Analog Input & Output

ECE 153B --- Jan 26, 2006
Introduction

- Anytime we need to monitor or control analog signals with a digital system, we require analog-to-digital (ADC) and digital-to-analog (DAC) conversion
  - Process control
  - Digital audio and video
  - Interfacing to any type of continuous (vs. discrete) voltage or current
Op – Amps (Operational Amplifiers)

- Op – Amps are the basic building blocks in analog input and output devices
  - Current-to-voltage converters, voltage amplifiers, buffers, active filters, sample-and-holds, etc.
- Characteristics are high gain, two analog signal inputs (inverting and non-inverting), and one or two analog signal outputs
- Generally, two DC supply voltages of opposite polarity
The Ideal Op – Amp

- Infinite input impedance
  - no current flows into input terminals
- Extremely high open loop gain ($A_{OL}$)
  - typically $10^4$ to $10^6$
- $V_o = A_{OL} (V_+ - V_-)$
  - differential amplifier
Common Op – Amp Circuits

- Because the open loop gain of an op – amp is so high, we generally employ “negative feedback” in circuit design.

- The closed loop gain is (to a first approximation) dictated entirely by the external feedback components:
  - Makes the design of linear circuits using op amps relatively straightforward
  - Analysis of transfer characteristics accomplished using *virtual ground analysis*
Common Op – Amp Circuits

(a) CURRENT TO VOLTAGE CONVERTER

(b) UNITY GAIN BUFFER

(c) INVERTING VOLTAGE AMPLIFIER

(d) INVERTING SUMMING AMPLIFIER

(e) NONINVERTING AMPLIFIER

(f) INTEGRATOR
Digital – to – Analog Converters (DACs)

- DAC accepts an $n$-bit parallel digital word as its input and provides an analog current or voltage as its output
  - input can be signed or unsigned positional binary number
- Several types of DAC
  - different topologies, different speeds, different accuracies, different output types (voltage vs. current)
Weighted Resistors into a Summing Junction --- DAC Type #1
Weighted Resistors into Summing Junction DAC

- Fast, low precision technique
  - Precision of resistors is critical
    - Smaller resistors (more significant bits) require proportionally higher precision resistors (tolerance)
    - Only good for a small number of bits as it becomes impractical to attain the required resistor tolerance
- Switches shown on schematic are actually transistors connected to incoming digital word
- B1 is most significant bit
Weighted Resistors Into Summing Junction DAC

- If input bit is 1, the switch is closed and the current is directed to summing junction of the op amp
  - Conversely if input bit = 0, the current is directed to ground

\[
V_{\text{OUT}} = -I_T R \\
= - \left( \frac{V_{\text{REF}} B_1}{2R} + \frac{V_{\text{REF}} B_2}{4R} + \frac{V_{\text{REF}} B_3}{8R} \right) R \\
= - V_{\text{REF}} \left( \frac{B_1}{2} + \frac{B_2}{4} + \frac{B_3}{8} \right) \\
= - V_{\text{REF}} \left( B_1 2^{-1} + B_2 2^{-2} + B_3 2^{-3} \right)
\]
Weighted Resistors into Summing Junction DAC

- If $V_{\text{ref}}$ is 10 volts, the maximum output will be
  - $10 \text{ V } (7/8) = -8.75 \text{ V}$
  - Could add inverting amplifier or DC offset to get positive results

- Step size is full scale value ($V_{\text{ref}}$) divided by $2^n$ (where $n$ is the number of bits)
  - Step size for this example is $10 / 8 = 1.25 \text{ V}$
    - This is the “resolution” of the DAC
      - Resolution is the size of the output step associated with a change of 1 least significant bit at the input
R – 2R Ladder --- DAC Type #2
R – 2R Ladder DAC

- Requires only 2 resistor values
  - Solves problem of absolute resistor precision in scaled resistor DAC
  - Resistors in R – 2R ladder DAC have to be precisely matched, but absolute value is not important
- Current into summing junction same as in scaled resistor DAC
R – 2R Ladder DAC

- Scale and step size also the same as scaled resistor DAC (for 3-bit, 10 V case)
- However, because resistor precision is relative for this design, the DAC can be scaled to many more bits
  - Additional bits provide greater resolution
  - For example:
    - 8-bit, 10 V R – 2R ladder DAC provides a step size (resolution) of 10 V / 2^8 = 39.06 mV
Scaled Current Sources – DAC Type #3

- DAC0802 (from ECE 153B experiment)
Scaled Current Sources DAC

- Generic View
Scaled Current Sources DAC

- Similar Approach to R – 2R Ladder DAC
- Bipolar Junction Transistors (BJTs) eliminate the number of floating nodes in the circuit
  - Reduces parasitic capacitance
  - Increases performance
- BJT emitters are sized to be proportional to the emitter current
  - 1x, 2x, 4x, etc.
DAC Interfacing

- Store bit pattern in external register (from processor) and apply reg contents continuously to DAC inputs
- Always some analog details to deal with …
  - Reference voltage or current
  - Full – scale setting
  - External passive components
- And (as always), when in doubt : read the data sheet
Multiplying DAC

- By using the full scale adjust (reference voltage) as an input on some DACs, you can create a “multiplying DAC” or simply an “MDAC”
  - Output = input (reference) voltage * digital code
- Multiplying DACs are used to implement digital gain control in microprocessor and embedded computer systems
Range of DAC Output

- **Terminology**
  - Unipolar: output all positive (or all negative)
    - a single power supply
  - Bipolar: output both positive and negative
    - signed
    - requires two power supplies

- **External op amp circuits**
  - To move range of output
  - To buffer or amplify output
Analog – to – Digital Converters (ADCs)

- Analog – to – Digital converters perform two basic operations
  - Quantization
    - mapping of a continuous signal into one of several possible ranges
  - Coding
    - assignment of a binary code to each discrete range
      - Binary, BCD, sign magnitude, 2’s complement, 1’s complement, offset binary, etc.

- Like DACs, there are several types
The Comparator

- Fundamental component of any ADC
  - essentially an open loop op amp
  - functions as a 1 – bit ADC
  - $V_i$ is input, $V_T$ is threshold voltage
Parallel or “Flash” ADC
Parallel or “Flash” ADC

- Input signal is fed to $n$ parallel comparators
- Each comparator attached to $n$ equally spaced reference voltages
  - generated by a resistor ladder
- Priority encoder generates a $\log_2 n$ output code
Parallel or “Flash” ADC

- Flash is fastest ADC (parallel)
  - up to ~300 Msps
  - small number of bits
    - usually < 10 due to cost
    - Internal component grows as $2^n$

- Because of high speed, sample and hold circuit is not necessary
  - S/H is necessary with slower converters
Sample and Hold Circuits

- Necessary if analog signal changing faster than conversion rate of ADC
  - Conversion must take place before the analog input changes ± ½ lsb or result is inaccurate
Successive Approximation ADC

• Generic view
Successive Approximation ADC

- MCP3002 (from ECE 153B experiment)
  - 10-bit conversion
  - 2 input channels
  - On-board sample and hold
  - Serial Interface
Successive Approximation ADC

- Use DAC and binary search to find correct conversion of $n$ bits after $n$ conversion steps
  - Slower than flash due to $n$ steps needed for $n$ bits of resolution

- Inputs
  - $V_{in}$: voltage to be converted
    - Sample and hold often needed
    - Sometimes (as in MCP3002) it is integrated
  - Start: external command to begin conversion
  - Clock: digital clock oscillator
Successive Approximation ADC

- **Outputs**
  - EOC : End of Conversion
  - Data out
    - Data \([n-1:0]\) if parallel output
    - Dout if serial

- **Conversion (sample) time**
  - 1 µs to 50 µs

- **Accuracy**
  - 8 to 12 bits
Successive Approximation ADC

- **Cost**
  - $5 - $400
    - Cost based on speed and accuracy

- **Potential issues**
  - unipolar vs. bipolar
  - range
  - sample and hold requirements
  - input impedance
Dual Slope Integrating ADC

- also known as Delta – Sigma (ΔΣ) ADC
Dual Slope Integrating ADC

- Strategy is to cancel the input current with a switched current source
  - Input drives an integrator whose output is compared with any fixed voltage (e.g., ground)
  - Depending on the comparators output, fixed length pulses of current are switched into the summing junction of the integrator at each clock transition
    - Maintains zero average current into summing junction
Dual Slope Integrating ADC

- A counter keeps track of the number of pulses switched to the summing junction for a given number of clocks (e.g., 4096)
- Count is output because it is proportional to input level

- Hardware integrating ADC are typically low-speed devices
- They are also capable of high accuracy at low cost due to minimal analog circuitry
Acknowledgements

The (non-datasheet) illustrations in this presentation came from the following textbooks: