Sub-microamp, intelligent Hall-effect sensing delivers 20-year battery life

TEXAS INSTRUMENTS

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With a careful balance of hardware and firmware, sensor systems can be built that deliver extended battery life.

The unique features of the DRV5000 family of Hall effect sensors, combined with the ultra-low power capabilities of the MSP430™ MCU, enable for the first time, smart physical presence-detection systems such as door or window security, and e-meters to remain directly powered from a single low-cost CR2032 coin cell for over two decades of continuous operation.

Compared to an always-active sensor system, an intelligent Hall-effect sensor system can be designed with its current consumption reduced from what are typically milliamps to less than a microamp — a reduction of over 1000x. This is achieved by combining the fast start-up time and wide-range operating voltage of the DRV5000 Hall sensor with the ultra-low-power capabilities of the MSP430 MCU. Such a sensing system with extremely low power consumption enables physical presence-detection applications, such as door or window security systems, and e-meters to be directly powered from a single low-cost CR2032 coin cell for over two decades of continuous operation.

The techniques described in this paper that enable ultra-low power (ULP) sensing include:

- Operating the system in ultra-low power standby mode as the normal mode
- Duty-cycling the sensor
- Exercising power-aware firmware

The simplified example circuit in **Figure 1** shows a very low-cost system that does not require any external calibration. The complete sub-microamp, intelligent Hall-sensing system detects the presence of a magnet and is powered directly from a CR2032 battery.
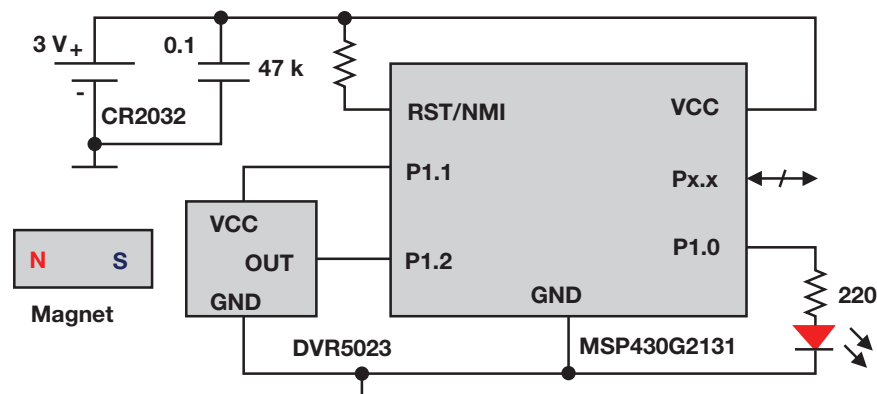

Figure 1. Sub-microamp, intelligent Hall-sensing system.

DRV5000 Hall sensors

The DRV5000 family of Hall sensors are easy-to-use 3-pin devices that have pins for power, ground, and an output. The DRV5023 in **Figure 1** has a digital output and will detect a magnetic field of 9 mT or greater. Though it depends on the magnet, the DRV5023 can deliver reliable detection within 1 cm of a common low-cost ceramic magnet. Other device derivatives are available with different sensitivity levels if needed. The digital output of the sensor is open in the absence of a magnetic field and pulled low in the presence of a sufficient south field. In the example circuit, a magnet in close proximity to the sensor is the "safe mode", and no magnet is the "alert mode." The absence of a south-field magnet is what is being monitored.

Because the DRV5023 has an exceptionally wide operating voltage range of 38 V down to as low as 2.5 V (Reference 1), the device can be directly powered from a 3-V CR2032 coin cell. The CR2032 discharge curve is essentially flat at 3 V until the battery is nearly depleted, allowing the majority of the capacity to be utilized with a cutoff at 2.5 V (Reference 3). At this cutoff voltage, the usable battery capacity is 200 mAh out of a total capacity of 240 mAh. Thus, 83% of the battery capacity can be used in the 3-V to 2.5-V voltage range.

The Hall sensor has a fast power-on time (50 µs maximum), which is utilized in the example. This allows the entire device to be power-gated off extensively to save energy and extend battery life.

An alternative Hall device is the omnipolar DRV5033 that detects and logically OR's a north or south magnetic field. If using an omnipolar device, the magnet may be oriented in the application with either a north or south pole perpendicular to the sensor for an equal output response. This attribute simplifies end-product assembly.

Normal mode is ultra-low-power standby mode

The system is controlled by the MSP430G2131 MCU, which is the lowest-cost variant of the MSP430 family. Like all MSP430 devices, this MCU is ultra-low power, especially in standby mode, which is defined as low-power mode 3 (LPM3). In LPM3, with an internal 12-kHz very-low power oscillator (VLO) running, a timer active, both memory and peripheral states retained, and brown-out reset (BOR) protection enabled, the entire device consumes only 0.5 µA at 3 V (Reference 2).

The 12-kHz VLO can also be divided by as much as 8 at the MCU clock tree for an even lower-frequency standby clock of approximately 1.5 kHz. This small change to the clocking system was proven on the bench to reduce standby current from 0.5 µA to approximately 0.3 µA. This is the normal mode of the device and the overall sensor system described in this paper.

At a programmed interval, the VLO clocked timer interrupts the CPU and wakes the device to full active mode in less than 1 µs. In active mode, a separate 1-MHz digitally-controlled oscillator (DCO) clocks the CPU and the VLO is only used to clock the wake-up timer. On wake-up, the CPU powers-up and measures the sensor and then returns immediately to LPM3 as long as the magnet is detected. In the absence of a magnetic field, an alert is issued.

Duty cycling the sensor

The Hall sensor has a bandwidth of 20 kHz, which is orders of magnitude greater than that needed for physical detection. In the example discussed, the normal sensor operation is for it to be completely power-gated off and periodically powered-up, measured, and then immediately power-gated back off. The purpose is to reduce the average power

consumption via the lowest practical active duty cycle. The longer the sensor can be power-gated off, the lower the average current.

Because the sensor only consumes typically 2.8 mA when active, any MCU general-purpose input output (GPIO) configured as an output can be directly used as a switchable power supply to the sensor; P1.1 is used in the example. From the MCU datasheet, a GPIO supplying 2.8 mA at 3 V will drop less than 100 mV, which is insignificant in the application. The open-drain output of the sensor can be connected to any one of the MCU's GPIO pins configured as an input with the optional pull-up resistor enabled. MCU pin P1.2 is used in the example.

In the example, if an adequate magnetic field is detected, which is the safe mode, the sensor will pull the output low. When the sensor is powered-up, only 50 µs is required for the sensor output to stabilize. Following power-up, the MCU simply reads the output of the sensor and makes the appropriate decision.

Power analysis

A typical active system would power both the sensor and MCU directly from the power source using several milliamps. In this power-hungry system, the sensor consumes 2.8 mA and the MSP430 uses 300 µA at 1 MHz. Also, the sensor is sampled as fast as the MCU can complete a firmware endless loop. In this mode, with a 1-MHz MCU clock rate, and assuming 10 clocks per sample loop, the sensor is sampled at 100 kHz. With both the sensor and MCU powered permanently, the current consumption of a typical system is then calculated as follows:

$I\_average$ (typ)
$= I\_sensor + I\_MCU$
$= 2.8$ mA $+ 0.3$ mA
$= 3.1$ mA

The ULP system solution described in this paper operates normally in standby mode at 0.3 µA. In standby, the sensor is completely power-gated off and only the MCU contributes to current consumption, which is treated as a constant. In the ULP solution, when active, the total system current consumption is 3.1 mA which is the same as in the typical system, but in this case only for short 65-µs bursts. Each active burst includes the sensor power-up (50 µs) and MCU firmware decision sequence (15 µs). The 65-µs active-time sequence is repeated at a 3 Hz rate (every 0.333 s), which is adequate for most presence-detection systems. With the system only active a total of 195 µs (65 µs × 3) every second, the active duty cycle is only 0.0195%.

The average current consumption for the total system, assuming a sample rate of 3 Hz, can then be calculated using the following equation:

$I\_average$ (3 Hz)
$= I\_standby + (I\_measurement \times$ active duty cycle)
$= 0.3$ µA $+ [3.1$ mA $\times (65$ µs $/ 0.333$ s$)]$
$= 0.9$ µA

If a sampling rate different from 3 Hz is required, the primary impact is power consumption – lower sampling reduces power, higher sampling increases power. The standby current is a constant. For example, if a faster sampling rate of 50 Hz (0.02 s period) is required, the average current is calculated as follows:

$I\_average$ (50 Hz)
$= I\_standby + (I\_measurement \times$ active duty cycle)
$= 0.3$ µA $+ [3.1$ mA $\times (65$ µs $/ 0.02$ s$)]$
$= 10.4$ µA

As previously described, the usable CR2032 capacity from 3 V to 2.5 V is 200 mAh. Dividing the battery capacity by the total average ULP current consumption of 0.9 µA, the theoretical number of hours of service for the system is calculated below.

Battery_life (3 Hz)

= battery_capacity / I_average

= 200 mAh / 0.9 µA

= 222,222 h (25 years)

Power-aware firmware

The firmware is very simple and straightforward. An initialization routine first configures the MCU main system clock to 1 MHz, the VLO to 1.5 kHz, configures the GPIO, and enables a 3-Hz watchdog timer (WDT) interrupt.

In the main the body of the firmware, an endless while (1) loop immediately places the MCU into LPM3 standby mode. At a 3-Hz rate, the CPU is interrupted by the WDT interrupt service routine (ISR), forcing an exit from LPM3. The Hall sensor is then powered up using GPIO P1.1, a 50-µs delay is called, and a single if-else statement is used to test the Hall sensor output on GPIO P1.2. If the output of the sensor is high, a sufficient magnetic field is not present and the appropriate alert action is taken. The alert action in the example is to illuminate an LED on P1.0. If the sensor output is low, the magnetic field is present and no action is taken. The body of the firmware is shown below:

```
while (1) {
   _BIS_SR(LPM3_bits + GIE);         // Enter LPM3
    P1OUT |= 0x02;                    // Power HALL
   __delay_cycles(50);               // 50us for HALL power-up
   if (P1IN & 0x04))                 // HALL not active?
   P1OUT |= 0x01;                    // yes, set P1.0 LED on
    else
    P1OUT &= ~0x01;                   // No, clear P1.0 LED off
   P1OUT &= ~0x02;                    // Disable HALL
 }

#pragma vector=WDT_VECTOR
__interrupt void watchdog_timer (void)
{
    _BIC_SR_IRQ(LPM3_bits);           // Clear LPM3 bits from 0(SR)
}
```

Conclusion

The complete firmware for the sub-microamp intelligent Hall-sensing system uses less than 200 bytes of Flash code space out of an available 2 KB on the MSP430G2131. A significant amount of customization is possible using the remaining code space. Aside from the system stack, no RAM is used. The LED alert used in the example could be replaced by a buzzer or even a low-power radio. Several Hall sensors can be connected to the same MCU depending on the available MCU GPIO pins.

A low-battery function may be desirable and can be added easily with a simple high-value resistor divider that is periodically powered by an MCU GPIO pin, which is the same voltage as that of the battery. This divided battery voltage can be measured approximately using the available MCU integrated comparator and the internal 0.55-V reference to derive the value of the battery voltage. For example, a divider with resistor values 10 k and 2.7 k ohms, and with a 2.6-V battery level applied, will equal the 0.55-V internal reference. This would be an excellent low-battery warning level. Such a battery test consumes less than 400 μA for the CPU, divider and comparator combined. This configuration requires less than 20 μs to complete the measurement and has an inconsequential impact on the overall consumption of system current.

During the LPM3 ULP standby mode, the MCU WDT is clocked by the VLO which is very low power, but the frequency is not extremely accurate. As such, it may be desirable to calibrate the inaccurate low-frequency VLO with the calibrated high-frequency DCO. A method of calibrating the VLO is described in TI's application note "Using the VLO Library" (Reference 4). In this case, the MCU Timer_A with single-clock timing granularity can be used to finely tune the wake-up interval, replacing the course WDT.

The circuit described in this paper has been tested. The power-consumption figures presented are typical and at room temperature. Realistically, the battery has leakage of 1% to 2% per year. Factoring in 2% annual battery self discharge, the described sensor system will still deliver 20-years battery life with 13-mAh reserve capacity – over two decades of continuous service from a common CR2032 battery.

References

1. DRV5023 Texas Instruments Datasheet
2. MSP430G2x31 Mixed Signal Microcontroller, Texas Instruments Datasheet
3. Energizer CR2032 Product Datasheet
4. Lane Westlund, "Using the VLO Library," Texas Instruments Application Report, April 2011.

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