Improve your Aim to Improve your Game

A look into the design of joysticks using precision magnetic rotary encoders

Simon Bramble

Introduction

Potentiometer based joysticks have long offered a low cost solution for applications from gaming to automotive. However, as low cost as the potentiometer may be, it still suffers from mechanical wear and tear and noisy performance. Solutions are available that offer better linearity, lower noise, higher precision and zero wear and tear. These solutions are based on magnetic, contactless Hall Effect technology.

The Hall Effect

In 1879, Edwin Herbert Hall discovered that if you apply a magnetic field to a current carrying conductor, it induces a voltage perpendicular to the current flow and magnetic field.

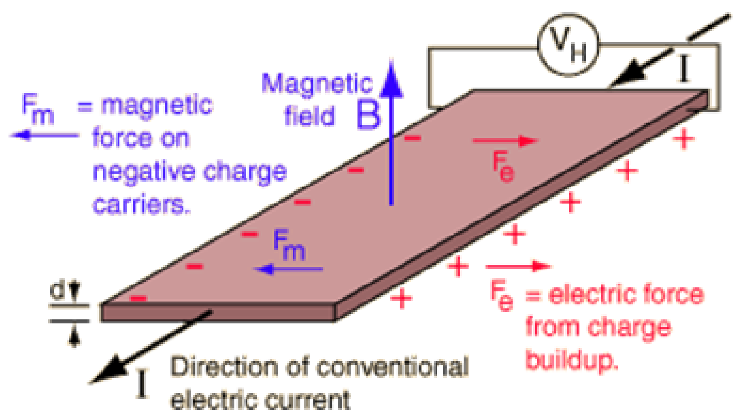

FIG 1
Voltage induced in a current carrying conductor, caused by the presence of a magnetic field

The thickness of the conductor, d, is inversely proportional to the voltage, making a standard silicon CMOS process very suitable for integrating Hall Effect sensors. Indeed this is what austriamicrosystems has done with its family of 8, 10 and 12 bit rotary encoders.

Rotary Encoders

The AS5xxx family of contactless rotary encoders implement four pairs of Hall Effect sensors mounted on a diameter of 2.2mm inside an integrated circuit. If a small single pole magnet is placed in close proximity above or below the chip, each Hall Effect sensor picks up a sinusoidal field as the magnet rotates. The phase difference between two adjacent Hall sensors is 90 degrees, thus sine and cosine waveforms are produced. Dividing the sine by the cosine gives the tangent of the angle and from this the angular rotation of the magnet can be deduced.

Although this is easy in principle, in practice the Hall devices are also sensitive to other magnetic fields, temperature variations and distance of the magnet from the chip. To make a rotary encoder that can be used in the real world, these limitations have to be eliminated.

Interference from external magnetic fields can be minimized by correct design and measurement of the Hall Effect sensors. Austriamicrosystems has designed its sensors to be very sensitive to magnetic fields directly above and below the chip, but completely insensitive to fields planar to the chip surface. Inferior Hall sensors can detect 3-axis fields so they not only measure fields perpendicular to the surface of the chip, but also planar to the surface of the chip. This makes these devices much more susceptible to interference from unwanted magnetic fields.

To further aid the removal of interference from external fields, the Hall sensors are measured differentially. As the magnet rotates, each sensor picks up a field that is 180 degrees out of phase with respect to the sensor opposite to it on the die. If this field is measured differentially, any ambient magnetic field present is common to both sensors and represents itself as a common mode output voltage from the Hall sensors and thus is eliminated when applied to a differential amplifier. This patented technique makes the AS5xxx family extremely insensitive to unwanted magnetic fields.

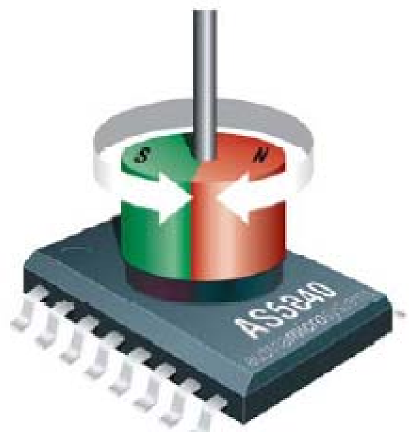

FIG 2

Changes in magnetic field due to temperature and distance have no effect on the angle measurement. Since we are looking at the ratio of the sine to the cosine waveforms from the Hall Effect sensors, any change in magnetic field will change the sine and cosine amplitudes equally, so the ratio (or tangent) remains unchanged. However, austriamicrosystems integrates an automatic gain control inside the device to enable detection of the magnetic field strength. This can give an early warning of mechanical displacement of the magnet, but detection of the vertical distance of the magnet can also enable the designer to implement a push button feature in the rotary encoder

The above patented technology forms the basis of the range of rotary encoders from austriamicrosystems. To make the devices suitable for use in the real world we provide a number of different outputs. Traditional potentiometer based joysticks output two analogue voltages representing the magnitudes of forward-reverse and left-right. To allow an easy upgrade path from potentiometers, the AS5043 has an integrated DAC thus giving an analogue voltage proportional to angular displacement. The chip can be programmed to allow the designer to set the zero to full scale voltage over the exact angle of his choice, not just 90 degrees or 45 degrees. The designer can program the approximate range of the joystick motion in software (with ranges of 45, 90, 180 or 360 degrees) then fine tune the analogue output using feedback resistors placed around the internal op amp of the AS5043.

Many applications now require a signal that is more immune to noise, so we also provide digital interfaces via SPI, PWM, quadrature, LSB and 3 phase commutation outputs.

One headache facing many production engineers is detecting the orientation of the magnet. If the Hall sensors detect the rotating field of a magnet, the magnet would normally have to be aligned to the desired zero angle point during factory calibration. All parts from austriamicrosystems integrate a non volatile zero set register. The angle can be read on startup, the orientation of the magnet can be determined and the chip can be programmed to offset any future readings by the value in the zero set register. The need to orientate the magnet during production is then eradicated. As the zero set register value is held in non volatile memory, this production step only has to be implemented once during the product's lifetime. The devices also have a counterclockwise bit that causes the encoder to increment its count with a counterclockwise rotation.

To further reduce the cost of ownership, austriamicrosystems also offers a calibrated solution 'out of the box'. No expensive five point linearisation calibration is needed on production thus saving further production time.

Recent trends in the automotive industry highlight the need for redundancy in the silicon to offer a backup in the case of failure. The AS52xx family of parts offer dual die integrated into one package. The 2 die are completely isolated, offering a redundant solution in one package. To further furnish the needs of the automotive industry, the AS51xx family of parts offer automotive qualification with some parts tested to 150 degrees centigrade.

Design of a Joystick

To test the rotary encoders 'in anger' it was decided to implement two of them in a joystick design – one to give an analogue voltage from 0 - 5V representing fully reverse to fully forward and another to give 0 - 5V from fully left to fully right. A potentiometer based joystick was purchased (FIG 3).

FIG 3

This highlights an interesting frustration of many hobby electronics engineers. You can design the greatest circuit, but unless you put your circuit into a professional housing, it will always look 'experimental' even if its performance is good. With a joystick housing purchased, the electronics had to be removed. FIG 4 show the original electronics with the miniature potentiometers at the top and to the right of the picture.

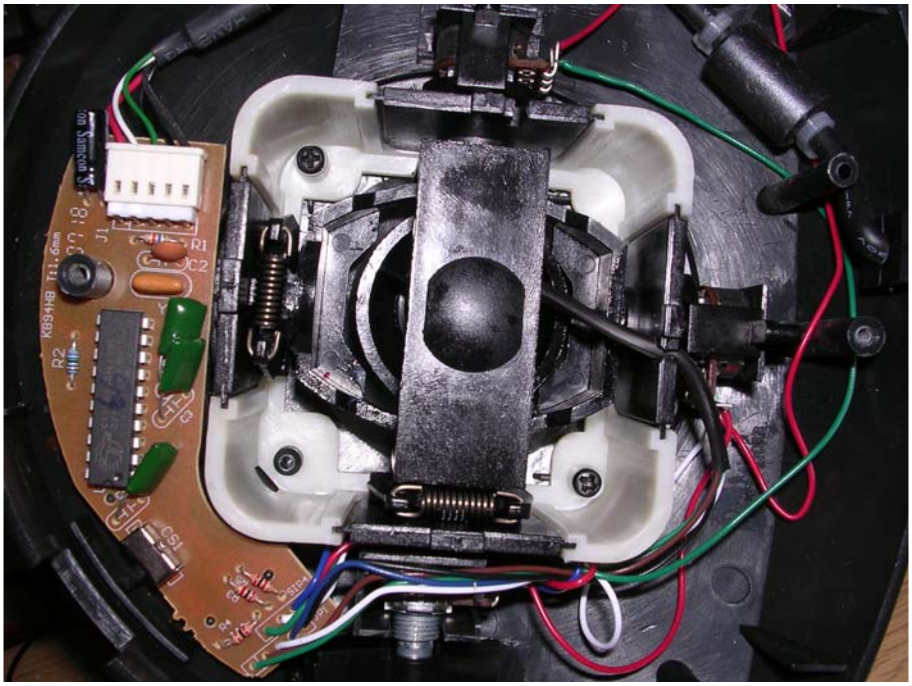

FIG 4

The two potentiometers were replaced by two AS5043 10 bit rotary encoders each with an on chip DAC and op amp. The bases of the potentiometers were removed from their shafts and replaced with 6mm magnets. The AS5043s were mounted on the base plates that held the potentiometers.

The devices were programmed using a PIC 16F627A. (A copy of the C code is available by emailing the author.) The code waits for the AS5043s to complete their self calibration routine then it implements an angle read. In this particular design example, the angle read is conducted with an untouched joystick, so the angle data represents the centre point of both left-right and forward-reverse encoders. The angle data also contains information on the status of the magnetic field and the corresponding linearity of the result.

The angle data is extracted and a count of 64 (equal to 22.5 degrees) is subtracted from each result to give a zero output at the extremes of position of each encoder. This reading is then programmed into the zero set register. The configuration bits are then set. These set the rotation direction of the encoder (clockwise/counterclockwise), set the full scale angle of the encoder (45, 90, 180, 360 degrees), full scale range (0-100% or 10%-90%) and the reference select bit (internal or external).

It is important to note that the microcontroller is only needed to program the one internal register. The part can still be used with the specified accuracy without a microcontroller. Also, once the AS5043 register is programmed, the microcontroller is redundant, so this step can be integrated into the production software

The final assembly is shown in FIG 5. The forward-reverse rotary encoder can be seen to the right of the picture. The potentiometer shaft with silver magnet at its end is circled in yellow. Each adaptor board is also clearly visible. Several stray leads can be seen. These are power supply leads or lead carrying the output voltages for demonstration purposes. A smaller microcontroller can be substituted as only six I/O lines were used. Individual lines were used for each Chip Select line (CSn), but the clock and data lines were common to each encoder. Separate Program lines were used as this aided diagnostics.

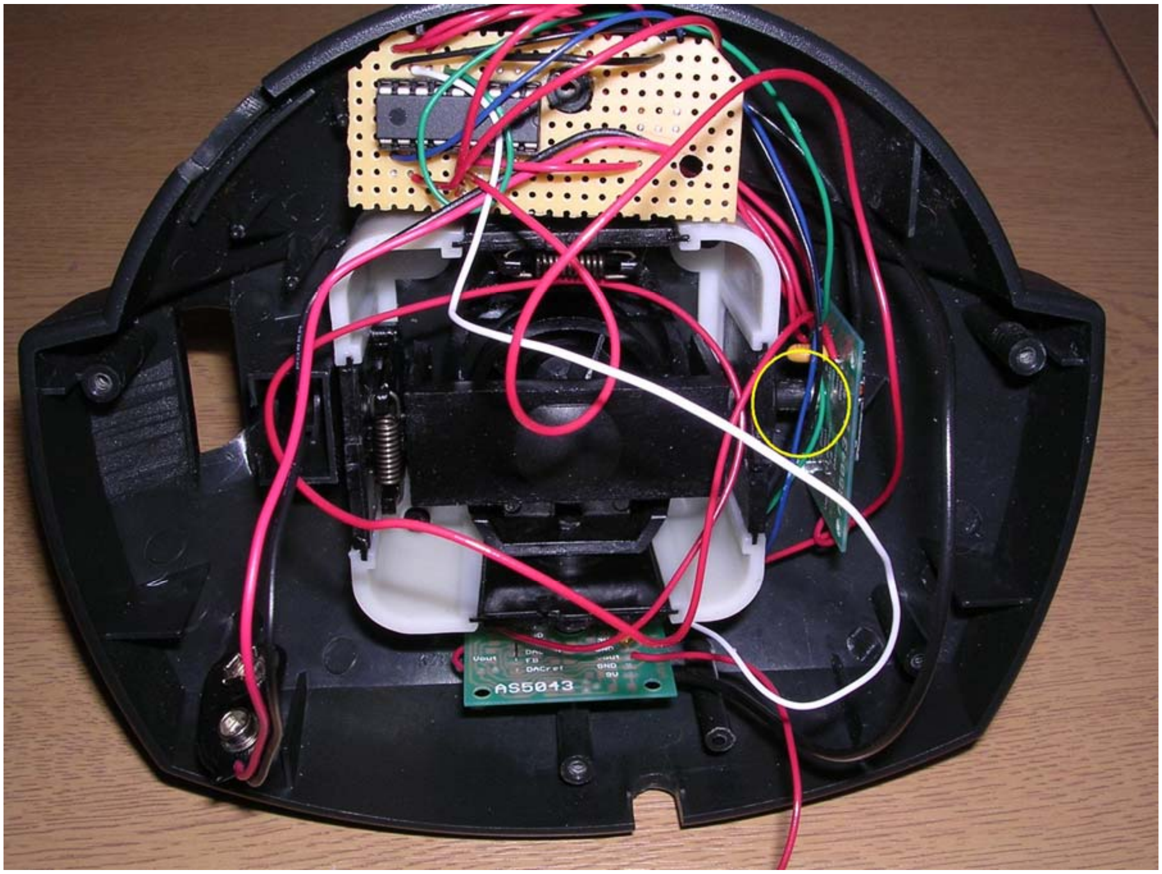

FIG 5

Results
The joystick worked extremely well. The adaptor boards carrying each AS5043 were populated with 7805 linear regulators, so the joystick worked with input votages from 7V to 40V. The board was tested with 9.00V and gave consistent results over the full range of motion of the joystick.

A 33uF tantalum capacitor was added to the input of the 7805 to protect against any noise on the supply rail. The circuit was intermittently shorted to the power supply in an attempt to crash either the microcontroller or the AS5043 and the circuit maintained correct operation.

Circuit Diagram

FIG 6 show the circuit diagram with the bit settings for both AS5043.

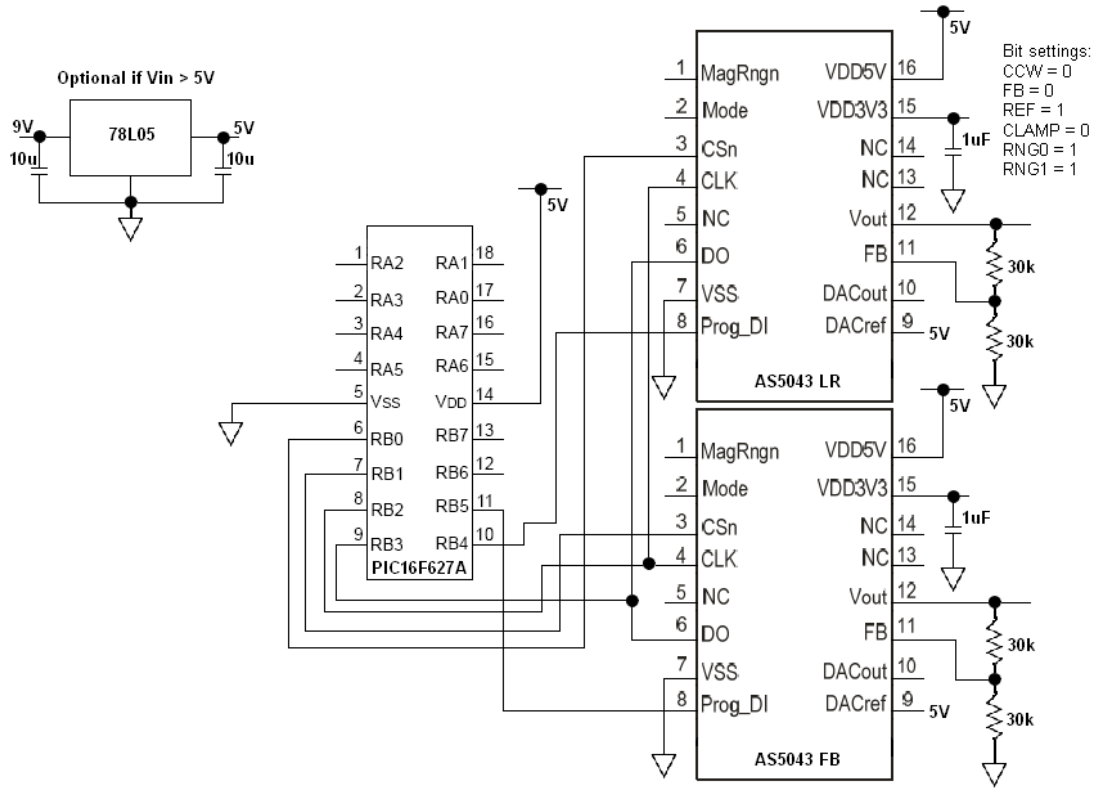

FIG 6

Summary

This article describes the operation of a rotary encoder. These devices are simple to use, have no mechanical wear and tear and give good accuracy ‘straight out of the box’. The article goes on to describe the design of a joystick with two 0-5V analogue outputs representing left-right and forward-reverse.

Biography

Simon Bramble has worked for austriamicrosystems UK for 2 years. He graduated with a degree in Electronics from Brunel University in West London in 1991 and has worked in the semiconductor industry for 10 years. He lives in Hampshire, UK with his wife and daughter. He aspires to lead the life of the idle rich. His wife says he is exactly half way there.