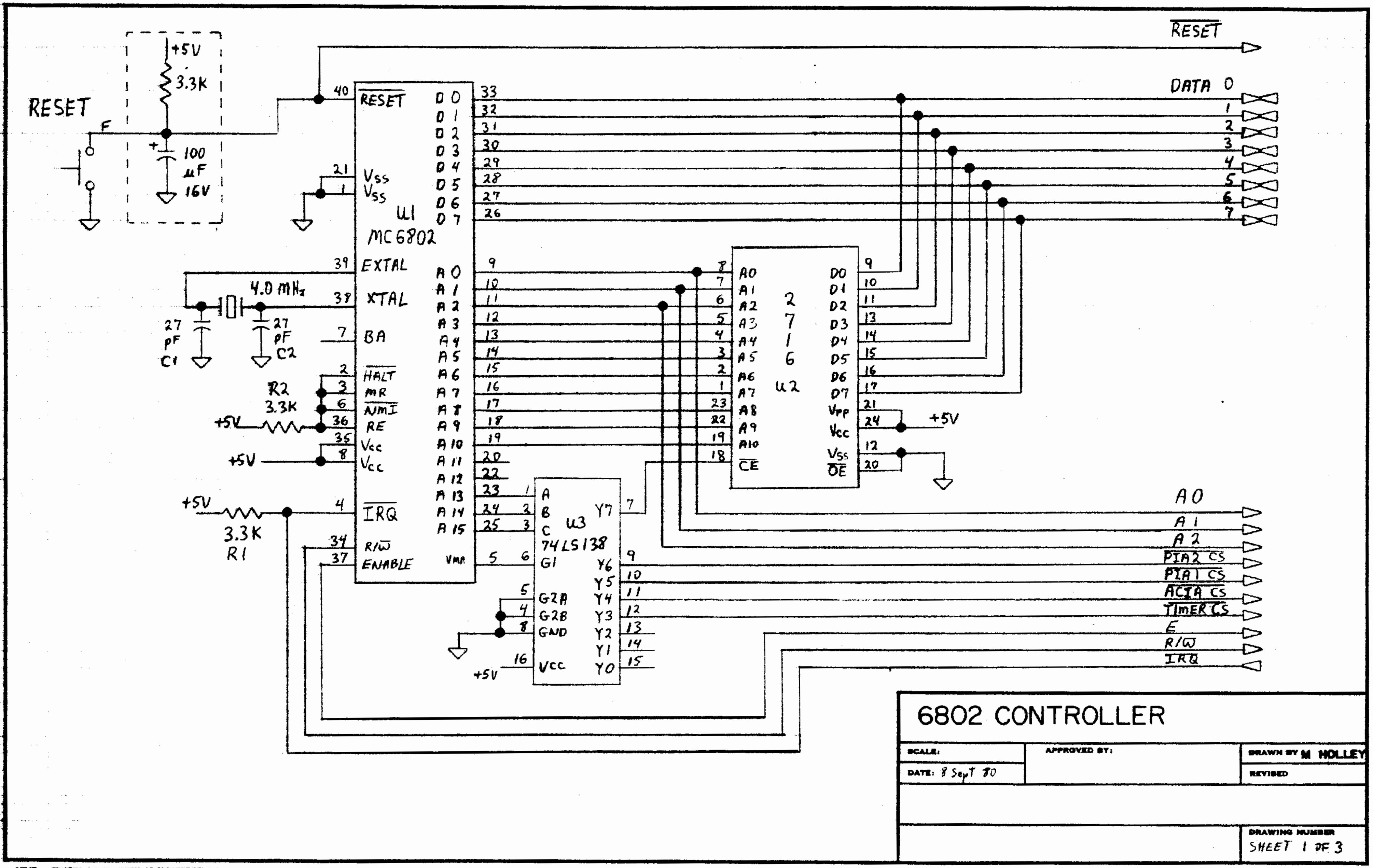
8. Temperature transducers shall operate up to 100 feet from control unit.

9. The temperature transducer shall operate in air or in contact with materials at ground potential. The transducer shall have a still air thermal time constant of 60 seconds or less.

10. The temperature transducer shall have a replacement cost of $50 or less.

11. The environment for the control unit shall be from 0 to 50 degrees C.

12. The power available is 120 volts, 60 cycle, 5 watts.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+5V
3.3K
100 µF 16V
U1
MC6802
RESET
Vss
Vss
EXTAL
XTAL
BA
HALT
MR
NMI
RE
Vcc
Vcc
IRQ
R/W
ENABLE
VMA
4.0 MHz
27 pF C1
27 pF C2
R2 3.3K
3.3K R1
2716
U2
CE
Vpp
Vcc
Vss
OE
U3
74LS138
G1
G2A
G2B
GND
VCC
DATA 0
A0
A1
A2
PIA2 CS
PIA1 CS
ACIA CS
TIMER CS
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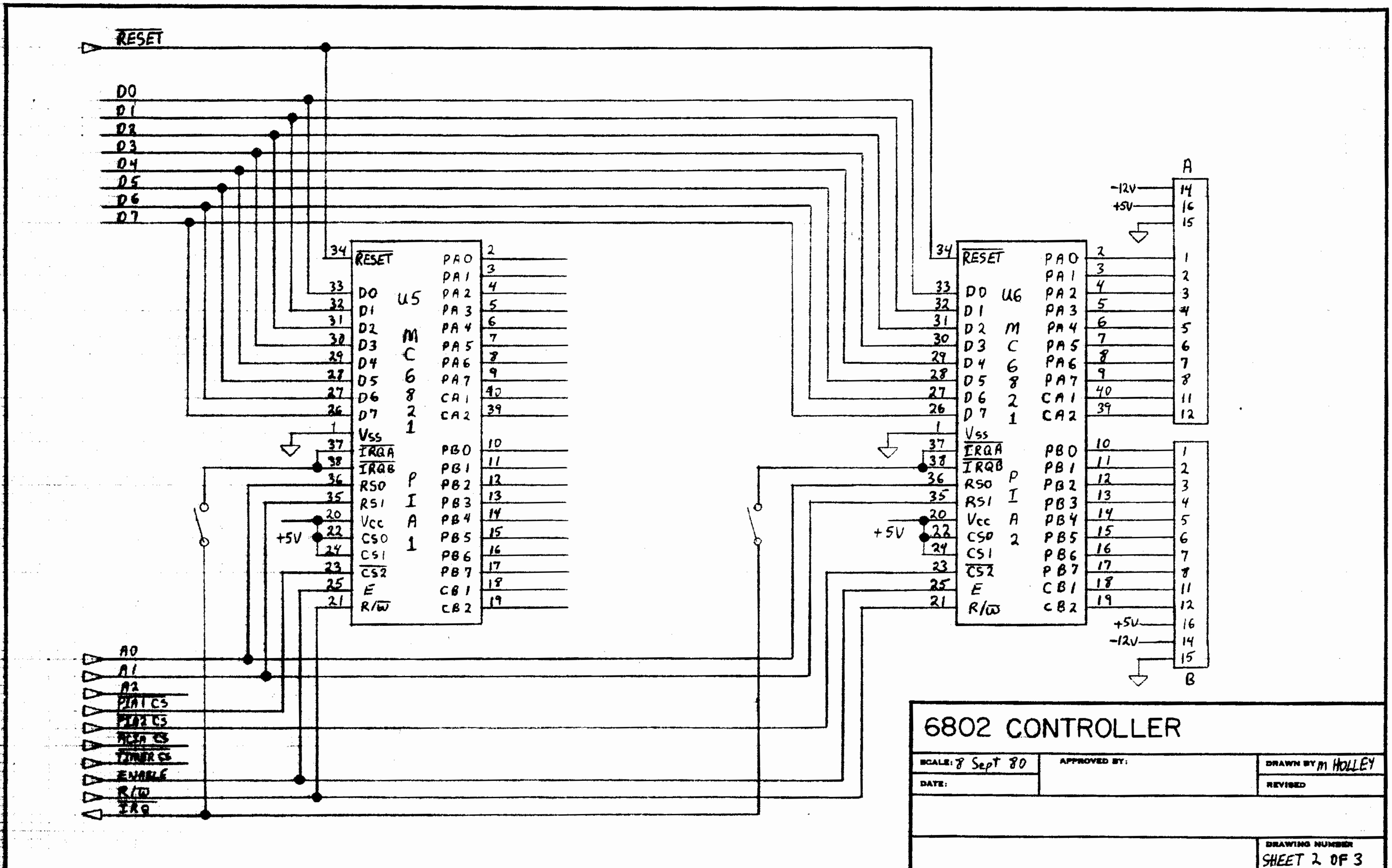

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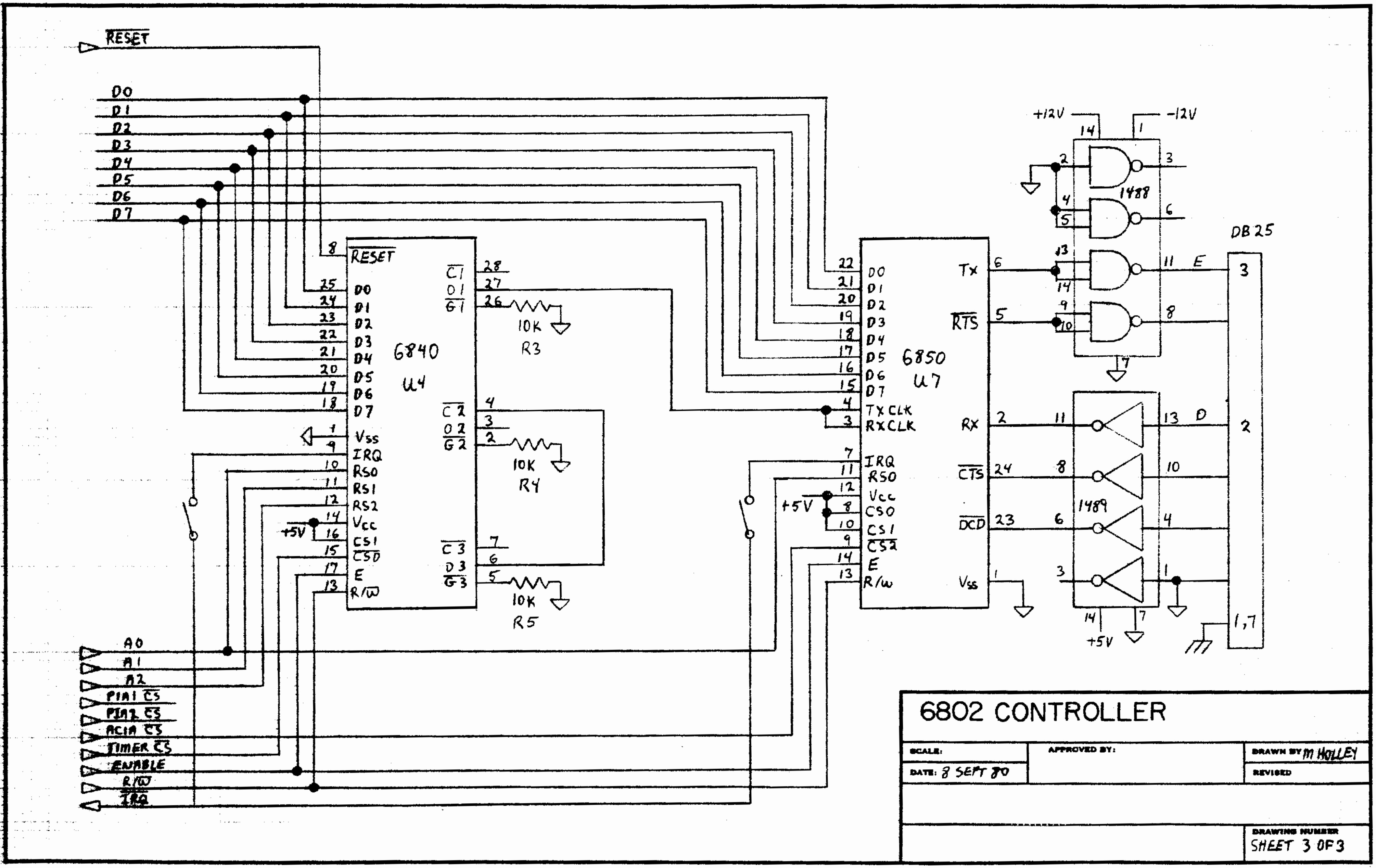

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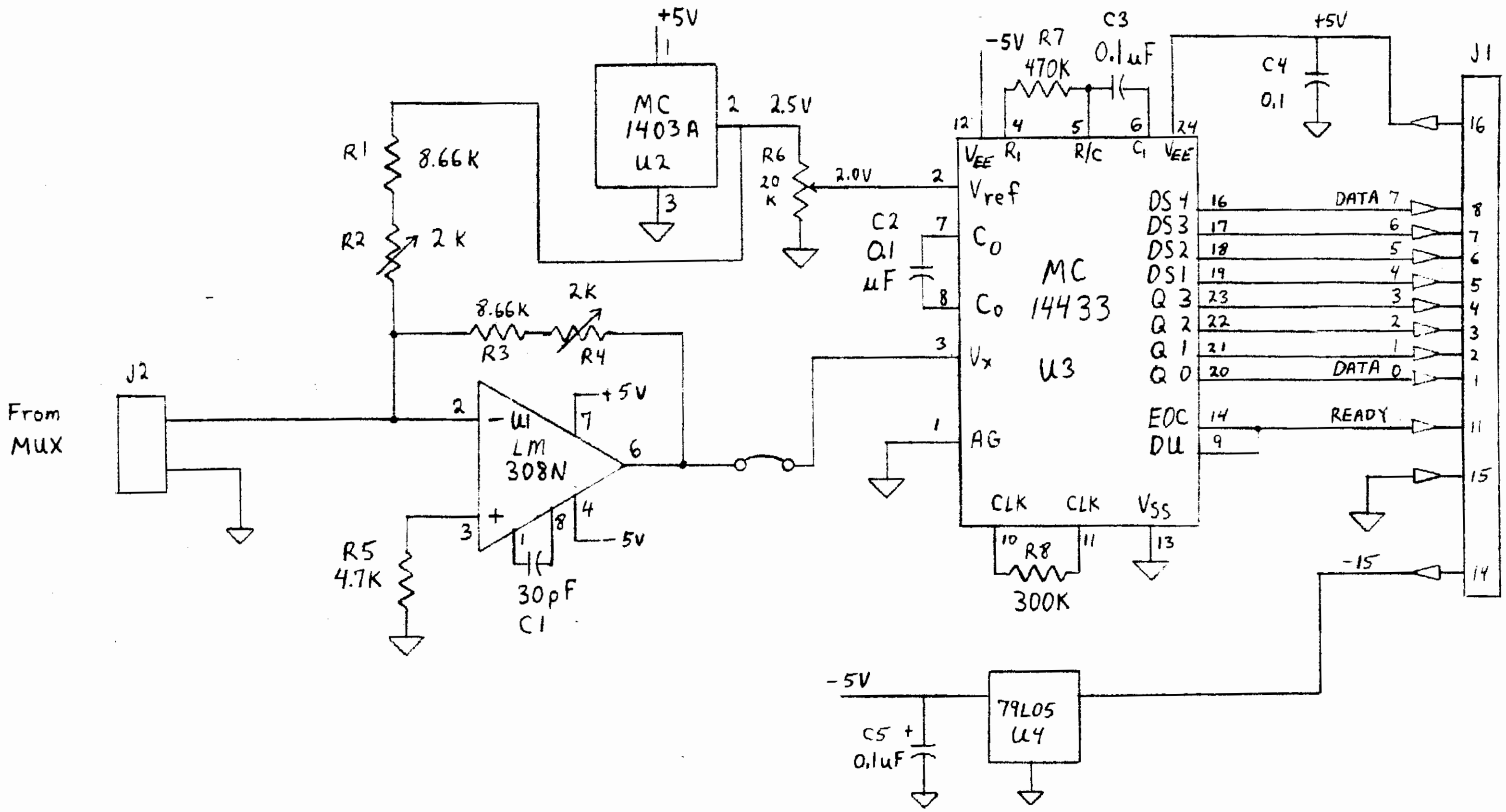

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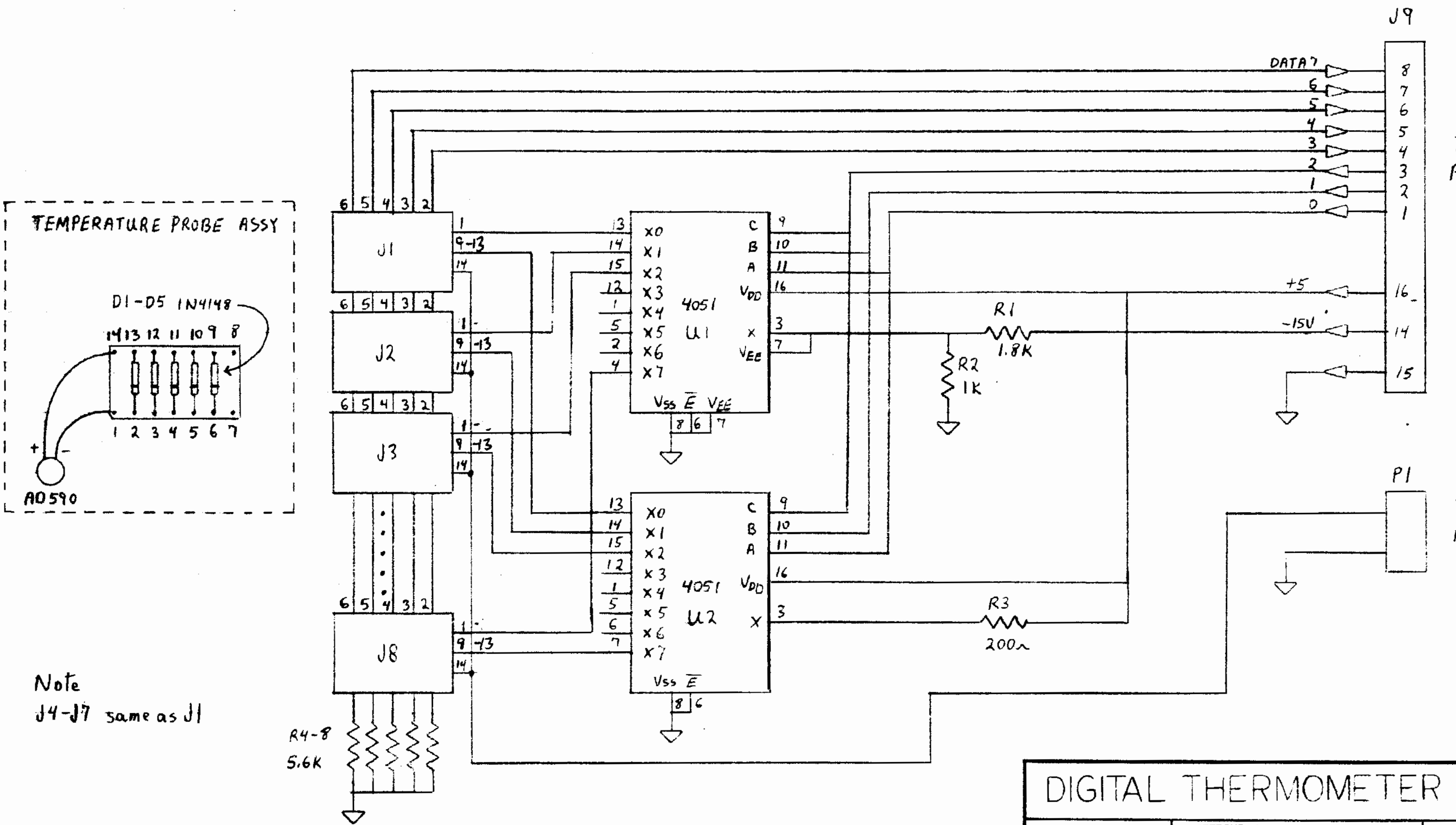

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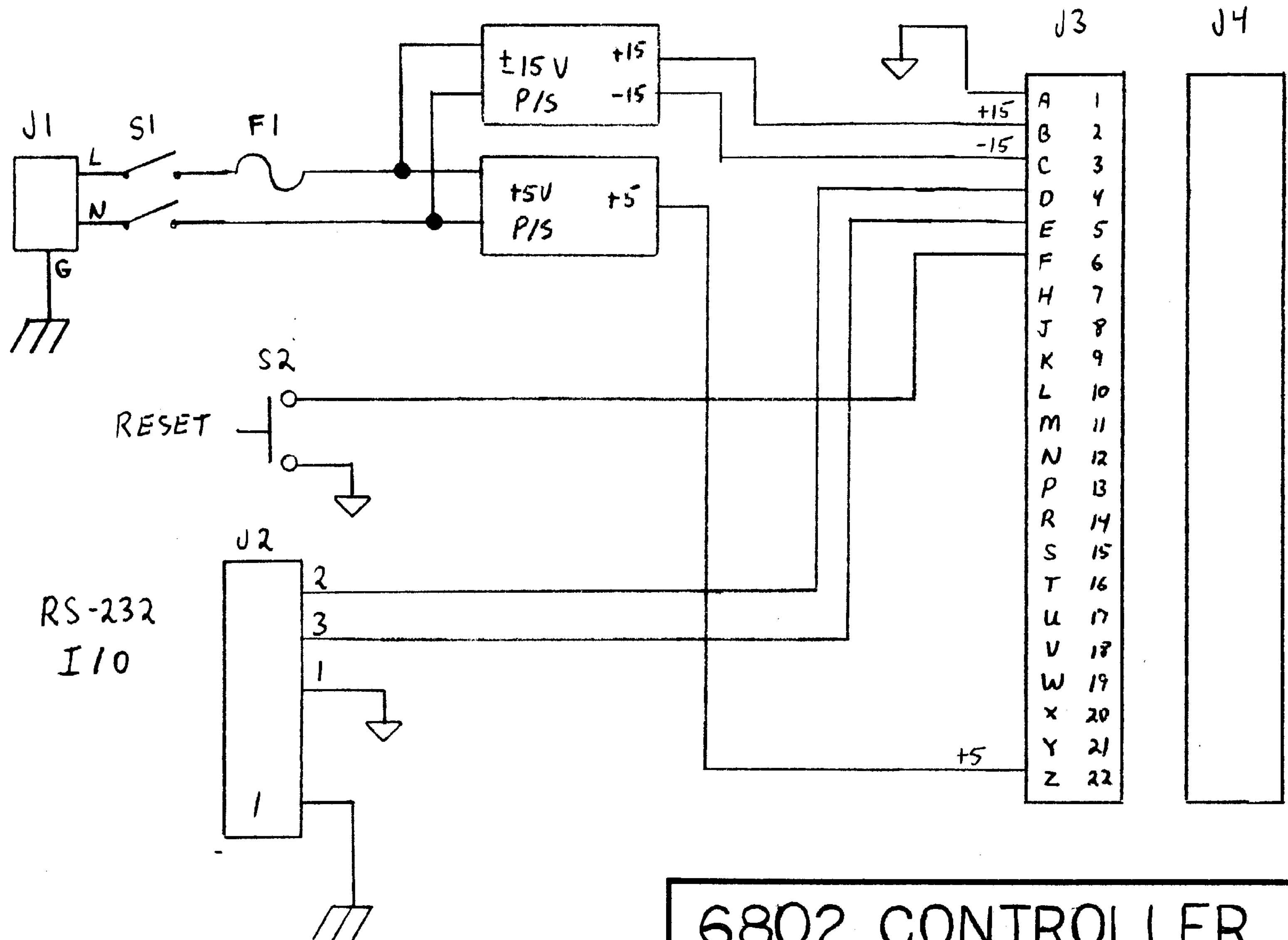

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