Interfacing to Microprocessor Based 5V Systems

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Introduction

As microcontrollers become more compact and powerful, the opportunity arises for the designer to use these digital powerhouses to pack more and more functionality onto small PCBs. A number of devices include 8 or even 10-bit A/Ds, to allow painless conversion from the analog realm into neat and simple digits. For situations where the on-chip A/D is not appropriate or nonexistent, many external A/D systems-on-a-chip are available. Linear Technology has the LTC1099, LTC1096/LTC1098 and the LTC1196/LTC1198 8-bit A/Ds; the LTC1090 thru LTC1096 10-bit A/Ds; and the LTC1290 through LTC1296 12-bit A/Ds.

As attractive as this possibility sounds, it seems the input signal is never in quite the form it needs to be in for easy digitization. It's either too small, too noisy, the impedance is too high, it's not referenced to ground, or some combination of these factors. The problem varies, but it seems there's always *something* that requires a little bit of signal conditioning prior to digitization.

Operational amplifiers are the obvious method of solving these problems, but there are a few snags. One of the most common design constraints on microcontroller based PCBs is to use only one 5V supply. Modern single supply op amps come close to allowing operation under these constraints, but with a few important exceptions the successful designer should be aware of. This note will outline some of these pitfalls, along with techniques for solving them.

The Search for a Rail-to-Rail Op Amp

The first approach is to simply find an op amp which will handle rail-to-rail inputs and outputs. One common method is to use a CMOS op amp, but it's not the panacea it is thought to be by some designers. In general, CMOS output stages do not suffer from the fixed voltage drops inherent in bipolar devices. Instead, the losses are ohmic in nature. As a result, when operating into high impedance loads,

the output of a CMOS amplifier typically comes very close to — probably within a few millivolts — the power supply rails.

So, the output is no problem. Now for the bad news, which resides at the inputs. While most CMOS amplifiers can handle inputs down to the negative supply rails (if not always with perfect accuracy), they can't get close to the positive rail. As a class, the input common mode range limit generally falls about 1V to 2.5V below the positive supply.

But there are more problems. In general, CMOS amplifiers have very good input leakage current characteristics, especially at low temperatures. This makes them well suited for high source impedance applications. The kicker, though, is the input offset voltage, which is generally in the millivolt range. This limits the CMOS device's usefulness to low gains. Unfortunately, many sensors have low output voltages which require rather high gains.

Of course, there is a way around these large input offset voltages. Zero drift op amps retain the desirable characteristics of the CMOS output stage while continuously autozeroing the input offset voltage. While many designers are prejudiced against zero drift op amps (especially those who have used older devices), modern "choppers" have eliminated most of the pitfalls. They provide a level of stability over temperature and time no other technology can match. See George Erdi's Design Note 42[1] for a revealing discussion.

In between these two extremes of DC accuracy there lies a middle ground, which entails making a composite amplifier for the job. As shown in Figure 1A, by using a good single supply bipolar op amp as a front end, with an inexpensive 4000 or 74C series CMOS gate as a back end, excellent results can be achieved. Jim Williams outlined
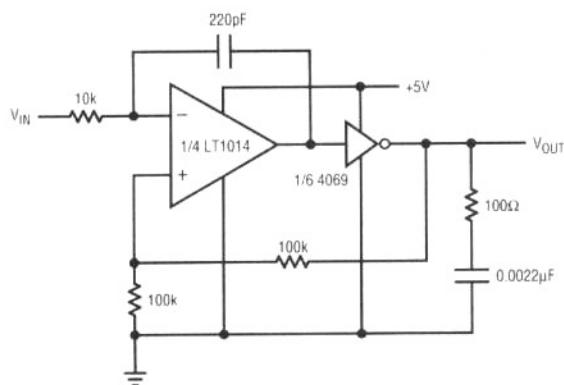

Note 1: LTC Design Notes, No. 42. *Chopper vs Bipolar Amps – An Unbiased Comparison* by George Erdi, December, 1990.

this method in AN18[2], and it works quite well. The front end amplifier's output simply sits at the CMOS gate's input threshold voltage, relieving it of the requirement to swing to the rails.

You can economize on the package count here versus the AN18 circuit. Since we're usually driving a CMOS A/D, with its inherent high input impedance, excellent results can be obtained using just one CMOS gate instead of six. Tests of the circuit using one gate, shown in Figure 1B and 1C, show that you can get within 1LSB or 2 LSBs of both rails, even for 10-bit circuits, for load impedances of 100kΩ or so. Thus, we can combine a good single supply op amp like the LT1013/LT1014 or LT1077/LT1078/LT1079, along with a 4069 hex inverter, and get very good accuracy combined with rail-to-rail output swing. The clever designer can combine leftover gates with the op amps, giving "free" performance enhancement.

Note 2: LTC Application Note 18, *Power Gain Stages for Monolithic Amplifiers* by Jim Williams, March, 1986.

Three things to watch for here are:

1. Be careful of noise if you have to route the analog signal all over the noisy digital data paths.

2. If you use a non-inverting gate, reverse the sense of the op amp inputs shown in Figure 1.

3. Be aware that the power supply current of the CMOS gate will go up, since it's operating in its linear region. I tested a few random parts, and found the average quiescent current was in the hundreds of microamps range. Micropower system designers may need to keep this in mind.

This composite amplifier still leaves us short of the mark in one way — common mode range. Single supply bipolar devices like the LT1013/LT1014 have a common mode input range limit of about 1V to 1.5V below the positive supply rail.
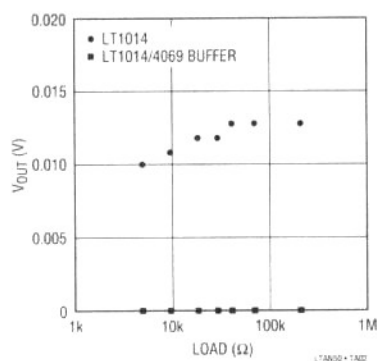
Figure 1B. Saturation Performance – Minimum V_{OUT}
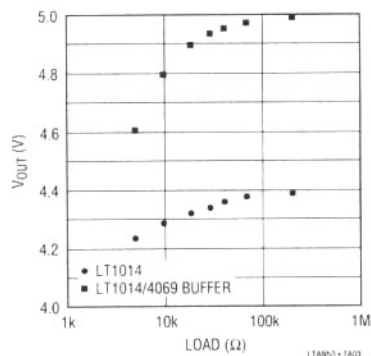
Figure 1C. Saturation Performance – Maximum V_{OUT}

LOAD	LT1014		LT1014/4069	
	MIN	MAX	MIN	MAX
200k	0.013	4.390	0	4.991
67k	0.013	4.380	↑	4.971
40k	0.013	4.360		4.951
30k	0.012	4.340		4.932
20k	0.012	4.320		4.893
10k	0.011	4.290	↓	4.797
5k	0.010	4.240	0	4.606

Figure 1A. LT1014 and 4069 Composite Amplifier

Giving Up the Search: Alternate Approaches

The easiest method for ensuring proper operation over a full 0V to 5V range is to cheat and use higher power supply voltages. Consider the case where your circuit has a local voltage regulator to provide +5V. You can utilize the input to this regulator to run the analog circuitry. A 6.5V power supply is enough to ensure that devices like the LT1013 and LT1078 will handle 0V to 5V at their inputs and outputs. While the raw supply may have unknown noise characteristics, this is usually handled by the op amp's power supply rejection ratio, which is over 100dB at low frequencies. If you're running off a switching power supply whose output is full of high frequency noise, a small R-C filter in the supply line will help this problem. See Figure 2 for an illustration of this technique.
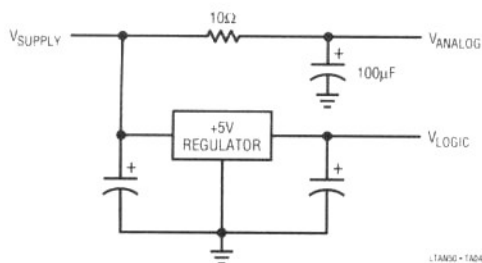
Figure 2. Clean Analog Supply from Input Supply Voltage

If these voltages aren't available from the input power supply, an LT1026 along with a couple of caps provides enough current drive to allow the use of dozens of low power op amps. At low currents, the LT1026 will provide ±9V, which is more than enough to ensure proper operation of inexpensive precision op amps like the LT1097 over a full 0V to 5V range at both the input and the output.

The usual objection to this approach is that it adds cost and requires another IC. This is true, and it may be an important factor in low cost designs. Also, some designers feel that the purity and beauty of their design is spoiled by the addition of other power supply voltages. However, these aesthetic properties manage to survive the affront of incorporating 5V only RS-232 interface chips, even though these devices utilize the same type of charge pump to generate bipolar RS-232 signals.

Realizing this, we can make the RS-232 device serve a dual purpose without requiring any additional parts on many designs, by pulling power from the interface chip's plus and minus rails. For instance, the charge pump on a LT1180 5V RS-232 RX/TX chip can easily provide 10mA to an external load while still meeting the RS-232 interface standard. Noise on these lines can be reduced by a 10Ω/1µF R-C filter. This will provide approximately 100:1 noise reduction at the power supply ripple frequency.

Even if you don't like the idea of generating additional power supplies on your board, you may not have a choice. For instance, if you wish to have a 5V reference on your A/D converter, you're going to need a more positive supply to run that reference.

To those who plan to simply use the V_{CC} line as their 5V reference, beware! This supply is typically noisy due to the rapid current changes caused by the logic chips. In addition, it has a poor ±5% initial tolerance, which amounts to nearly ±13 counts of error in an 8-bit system. Adding a trimmer to adjust the system for proper readings is only a partial solution, since it doesn't allow for the regulator's unspecified time and temperature drift, which will also be poor. These factors are not problems for systems which use transducers with ratiometric output that use the power supply for both the transducer drive and the A/D reference, thereby cancelling any errors in voltage.

One way to reduce this problem is to use Linear Technology's precision fixed output voltage regulators, which have tighter output voltage specs than industry standard parts. For instance, the LT1086-5 has a ±1% initial tolerance, and ±2% over temperature, cutting the initial error to ±3 counts. Compared to industry standard regulators like the 7805, these devices may suffice as a reference in some applications. If you go this route, consider using an R-C filter on the reference path to help kill the noise caused by the digital load.

To those who decide to use a real +5V reference, your problems aren't over just yet. As shown in Figure 3, the typical ±5% power supply tolerance results in a minimum voltage of 4.75V. Using an LT1029 or LT1019 +5V reference, the maximum output voltage is 5.01V. Now you have a system where, worst case, the reference voltage is 0.26V higher than the power supply. This is a problem for any A/D.

Figure 3. Power Supply Voltage Higher Than Reference Voltage

But this isn't the only place where this issue crops up. If you use the LT1026 voltage converter, your op amps are running on ±9V. With these supply voltages, they are capable of merrily swinging ±6V or ±7V at their outputs, so the A/D inputs present the same unhappy possibilities. Even if allowing the inputs to go beyond the power supply range does not damage or latch up the A/D, it will almost always cause improper readings on the other channels.

The best solution here is system dependent. Some ICs will require Shottky diode clamps on any input capable of exceeding the power supply range to prevent latch-up and possible damage. Others may only require series input resistors for the analog input, but you must test such a combination to make sure that:

1. The conversion speed and accuracy is not degraded by the R-C formed by the input resistor and the A/D's intrinsic capacitance.

2. Errors are not introduced due to input leakage current, especially at elevated temperatures.

3. On a multiple channel A/D, one over range input will not affect the other channels.

If you must ensure that a signal does not go beyond the A/D's power supply range, you can employ the circuit shown in Figure 4. These clamps will hold the input within the legal range as long as the input signal's slew rate does not exceed the clamp amplifier's ability to come out of saturation and limit. The buffer amplifier may be necessary in applications that require low output impedance.

Ensuring that the 5V reference does not exceed the power supply is a slightly different story. While a series resistor may prevent damage to the A/D, accuracy at high voltage inputs will be degraded. Here a different approach is required.

Figure 4. Precision Limiter for Analog-to-Digital Converter Inputs

If both initial and long-term accuracy requirements are low, or a ratiometric system is used, the previously discussed filtered V_{CC} approach is the simplest. This automatically solves the V_{REF} overvoltage problem.

If you have to use a stable reference, there are other approaches. If you need local regulation on your board, you can utilize an LT117 or LT1086 in the circuit shown in Figure 5. The superior reference used in these parts allows them to be set to a voltage which will always be higher than the 5V reference, yet is lower than the 5.25V maximum logic ICs are specified for.

Figure 5. +5V Regulator with 5V > V_{OUT} > 5.25V

However, if your PCB doesn't use local regulation, but brings in a nominal +5V supply from an external source, you're stuck. The typical power supply tolerance means that, unless you take steps to raise the supply voltage on your board, you can't work with a 0V to 5V signal "straight in."

Rescaling the Output to 0V to 2.5V

This is accomplished by realizing that we normally really don't have to use a 0V to 5V input swing on our A/D. Most

A/Ds provide both high and low reference inputs, rather than tying them to the power supply terminals. In fact, given the noisy state of the average digital power supply, the IC manufacturer generally has no choice! We can take advantage of this by using a lower reference voltage that is within the swing capabilities of the unaided single supply op amp.

Most single supply op amps can swing to within 1V of the positive power supply when lightly loaded. Looking over the range of available references leads us to pick 2.5V as a convenient value. References like the LT1004-2.5 and LT1009 are inexpensive and give good accuracy at this voltage level. This reference voltage allows plenty of margin on the output swing at the high end, as well as keeping us out of trouble with the input common mode range. In addition, it's not impossibly low for the A/D. Most 8 and 10-bit designs will work adequately at this reference voltage.

Now we get to the low end. Linear Technology bipolar single supply op amps use a unique output topology which allows them to pull their output down to less than 10mV with good linearity. In an 8-bit, 2.5V reference system, this amounts to an error of approximately 1 count. This grows to 4 or 5 counts in 10-bit systems. However, keep in mind, you can't really use the A/D's full range most of the time — you have to allow some margin for circuit tolerances at both the high and low ends of the A/D's

range. Most 10-bit systems will not be noticeably compromised by having 5 counts unavailable at the low end.

But suppose you can't deal with that additional error. There is a simple way to get those lowest few counts back, using a technique known as a synthetic ground. Rather than using the power supply's ground terminal as the common point for the amplifier chain, you use a resistor divider to create an arbitrary ground point offset above power supply ground. This is shown in Figure 6.

Since we only need a few millivolts of offset here, we can use a low value resistor for the bottom of the divider chain. This gives a stable voltage at synthetic ground without drawing a lot of current. To the op amp, it's exactly as though we have power supply voltages of, say, 4.95V and -0.05V.

We can take advantage of the lower reference voltage input on the A/D and feed the synthetic ground into there. Thus, 0 counts will always be equal to the value of synthetic ground, and full scale will be equal to synthetic ground plus the reference voltage.

Some designers may feel uncomfortable without a hardwired ground terminal. In most systems, ground is an arbitrary point, such as the bottom of a bridge rectifier in the power supply. As long as the synthetic ground and the power supply ground are not both tied to a common point, such as AC power supply ground, there's no problem. This

Figure 6. Synthetic Ground

technique is especially good when the voltage being measured is generated by a floating transducer whose output is not committed to ground.

But we're not yet *completely* free of gotchas. You'll have to remember to make all voltage measurements referenced to the synthetic ground, rather than instinctively clipping your DVM lead to power supply ground. This can be a difficult point to get across to troubleshooting personnel. Also, watch out for ground loops when you hook AC powered voltmeters or oscilloscopes to your synthetic ground point.

The most valid complaint is that a cable running from a remote transducer to your circuit will not have a "hard" ground. This is true, and the few ohms to "real" ground could be troublesome in some cases. However, if you use shielded cable, the shield can be isolated from circuit ground and connected to power supply or earth ground. Additionally, the synthetic ground point can be coupled to ground through a bypass cap, giving an AC ground. Be sure to pick a value which will not do funny things to your circuit parameters at the frequencies of interest.

So, now, using this technique, we can finally handle the 0V to 5V input with only 0V and 5V supplies that started this discussion in the first place using the 0V to 5V input in Figure 6. Here, the 5V signal is run through a precision 2:1 divider which is formed by a matched resistor package, such as the Beckman 698-3-R100K-D. These resistors are matched well enough to allow 8-bit accuracy with no trimming. As detailed above, this shifts the 0V to 5V output to a more manageable 0V to 2.5V.

Further, the output of the 2:1 divider is committed to our synthetic ground, rather than the power supply system ground. Using an LT1009 2.5V reference gives us an 8-bit accurate system with no adjustments. The only caveat remaining is that the 0V to 5V signal source and the PCB containing our A/D must not share a common ground, otherwise we must abandon the synthetic ground approach and lose the bottom LSB or two.

The Resolution Issue: When Eight (Bits) Is Not Enough

Resolution, along with memory and megahertz, are some of the things digital systems never have enough of. Linear Technology manufactures a line of 10 and 12 A/Ds which address this need nicely.

But what if 8 bits isn't quite enough, and you need just one more bit? It's hard to justify the cost of another A/D, especially when the microcontroller you're using has one on board already.

The circuit in Figure 7 will add another bit of resolution cheaply. It uses one quad op amp and the same precision resistor package referenced above to "fold" a 0V to 2.47V input to an A/D range of 1.235V to 2.47V while providing a comparator to sense whether the input is in the upper or lower half of the range.

Op amps U1A and U1B, along with RN1 to RN6, form a full wave rectifier with a "center" point equal to the reference voltage, V_{REF_LOW}. Input voltages above V_{REF_LOW} are passed through the rectifier unchanged, while those below V_{REF_LOW} are inverted and shifted upwards according to the equation:

$$V_{OUT} = 2 \times V_{REF\_LOW} - V_{IN}$$

The accuracy of this section is held within 8 bits by the accurate matching of the package's resistors and the low errors in the op amps shown in the figure. If lower power consumption is required, the LT1014 op amps can be replaced by the LT1079 or LT1179.

The 9th bit is formed by the comparator U1C. The output of this comparator will trigger a standard CMOS gate, or its value can be read into a free A/D channel. Note that when the 9th bit is low, the readings are biased upwards and inverted. The proper sense can be restored to the reading in software.

The A/D's positive reference voltage (V_{REF_HIGH}) is set to exactly twice the LT1004-1.2 reference's voltage by op amp U1D. The gain of this circuit is set at precisely 2 by the 7th and 8th resistors in the resistor package. Thus, the A/D sees the input signal changing between 1.235V and 2.47V.

This circuit does require a negative voltage to operate, although it does not have to be regulated.

Even More Resolution

There are times when even more than 12 bits of resolution are required. An example is when the A/D has to monitor a variable which can take on a number of different ranges, each of which requires good precision. For instance,

Figure 7. 8-Bit to 9-Bit Converter

industrial temperature monitors use many different kinds of thermocouples, and each of them can be used over a wide range. If the instrument is required to have a display range of 0°F to 2000°F and a resolution of 0.1°F without requiring gain or offset changes, you'd need an A/D with at least 20,000 counts. This implies a 17-bit A/D, an expensive proposition.

There is a less costly approach if you're monitoring a slowly changing parameter like temperature. A voltage to frequency converter can be used to convert the input variable into a precision pulse train. By counting these pulses over a fixed time length, a very accurate voltage reading can be made. This is particularly easy to do in software, as most microcontrollers have an input capture function which allows them to count incoming pulses conveniently.

A simple way to do this is shown in Figure 8. This is a variation on the circuit Jim Williams showed in AN3[3], Figure 12. The major modification made here is that a

Note 3: LTC Application Note 3, *Applications for a Switched-Capacitor Instrumentation Building Block* by Jim Williams, July, 1985.

Figure 8. Single Supply Voltage to Frequency Converter

single supply is used rather than the dual ±15 supplies employed in the earlier circuit. This necessitates the switch to a single supply comparator, the LT1018.

The circuit operates by balancing the current flowing into the input with discrete packets of charge delivered by the flying capacitor C_T (C2). This capacitor is charged up to a 1.2V reference level when the LTC1043 analog switch's pin 11 and pin 12 are connected to pins 7 and 13 respectively.

As the input voltage charges up capacitor C1, the inverting input of the LT1018 comparator rises slightly above ground, forcing the comparator's output low. This causes the analog switch to change states bringing C2's positively charged end to ground on pin 8 and forcing pin 14 negative. This negatively biased charge then balances the positively biased charge stored on the input capacitor. A delay, provided by C3 and R3, ensures that all of C2's charge is transferred to C1. Clamp diode D1 protects the comparator's noninverting input from excessive negative excursion.

As the input voltage rises, the input capacitor charges more quickly, thus requiring more frequent "hits" of C2's charge to balance the circuit. This action forms a voltage to frequency converter with the following equation:

$$F_{OUT} = \frac{V_{IN}}{\left(R_{IN} \times V_{REF} \times C_T\right)} \qquad \text{(See note 4)}$$

Typical performance specifications are:

$V_{IN} = 0V$ to $5V$

$F_{OUT} = 0kHz$ to $5kHz$

Linearity = 0.0025%

PSRR = 0.1%/V

TC = 200ppm/°C

$I_q = 3mA$

Note 4: Note the accidental inversion of the C_T term in the AN3 equation.

Although a 5kHz full-scale frequency is shown, output frequencies in the tens of kHz are possible by rescaling R1, C2 or both. Applications requiring very high resolution may require long pulse accumulation times. For slowly changing variables like temperature this is generally not a problem.

Start-up or overdrive can cause this circuit's AC coupled loop to latch. If the output of the comparator is forced low for an extended period, the analog switch forces C2 to the inverting input of the comparator before it is charged up. This is a stable condition, so oscillation will not commence. The problem is cured by the addition of C4 and D2. When the comparator's output is low, the LTC1043's internal oscillator "sees" C4 to ground and begins oscillating if this state persists. The free running oscillation pumps charge out of C1 until normal operation commences. Under normal conditions, the comparator's output state controls the analog switch through D2.

Another potential problem is that the reversed sense of C2 forces pin 14 of the LTC1043 and the inverting input of the LT1018 below ground. This is usually poor practice. However, the size of the input capacitor has been chosen to limit the excursion below ground to a safe level. The input capacitor should not be made any smaller without careful testing to ensure linearity at high temperatures.

This circuit meets the ideals outlined in the beginning of this note in that it only requires one supply to handle a 0V to 5V input signal. In fact, the input can swing to levels greater than the power supply, since the op amp/comparator is used in the inverting mode — its summing junction is held close to ground at all times.

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