LM2901,LP339

AN-607 Pulse Width Modulation A/D Conversion Techniques with COP800 Family Microcontrollers

Literature Number: SNOA118
Pulse Width Modulation A/D Conversion Techniques with COP800 Family Microcontrollers

1.0 BASIC TECHNIQUE

This application note describes a technique for creating an analog to digital converter using a microcontroller with other low cost components. Many applications do not require the speed associated with a dedicated hardware A/D converter and it is worth evaluating a more cost effective approach.

With a high speed CMOS microcontroller an eight bit A/D can be implemented that converts in approximately 10 ms. This method is based on the fact that if a repetitive waveform is applied to an RC network, the capacitor will charge to the average voltage, provided that the RC time constant is much larger than the pulse widths. The basic equation for computing the analog to digital result is:

\[ V_{in} = V_{ref} \frac{T_{on}}{T_{on} + T_{off}} \]  

(1)

With this equation it is necessary to precisely measure several time periods within both the T on and T off in order to achieve the desired resolution. Additionally, the waveform would have to be gradually adjusted to allow for the large RC time constant to settle out. This results in a relatively long conversion cycle. Modifying the equation and technique slightly, significantly speeds up the process. This technique works by averaging several pulses over a fixed period of time and is based on the following equation:

\[ V_{in} = V_{ref} \frac{\text{Sum of } T_{on}}{\text{Sum of } (T_{on} + T_{off})} \]  

(2)

2.0 IMPLEMENTATION

Figure 1 describes the basic circuit schematic that uses a National Semiconductor COP822C microcontroller, a low cost LM2901 comparator, two 100k resistors, and a 0.047 mfd film capacitor. The CMOS COP822C microcontroller provides a squarewave signal with logic levels very close to GND and VCC. This generates a small ramp voltage on the capacitor for the LM2901 quad comparator input.

To minimize error, a tradeoff must be made when selecting the resistor. The microcontroller output (L1) should have a large resistor to minimize the output switching offset (Vos), and the comparator should have a small resistor due to error caused by Ibs (input bias offset current).

Once the resistor is determined, the capacitor should be chosen so that the RC time constant is large enough to provide a small incremental voltage ramp. This design has a sample time of 20 µs and has a 4.7 ms time constant with a 0.047 mfd film type capacitor which has low leakage current to prevent errors. Since a 100k resistor is used in the RC network for one comparator input, another 100k resistor is required for the V out input to balance the offset voltage caused by the comparator I b (input bias current).

Figure 2 illustrates the relationship between the microcontroller squarewave output and the capacitor charge and discharge. Every 20 µs the comparator is sampled. If the capacitor voltage (Vc) is below V in the RC network will receive a positive pulse. The inverse is true if Vc is above V in at sample time. Note that with this approach, the PWM waveform is broken up into several small pulses over a fixed period instead of having a single pulse represent the duty cycle; thus a relatively small RC time constant can be used.

Mathematical Analysis:

let \( n \) = total number of T on pulses and \( m \) = total number of T off pulses then \( V_c(0) = V_{in} + n(V_{out} - V_c) (1 - e^{-t/RC}) - m(V_c - V_c) (1 - e^{-t/RC}) \)

let \( V_c = V_{in} \) at start of conversion and \( K = (1 - e^{-t/RC}) \)

then \( V_{in} = V_{in} + K n V_{out} - K n V_{in} + K m V_{0} \)

0 = K n V_{out} + K n V_{0} - K V_{in} (n + m)

let \( V_{out} = V_{ref} - V_{os} \)

solving for \( V_{in} \):

\[ V_{in} = n V_{ref}/(n + m) \]

\[ -m V_{os} - n V_{0} (1/(n + m) \]  

(3)

Note that the RC value drops out of the equation and therefore is not an error factor.

FIGURE 1. Basic Circuit

FIGURE 2. PWM Signal
3.0 SOFTWARE DESCRIPTION

Single Channel
Referring to the flow chart in Figure 3, and the code listed in Figure 4, the software counters \( T_{on} \) and \( TOTAL \) are first preloaded with the FF. The accumulator and register 0F1 are then loaded with 2 to provide for an initialization and final conversion cycle. Next, the L port is configured to complete the initialization of the microcontroller.

The comparator output is checked with the IFBIT 0,0D2 instruction. This will determine whether the RC network will receive a positive (\( V_{ref} \)) or ground pulse. You can think of the microcontroller as part of the feedback path of the comparator. The microcontroller uses the comparator output to decide what level output on L1 is required to keep the capacitor equal to the unknown input voltage. Each time the negative or GND pulse is applied, the \( T_{on} \) counter is decremented by DRSZ. Similarly, each time a sample loop is completed the \( TOTAL \) counter is decremented by DRSZ. Note that NOP instructions are used in the high and low loops. These are necessary to provide exactly the same cycles for a high or low L1 output pulse.

Once the \( TOTAL \) register is decremented to zero, the initialization loop is completed. Immediately afterwards, the \( L1 \) output is put in TRI-STATE mode to minimize capacitor voltage variations while other instructions are completed. After the first conversion, the IFEQ A,0F1 instruction will be true and the \( T_{on} \) and \( TOTAL \) registers will be reloaded with FF. Following this, the L1 pin is restored as a high output and the 0F1 multiplier is decremented.

At this point the capacitor is equal to \( V_{in} \) and the actual conversion is started. When the \( TOTAL \) register is decremented to zero (255 samples later), the conversion is complete. \( T_{on} \) will not be reloaded since 0F1 was decremented and IFEQ A,0F1 will no longer be true. The accumulator is then loaded with \( T_{on} \) and stored in RAM location 00 with X A,00.

The final two instructions (RBIT 1,LCONF & RBIT 1) are optional depending on the application and the amount of additional code required. This will prevent the capacitor from decaying appreciably between conversions and allow for a much quicker capacitor initialization time. Otherwise more time may be required, or a diode speed-up circuit as shown in Figure 7d is required to fully charge the capacitor prior to starting the actual conversion.

Eight Channel
This is basically the same as that for the single channel. Referring to the flow chart in Figure 5 and the code in Figure 6, the differences are in the front and back ends. Before the conversions are started, the X register is initialized to 00 for RAM location 00. The accumulator is then loaded with the current RAM pointer (LD A,X), OR’ed with the LDATA (OR A,LDATA), and finally the LDATA register is modified to provide for the proper output select (X A,LDATA).

Following the actual conversion cycle, the result is stored at the current RAM pointer (X A,(X +1)) which also auto-increments the X register. The next conversion will use this to select the next channel and determine where to store the result. Once the eighth channel is converted, the IFEQ A,X instruction will be true and the RAM pointer will be reset (LD X,#00) before the next conversion is started.
The program listed below will work in any COP800 microcontroller (i.e. COP820, COP840, COP880, COP888). SET UP FOR .047 mfd CAP.,
100K RES, @1 MICRO. CYCLE TIME. THE FIRST CONVERSION
INITIALIZES, AND 2nd IS THE RESULT STORED IN RAM LOCATION 00.

CHIP 820
LCONF=0D1
LDATA=0D0
TON=0F2
TOTAL=0FO

;LD A,#02 ;USED TO DETERMINE WHEN TO RELOAD
LD TOTAL,#0FF ;RELOAD TOTAL COUNTS
LD 0F1,#02 ;MULTIPLIER (255 TO INIT. PLUS 255 FOR RESULT)
LD 0FE,#0D0 ;LOAD B REG TO POINT TO LDATA REG.
LD LCONF,#02 ;L PORT CONFIG REG, L0=INPUT, L1=OUTPUT
LD 0F0,#02 ;L PORT DATA REG, L0=WEAK PULL UP, L1=HIGH

LOOP: IFBIT 0,0D2 ;TEST COMPARATOR OUTPUT
JF HIGH ;JUMP IF Lo=1
NOP
NOP
;EQUALIZE TIME FOR SETTING AND RESETING
RBIT 1,[B] ;DRIVE LI LOW
DRSZ TON ;DECREMENT TON WHEN DRIVING LOW
JMP COUNT

HIGH: SBIT 1,[B] ;DRIVE LI HIGH
NOP
NOP
NOP
NOP
;EQUALIZE HIGH AND LOW LOOPS
COUNT: DRSZ TOTAL ;DECREMENT TOTAL COUNTS
JF LOOP
RBIT 1,LCONF ;TRISTATE L1 TO MINIMIZE ERRORS FROM EXTRA
RBIT 1,[B] ;CYCLES
IFEQ A,0F1 ;CHECK INITIALIZATION LOOP COMPLETE
JF RELOAD ;JUMP IF TRUE.
JF DEC ;JUMP IF NOT END OF 2nd LOOP

RELOAD: LD 0F0,#0FF ;SYNC TOTAL AND TON COUNTERS
LD 0F0,#0FF ;SYNC TOTAL AND TON COUNTERS
DEC: SBIT 1,[B] ;SET LI HIGH
SBIT 1,LCONF ;RESTORE LI AS OUTPUT.
DRSZ 0F1 ;DECREMENT MULTIPLIER UNTIL ZERO
JMP LOOP ;CONTINUE A/D UNTIL AFTER 2nd CONVERSION
LD A,TON ;LOAD A WITH TON
X, A,00 ;STORE RESULT IN RAM LOCATION 00
.end

FIGURE 4. Single Channel PWM A/D Listing
FIGURE 5. 8 Channel PWM A/D Flow Chart
;L0,1,2 SELECTS CHANNEL OF CD4051 8:1 MUX, L3 IS THE COMP.
;OUTPUT, AND L4 DRIVES THE RC. RESULTS STORED IN RAM 00–07.
.CHIP 820
LDATA=0D0
LCONF=0D1
TON=0F2
TOTAL=0F0
LD X,#00 ;INITIALIZE X REG FOR 1st RAM LOC.
CONVER: LD TOTA L,#0FF ;PRELOAD TOTAL COUNTS
LD OP1,#002 ;TOTAL LOOP COUNTER
LD TON,#0FF ;PRELOAD Ton
LD OPE,#0D0 ;INIT. B REG TO POINT TO LDATA REG
LD LDATA,#018 ;LDATA, L0–L2 LOW, L3=FULLUP, L4=HIGH
LD A,X ;USED CURRENT RAM POINTER TO SELECT-
OR A, LDATA ;PROPER A/D CHANNEL.
X A,LDATA ;MODIFY LDATA FOR CHANNEL SELECTION.
LD LCONF,#017 ;LCONF REG. L0–L2, L4=OUTPUT, L3=IN
LOOP: IFBIT 3,0D2 ;TEST COMPARATOR OUTPUT AT L3 INPUT
HIGH: JMP HIGH ;JUMP IF L3=HIGH
NOP
NOP
NOP ;EQUALIZE TIME FOR SET AND RESET
RPIT 4,[B] ;DRIVE L4 LOW WHEN COMPARATOR IS LOW.
DRSZ TON ;DECREMENT Ton WHEN APPLYING NEG. REF.
JMP COUNT ;JUMP TO COUNT UNTIL TON REACHES ZERO
LOW: SBIT 4,[B] ;DRIVE L4 HIGH WHEN COMPARATOR IS HIGH
NOP
NOP
NOP
NOP
COUNT: SBIT 4,[B] ;EQUALIZE HIGH AND LOW LOOP TIMES
DRSZ TOTAL ;DEC. TOTAL COUNTS EACH LOOP
JMP LOOP ;JUMP UNLESS TOTAL CNTS.=0
RBIT 4,LCONF ;TRISTATE L4 TO MINIMIZE ERROR
RBIT 4,[B] ;"L4
LD A,#02 ;USE TO DETERMINE WHEN TO RELOAD
IFEQ A,0F1 ;CHECK FOR 2nd CONVERSION COMPLETE
JF RELOAD ;IF TRUE.
JF DEC ;OTHERWISE JUMP TO DEC
RELOAD: LD TON,#0FF ;RELOAD TON FOR START OF NEXT CONV.
LD TOTAL,#0FF ;SYNC TON AND TOTAL COUNTERS
DEC: SBIT 4,[B] ;SET L4 HIGH
DRSZ OP1 ;DECREMENT TOTAL LOOP UNTIL ZERO
JMP LOOP ;DONE WHEN OP1 IS ZERO.
LD A,TON ;LOAD A WITH TON RESULT
X A,[X+] ;STORE RESULT AT CURRENT RAM POINTER
LD A,#08 ;CHECK [X] RAM POINTER FOR
IFEQ A,X ;EIGHTH CHANNEL CONVERTER
LD X,#00 ;RESET RAM POINTER IF [X]=8
JMP CONVER
.END

FIGURE 6. 8-Channel PWM A/D Listing
4.0 ACCURACY AND CIRCUIT CONSIDERATIONS

The basic circuit will provide 8 bits ±1 LSB accuracy depending on the choice of comparator, and passive components. With this type of design several tradeoffs and error sources should be considered. First of all, conversion equation 2 assumes that the microcontroller output switches exactly to GND and VCC (or Vref). The COP822C will typically switch between 10 mV and 20 mV from GND and VCC with a light load. This will cause an error equal to the offset voltage times the duty cycle (equ. 3). Fortunately, the offsets tend to cancel each other at mid range voltages. At near GND and VCC input voltages the offsets are minimal due to the very small voltage drop across the resistor. If the error is undesirable, the offset voltage can be reduced by paralleling outputs with the same levels together, or by using a CMOS buffer such as a 74HC04 to drive the RC network (see Figure 7 for suggested circuits).

Another possible source of error is with the LM2901 worst case input bias offset current of 200 nA over temperature. This will cause an error equal to Rin x Ibos, which equals 20 mV with a 100k resistor. Either the resistor or the Ibos can be reduced to improve the error. If the resistor is reduced then the L port offset voltages will increase so the preferred approach is to select a comparator with lower Ibos such as the LP339 which has an Ibos of only ±15 nA. The comparator Vos may also introduce error. The LM2901 Vos is ±9 mV, the LP339 Vos is only ±5 mV. An added benefit of using the LP339 is that since the Ibos is so small, the resistor for the RC network can be larger. In addition, one RC network could be used for several comparator input channels (refer to Figure 7A).

By using the LM604 (Figure 7B) the basic software can be easily extended for converting several channels. This will only require a control line to be selected before a conversion is started. Since the LM604 needs to be powered from a higher voltage than the input voltage range, the output voltage will also be higher than the microcontroller supply. This requires a current limiting resistor to be used in series between the LM604 output and the COP8XX. Note that two or more LM604’s can be paralleled for providing several more A/D channels by utilizing the EN control input that can TRI-STATE the LM604 output when high.

When more than 4 channels of analog signals are required to be measured, the circuit in Figure 7(9) is recommended. This circuit utilizes an inexpensive CD4051 8:1 multiplexer with a single comparator (which could be on-board the micro). When measuring several input voltages that can vary, TRI-STATING the output driving the RC between conversions is not possible. It is necessary to provide 6x RC time constants to charge the capacitor to within 0.25%. Note that there are two 1N4148’s across the comparator inputs. The diodes provide a quick capacitor charge path providing that the total input resistance is much smaller than the resistor used in the RC network (a 2k resistor will meet the requirements within 255 sample times). Once the capacitor is charged to within about 0.6V, the diodes will start turning off. At this point the microcontroller will start dominating the charge/discharge of the capacitor. After the initialization cycle is complete, the capacitor is very close to the unknown Vin and the diodes are effectively out of the circuit.

Depending on the speed and accuracy requirements, the total number of counts used in the conversion can be changed. Increasing the counts will give more accuracy with the practical limit of about 9–10 bits. With increased resolution, the capacitor ramp voltage per sample time should be decreased so that the capacitor can be initialized to within 1 LSB prior to conversion. This can be done by either increasing the RC time constant, or by using an initialization routine with a shorter sample time. The conversion time will depend on the total counts and the microcontroller oscillator frequency as described below:

\[ T_{con} = \frac{\text{Total counts} \times (20 \text{ cycles}) \times (\text{instruction cycle time})}{\text{Number of comparators}} \]

Another factor to consider is when a non-ratiometric conversion is required, the reference voltage must have the tolerance to match the desired accuracy.

![A. Multiple Channels with LP339 Low Ibos Comparator](image)

![FIGURE 7. Suggested Circuits](image)
5.0 CONCLUSION

The PWM A/D technique described in this application note provides a relatively fast discrete implementation with substantial cost savings compared to a dedicated hardware A/D. Minimal microcontroller I/O and software is required to interface with a comparator and RC network. Depending on the application requirements, the designer can tailor the basic 8-bit A/D a number of ways. By varying the total software counts, the desired speed and resolution can be adjusted. The number of A/D channels will determine the number of comparators used. In choosing the comparator, it is recommended that the designer refer to the data sheets and match the $I_{\text{BO}}$ and $V_{\text{OS}}$ to the desired accuracy.

When other than a 1 $\mu$s instruction cycle is used, the RC time constant of 4.7 ms should be scaled to provide for a maximum peak-peak ramp voltage of <1 LSB of the desired accuracy. For example, if 8-bit accuracy is desired and the instruction cycle time is now 4 $\mu$s instead of 1 $\mu$s, multiply 4.7 ms by 4 to calculate the new RC.

Keep in mind that the comparator input voltage is limited so that you do not get erroneous/nonlinear results. Another possible problem is during development. When doing in-circuit emulation with the development equipment, note that there will be ground loops in the cable thus causing errors in your measurements. You can reduce this by connecting an extra GND and VCC wire between your prototype and development system power and GND. It is still possible to see offsets in the sockets holding the COP8XX in the development board, however this should be relatively small. The best test is to take accurate measurements with an emulator in the actual prototype circuit.
LIFE SUPPORT POLICY

NATIONAL'S PRODUCTS ARE NOT AUTHORIZED FOR USE AS CRITICAL COMPONENTS IN LIFE SUPPORT DEVICES OR SYSTEMS WITHOUT THE EXPRESS WRITTEN APPROVAL OF THE PRESIDENT OF NATIONAL SEMICONDUCTOR CORPORATION. As used herein:

1. Life support devices or systems are devices or systems which, (a) are intended for surgical implant into the body, or (b) support or sustain life, and whose failure to perform, when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in a significant injury to the user.

2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.
IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI’s terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI’s standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

TI products are not authorized for use in safety-critical applications (such as life support) where a failure of the TI product would reasonably be expected to cause severe personal injury or death, unless officers of the parties have executed an agreement specifically governing such use. Buyers represent that they have all necessary expertise in the safety and regulatory ramifications of their applications, and acknowledge and agree that they are solely responsible for all legal, regulatory and safety-related requirements concerning their products and any use of TI products in such safety-critical applications. TI products are neither designed nor intended for use in such safety-critical applications.

TI products are neither designed nor intended for use in military/aerospace applications or environments unless the TI products are specifically designated by TI as military-grade or "enhanced plastic." Only products designated by TI as military-grade meet military specifications. Buyers acknowledge and agree that any such use of TI products which TI has not designated as military-grade is solely at the Buyer's risk, and that they are solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI products are neither designed nor intended for use in automotive applications or environments unless the specific TI products are designated by TI as compliant with ISO/TS 16949 requirements. Buyers acknowledge and agree that, if they use any non-designated products in automotive applications, TI will not be responsible for any damages arising out of the use of TI products in such automotive applications.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Audio</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amplifiers</td>
<td>amplifier.ti.com</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data Converters</td>
<td>dataconverter.ti.com</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DLP® Products</td>
<td><a href="http://www.dlp.com">www.dlp.com</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSP</td>
<td>dsp.ti.com</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clocks and Timers</td>
<td><a href="http://www.ti.com/">www.ti.com/</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interface</td>
<td>interface.ti.com</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logic</td>
<td>logic.ti.com</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Mgmt</td>
<td>power.ti.com</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microcontrollers</td>
<td>microcontroller.ti.com</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RFID</td>
<td><a href="http://www.ti-rfid.com">www.ti-rfid.com</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OMAP Mobile Processors</td>
<td><a href="http://www.ti.com/">www.ti.com/</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wireless Connectivity</td>
<td><a href="http://www.ti.com/wirelessconnectivity">www.ti.com/wirelessconnectivity</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applications</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial</td>
<td><a href="http://www.ti.com/industrial">www.ti.com/industrial</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation and Automotive</td>
<td><a href="http://www.ti.com/aut">www.ti.com/aut</a></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Video and Imaging</td>
<td><a href="http://www.ti.com/video">www.ti.com/video</a></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mailing Address: Texas Instruments, Post Office Box 655303, Dallas, Texas 75265
Copyright © 2011, Texas Instruments Incorporated