

## Lab 7f Temperature Data Acquisition System

This laboratory assignment accompanies the book, *Embedded Microcomputer Systems: Real Time Interfacing*, Second edition, by Jonathan W. Valvano, published by Thomson, copyright © 2006.

- Goals**
- Study ADC conversion, Nyquist Theorem, Valvano Postulate,
  - Develop a temperature measurement system using a thermistor,

- Review**
- Operation of the ADC system in the 9S12C32 data sheet,
  - Data sheets on the TLC2274 quad op amp IC, and AD623 instrumentation amp
  - Valvano Chapters 11,12 on thermistors, analog amplifiers, analog low pass filters, and ADC's, data acquisition systems.

- Starter files**
- OC, ADC, LCD, therm10.xls, lpf.xls

### Background

This experiment will use the 10-bit ADC converter on the 9S12 to construct a digital thermometer. You are free to choose any the temperature range that suites your experimental conditions (e.g., 10 to 40 °C). The current temperature will be displayed as a fixed-point number on the LCD. Your resolution of temperature measurement should be at least 0.1 °C. However, it is appropriate to use the 0.01 fixed-point routines developed in Lab 1. The temperature component is 0 to 10 Hz.

Figure 7.1 shows the data-flow graph of the temperature data acquisition system. The thermistor converts temperature to resistance, the analog amp and filter convert resistance to 0 to +5V analog voltage, and the ADC converts analog voltage to 10-bit integer. The periodic ISR creates the real time sampling, and data is passed to the foreground using any appropriate data structure (shown as **Data** in Figure 7.1). The main program converts integer to fixed-point data using a table lookup-interpolation scheme. The results are displayed on the LCD.

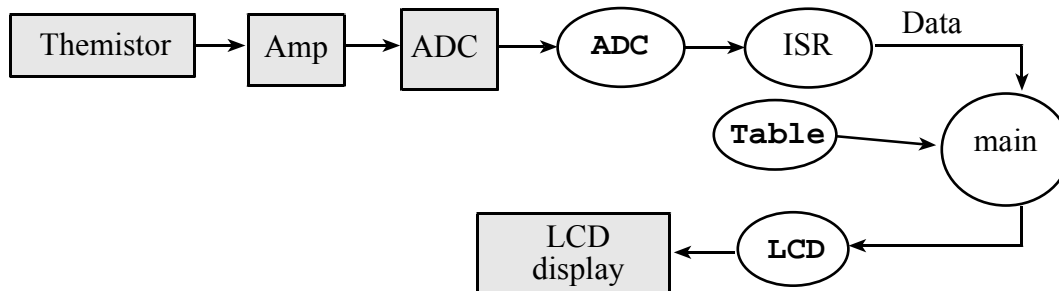


Figure 7.1. Data-flow graph of the data acquisition system.

Figure 7.2 shows one possible call-graph. Each of the modules (**LCD**, **ADC**, **Data**) has separate header and implementation files. Notice the main program does not directly access the **ADC** or **LCD** hardware. The module **Data** can employ any appropriate method to pass data from background to foreground.

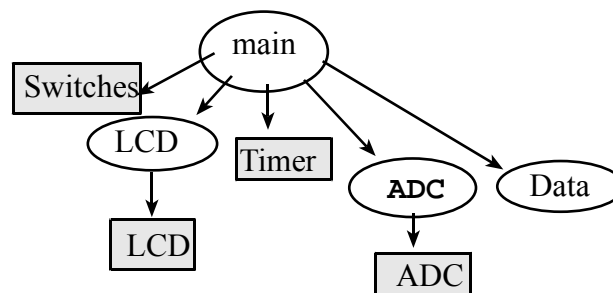


Figure 7.2. One possible call-graph of the data acquisition system.

Figure 7.3 shows a typical multichannel data acquisition system. The transducer converts a signal into a resistance. The bridge converts the resistance into a voltage. The amplifier output matches the full-scale range of the

ADC. A low-pass analog filter, with a cutoff frequency of about  $\frac{1}{2}$  the sampling rate, removes high frequencies that might otherwise cause aliasing. A low-pass analog filter will be implemented in this lab.

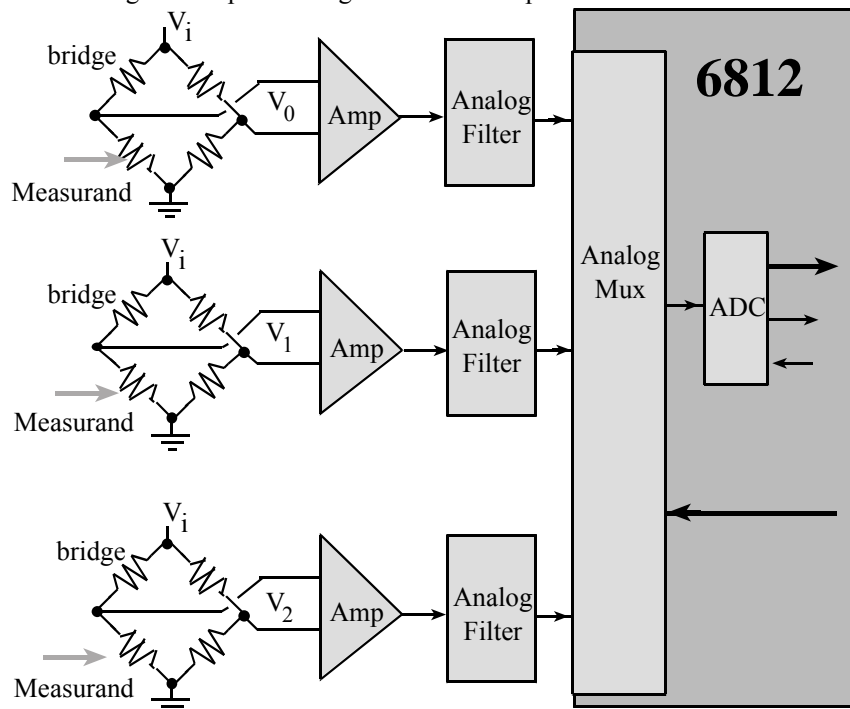


Figure 7.3. Block diagram of a multiple channel data acquisition system.

### 1. Temperature-Resistance Calibration of the Thermistor:

The thermistor resistance varies nonlinearly with its temperature. It is very important to use temperature units of Kelvin in this equation and not °C.

$$R = R_0 e^{+\beta/T} \quad (\text{where } T \text{ is temperature in degrees Kelvin})$$

The thermistors in this lab have a resistance of about 30 k $\Omega$  at 25 °C.

### 2. Choose a sampling rate

In this lab, we will process temperature signals (0 to 10 Hz). According to the Nyquist Theorem, we need a sampling rate greater than 20 Hz. Output compare interrupts will be used to sample the ADC in a background thread. This high priority interrupt will establish the sampling rate. This selection of sampling frequency will affect the design of analog and digital filters. So, when you change the sampling rate, you will have to redesign the filters.

**Nyquist Theorem:** If  $f_{\max}$  is the largest frequency component of the analog signal, then you must sample more than twice  $f_{\max}$  in order to faithfully represent the signal in the digital samples. For example, if the analog signal is

$$A + B \sin(2\pi ft + \phi)$$

and the sampling rate is greater than  $2f$ , you will be able to determine A, B, f, and  $\phi$  from the digital samples.

**Valvano Postulate:** If  $f_{\max}$  is the largest frequency component of the analog signal, then you must sample more than ten times  $f_{\max}$  in order for the reconstructed digital samples to look like the original signal when plotted on a voltage versus time graph.

### 3. Hardware Interface

Figure 7.4 shows one possibility for the analog electronics of the digital thermometer. You will add an analog filter in this lab. Choose the cutoff frequency of the LPF to be about  $\frac{1}{2}$  the sampling rate. The amplifier should convert the entire temperature range into the 0 to +5 V ADC range. Because you are using rail-to-rail op amps, the entire system can be powered by a single +5 V supply. PLEASE DO NOT USE +12 OR -12 V SUPPLIES IN THIS LAB. If you have received free samples from Analog Devices, TI and Maxim, you may design

your system using state of the art components. The gain of the AD623 or AD627 amplifier is determined by the resistor  $R_G$ .

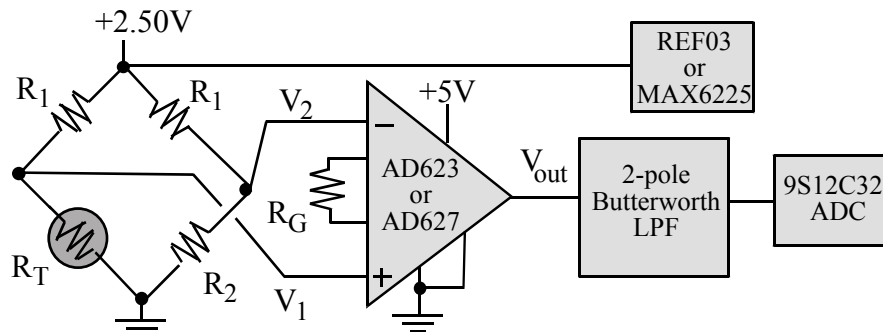


Figure 7.4. Possible thermistor interface (easy to construct, but more expensive).

We need an instrumentation amp (premade or built) because of its high input impedance and good CMRR. This semester, there are AD623 instrumentation amplifiers that can be checked out of the second floor lab. You may wish to build your own instrumentation amplifier using 3 op-amps, as shown in Figure 7.5. The gain of the 3-op-amp instrumentation amplifier is a function of the resistors  $R_3$ ,  $R_4$ ,  $R_5$  and  $R_6$ . The TLC2274 operates rail-to-rail, which means its output can swing all the way from 0 to +5 V. The TLC2274 can operate on a single +5V supply. *In fact, if you connect it up to the usual +12 –12 V supplies, you will damage the device and damage your 9S12.*

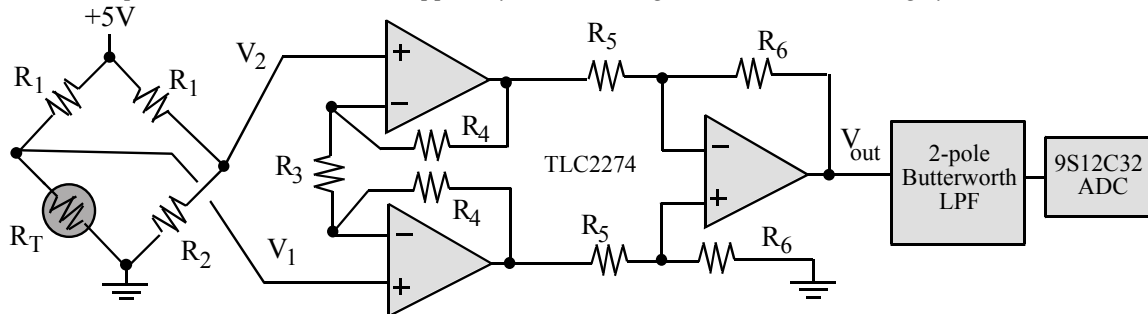


Figure 7.5. A good thermistor interface (harder to construct, but cheaper to build).

The advantage of using an instrumentation amp (with its high  $Z_{in}$ ) is you can analyze the transfer function from  $R_T$  to  $V_1$  considering only the bridge input (+2.50 or +5V),  $R_1$  and  $R_T$ . Normally, the  $R_1$  resistor in the bridge is chosen large enough to prevent self-heating the thermistor. Assume the dissipation constant to be about  $1 \text{ mW}/^\circ\text{C}$ . Limit the thermistor power to 0.1 mW so that the self-heating error is below  $0.1^\circ\text{C}$ . The  $R_2$  resistor in the bridge establishes one of the extreme values of the temperature range. For example, when the thermistor resistance,  $R_T$ , equals  $R_2$ , then the bridge output voltage is 0. The gain of the differential amplifier, along with the ADC range (0 to +5 V in our case) will determine the temperature range of the system.

#### 4. Software Conversion:

Using the calibration data, the nonlinear thermistor equation, the characteristics of your analog circuit and the response of the 9S12's ADC, determine the ADC output sample for each temperature for about 5 to 10 temperature points within your selected temperature range. There is an Excel spreadsheet to assist you. Show both, a table of figures and a plot of this data. Include appropriate intermediate voltages in the table (e.g., thermistor resistance, bridge output, and analog circuit output.) Design a software conversion routine that calculates temperature from the ADC sample. You should consider various methods:

- linear equation (don't use because it has errors too large),
- nonlinear equation,
- large table lookup (one entry for each ADC value, i.e., 1024 entries),
- small table lookup ( $\approx 16$  entries) with linear interpolation in between.

The 9S12 has special table lookup and interpolation op codes, so you may wish to consider writing the conversion in assembly language. See the **TBL.RTF** and **ETBL.RTF** examples on the **TEaS** simulator.

#### 5. Software:

The program will continuously sample the ADC at a sampling frequency,  $f_s$ , selected in part 2. The ADC must be implemented using interrupts. The main or foreground thread will calculate temperature from the ADC sample, and then display the measured temperature on the LCD display. The LCD may be too slow to be able to erase and redraw each measurement. Rather, it will be faster to move the LCD cursor and redraw only the new temperature measurement.

### Preparation (do this before your lab period)

1. Perform a very crude temperature calibration experiment with two points somewhere in your temperature range of 10 to 40 °C. The thermistor resistance varies nonlinearly with its temperature. For example, the skin temperature in the axilla region (arm pit) is about 36°C=309K, and the room temperature is about 25 °C. Use the Excel spreadsheet, [therm10.xls](#), to determine  $R_0$  and  $\beta$  from the two calibration points. Place the calibration data into a header file (e.g., [calib.h](#)), that when included will define the parameters for your thermistor. In particular, if you change thermistors or recalibrate, only changes to this header file will be required.

2. Review the technical information on the ADC system of 9S12. What initiates the conversion process? What are two ways of knowing that the conversion process has been completed? Place the answers to these questions in the beginning comment section of your main program. You may use the example ADC programs, but it is your responsibility to understand the modes (8/10-bit, right/left justified, signed/unsigned format, scanned mode, and continuous mode).

3. Choose one of the options as discussed in hardware section and design the appropriate thermistor amplifier. Be prepared during checkout to discuss the reasons for your choice of design. You must add a two-pole Butterworth low-pass anti-aliasing analog filter. Show name and number of all the pins involved including power. Add bypass capacitors on all chips. Why is it important to connect bypass capacitors across the power pins for the analog IC components? Label all resistance and capacitance values and types. For example, 1k $\Omega$  5% carbon, or 0.01 $\mu$ F 5% ceramic. Include the interface to the LCD. Draw the circuit using a CAD tool like ExpressSCH.

4. Write the DAS software required for this lab. In particular review the procedure sections. A “syntax-error-free” hardcopy listing for the software is required as preparation. The TA will check off your listing at the beginning of the lab period. You are required to do your editing before lab. The debugging will be done during lab. Document clearly the operation of the routines.

5. Type the following main program, modifying it so that the system will sample at 1000 Hz.

```
unsigned short DataBuffer[100];
unsigned short Count=0;
void back(void){ unsigned short data;
  if(Count<100){
    data = ADC_In(0x85); // right justified channel 5
    DataBuffer[Count++] = data;
  }
}
void main(void){unsigned short i;
  ADC_Init();           // Activate ADC, Input to 9S12 ATD PAD5
  SCI_Init(38400);      // SCI output to PC
  OC_Start(1,&back);    // start background thread, 1 kHz
  while(Count<100){}; // copy ADC to buffer in background
  for(i=0; i<100; i++){
    SCI_OutUDec(DataBuffer[i]); SCI_OutChar(10);SCI_OutChar(13);
  }
}
```

### Procedure (do this during your lab period)

1. *Basic understanding:* The purpose of this section is to verify the **Nyquist Theorem** and the **Valvano Postulate**. Generate a continuous waveform (1 to +4V) with an adjustable frequency from 10 Hz to 10 kHz. Consider using a function generator, or the capacitor voltage of a 555 timer. First connect the analog waveform to a scope and verify the voltage range is between 0 and +5V. **VOLTAGES OUTSIDE THIS RANGE WILL DAMAGE THE 9S12.** Next connect the signal to an analog input, e.g., PAD5. In this part, we will not be using the thermistor or analog amplifier. Use the software system from Preparation 5) to capture 100 data points at 1 kHz sampling. Collect data for frequencies 100 Hz (Valvano Postulate), 500 Hz (Nyquist), and 2 kHz (aliased). Use the SCI output to transfer data to the PC. Plot the results by connecting the data points with a straight line. Describe the concepts of

Nyquist Theorem, Valvano Postulate, and aliasing using this specific data. Be prepared to explain your results during checkout.

2. *Static analog circuit test:* Perform these tests before connecting the circuit to the 9S12. Construct and evaluate the thermistor circuit. One by one replace the thermistor with 4 regular resistors that have resistances within the typical range of your thermistor. One test resistor should have a resistance equal to the resistance of the thermistor near the maximum temperature, and another test resistor should have a resistance equal to the resistance of the thermistor near the minimum temperature. Record the voltage values at strategic places in your analog circuit. What voltage output do you get when the thermistor is disconnected? What voltage output do you get when the thermistor wires are shorted? You should modify your temperature measurement system to output specific error conditions if the thermistor is shorted or disconnected.

3. *Dynamic analog circuit test:* Again, perform these tests before connecting the circuit to the 9S12. Disconnect the thermistor, and connect a sine-wave signal generator in its place. Make sure the voltage level of the signal generator is within range, so that the inputs and outputs of your analog circuit are not saturated. Record the sine-wave amplitudes of the input and output voltages. Start at about 1 Hz and collect measurements at ten different frequencies. Make sure you choose frequencies large enough to see the gain roll off. Calculate the gain at each frequency. Plot the gain versus frequency response of your circuit.

4. *Analog-to-Digital Conversion:* Before connecting the input signal to ADC it should be verified that the range of the input signal is between +0 and +5 volts. Connect the output of your thermistor amplifier to the input of the 9S12 ADC system. Use your four fixed resistors and collect digital samples and software calculations of temperature. Add these three columns of data to the data collected in part 2.

5. *Reproducibility:* Place the thermistor in a location of constant temperature (axilla) and record 20 independent temperature measurements. Calculate the standard deviation of these data and report  $\sigma$  as reproducibility.

6. *System checkout:* Run your hardware/software system to verify operation. Connect the output of your thermistor amplifier to the input of the 9S12 ADC system and demonstrate the operation of the digital thermometer. Your temperature resolution should be at least 0.1 degree C.

### **Deliverables (exact components of the lab report)**

A) Objectives (1/2 page maximum)

B) Hardware Design

Circuit diagram of the thermistor and LCD interfaces

C) Software Design (a hardcopy software printout is due at the time of demonstration)

1) Calibration data (**calib.h** file)

2) Low level ADC interface (**ADC.c** and **ADC.h** files)

3) Main program used to measure temperature

D) Measurement Data

1) Two resistance temperature measurements

2) Calibration fit to the equation  $R = R_0 e^{+\beta/T}$

3) Sketch three waveforms (procedure 1)

4) Static circuit performance (procedure 2,4)

5) Dynamic circuit performance (procedure 3)

6) Reproducibility (procedure 5)

E) Analysis and Discussion (1 page maximum)

### **Checkout (show this to the TA)**

You should be able to demonstrate the proper operation of digital thermometer. You can use a light bulb to heat the thermistor above 65°C, but I suggest you stay away from ice or fire.

**A hardcopy printout of your software will be given to your TA, and graded for style at a later time.**

### **Hints**

1) This is a long lab with many parts, so start early.

2) Don't try to complete the experiment in one full swoop. Run the hardware test program given above before testing your software. Debug the system in an analytical, step-wise manner.

3) Please do not use regular op amps that require  $\pm 12$  V supplies. An advantage of the single supply op amp with rail-to-rail outputs is that the output of your analog amplifier will remain within the 0 to +5V ADC range at all times.

4) Circuits built with either the AD623 or AD627 are very easy to implement and have much improved performance over instrumentation amps built with three op amps.

**Design of a high precision thermometer (informational purposes only)**

A precision thermometer, an ohmmeter, and a water bath are required to calibrate thermistor probes. The following empirical equation yields an accurate fit over a wide range of temperature:

$$T = \frac{1}{H_0 + H_1 \ln(R) + H_3 [\ln(R)]^3} - 273.15$$

where T is the temperature in °C, and R is the thermistor resistance in ohms. The cubic term was added in order to improve accuracy. It is preferable to use the ohmmeter function of the eventual instrument for calibration purposes so that influences of the resistance measurement hardware and software are incorporated into the calibration process.

The first step in the calibration process is to collect temperature (measured by a precision thermometer) and resistance data (measured by the ohmmeter process of the instrument). The thermistor(s) to be calibrated should be placed as close to the sensing element of the precision thermometer as possible. The water bath creates a stable yet controllable environment in which to perform the calibration. About 10 to 20 data points should be collected throughout the temperature range of interest.

The second step is to use nonlinear regression to determine  $H_0$ ,  $H_1$ , and  $H_3$  from the collected data. The following nonlinear transforms will linearize the problem

$$x = \ln R, \quad y = (\ln R)^3, \quad z = \frac{1}{T + 273.15}$$

where T is in °C. The problem is then transformed into the following linear equation

$$z = H_0 + H_1 \cdot x + H_3 \cdot y$$

Let n be the number of data points. Linear regression is used to determine the unknown coefficients from the x,y,z data. The following equations are used to calculate the coefficients  $H_0, H_1, H_3$  from the calibration data.

$$A_{11} = \sum x^2 - \frac{(\sum x)^2}{n}$$

$$A_{22} = \sum y^2 - \frac{(\sum y)^2}{n}$$

$$A_{12} = \sum xy - \frac{\sum x \sum y}{n}$$

$$\Delta = A_{11} \cdot A_{22} - (A_{12})^2$$

$$C_1 = \sum xz - \frac{\sum x \sum z}{n}$$

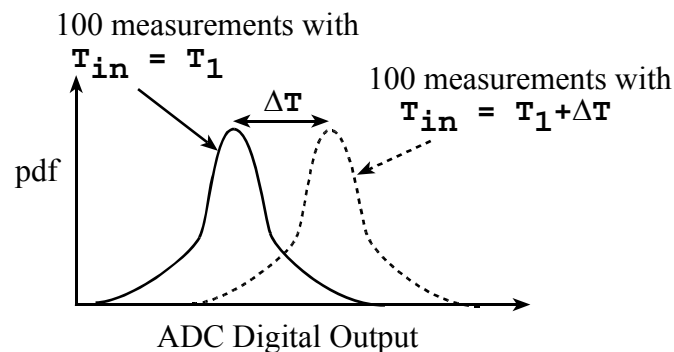
$$C_2 = \sum yz - \frac{\sum y \sum z}{n}$$

$$H_1 = \frac{A_{22} \cdot C_1 - A_{12} \cdot C_2}{\Delta}$$

$$H_3 = \frac{A_{11} \cdot C_2 - A_{12} \cdot C_1}{\Delta}$$

$$H_0 = \frac{\sum z}{n} - H_1 \cdot \frac{\sum x}{n} - H_3 \cdot \frac{\sum y}{n}$$

If we wanted to measure resolution, we would take a set of measurements with a known input temperature of  $T_1$ . Then we would increase the temperature to  $T_1 + \Delta T$ . If the system can reliably detect the change in temperature, then we would claim the measurement resolution is  $\Delta T$ .



The underlined sections identify components that must be performed and included in the lab report.