Introduction

The following paragraphs will provide a detailed description of the hardware design and printed circuit board (PCB) that is being fabricated to demonstrate design feasibility. This description will start with an overview of the system design to show how a high resolution (20 bit) voltage reference can be obtained combining multiple pulse width modulation (PWM) signals of lesser resolution.

System Design

The PIC32 has five 16 bit pulse width modulation circuits available. While this is a vast improvement over the prior 8 bit PIC microcontrollers, when higher than 16 bit resolution is needed, a single PWM circuit is not sufficient.

The proposed design approach combines multiple PWM (3) to provide better resolution than any of the individual PWM circuits.

Some might say why not use two PWM circuits where the analog output of one PWM circuit is scaled appropriately and combined with the analog output of another PWM circuit to provide the required resolution. In theory, this can be done, but in practice, it is extremely difficult if not impossible to match the gains of the most significant bit (MSB) and least significant bit (LSB) outputs so that the final 20 bit result is monotonic.

My design approach combines the PWM circuits in the different way. Two of the PWM circuits use the master reference to provide the course resolution. Then, a third PWM circuit switches between the analog outputs of the first two PWM circuits to provide the final high resolution output. In this way no gain matching is required and the final output is inherently monotonic to higher resolutions. There are still the voltage offsets of the buffer amplifiers from the first two PWM circuits to consider. But these offsets can be compensated more easily than the full range gain matching required when using only two PWM circuits.

In this 20 bit design, both of the course and fine resolution stages will be 10 bits. It is not mandatory that the number of bits of the two stages be equal, but the final voltage reference settling time is fastest when they are.

Although I describe the course and fine resolution stages as 10 bit and the final result as 20 bit, I will be using a few less states than the full 10 and 20 bit number possible to make the LSB step size more convenient. For example, I will be using 1,000 states in both stages instead of the 1024 states possible with 10 bits. Thus, with two stages of 1000 states, there will be 1,000,000 states in the final resolution. So, with a 10 volt master reference, the LSB step size will be 10 microvolts.

This design approach is not limited to 20 bit resolution for the reference output. Since each PIC32 PWM circuit can be up to 16 bits, two stages could theoretically give a output resolution of 32 bits and a step size of less than 10 nanovolts. However, circuit variations will become increasingly critical as resolution increases. If this first demonstration board is successful at 20 bits, I will increase the resolution further in the next phase to determine what is the practical limit.

Hardware Design

PIC32 Interface

Figures 1-4 show the schematics for a printed circuit demonstration board for the PIC32 design Contest.

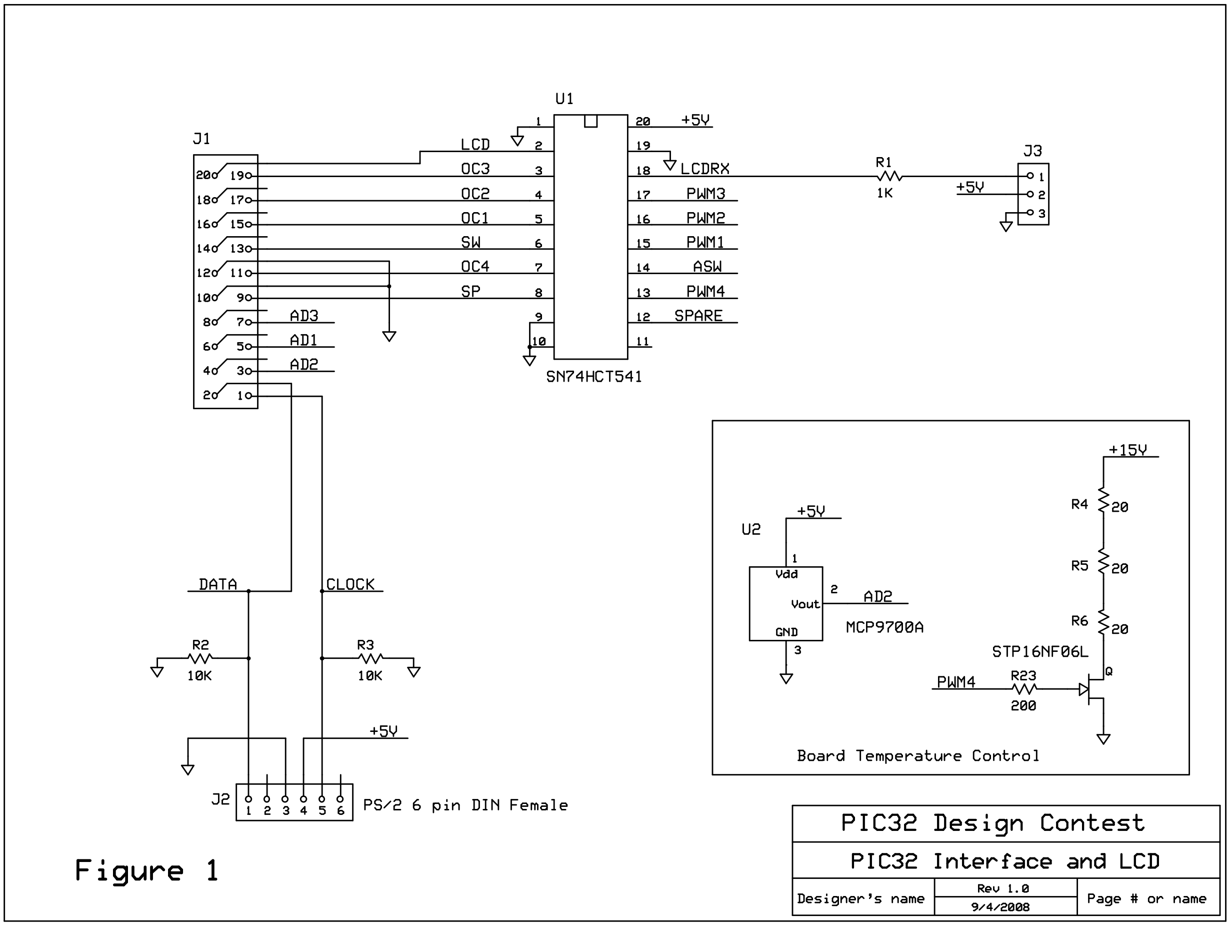

Figure 1

Figure 1 shows the interface between the demonstration board and the PIC32 Starter Board, the PIC32 I/O Expansion Board, and the Prototype PICtail Plus Daughter Board. A 20 pin IDC cable will connect my board to the PICtail Plus board which will in turn be plugged into the I/O expansion board. The PICtail Plus board will have jumper wires connected between the 20 pin header and through hole pads on the board. These pads connect back through the expansion board and starter board to the appropriate pins on the PIC32 chip.

The SN74HCT541 logic driver is used to match the 3.3 volt output signals from the PIC32 to the 5 volt MOSFET driver and analog switch on the demo board and the LCD and PS/2 keyboard peripheral devices off of the board.

The resistors R2 and R3 divide the open collector output of the keyboard if PORTB inputs are used for the keyboard function. Their nominal value is 10K, but the actual value may vary based on the value of the open collector resistors in the keyboard.

This control of board temperature reduces the temperature gradients across the board and therefore reduces the thermoelectric potentials that can be generated when different metals (copper, tin, etc) are in contact at solder joints. The temperature control circuit consists of the MCP9700A temperature sensor, the STP16NF06L power FET, and the three 20 ohm heater resistors which will be attached to the board with epoxy for better thermal transfer. Resistor R23 reduces the peak transient current in the logic driver when switching the power FET. The MCP9700A temperature sensor has a sensitivity of 10 mv per degree Celsius. Thus with the LSB of the 10 bit A/D converter in the PIC32 at approximately 3 mv, the nominal temperature control resolution of the circuit will about +/- 0.3 degrees Celsius. There will be averaging of the A/D samples in the temperature control loop which should somewhat improve the control resolution.

Voltage Reference

Figure 2 shows the circuits which generate the 20 bit voltage reference. Signals PWM1 and PWM2 generate two course 10 bit resolution reference voltages. They use the matched drivers in the TC4427 MOSFET driver to translate the on/off switching levels from 5 volt logic levels to the 10 volt master reference voltage generated by the LT1236 voltage reference shown in figure 4. The output of the TC4427 is very lightly loaded so that the output voltage goes the full range from zero volts to the 10 volt reference level.

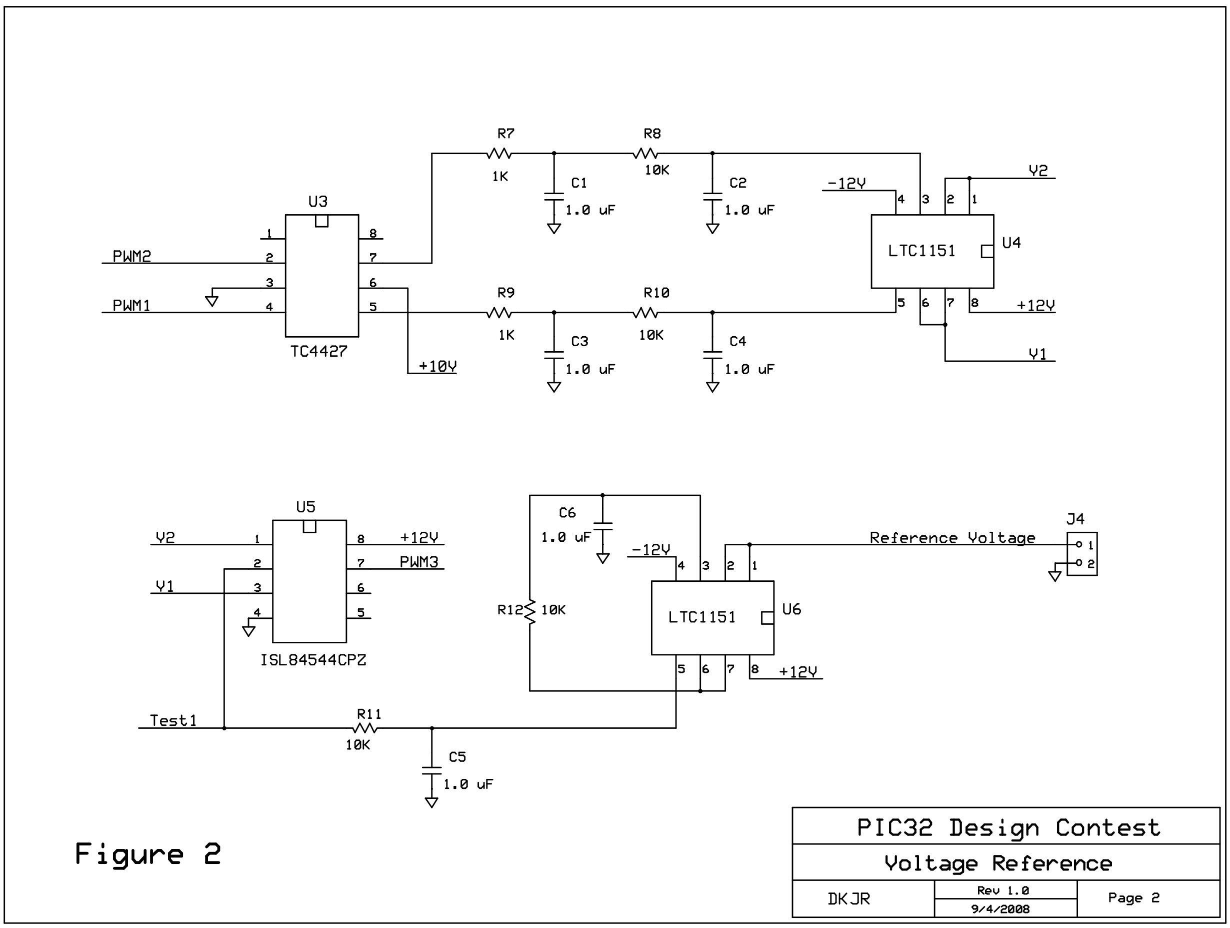

Figure 2

Resistors R7, R8, and capacitors C1, C2 filter the PWM1 signal while resistors R9, R10, and capacitors C3, C4 filter the PWM2 signal. These filters average the PWM signals to provide DC voltages which are proportional to the on time (at 10 volts) divided by the total PWM period. Dual unity gain amplifiers in the LTC1151 buffer the filtered signals to generate DC voltages V1 and V2.

Since the PWM1 and PWM2 signals both have 10 bit resolution (1000 states) their step size is 10 volts divided by 1000 or 10 millivolts. If the code for PWM2 is one number higher than the code for PWM1, then V2 is 10 mv more positive than V1. For example if the code for PWM1 is 100, then V1 is 100/1000*10 = 1.0 volt and V2 is 101/1000*10 = 1.01 volts.

The V1 and V2 voltages are inputs to a ISL84544 SPDT analog switch. The output (pin 2) of the ISL84544 is switched between V1 and V2 by PWM3. When PWM3 is low, V1 is passed to the output and when PWM3 is high, V2 is passed to the output. The final reference voltage depends on the code of PWM3 which determines how long the analog output is switched to V1 and how long the analog output is switched to V2.The analog switch output signal is filtered by resistors R11 and C5 and buffered with one of the LTC1151 dual amplifiers and then is filtered further by resistors R12 and C6 and buffered with the other LTC1151 amplifier.

The reference voltage DC value is V1 plus the on time of PWM3 divided by the total PWM3 period times the 10 mv voltage difference between V2 and V1. for example, if the codes for PWM1 and PWM2 are 100 and 101 as before and the code for PWM3 is 50, then the VREF output is 1.0 volts plus 50/1000*0.01 = 1.0005 volts. Since PWM3 (like PWM1 and PWM2) also has 10 bit resolution, the step size of the reference output is 10 microvolts (the 0.01 volt difference between V2 and V1 divided by 1000).

All this sounds straightforward enough. However, things are not quite that simple. With the three PWM approach, I have eliminated the gain matching needed for the two PWM solution. But, there are still voltage offsets which can degrade the voltage reference accuracy. These include leakage currents in capacitors C1-C6, the input bias and offset currents of the LTC1151 amplifiers and the voltage offsets of the LTC1151 amplifiers. In addition, thermoelectric potentials between different parts of the voltage reference circuits can also generate voltage offsets.

The design goal is to keep all of the offsets less than the 10 microvolt step size. The bias and offset currents of the LTC1151 amplifiers are 20-200 picoamps at room temperature. With a 10K resistor, this gives an offset voltage of up to +/- 2 microvolts for each amplifier. The offset voltage of the LTC1151 amplifiers is specified at a nominal value of +/- 0.5 microvolts and a maximum of +/- 10 microvolts at room temperature.

The leakage current in the capacitors is specified as an equivalent parallel resistor. For 1uF capacitors the parallel resistor is specified as equal or greater than 1 Gohm for multilayer ceramic capacitors and equal or greater than 3 Gohm for polypropylene capacitors. The minimum specified resistance of 1 Gohm or 3 Gohm sounds like a high resistance but for 10 volts on the capacitor and a series 10K resistor like R8, the voltage drop across the resistor is 100 microvolts for the ceramic capacitor and 33 microvolts for the polypropylene capacitors. When I tested a single sample of each capacitor type, the measured resistance was 2-3 times higher than the minimum for the ceramic capacitor and greater than 10 times higher than the minimum for the polypropylene capacitor. Thus for a 10K filter resistor in series with the capacitor, this initial test shows that voltage drop with a polypropylene capacitor should be less than 3 microvolts and even lower for a smaller resistor. More testing needs to be done, but it is clear that the Panasonic polypropylene capacitors can have much lower leakage than the AVX ceramic capacitors tested.

If all of the offsets were maximum in the same direction, the total V1 or V2 offset could be between 10 and 20 microvolts. The monotonicity of voltage reference output would depend on both the magnitude of the offsets and the direction. For many (most) cases, the individual V1 or V2 voltage offsets probably will not all be at the maximum or there could be offset compensation. This compensation can occur in two ways. First, the individual voltage offsets could have plus or minus values about the nominal V1 and V2 voltages causing a reduction in the final V1 and V2 offsets. Or, V1 and V2 individually may have larger offsets but in the same direction (+ or -) with the offset difference between them less than 10 microvolts. In either case the voltage reference output would still be monotonic to 20 bits.

Finally, thermoelectric potentials are reduced by controlling the board temperature. The actual temperature of the board is not important, but keeping the board temperature at a constant value is important. With no external gain on the MCP9700A temperature sensor, the expected temperature variations can be keep to approximately +/- 0.3 degrees Celsius (limited by the 10 bit resolution of the PIC32 A/D). If finer temperature control is needed, the MCP9700A output will need to be amplified to increase the temperature resolution.

A/D Converter

Figure 3 shows the precision A/D converter circuits. The analog input to be converted and the voltage reference are both inputs to the ISL84544 analog switch U7. Signal SW alternately connects the analog input and voltage reference to the common output (pin 2) at a 20 Hz rate. If the analog input and reference are not at the same potential, a square wave is generated with amplitude proportional to the voltage difference between the analog input and reference. This signal is AC coupled with capacitor C7 into a high gain (5000) amplifier using one of the MCP6022 dual op amps. Diodes D1 and D2 limit the voltage into the amplifier. The other MCP6022 op amp buffers a bias voltage of 2.5 volts for the high gain amplifier. Finally, the output of the amplifier (pin 7) is divided by two and sent to the 10 bit A/D in the PIC32.

Every 50 ms, the PIC32 A/D samples AD1 and subtracts the analog input from the reference to generate the difference signal. If the difference signal is positive, the voltage reference is increased and if the difference is negative, the voltage difference is decreased. When the difference signal is zero, the voltage reference is the same as the analog input and is read out to the LCD display as the A/D conversion output with 20 bit resolution.

To speed up this process, a reading of the scaled analog input is first performed by converting AD3 with the PIC32 A/D. This course sample of the analog input is used to initially set the voltage reference to approximately the analog input value.

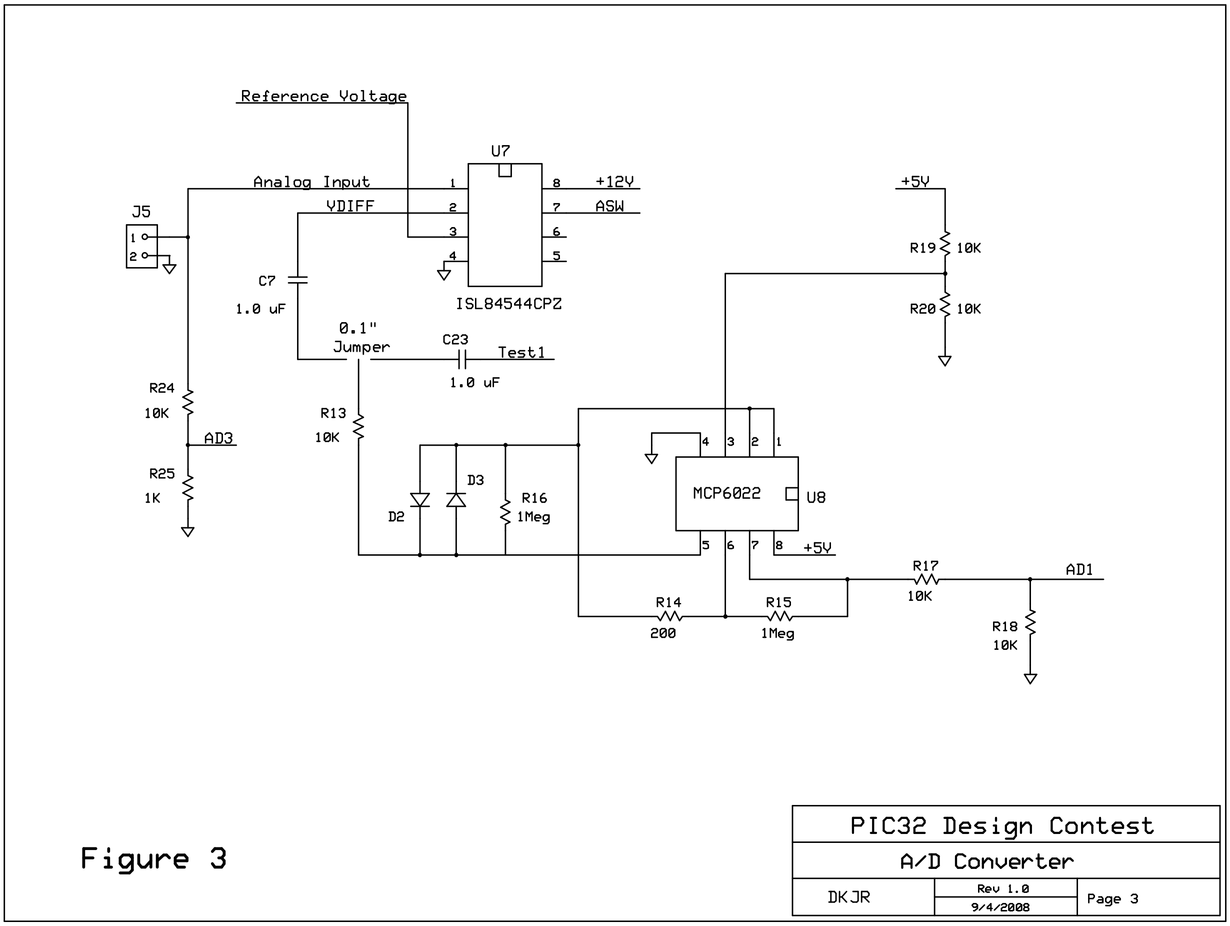

Figure 3

Finally, to aid in board testing, the high gain amplifier can be manually connected to the course resolution stage of the voltage reference (Test1). When, PWM1 and PWM2 are set to the same code, the signal measured at AD1 will be the difference in the offset voltages of V1 and V2. If this difference is less than 10 microvolts, the voltage reference output will be monotonic to 20 bits.

Power

Figure 4 shows the power supply circuits for the demonstration board. The +5, +/-12, and +15 power supplies are external supplies with are filtered with 10uF and 0.1uF capacitors. The +15 supply is nominally 15 volts, but will be adjusted depending on how much power needs to be dissipated in the three 20 ohm heater resistors to control the board temperature.

The 10 volt master reference voltage is generated by the LT1236 voltage reference. Small changes in the voltage can be made by adjusting potentiometer R22. The LT1236 has several grades with grade A having the tightest voltage specification (0.05%, 2ppm drift). However, the better grades were not stock items at Digikey, so a C grade part (0.1%, 10ppm drift) will be used in this phase of the contest

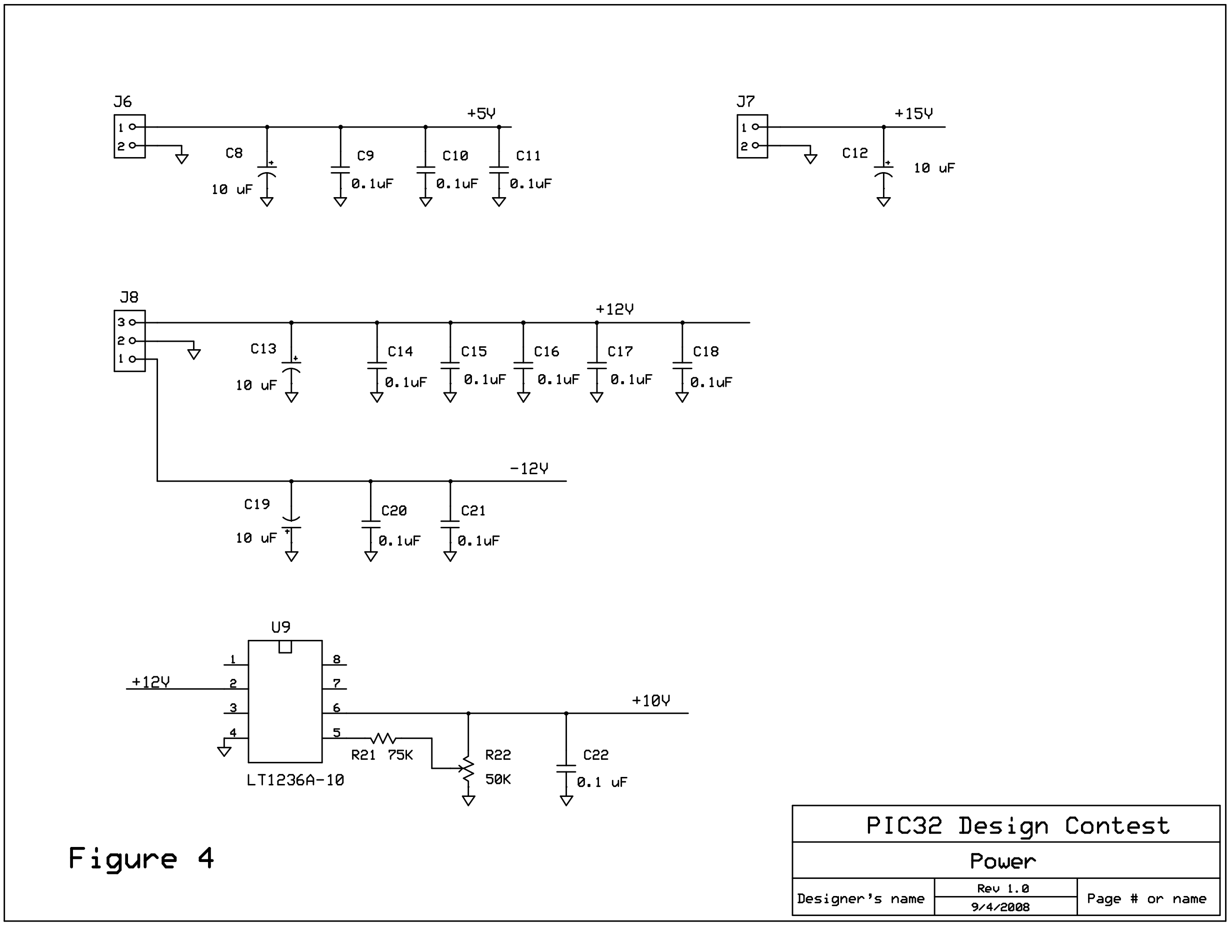

Figure 4

Demonstration Board Testing

After extensive debug, testing, and fine tuning, reference voltage data was collected and is shown in Table 1 and Table 2. Table 1 shows the performance of the two course resolution stages driven by PWM1 and PWM2. Since the course resolution stages cover the full 10 volt range with 1000 steps, a PWM code of 100 represents a voltage of 1.0 volts and each additional increment of 100 results in an additional 1.0 volts. A Datron 1081 voltmeter was used to measure the voltage data. The standard display of this meter is 7 digits. When in an averaging mode the display is extended to 8 digits. On the 10 volt scale, the least significant digit represents single digit microvolts on the expanded display.

The results in table 1 show that the relative accuracy (to 10 volts) over the full range is less than 100 microvolts (claims of absolute accuracy would need verification traceable to NIST standards). The largest source of error is at zero volts. This needs further testing to determine the cause. The results from PWM1 and PWM2 track very well with a difference of less than the 10 microvolts (except for zero volts). This is less than the LSB step size of the reference voltage output. Thus the voltage reference is monotonic to 20 bits over most of the 10 volt range.

PWM Code	Expected Voltage	PWM1 Output	PWM1 Output
0	0.0	0.000083	0.000067
100	1.0	1.000012	1.000003
200	2.0	1.999982	1.999984
300	3.0	2.999970	2.999968
400	4.0	3.999960	3.999958
500	5.0	4.999965	4.999964
600	6.0	5.999970	5.999972
700	7.0	6.999977	6.999984
800	8.0	7.999983	7.999988
900	9.0	8.999993	8.999995
1000	10.0	9.999987	9.999984

Table 1 Course Resolution Stage Data

Table 2 show the fine resolution data of the voltage reference output where PWM1 is set to 1.0 volts, PWM2 is set to 1.01 volts (course resolution step size of 10 millivolts) and PWM3 is incremented. Since the fine 10 millivolt range of PWM3 is covered by 1000 steps, a code of 100 represents a voltage of 1.0 millivolts. The Datron meter was again used to collect data using the same10 volt scale with averaging. There is a small 20 microvolt offset in this data, but the precision of this data is less than 10 microvolts.

PWM Code			Expected voltage	Reference Voltage Output
PWM1	PWM2	PWM3		
100	101	0	1.000	1.000024
100	101	100	1.001	1.001021
100	101	200	1.002	1.002019
100	101	300	1.003	1.003018
100	101	400	1.004	1.004018
100	101	500	1.005	1.005018
100	101	600	1.006	1.006018
100	101	700	1.007	1.007019
100	101	800	1.008	1.008018
100	101	900	1.009	1.009017
100	101	1000	1.010	1.010012

Table 2 Fine Resolution Stage Data

I am quite pleased with these results. Although this level of performance is what my design analysis said was possible, frankly, I was somewhat skeptical that I would be able to achieve these results. Anyone who has worked with very small precise voltages knows what I mean.

There is still work to be done. There was some reference voltage drift with time during the data collection and manual estimates were made to determine the mean value of the data. For these measurements, the circuit board was in the open on the bench and there was no temperature control of the board. The next step will be to put the board in a box and program the temperature control loop. In addition, the code to drive the voltmeter function will be added along with the code to input data from the keyboard and display data on the LCD.

Finally, R7, R9, and R11 were increased to 290K to improve accuracy. These values are now big enough so that the bias and offset currents of the LTC1151 are beginning to cause large enough voltage offsets in the course and fine PWM outputs to dominate the other sources of error. I would like to increase these resistors even further, but then the offsets due to the input bias would become greater without other compensation techniques.