AND8413/D

Former Catalyst Document Number AN7

Programmable Analog Functions

ON Semiconductor®

http://onsemi.com

APPLICATION NOTE

Abstract: Analog circuits are made programmable by using digitally programmable potentiometers (DPPs ™) to vary the key circuit parameters. This application note provides the analog design engineer with basic reference designs and circuit ideas for controlling the key parameters of analog circuits using digitally programmable potentiometers connected to a computer bus or microcontroller.

Bringing Digital to the Analog World
Programmable Voltage Amplifier
Programmable Instrumentation Amplifier
Programmable Dual−Gain Amplifiers
Programmable Square Wave Oscillator (555)
Programmable Duty Cycle
Programmable Bandpass Filter
Programmable Voltage Regulator
Programmable Current Source/Sink
Programmable Schmitt Triggers
Programmable Transimpedance Amplifier

BRINGING DIGITAL TO THE ANALOG WORLD

The potentiometer is a three−terminal, variable, resistive divider analog device. It is used primarily to control, regulate, or adjust a characteristic or parameter of an analog circuit. The changing of the potentiometer's wiper's position along the resistive divider provides the variability in a circuit. As opposed to the mechanical potentiometer where the control of the mechanical potentiometer's wiper is physical, the control of the electronic potentiometer's wiper is digital. The digital control signals of the electronic potentiometer are commonly connected to a computer bus where the computer's power of high speed programming, control, and computation are brought to bear in the analog circuit. The potentiometer varies an analog function; digital signals vary the potentiometer; thus, computer generated digital signals vary the analog function. Figure 1 illustrates the concept of computerizing an analog function in block diagram form. Any analog circuit whose parameters depend on a resistance is a candidate for application of a digitally programmable potentiometer. The potentiometer can be configured as a two−terminal variable resistance or a three−terminal resistance divider and is used to control voltage, current, resistance, inductance, capacitance, power, frequency, time, duty cycle, gain, Q, bandwidth, etc. The mixed signal DPP provides the design engineer with a superior analog component that is digitally controlled, programmable, flexible, small size, and low weight. The DPP provides the manufacturing engineer with a cost effective component that has a short programming time, is reliable, compatible with automated assembly test techniques, and has low field service costs.
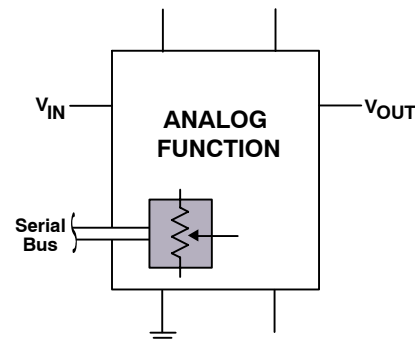

Figure 1. Programmable Analog Functions

The number of basic functions in the analog domain are limited; they are amplification, oscillation, regulation, filtering, and conversion and the circuits which implement these functions are amplifiers, oscillators, regulators, filters, and converters. The most important of these circuits is, of course, the amplifier. These fundamental circuits are the basic building blocks in analog systems. Typical examples of each of these circuits will illustrate the computerization of the analog functions. Hence, they become programmable analog circuits. While the number of basic analog circuits are limited, they are repeatedly and uniquely used as building blocks to implement more advanced analog functions at the system or end product level. The designs feature the use of the 32−tap CAT5114 and CAT5112 DPPs with an increment/decrement interface in single supply applications.

PROGRAMMABLE VOLTAGE AMPLIFIER

The circuit in Figure 2 is a noninverting, single−supply, voltage amplifier circuit whose voltage gain is programmed using a digitally programmable potentiometer. The voltage gain is established by a traditional noninverting operational amplifier circuit and the circuit's lower cutoff frequency is established by a first−order, R_3C low pass filter implementing the bias network. Variability through the movement of the wiper and programmability through the pot's instruction set are added to the circuit by the ON Semiconductor digitally programmable potentiometer (DPP).

The ac voltage gain for the circuit has the form of

$$\frac{V_o}{V_s} = \frac{G_o \, j\omega}{j\omega + \omega_c}$$

G_0 is the programmable closed−loop passband gain

$$G_0 = 1 + \frac{R_2}{R_1} = 1 + \frac{(1-p)R_{POT}}{pR_{POT}} = \frac{1}{p} \qquad \begin{array}{l} 0 \le p \le 1, \\ 1 \le G \le 31 \end{array}$$

where p reflects the proportionate position of the wiper from one end of the pot (0) to the other end of the pot (1). The gain versus p or wiper position, shown in Figure 3, is logarithmic−like and is programmable from 1 to 31 for a 32−tap pot. The gain of this noninverting amplifier is relatively stable with respect to temperature because the gain depends
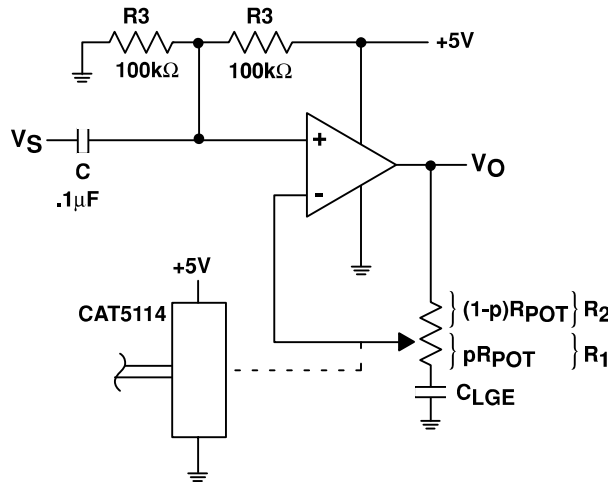
Figure 2. Programmable Voltage Amplifier

on the wiper position and not R_{POT}. The temperature dependence of R_{POT} is relatively high and is not guaranteed. The amplifier's lower cutoff frequency f_C is established by the input R_3−C network:

$$f_c = \frac{\omega_c}{2\Pi} = \frac{1}{2\Pi(R_3/2)C} = 32 \text{ Hz}$$
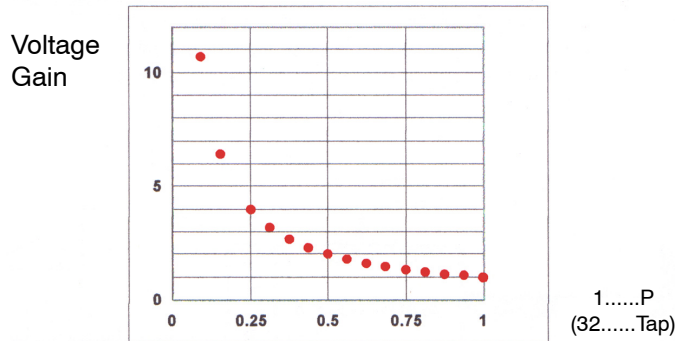
Figure 3. Gain versus Wiper Setting

PROGRAMMABLE INSTRUMENTATION AMPLIFIER

The circuit in Figure 4 is a three−amplifier implementation of an instrumentation amplifier in a single−supply circuit. The implementation, in essence, consists of two noninverting amplifiers (A_1 and A_2) and a differential amplifier (A_3). The voltage gain of the circuit is programmed by a digitally programmed potentiometer (DPP) R_1 and is given as

$$\frac{V_o}{V_2 - V_1} = 1 + \frac{10\ k\Omega}{R_1}$$

R_1 is configured as a variable resistance. The practical gain for the amplifier with a 32 tap DPP varies from 2 to about 25. For higher resolution and higher gain applications, the 100 tap version of the DPP should be used.

$A_1 = A_2 = A_3 = 1/4$ LM 6064
$R_2 = R_3 = R_4 = 5k\Omega$
$R_{POT} = 10k\Omega$
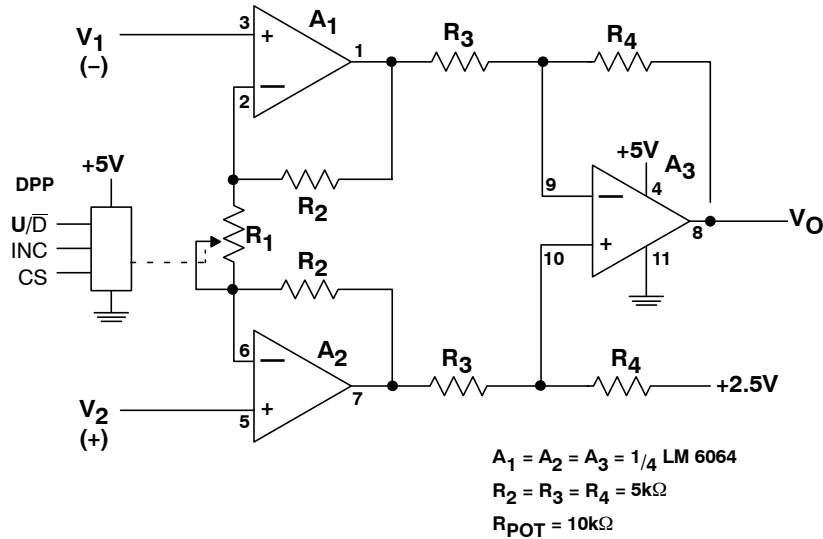
Figure 4. Programmable Instrumentation Amplifier

The instrumentation amplifier is ideally suited for bridge, sensor, and data acquisition amplifier applications where high gain, high common mode rejection ratio and high input resistance are required.

PROGRAMMABLE DUAL−GAIN AMPLIFIERS

The circuit in Figure 5 is an inverting amplifier and, for a given potentiometer setting, has two values of gain; one for positive input voltages (V_{O1}/V_S) and the other for negative input voltages (V_{O2}/V_S). The steering diodes D_1 and D_2 of this circuit establish the polarity of the output voltages and select the gain channel. For single supply circuits, the use of Schottky diodes extends the useable output voltage range. The diodes are within the closed loop and do not impact the value of the gain. The circuit gains in terms of the programming of the digitally programmable potentiometer DPP1 are

$$\frac{V_{O1}}{V_S} = G_1 = -\frac{(1-p)R_{POT}}{R}\ \text{for}\ V_S > 0$$

and

$$\frac{V_{o2}}{V_S} = G_2 = -\frac{(p)R_{POT}}{R}\ \text{for}\ V_S < 0$$

where p varies from 0 to 1 and represents the relative pot setting and R_{POT} represents the end to end resistance. For the values shown in the schematic of this single supply circuit, the gains are individually programmable from 0 to −10. They are however complementary, i.e., there sum equals −10.

The transfer characteristic (V_O versus V_S) in Figure 6 illustrates graphically the programmable dual−gain aspect of the circuit. Figure 7 shows another version of the dual gain amplifier. This version uses a second potentiometer and provides independent values of gain for each polarity of the input voltage.

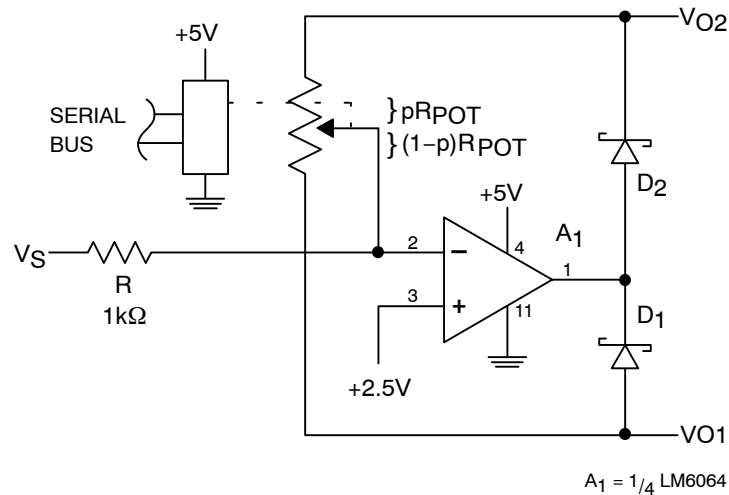**Figure 5. Dual Gain Amplifier**

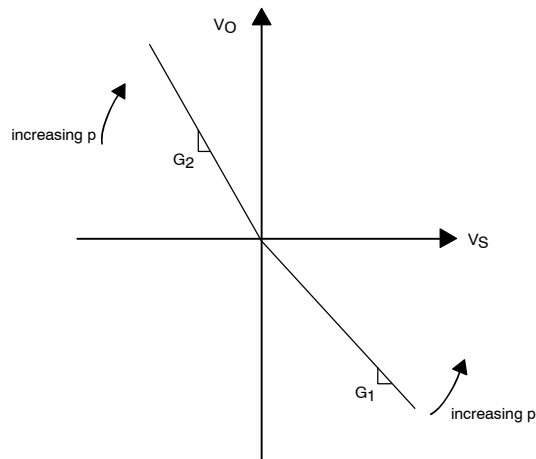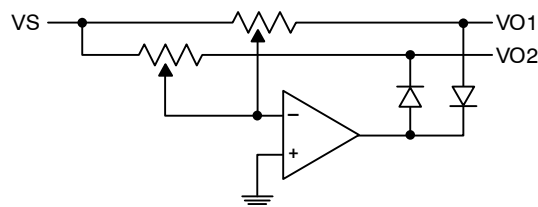**Figure 6. Transfer Characteristic**

Figure 7. Dual Independent Gain Amplifier

PROGRAMMABLE SQUARE WAVE OSCILLATOR (555)

The circuit in Figure 8 is a square wave oscillator with programmable control of frequency (f_{OSC}) and duty cycle (DC). The circuit uses the ubiquitous 555 timer IC connected in the astable mode and ON Semiconductor's CAT5114 digitally programmable potentiometer (DPP). For this traditional configuration, resistances R_A and R_B and capacitor C establish the frequency of oscillation and duty cycle. They are given as

$$f_{OSC} = \frac{1.44}{(R_A + 2R_B)C}, \quad DC = \frac{R_A + R_B}{R_A + 2R_B}$$

If R_A and R_B are replaced by R1, R2, and the potentiometer resistances pR_{POT} (wiper resistance to one end) and $(1-p) R_{POT}$ (wiper resistance to the other end),

$$DC = \frac{R_1 + R_2 + R_{POT}}{R_1 + 2R_2 + R_{POT}(2-P)}$$

The factor p is a dimensionless number that reflects the relative position of the wiper from one end (0) of the potentiometer to the other end (1) and R_{POT} is the pot's end−to−end resistance. The role of resistors R_1 and R_2 is to control the range over which the frequency and duty cycle can be adjusted. The larger R_1 and R_2 are relative to the R_{POT}, the greater the 'effective' resolution but the narrower the range of adjustment. The greatest range of adjustment occurs for $R_1 = R_2 = 0$. For this case,

$$f_{OSC} = \frac{1.44}{R_{POT}(2-p)C}, \quad DC = \frac{1}{(2-p)}$$

For $R_1 = R_2 = 0$, $R_{POT} = 10$ kΩ, and C = 0.01 μF,

$$7.20 \text{ kHz} \leq f_{OSC} \leq 14.4 \text{ kHz and } 0.5 \leq DC \leq 1.$$

The nominal value of f_{OSC} is 10.8 kHz with about a $\pm 33\%$ adjustment range. The duty cycle is fully adjustable.

If $R_1 = R_2 = R_{POT} = 10$ kΩ and C = 0.003 μF,

$$9.66 \text{ kHz} \leq f_{OSC} \leq 12.0 \text{ kHz and } 0.6 \leq DC \leq 0.75$$

The nominal value of f_{OSC} is again 10.8 kHz but with a $\pm 20\%$ adjustment range. The adjustment of the duty cycle is limited in this case from 0.6 to 0.75. The desired programming resolution for frequency of oscillation and duty cycle can be achieved either through the potentiometer's number of taps (programming steps) or the use of R_1 and R_2.

The circuit uses ON Semiconductor's CAT5114 32−tap digitally programmable potentiometer (DPP). This circuit can be used as a general purpose, programmable oscillator or the oscillator circuit with its simple, asynchronous increment/decrement interface can be used as a building block in real time, closed−loop feedback type applications.
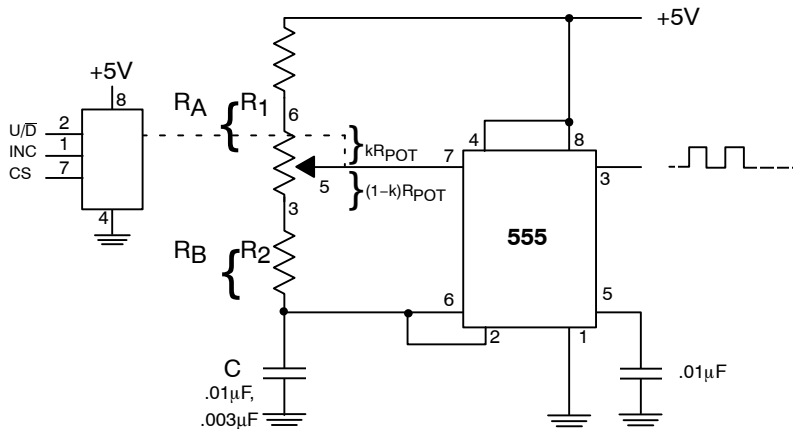

Figure 8. Dual Independent Gain Amplifier

PROGRAMMABLE DUTY CYCLE

The circuit in Figure 9 is a modification of the traditional one−comparator implementation of a square wave oscillator. The positive feedback network establishes the upper (+3.75 V) and lower voltage (+1.25 V) limits for the comparator while the negative feedback network provides a rising and falling exponential waveform. The digitally programmable potentiometer DPP_1 and the steering diodes D_1 and D_2 establish independent charge and discharge paths for the capacitor C. Hence,

$$T_{disch} = pR_{POT} C \ln 3$$

$$T_{charge} = (1-p)R_{POT}C \ln 3$$

where p represents the pot's relative (0−1) wiper setting and R_{POT} represents the pot's end to end resistance. The pot setting programs the duty cycle for the output signal. The total period of the square wave oscillator ($T_{disch} + T_{charge}$) output is

$$T = R_{POT} C \ln 3$$

The oscillator's period, and thus frequency, is constant. For the values shown, the frequency is 910 Hz and the duty cycle can be varied from less than 15% to more than 92%.
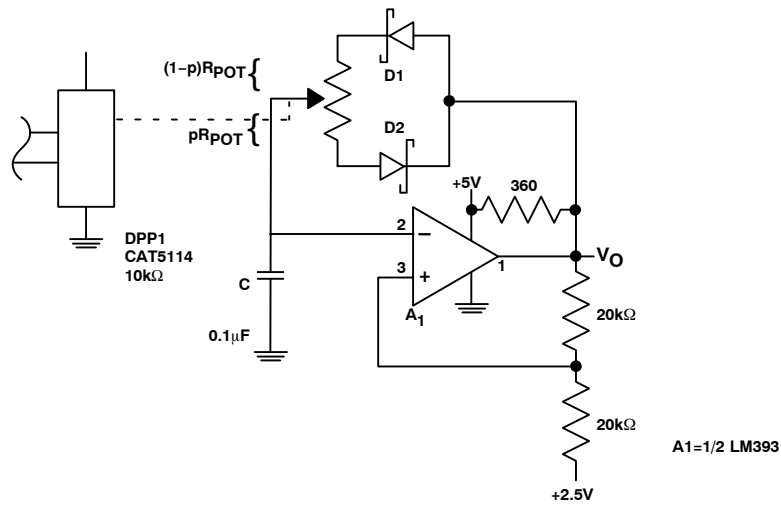
Figure 9. Programmable Duty Cycle

PROGRAMMABLE BANDPASS FILTER

The circuit in Figure 10 is a second−order, bandpass filter whose center frequency is varied using a digitally programmable potentiometer (DPP). The filter is a member of the Infinite Gain Multiple Feedback (IGMF) class which is characterized by a fixed five−component (three R_S and two C_S) configuration. The three key parameters for the bandpass filter are characteristic or center frequency w_O, passband gain A_O, and the figure of merit Q. The gain expression or transfer function for the circuit is

$$\frac{V_O}{V_S} = \frac{-s/R_1C}{s^2 + (2/R_3C)s + (R_1 + R_3)/R_1R_2R_3C^2}$$

$$= \frac{A_Os(\omega_0/Q)}{s^2 + s(\omega_0/Q) + \omega_0^2}$$

where

$$f_0 = \frac{1}{2\Pi C} \sqrt{\frac{(R_1 + R_2)}{R_1R_2R_3}} = \frac{1}{2\Pi C} \sqrt{\frac{(R_1 + pR_{POT})}{R_1pR_{POT}R_3}}$$

$$A_0 = -\frac{R_3}{2R_1},$$

$$Q = \frac{1}{2}\sqrt{\frac{(R_1 + R_2)R_3}{R_1R_2R_3}} = \frac{1}{2}\sqrt{\frac{(R_1 + pR_{POT})R_3}{R_1pR_{POT}R_3}}$$

$$BW = \frac{f_0}{Q} = \frac{1}{\Pi R_3 C}$$

The relative position of the wiper is mathematically modeled as a dimensionless number p and varies from 0 (one end of the pot) to 1 (the other end of the pot). A useable range for p in this application is from 0.05 to 1.0.

R2 is independent of gain (A_0) and bandwidth (BW) and can be used to independently vary the center frequency f_0 (and Q). Using digitally programmable potentiometers (DPPs) to vary key parameters in filters (and other analog circuits) saves the cost of using expensive, precision resistors and capacitors to guarantee a circuit's performance. ON Semiconductor's CAT5114 potentiometer has a increment/decrement asynchronous interface which lends itself to closed−loop, feedback type applications. For example, the center frequency of the tunable bandpass filter could be varied in a closed loop configuration to match the frequency of an incoming sinusoidal signal in a signal processing system.

For the circuit values shown, the passband gain is minus one, the bandwidth is 3.2 kHz, and the center frequency can be varied from 5.5 kHz to 22 kHz. For the wiper set half way, p = 0.5, the filter's center frequency is 7.5 kHz.
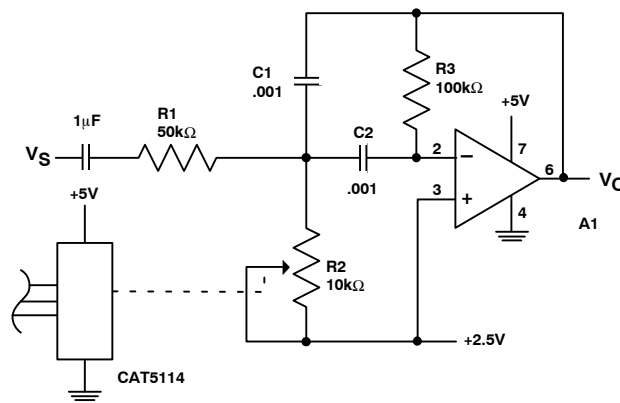
Figure 10. Programmable Bandpass Filter

PROGRAMMABLE VOLTAGE REGULATOR

In mixed signal systems, the compatibility of the voltages of the analog, digital, and mixed signal devices can be an issue when they meet in the same circuit. For example, the LP2952 in Figure 11 is one of a series of voltage regulators designed for analog output voltages from 1.2 V to 30 V. The regulator also has digital controls in the form of an input digital signal for shutting down to conserve power and an output digital signal indicating an output undervoltage condition. The digitizing of the voltage regulator in a processor based system can be completed by programming the output voltage using the mixed signal, digitally programmable potentiometer (DPP). The DPP brings variability to the regulator output voltage through its analog potentiometer and programmability through its digital control signals and serial bus. With the 2952 type regulator, system designers can use the basic device to provide voltage regulation and use digital signals to address power and low voltage concerns and program the output voltage. One problem is most digitally programmable potentiometers are designed for +5 V or ±5 V analog systems. This problem can be overcome by placing the variable resistance of the DPP in the ground leg of the regulator's programming resistors, $R_1 - R_3$, as shown in Figure 6. The voltage at the feedback (FB) pin is the regulator's internal reference of 1.235 V. The internal reference is within the 5 V limitation of the analog potentiometer which does not see the high regulator output voltage in this position. The output voltage for this circuit is given as $V_O(reg) = 1.235$ V$\{1 + R_1/(R_2 + R_3)\}$.

For $V_{IN}(unreg)$ of 15 V, the regulator output voltage of Figure 6 will vary from 2.5 V to 13.5 V. Discrete resistors R_1 and R_2 and the potentiometer's end−to−end resistance R_{POT} are used to control the range over which the potentiometer will program the output voltage. These resistors and the number of taps of the DPP are used to define the resolution. The digitally programmable potentiometer shown in ON Semiconductor's low cost, 32 tap CAT5114. This potentiometer has an increment/decrement interface which lends itself to a closed−loop, automated calibration procedure which saves production test time and provides additional security. The circuit can be used as a bias supply or programmable voltage source.
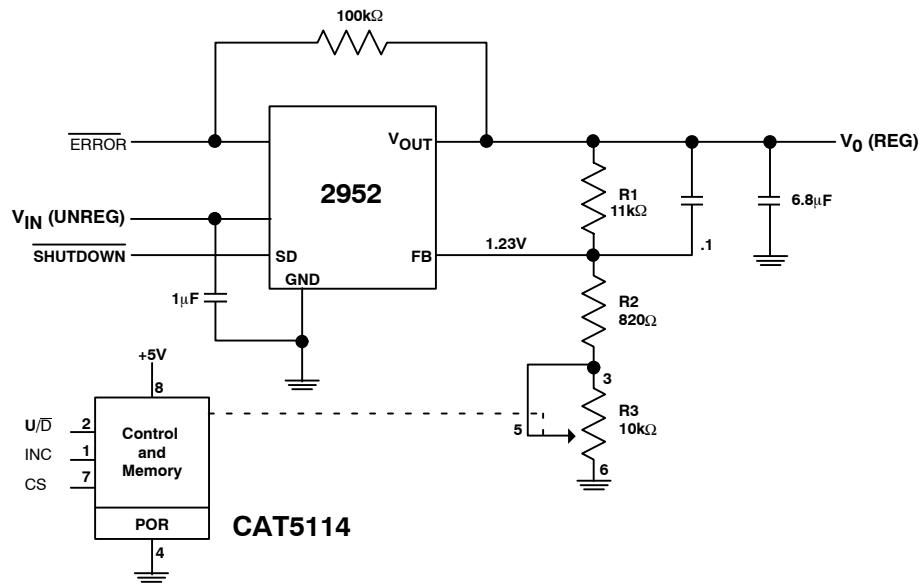
Figure 11. Programmable Voltage Regulator

PROGRAMMABLE CURRENT SOURCE/SINK

The circuit in Figure 12 is a voltage−controlled, constant current source whose value is programmed using the ON Semiconductor 5112 digitally programmable potentiometer (DPP). The output current $I_S = -V_S / R$ where V_S is the buffered wiper output voltage of the DPP. The circuit can either source ($V_S < 2.50$ V) or sink current ($V_S > 2.50$ V). The source is implemented using a summing/differential amplifier (A_1) and a voltage follower (A_2). The constant voltage V_S across the constant resistor R establishes the constant current. The A_2 circuit raises the output voltage of A_1 by the amount of the load voltage thus maintaining a constant voltage V_S across R.

For the circuit values shown, the output current can be programmed from 0 to ± 1 mA in 64 μA steps
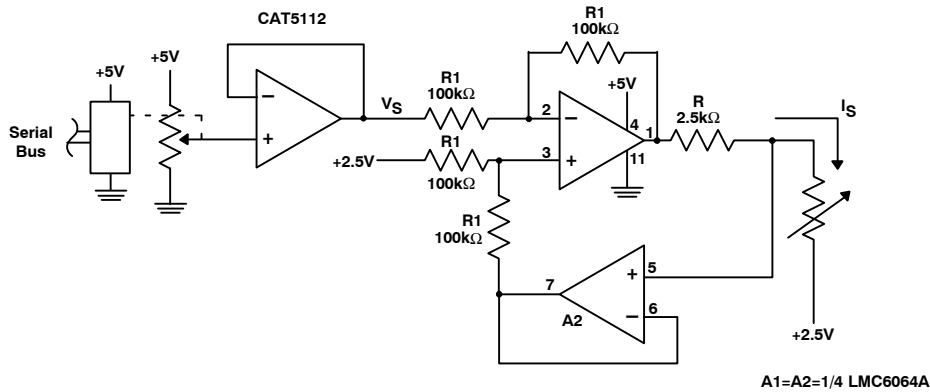
Figure 12. Programmable Current Source/Sink

PROGRAMMABLE SCHMITT TRIGGERS

The circuit in Figure 13 is a single−supply version of a programmable Schmitt Trigger or a comparator with hysterisis. The function is implemented using a comparator A_1 and a digitally programmable potentiometer (DPP). The lower (V_{LL}) and upper (V_{UL}) limits of the hysterisis characteristic are a function of the relative setting of the potentiometer's wiper and are given as

$$V_{LL} = (1 - p)2.5 \text{ V} \quad \text{and} \quad V_{UL} = 2.5 \text{ V} + (p)2.5 \text{ V}.$$

where p is a dimensionless number from 0 to 1 and represents the potentiometer wiper's position from one end of the pot (0) to the other end (1). The characteristic's lower limit can be programmed from 0 V to 2.5 V and the upper limit can be programmed from 2.5 V to 5 V. The circuit's transfer characteristic (V_O versus V_S), Figure 14, illustrates the hysterisis curve and the lower and upper limits. The two limits are complementary, i.e. their values sum to 5 V, and hence are not independently programmable.

The lower and upper limits of the characteristic can be independently programmed by adding steering diodes D_1 and D_2 and a second potentiometer as shown in Figure 15. For this circuit,

$$V_{LL} = (1 - p_2)2.5 \text{ V} \quad \text{and} \quad V_{UL} = 2.5 \text{ V} + (p_1)2.5 \text{ V}.$$

With ON Semiconductor's 32 tap DPPs, the lower limit can be programmed from 0 to 2.5 V in 81 mV increments

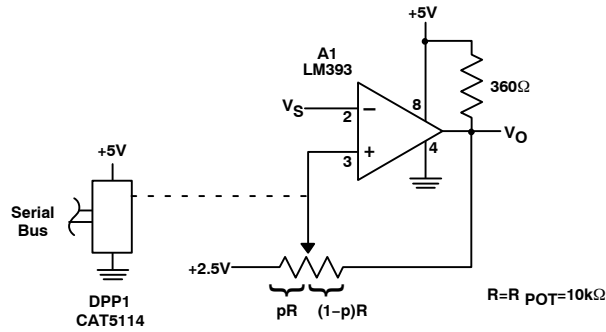and the upper limit can be independently programmed from 2.5 V to 5 V with the same resolution.

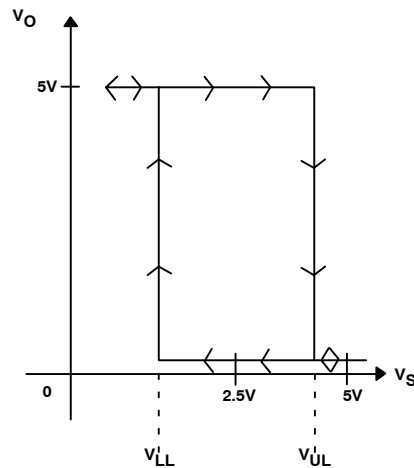**Figure 13. Programmable Schmitt Trigger**
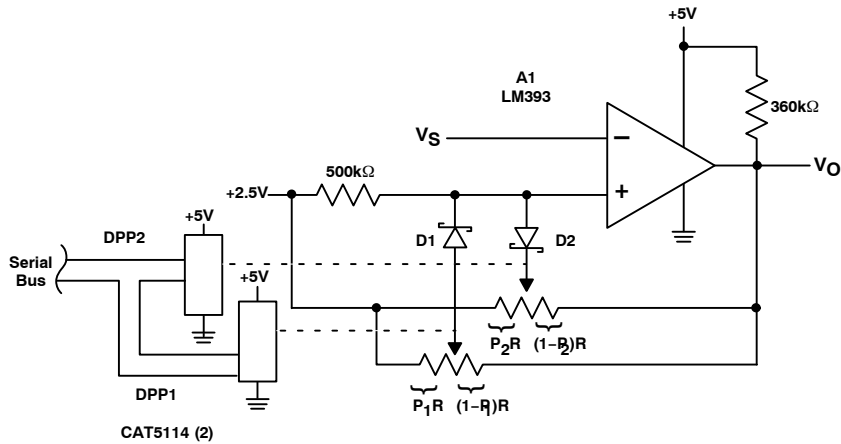
Figure 14. Transfer Characteristic

Figure 15. Schmitt Trigger with Independently Programmable Limits

PROGRAMMABLE TRANSIMPEDANCE AMPLIFIER

The circuit in Figure 16 is an input current (I) to output voltage (V) convertor, or transimpedance amplifier, with programmable gain. The circuit is a current to voltage convertor circuit (A_1) cascaded with an inverting amplifier circuit (A_2) with a common digitally programmable potentiometer (DPP) varying the gains of the two. Transducers like photodiodes and photovoltaic cells, with their high output impedance, are best modeled as current sources. Their output current is typically converted to a voltage for further signal processing.

The potentiometer resistances are modeled as pR (= pR_{POT}) and (1−p)R where p is a number that varies from 0 to 1 and reflects the proportionate position of the wiper from one end (0) of the potentiometer to the other end (1). The programming of the location of the wiper changes the scale factor between the input current and output voltage without changing the values of any of the resistances and avoids the use of high value resistors in measuring low values of current. For this circuit,

$$\frac{V_O}{I_S} = -\left\{330\ \Omega + pR\right\}\frac{1\ M\Omega}{330\ \Omega + (1-p)10\ k\Omega}$$

The gain of the transimpedance amplifier (V_O/I_S) is pseudo−logarithmic and varies from 31kΩ to 31MΩ as p is varied from 0 to 1. With these resistances, over four decades of current can be measured from less than 6 nA to over 60 μA. The circuit usΩs the low cost, 32 tap ON Semiconductor CAT5114 with a increment/decrement serial interface. This simple, asynchronous interface can be computer controlled or driven by logic and lends itself to automated calibration and test−and−measurement procedures.
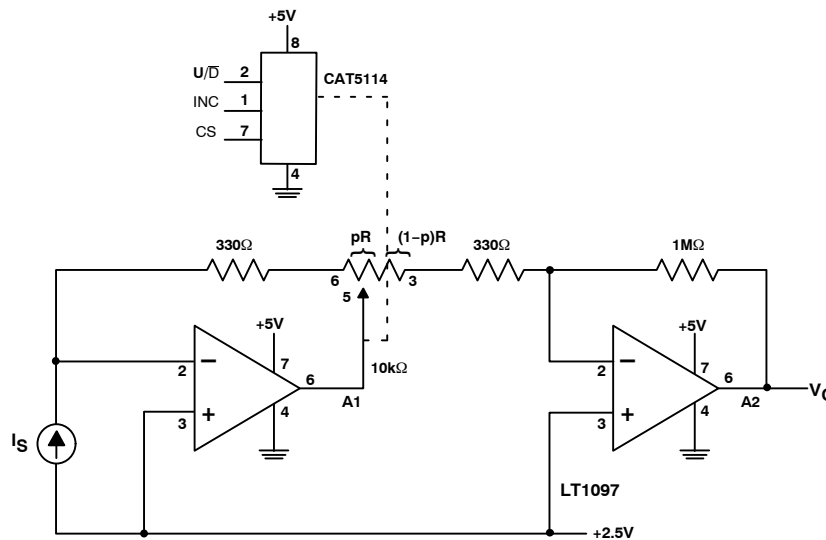
Figure 16. Programmable I to V Convertor

REFERENCES:

1. "Op Amp Network Design" by John R. Hufault, John Wiley and Sons, New York, 1986, pp. 102, 103
2. "Operational Amplifiers" by Charles F. Wojslaw and Evangelos A. Moustakas, John Wiley and Sons, New York, 1986
3. "IC Op Amp Cookbook" by Walter G. Jung, Howard Sams, Indianapolis, 1979
4. "Operational Amplifiers" by G.B. Clayton, Butterworth Scientific, London, 1982
5. "Linear Potentiometer Implements Logarithmic Gain" by W. Stephen Woodward, EDN, October, 23, 1997
6. "PWM Circuit uses One Op Amp" by Ferran Bayes, EDN, July 6, 2000
7. "Decompensated Op Amp Gain is Adjustable from Zero to Open−Loop" by Stephen Woodward, ED, June 4, 2001
8. "Bipolar Single−Supply Schmitt Trigger Extends DPM Range" by Andrea Sosso, ED, October 16, 2000
9. "Building the Analog Tool Kit", Signal Conditioning Seminar, Texas Instruments Publication, 2001
10. "Linear Applications Handbook, Volume III", Linear Technology Publication, 1997
11. "Digital Potentiometer Controls AGC Circuit" by Tavares, Tavares, and Piedade, EDN, August 3, 2000
12. "RTD Auto−nulling Delta−T Thermometer" by Stephen Woodward, ED, June 28, 1999
13. "IC Timer Cookbook" by Walter G. Jung, Howard Sams and Co.
14. LP2952/53 Voltage Regulator Data Sheets, National Semiconductor Publication

DPP is a trademark of Semiconductor Components Industries, LLC (SCILLC).