Sensing Light with a Programmable Gain Amplifier

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INTRODUCTION

Photo sensors bridge the gap between light and electronics. Microchip's Programmable Gain Amplifiers (PGAs) are not well suited for precision applications (such as CT scanners), but they can be effectively used in position photo sensing applications minus the headaches of amplifier stability. When the two, six or eight-channel PGA is used in this system, the other channels can be used for other sensors or an array of photo sensors without an increase in signal conditioning hardware or PICmicro® microcontroller I/O pin consumption. The multiplexer and high-speed conversion response of the PGA / Analog-to-Digital (A/D) conversion allows the photo sensor input signal to be sampled and quickly converted to the digital domain. Switching from channel-to-channel is then easier with the Serial Peripheral Interface (SPI™) from the PICmicro microcontroller to the PGA.

The PGA can be configured with a photo sensor in two different settings, as illustrated in Figure 1. These circuits are appropriate for signal responses from DC to ~100 kHz.

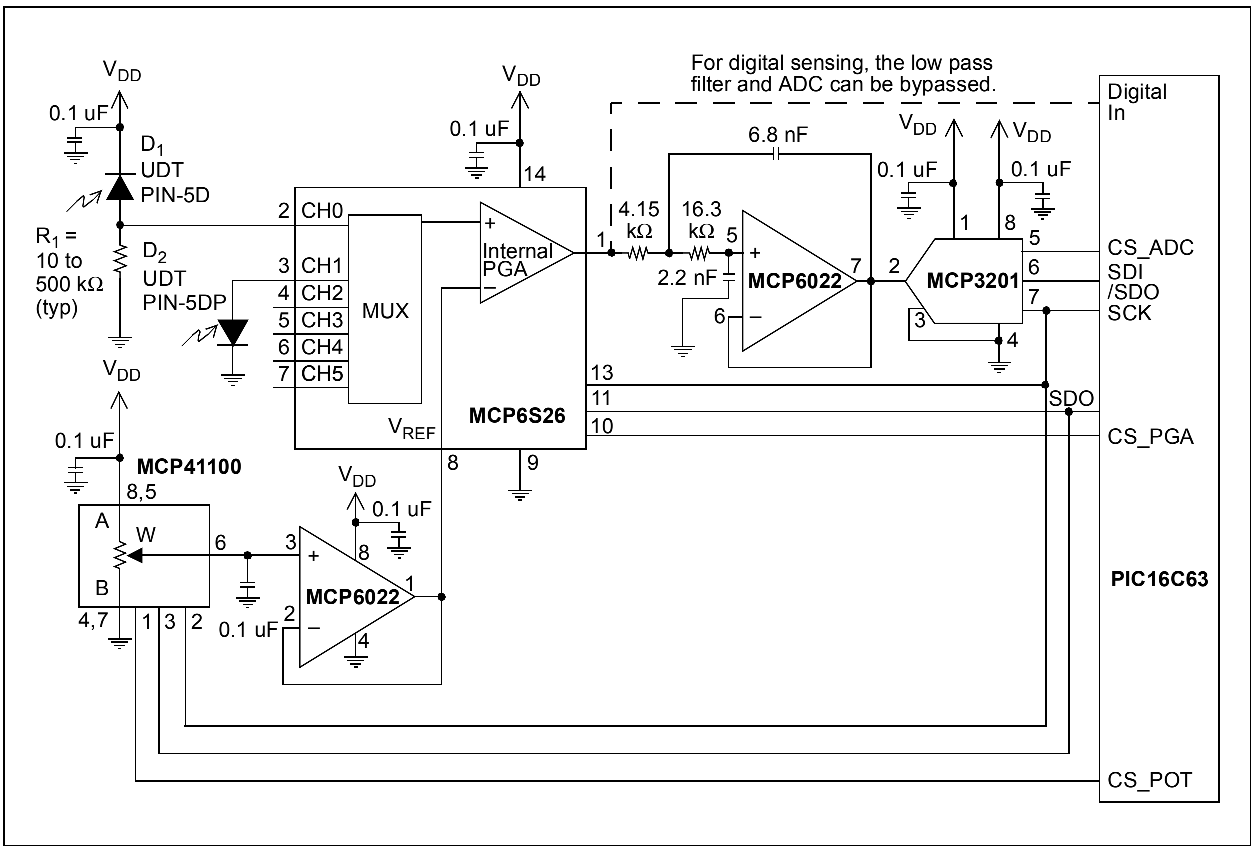

FIGURE 1: Photo sensors can be connected directly to Microchip's PGA. Based on the level of luminance to the photo sensor, the gain of the signal can be changed through the SPI™ port of the MCP6S26, six-channel PGA.

THE PHOTO SENSORS, VOLTAGE REFERENCE AND PGA

The photo sensor connected to CH0 of the MCP6S26 in Figure 1 uses the photo sensor diode (D_1) in its photoconductive mode. When a diode is configured in its photoconductive mode, it has a reverse voltage bias applied. In this mode, the photo sensor is optimized for fast response to light sources. An ideal application for a diode configured in the photoconductive mode is digital communications. The reverse biasing of D_1 will create some current leakage and a voltage drop across the resistor (R_1). If the offset caused by this leakage current is not tolerable, it can be calibrated by adjusting the value of R_1. In this scenario, pin 8 (V_{REF}) of the PGA would be grounded.

The voltage generated by the photo sensor is gained by the PGA. Consequently, in this configuration, the PGA would be programmed to higher gains and the value of the resistor R_1, should be selected as low as possible. This resistor selection is dependant on the characteristics of the photo sensor. A reasonable range for R_1 would be 10 kΩ to 500 kΩ.

The photo sensor D_2, connected to CH1 in Figure 1, is configured in its photovoltaic mode. For a photo sensor to be configured in this mode, it must be zero biased. The configuration shown in Figure 1 is not ideal in this mode because the voltage across the photo sensor is not forced to zero by the amplifier. However, the photo sensor gives an output voltage response near ground for no light and will increase with changes in light. The PGA gain for this circuit is dependent on the changes in luminance in the system and the specific photo sensor. Higher gains will give you a better dynamic range on the output of the PGA.

PGA Reference Voltage for Linear Operation

The voltage reference to the PGA can be set using a voltage reference device. A variable voltage reference may be required because of the various requirements on other channels of the PGA. If a variable voltage reference is needed, the circuit in Figure 1 can be used.

The input range of the reference voltage pin of the PGA is V_{SS} to V_{DD}. In this case, V_{SS} = Ground and V_{DD} = 5V. The transfer function of the PGA is equal to:

EQUATION

$$V_{OUT} = GV_{IN} - (G - 1)V_{REF}$$

With this ideal formula, the actual restrictions of the output of the PGA should be taken into consideration. Generally speaking, the output swing of the PGA is less than 20 mV below the positive rail and 125 mV above ground, as specified in the MCP6S2X PGA data sheet (DS21117). However, to obtain good, linear performance, the output should be kept within 300 mV from the rails. This is specified in the conditions of the “DC gain error” and “DC output non-linearity” in the MCP6S2X product data sheet.

Consequently, beyond the absolute voltage limitations on the PGA voltage reference pin, the voltage output swing capability further limits the selection of the voltage at pin 8. This is illustrated in Figure 2 and Figure 3.

Photo sensors can be connected directly to the PGA with reasonable accuracy. Based on the level of luminance to the photo sensor, the gain of the signal can be changed through the SPI port of the MCP6S26, six-channel PGA.

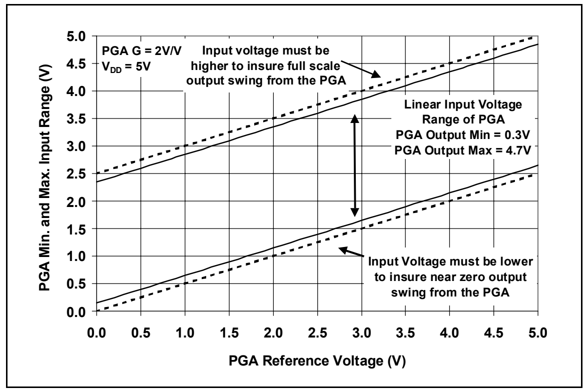

FIGURE 2: *If the programmed gain of the PGA is 2 V/V, the suggested voltage applied to the V_{REF} (pin 8) is shown in this graph in order to keep the PGA in its linear region (solid lines) and to achieve good digital output states (dashed lines) from the PGA.*

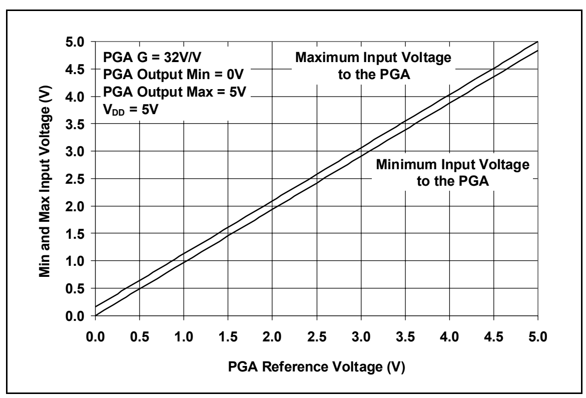

FIGURE 3: *If the programmed gain of the PGA is 32, the suggested voltage applied to the V_{REF} (pin 8) is shown in this graph in order to keep the PGA in its linear region.*

As shown in Figure 2 and Figure 3, the reference voltage of the PGA should be programmed between the expected input voltage range of the PGA. For instance, in a gain of 2 V/V (Figure 2, solid lines), with an input range of 1.0V to 3.2V, the voltage reference at pin 8 of the MCP6S26 should be equal to 1.7V for optimum performance.

The formulas used to calculate the limits in Figure 2 and Figure 3 are

EQUATION

$$V_{IN}(min) \geq (V_{OUT}(min) + (G - 1)V_{REF})/G$$

$$V_{IN}(max) \geq (V_{OUT}(max) + (G - 1)V_{REF})/G$$

where:

V_{IN} = input voltage to the PGA.

V_{OUT}(min) = minimum output voltage of PGA = V_{SS} + 0.3V.

V_{OUT}(max) = minimum output voltage of PGA = V_{DD} - 0.3V.

G = gain of the PGA.

V_{REF} = Voltage applied to the PGA's V_{REF} pin.

PGA Reference Voltage for Digital Operation

The reference to the PGA in Figure 1 (MCP6S26, pin 8) is provided by the digital potentiometer, MCP41100. Alternatively, the voltage reference pin of the PGA can be driven with a D/A voltage-out converter, a dedicated voltage reference chip, a resistive divider circuit or tied to ground or V_{DD}. In all cases, the voltage reference source should be low-impedance. A digitally-controlled variable voltage reference may be required because of the various requirements on other channels of the PGA. If a variable voltage reference is required, the circuit in Figure 1 can be used.

As stated in the previous section, the input range of the reference voltage pin is V_{SS} to V_{DD}, with the transfer function of the PGA equal to:

EQUATION

$$V_{OUT} = GV_{IN} - (G - 1)V_{REF}$$

To keep the PGA close to the output rail, the PGA output limits described in the previous section have been changed to V_{OUT}(min) = 0V as a minimum and V_{OUT}(max) = 5V as a maximum (although the outputs will only go to ~20 mV from ground and ~125 mV below the positive rail).

This concept is illustrated in Figure 2 (dashed lines) with a programmed gain of 2 V/V. This concept is not illustrated in Figure 3 with a programmed gain of 32 V/V because it is difficult to graphically see the difference between the linear region of operation and the digital region of operation.

HANDLING THE OUTPUT OF THE PGA

In Figure 1, the output of the PGA is shown as having two possible paths. The solid lines of this circuit follow the analog path that has a low pass, anti-aliasing filter, followed by an ADC and then into the a PICmicro microcontroller. The second path is indicated with the dash lines above the filter and ADC. This is a purely digital path where the PGA circuit should be designed to operate as a comparator instead of an analog component.

Getting a Linear Response

To get a linear response from the photo sensor, the signal path takes the photo sensor signal from the output of the PGA, through an anti-aliasing filter, into an ADC and then to the PICmicro microcontroller for further processing.

For this function, the PGA should be calibrated to be in a linear mode. This calibration can be done graphically as described above or with an iterative process. The first step is to calibrate the maximum luminance on the photo sensor. The output of the PGA should be at least 300 mV below the power supply (V_{DD}). This is done by adjusting the gain of the PGA. Once this is achieved, the minimum luminance should be calibrated. This is accomplished by exposing the photo sensor to the minimum luminance condition and adjusting the voltage at the V_{REF} pin so that the output of the PGA is above 300 mV from V_{SS}. Once this is complete, you should return to the maximum luminance condition to verify that the output of PGA is still in its linear region, more than 300 mV below V_{DD}.

At the output of the PGA, an anti-aliasing filter is inserted. This is done prior to the A/D conversion in order to reduce noise. The anti-aliasing filter can be designed with a gain of one or higher, depending on the circuit requirements. Again, the MCP6022 operational amplifier is used to match the frequency response of the PGA. Microchip's FilterLAB® software can be used to easily design this filter's frequency cut-off and gain.

The anti-aliasing filter in this circuit is a Sallen-Key (non-inverting configuration) with a cut-off frequency of 5 kHz. This frequency should be selected to match the frequency response of interest from the photo sensor, as well as the other channels at the input of the PGA. For more information concerning the design of anti-aliasing filters, refer to Microchip Technology's AN699, "Anti-Aliasing, Analog Filters for Data Acquisition Systems" (DS00699).

The signal at the output of the filter is then connected to the input of a 12-bit ADC, MCP3201. In this circuit, if noise is kept under control, it is possible to obtain 12-bit accuracy from the converter. Noise is kept under control by using an anti-aliasing filter (as shown in Figure 1), appropriate bypass capacitors, short traces, linear supplies and a solid ground plane. The entire system is manipulated on the same SPI bus of the PIC16C63 for the PGA, digital potentiometer and ADC with no digital feed-through from the converter during conversion.

Opting for the Digital Response

This signal path in Figure 1 is indicated by a dashed line coming out of the PGA and proceeding directly to the PICmicro microcontroller. Since the levels of this line should be high and low, the PGA should be configured to produce signals near the power supply rails. The calibration of this system can be performed as discussed above or by using an iterative method, as described below.

The first step to iterative calibration is to calibrate the maximum luminance on the photo sensor. The output of the PGA should be several millivolts below the power supply (V_{DD}). This is accomplished by adjusting the gain of the PGA. In this condition, the output of the PGA is pushed to exceed the power supply voltage with little effect. If the PGA gain is set too high, the device will go into a deep saturation. This will slow down the recovery time of the PGA from high to low.

Once the maximum luminance is properly adjusted, the minimum luminance should be calibrated. This is done by exposing the photo sensor to the minimum luminance condition and adjusting the voltage at V_{REF} so that the output of the PGA is a few tens of millivolts above V_{SS}. Once this is complete, you should return to the maximum luminance condition to verify that the output of PGA is still close enough to V_{DD}.

Performance Data

This data was taken using an MCP6S26 and one of each of the photo sensors from UDT™ sensors. The selected photo sensors for this application note are not necessarily the appropriate diodes for all applications. V_{DD} was equal to 5V and V_{SS} equal to ground. The data is reported reliably, but does not represent a statistical sample of the performance of all devices in the product family.

LINEAR RESPONSE

The photo sensor used in this application note for D_2 is a PIN-5DP/SB from UDT sensors. The size of the photo sensor is 5.1 mil^2, with a rated capacitance across the diode at zero bias of 450 pF (typ). This photo sensor is a Super Blue Enhanced diode from UDT sensors with a responsivity 0.6 A/W at 970 nm. The shunt resistance at zero bias is 150 MΩ (typ). This photo sensor is suitable for sensing low level light.

The PIN-5DP/SB was biased in its photovoltaic mode, as illustrated in Figure 1. When the photo sensor was placed in a dark environment, the output voltage of the PGA was 1.8 mV. This output voltage was above V_{SS} and was limited by the output swing of the PGA.

When this set-up was exposed to the lab lighting, the luminance dictated maximum PGA gain of 10 V/V. This gain was found through experimentation. The circuit response under full exposure is shown in Figure 4 and Figure 5.

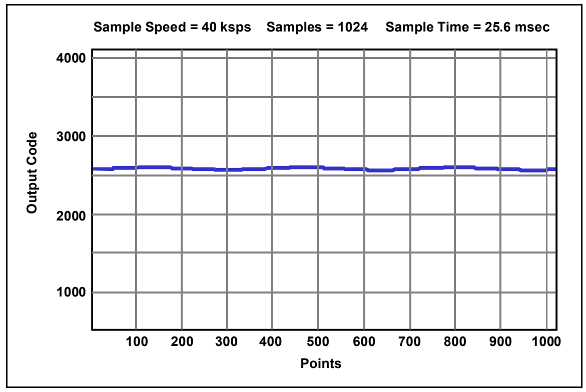

FIGURE 4: *Using the circuit in Figure 1, the output code from the 12-bit ADC is collected while the lab is fully lit.*

In Figure 4, the average center code is 2582, which translates to a voltage is 3.15V with a 5V reference on the ADC. There is a small signal riding on this output response. This small signal is magnified and shown in Figure 5. The small signal frequency measured was 120.9 Hz, the ac frequency from the lab lights.

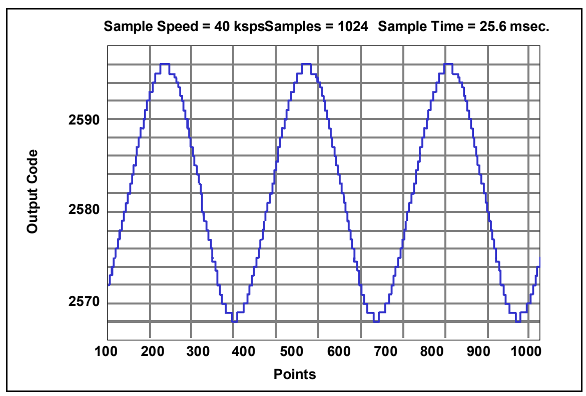

FIGURE 5: *The data taken in Figure 4 has been amplified to view the small signal.*

DIGITAL RESPONSE

The photo sensor used for D_1 is a UDT, PIN-5D. It's silicon size is the same as D_2 at 5.1mil^2, however, its responsivity at 410 nm is 0.2 A/W. This photo sensor is specifically manufactured for digital, high-speed response, having a parasitic capacitance across the element of 15 pF with a -10V reverse bias.

The Dark Current leakage of this photo sensor with a reverse bias of -10V is specified as 3 nA (max). This specification was used to calculate an appropriate value for R_1.

EQUATION

$$R_1 \leq \frac{G \bullet V_{OUT}(min)}{I_{DC}(max)}$$

$$R_1 \leq \frac{1V/V \bullet 1V}{3\ nA}$$

$$R_1 \leq 333\ m\Omega$$

where:

$V_{OUT}(min)$ = V_{IL} of a Schmitt Trigger buffer input pin of the PIC16C63 and

$I_{DC}(max)$ = the maximum Dark Current leakage of the photo sensor

R_1 was chosen to be 10 kΩ for noise reduction purposes. In this test, the MCP6S26 was programmed to a gain of 1 V/V. The output swings from 100 mV to 4.95V, dependent on the level of light exposure.

CONCLUSION

Position sensing with the MCP6S2X PGA devices from Microchip Technology Inc. is easily implemented. The connections described in this application note can easily be implemented in a sensing system that has several channels for other functions. The MCP6S2X family of PGAs have one, two, six or eight-channel devices in the product offering. Changing from channel to channel may entail a gain and reference voltage change. This would require that three, 16-bit communications occur between the PGA and digital potentiometer. With a clock rate of 10 MHz on the SPI interface, this would require approximately 3.4 ms; 1.7 ms per device. Additionally, the PGA amplifier would need to settle. Refer to the MCP6S2X PGA data sheet (DS21117) for the settling time versus gain specification.

The PGA, a device from Microchip Technology Inc., not only offers excellent offset voltage performance, but the configurations in these optical sensing circuits are easily designed without the headaches of stability that the stand-alone amplifier circuits present to the designer. Stability with these programmable gain amplifiers have been built-in by Microchip engineers.

References

AN699, "Anti-Aliasing, Analog Filters for Data Acquisition Systems", Bonnie C. Baker, Microchip Technology Inc. (DS00699).

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