Design Considerations for an Absolute Steering Angle Encoder Demo

Introduction

Linear optical sensor arrays have been utilized in absolute rotary and linear encoders since the mid 1990's as a cost effective and robust solution for industrial applications. These sensors continue to be used in new applications due to their ability to accurately measure mechanical position and movement in a robust manner.

One of the markets where optoelectronic sensors have gained significant adoption is the automotive industry. Texas Advanced Optoelectronic Solutions (TAOS, Inc.) and Microchip Technology Inc., working in a collaborative effort, have developed an absolute rotary encoder demonstration unit. The purpose for this unit is to provide the first part of what eventually will become a reference design for those engineers looking for some guidance and discussion of the design issues and tradeoffs they may face as they move toward a production intent design.

Below are the target specifications for the rotary encoder demo:

- **Resolution:** 0.088 degrees (i.e. 4096 codes/revolution, or 12-bits)
- **Maximum Turning Rate:** 2000 degrees/sec.
- **Minimum Response:** 100 readings/sec.

This paper describes the design considerations required to meet the specifications using a Microchip Technology microcontroller (PIC16F819) and a TAOS Inc. TSL1401R. This demonstration and the following documentation is not intended as a production intent design but rather a starting point for those individuals desiring to gain a greater understanding of absolute encoders.

Optical Rotary Encoder Configuration

The basic arrangement of the optical rotary encoder consists of an infrared LED (IRED) positioned above a partly transparent code disk, below which a linear sensor array is located (see Figure 1). The code wheel is printed with an opaque bar code pattern that encodes the absolute position information. Light from the IRED passes through the transparent portions of the disk and reaches the linear array, while the opaque

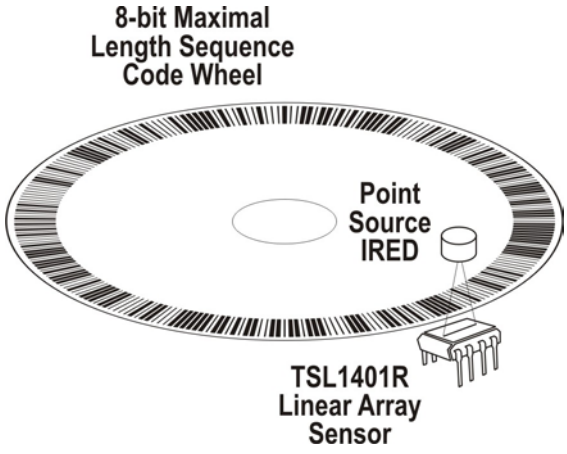


Figure 1 - Optical Rotary Encoder

bars cast shadows forming dark regions on the linear array. This light and dark bar pattern on the linear array produces signals that vary from zero, or dark level, to full white-level and saturation. The linear array signal is then input to a microcontroller where the pattern is decoded and interpreted as a unique angular position.

Code Wheel

A key optical element in the absolute optical rotary encoder is the code wheel. The angular resolution and size requirements for the encoder are key considerations when considering the type of code to be used on the code wheel. For this design, a single-track, maximal-length sequence code is used. The basics of this coding technique are covered in the TAOS document, *Position Detection using Maximal Length Sequences* by David H. Mehrl. A maximal-length sequence code was chosen over multi-track Gray-coding due to its simplicity and lack of critical alignment requirements. It is a method very well suited to linear array sensors such as the TSL1401R.

The first consideration is how many bits to encode on the wheel. The number of bits used in the maximal-length sequence code will determine the number of unique positions on the wheel. The answer to this was derived from the length (8.1mm) and optical resolution (.0635mm) of the linear sensor array and the diameter of the code wheel. The code wheel diameter was dictated by the size of a readily available housing, resulting in a 46mm active diameter (144mm circumference). To properly read a code on the wheel, we have a requirement that the viewing area (length) of the array spans several more than the number of bits in the code. With a seven-bit code, for example, we would have 127 bits spread out over a 144mm circumference, or 0.88 bits/mm. With the 8mm-long sensor, we could see 8 • 0.88 = 7.04 bits, which does not meet the above requirement. With an eight-bit code we have 255 encoded bits in the same 144mm circumference, which increases the physical density of the code and gives us 14 bits across the length of the sensor, which satisfies the requirement for sensor viewing area. We also must ensure that we have adequate optical resolution on the sensor to resolve the bars, which represent bits on the code wheel. Since the linear array has 128 pixels over the 8.1mm length, this gives 128 / 14 = 9 pixels per bit, which should also be adequate. If we went to a nine-bit code, we could see 28 bits at a time, but each bit would cover only 4.5 pixels. That is too few pixels to reliably resolve the bars, so eight was chosen as the best number of bits to encode on the wheel.

The usual maximal-length sequence code can be generated using a shift register and a handful of XOR gates, or by simulating such a method in a computer program. For an n-bit code, the length of such a sequence will be $2^n - 1$. This is because a code of all zeroes cannot occur. If initialized with such a code, the shift register will remain stuck there. In designing an encoder, this is a rather inconvenient situation. For computational simplicity, we'd like the number of unique codes on the code wheel to be a power of 2. It turns out that simply inserting an extra zero into the longest sequence of zeroes of the shift-register-generated code works fine. For example, a normal eight-bit maximal-length sequence will consist of 255 bits (128 ones and 127 zeroes) and contain the subsequence …100000001… That is to say that the eight-bit code 10000000 is immediately followed by the code 00000001. By sticking in the extra zero at this point, we obtain …1000000001…, which yields the 8-bit code sequence …, 10000000, 00000000, 00000001, …

The next consideration involves how to encode these bits on a code wheel. In the Mehrl paper, NRZ encoding was used. That is, the bits were assigned contiguous cells, and the entire cell was either black or white, depending on the value of the bit. Because we actually need 12 bits of resolution, we need to be able to infer the remaining four bits from the fine-scale position of the eight-bit code we read. But, in order to do this, each code bit, whether a one or a zero, needs to have an edge or two that we can discern. This is called "self-clocking", and various methods are available to do this. One of the most popular, Manchester encoding, also has the advantage of a low spatial frequency. In this encoding method, each bit is represented as a transition at the center of its cell. A "one" bit is encoded as a low-to-high transition; a "zero" bit, high-to-low. Manchester encoding has a couple disadvantages for this application, however:

1. It is not always possible, given a snapshot of a few bits, to discern which transitions are at the centers of their bit frames and which ones are at the edges. For example, an isolated string of all “ones” will look identical to an isolated string of all “zeroes”. Clock synchronization needs to occur over a sequence that includes a mixture of “ones” and “zeroes” to be effective.
2. Manchester encoding is asymmetrical. This is to say that rising edges and falling edges do not surround the center of a bit frame equally. Each bit’s “position” is determined by the location of its central rising, or falling, edge. If a sensor were detecting bars slightly out of focus using a fixed analog threshold, say, changes in the overall pixel response would shift the apparent bar locations and throw off the results. Rising edges would appear to shift left as the overall pixel response increased; falling edges would shift right.

For these reasons, it was decided to use a symmetrical pulse-width modulation scheme. Wide bars would represent the “one” bits; narrow bars, the “zeroes”. Each bar would be centered within its bit frame, so the spacing from the center of one bar to the center of the next would always be the same. Moreover, any changes in overall pixel response might make a given bar look slightly wider or narrower, but wouldn’t change its apparent center position, because its edges would “move” in opposite directions. Naturally, the bigger the ratio between wide bars and narrow bars, the more reliably they can be discriminated. But there’s a limit relating to the resolution of the linear sensor array. You don’t want bars so skinny that the sensor can’t see them. For this reason, a three-to-one ratio was chosen. Wide bars are 75% of a bit frame wide; narrow bars, 25%. This leaves a minimum 25% gap between the widest bars. At nine pixels per bit frame, the narrowest bar will cover 2.25 pixels. Actually, because of blurring, it covers a little more than that, and the perceived ratio is somewhat less than 3-to-1.

Examples of the code representations discussed, plus a non-symmetrical PWM code, are shown below:

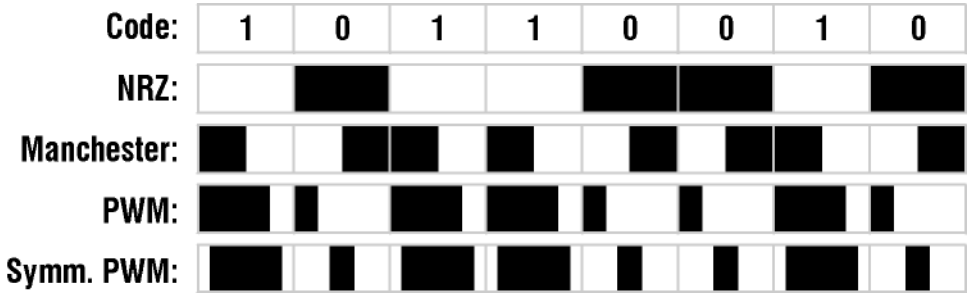


Figure 2 - Binary Code Representations

The actual eight-bit code was generated using a simulated shift-register/gate combination that employed the maximum number of XORs possible. This was done to facilitate future error correction, discussed in the last section of this paper. Taps were taken from bits 2, 4, 5, 6, 7, and 8. The following Perl script generates the sequence (adding the extra “0”). It prints out both an array used for the Postscript program that generates the code wheel and statements that plug into the PIC® microcontroller encoder firmware source as a lookup table.

```
use strict;
my $len = 8; my @taps = (2,4,5,6,7,8);
my $seq = '1' x $len;
my %mark;
my $zero = 0;
my $circum = '';
foreach (0 .. 2 ** $len - 1) {
   #print "$seq\n";
   my $digit;
   if ($seq =~ /^0+$/) {
      $digit = '1';
   } elsif ($seq =~ /^0+1$/ && !$zero) {
      $digit = '0';
```

```
      $zero = 1
   } else {
      my $nxt = 0;
      foreach my $tap (@taps) {
         $nxt += substr($seq, $tap - 1, 1)
      }
      $digit = sprintf('%1.1d', $nxt % 2)
   }
   $seq = $digit . substr($seq, 0, $len - 1);
   $circum .= $digit;
   $mark{bin($seq)} = $_;
}

if (keys %mark != 2 ** $len) {
   print "Wrong number of codes."
}

my $size = length($circum);
print "\n\n";
foreach (0 .. $size / 16 - 1) {
   print $_ ? '       ' : '/seq [ ';
   print join(' ', split(//, substr($circum, $_ * 16, 16)));
   print $_ == $size / 16 - 1 ? ' ] def' : "\n"
}

print "\n\n\n";
foreach (0 .. $size - 1) {
   print "\tRETW\t" unless $_ % 8;
   printf "%3.3XH", $mark{$_};
   if ($_ % 8 == 7) {
      printf "\t;%2.2X - %2.2X\n", $_ & 0xF8, $_
   } else {
      print ','
   }
}

sub bin {
   return unpack("N", pack("B32", substr('0' x 32 . shift, -32)))
}
```

The code wheel was created using a direct-to-film Postscript printer with a resolution of 2540dpi. It was decided to use dark bars on a clear background because the opaque portions of the film have cleaner light-transmission characteristics than the clear portions, due to possible surface scratches and smudges on the latter. The Postscript code for generating one each of a balanced PWM disk, a standard (left-justified) PWM disk, a Manchester disk, and a balanced PWM linear encoder strip is shown below.

```
% Postscript code for generating maximal-length sequence encoder disks and strips.
% Address inquiries to Bueno Systems, Inc. (info@buenosystems.com)
% Circular text routines are adapted from examples in Adobe's "Postscript Language
% Tutorial and Cookbook", Copyright 1985, Adobe Systems, Inc.

72 72 scale

/seq [ 0 0 1 1 1 0 0 1 1 0 0 1 1 1 1 0
       0 1 0 1 1 0 1 0 0 1 1 0 1 0 0 0
       1 1 1 0 1 0 0 1 0 0 0 0 0 1 1 0
       1 1 1 1 0 1 0 1 0 1 1 0 1 1 0 0
       1 0 0 0 1 0 0 1 0 0 1 0 1 1 1 1
       1 0 1 0 0 0 0 1 0 0 1 1 0 0 0 1
       0 1 0 1 1 1 1 0 0 0 0 0 1 0 0 0
       1 1 0 0 0 0 0 0 0 0 1 0 1 0 0 1
       0 1 0 1 0 1 0 0 0 1 0 1 1 1 0 1
       1 1 0 1 0 1 1 1 0 0 1 0 0 1 1 1
       0 1 1 0 0 0 0 1 0 1 1 0 0 0 1 1
       1 1 1 1 0 1 1 0 1 0 1 1 0 0 1 1
       0 1 1 0 1 1 1 0 0 0 0 1 1 1 0 0
       0 1 1 0 1 0 1 0 0 1 1 1 1 1 0 0
```

```
       0 1 0 0 0 0 1 1 0 0 1 0 1 0 0 0
       0 0 0 1 1 1 1 0 1 1 1 1 1 1 1 1 ] def

/bits (8) def
/dia 1.95 def
/stripe .15 def

/outerrad dia 2 div def
/innerrad outerrad stripe sub def

/pi 3.1415923 def
/n seq length def

/findhalfangle
  { stringwidth pop 2 div
    2 xradius mul pi mul div 360 mul
  } def

/outsideplacechar
  { /char exch def
    /halfangle char findhalfangle def
    gsave
      currentpoint translate
      halfangle neg rotate
      radius 0 translate
      -90 rotate
      char stringwidth pop 2 div neg 0 moveto
      char show
    grestore
    halfangle 2 mul neg rotate
  } def

/insideplacechar
  { /char exch def
    /halfangle char findhalfangle def
    gsave
      currentpoint translate
      halfangle rotate
      radius 0 translate
      90 rotate
      char stringwidth pop 2 div neg 0 moveto
      char show
    grestore
    halfangle 2 mul rotate
  } def

/OutsideCircleText  % text size centerangle radius
  { /radius exch def
    /centerangle exch def
    /ptsize exch def
    /str exch def
    /xradius radius ptsize 4 div add def
    gsave
      centerangle str findhalfangle add rotate
      str
        { /charcode exch def
          ( ) dup 0 charcode put outsideplacechar
        } forall
    grestore
  } def

/InsideCircleText  % text size centerangle radius
  { /radius exch def
    /centerangle exch def
    /ptsize exch def
    /str exch def
    /xradius radius ptsize 3 div sub def
    gsave
```

```
      centerangle str findhalfangle sub rotate
      str
        { /charcode exch def
          ( ) dup 0 charcode put insideplacechar
        } forall
    grestore
  } def

/MakePWM { % x y moveto ratio ---
   /ratio exch def
   gsave
   currentpoint translate
   /dth 360 n div ratio 1 add div def
   0 1 seq length 1 sub {
      /i exch def
      /th0 i n div 360 mul def
      /th1 seq i get ratio 1 sub mul 1 add dth mul th0 add def
      newpath
      0 0 outerrad th0 th1 arc
      0 0 innerrad th1 th0 arcn
      closepath
      0 setgray fill
   } for
   .01 setlinewidth
   -.1 0 moveto .1 0 lineto
   0 -.1 moveto 0 .1 lineto stroke
   0 0 .1875 0 360 arc stroke
   /Helvetica findfont .06 scalefont setfont
   0 0 moveto
   (TAOSENC v2.0       8-bit Maximal Length PWM Sequence) .06 270 innerrad .06 sub
InsideCircleText
   grestore
} def

/MakeBalancedPWM { % x y moveto ratio ---
   /ratio exch def
   gsave
   currentpoint translate
   /dth 360 n div ratio 1 add div def
   0 1 seq length 1 sub {
      /i exch def
      /th0 i n div 360 mul seq i get ratio 1 sub mul 1 add dth mul 2 div sub def
      /th1 seq i get ratio 1 sub mul 1 add dth mul th0 add def
      newpath
      0 0 outerrad th0 th1 arc
      0 0 innerrad th1 th0 arcn
      closepath
      0 setgray fill
   } for
   .01 setlinewidth
   -.1 0 moveto .1 0 lineto
   0 -.1 moveto 0 .1 lineto stroke
   0 0 .1875 0 360 arc stroke
   /Helvetica findfont .06 scalefont setfont
   0 0 moveto
   (TAOSENC v2.0       8-bit Maximal Length Balanced PWM Sequence) .06 270 innerrad
.06 sub InsideCircleText
   grestore
} def

/MakeManchester { % x y moveto ratio ---
   gsave
   currentpoint translate
   /dth 360 n div 2 div def
   0 1 seq length 1 sub {
      /i exch def
      /th0 i seq i get 2 div add n div 360 mul def
      /th1 th0 dth add def
```

```
      newpath
      0 0 outerrad th0 th1 arc
      0 0 innerrad th1 th0 arcn
      closepath
      0 setgray fill
   } for
   .01 setlinewidth
   -.1 0 moveto .1 0 lineto
   0 -.1 moveto 0 .1 lineto stroke
   0 0 .1875 0 360 arc stroke
   /Helvetica findfont .06 scalefont setfont
   0 0 moveto
   (TAOSENC v2.0       8-bit Maximal Length Manchester Sequence) .06 270 innerrad .06
sub InsideCircleText
   grestore
} def

/MakeLinearPWM { % x y moveto length width ratio MakeLinearPWM
   gsave
   0 setgray
   0 setlinewidth
   currentpoint translate
   /ratio exch def
   /wid exch def
   /len exch def
   /dx len n div ratio 1 add div def
   0 1 n 1 sub {
      /i exch def
      /x0 i n div len mul seq i get ratio 1 sub mul 1 add dx mul 2 div sub def
      /x1 seq i get ratio 1 sub mul 1 add dx mul x0 add def
      newpath x0 0 moveto x0 wid lineto x1 wid lineto x1 0 lineto closepath fill
   } for
}  def

2 2 moveto 3 MakeBalancedPWM
4.25 2 moveto 3 MakePWM
6.5 2 moveto 3 MakeManchester

1 .5 moveto 6.5 .355 3 MakeLinearPWM
```

This program will produce the output shown below.

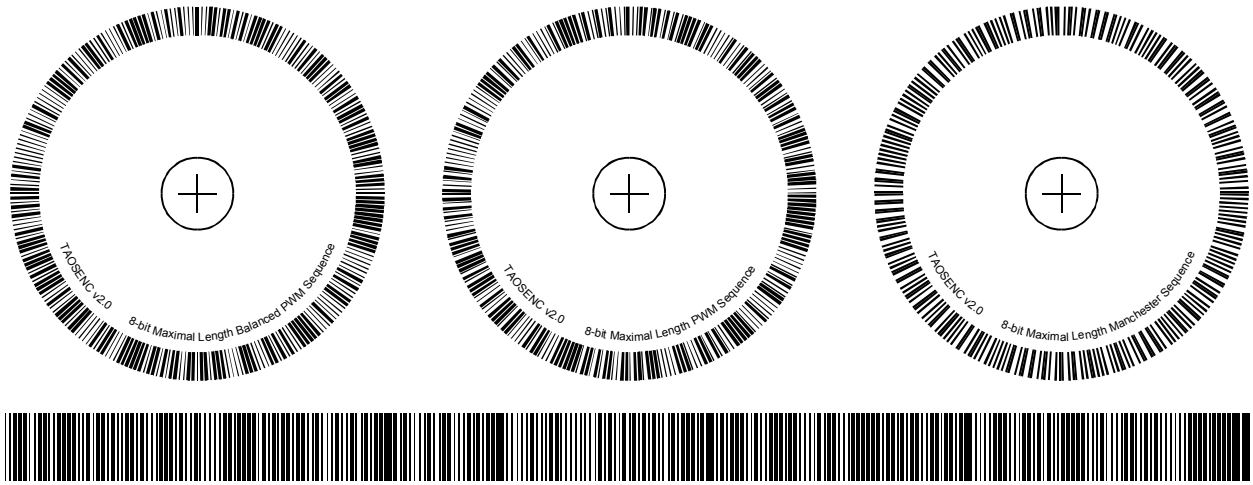


Figure 3 - Output of Example Postscript Code

Light Source

To image the film code wheel onto the sensor, two methods may be employed: 1) lensing, and 2) direct projection. In the former, a lens is required between the sensor and the film, which will focus an image of the film onto the sensor. The latter method requires only a point source of light opposite the film from the sensor. Light emanating from the source will cast shadows on the sensor corresponding to the dark areas of the film. Because of its simplicity, lower cost, and minimal space requirements, the direct projection method was chosen.

To obtain the most sharply defined shadows, the smallest practical point-light source should be used. The bigger the light source, the fuzzier the shadows will appear to the sensor. For a given light-to-dark or dark-to-light transition, the apparent width of the "fuzziness" is given by the formula,

Fuzziness = Light diameter • Film-to-sensor distance / Light-to-film distance

For this reason, we want to keep the film as close to the sensor and as far away from the light as possible. The fuzziness should be no more than a fraction of a pixel, if possible, or, in the case of the TSL1401R, to a fraction of 63.5 microns. There are point source infrared-emitting diodes (IREDs) that have emitting surfaces around this scale. The one chosen for this application is the Optek OP230WPS. It has a 100-micron-square emitting area. By positioning the IRED at a distance from the film and the film close to the sensor, this fraction-of-a-pixel criterion can be achieved. Keeping the source back from the film also reduces the intensity (cosine law) falloff that occurs near the ends of the sensor as well as any parallax distortion caused by fluctuating film-to-sensor distances. Of course, if it is too far back, the overall intensity reaching the sensor may become too low, due to the inverse-square law.

The requirement that the encoder be able to read the film while it is moving at 2000 degree/sec places severe restrictions on how much integration time can elapse during one exposure. Too long an integration time will result in severely blurred images. The speed requirement works out to about 1422 code bits passing each pixel per second. Since each code bit is about nine pixels wide, a moving code-bit shadow will race across the sensor face at about 12800 pixels per second or, inverting, 78 microseconds per pixel. So, in order to "freeze" this motion to take a reading, we need an exposure time that's a fraction of 156 microseconds. Because the TSL1401R is an integrating light sensor, one might be tempted to limit its integration time to obtain the necessary "shutter speed". But during each integration, all 128 pixels need to be read out before the next integration can be started. To do this with an integration time of 20μSec, for example, would require a pixel clock and A/D converter speed of 6.4MHz. Therefore it was decided to strobe the IRED during integration and use as long an integration time as needed to obtain the sensor data and perform the necessary computations. This creates the necessity for zero ambient light. That's because any outside light will contribute to the pixel response *over the whole integration period* and not just during the IRED strobe pulse. Therefore, just a little ambient light (noise) could easily swamp out light from the IRED (signal). This requirement is met by putting the code wheel and all the electronics in a light-tight enclosure.

Pixel Data Input and Auto-Exposure

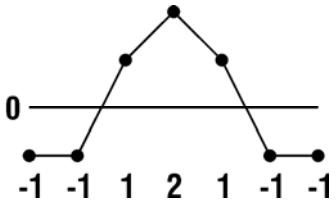
The analog pixel data from the TSL1401R is converted to digital values by the PIC16F819's built-in 10-bit A/D converter. Not much light reaches the sensor in each exposure, given the short IRED pulses, so the peak voltage from the TSL1401R's output is well below its 5V saturation level. For this reason, only the eight least-significant bits of the 10-bit A/D result are used. This gives us a more obtainable full-scale value of 1.25 volts.

The IRED driver doesn't incorporate any current regulation – only a current-limiting resistor. Because the light intensity of the IRED can vary under these circumstances, there needs to be a way to regulate the pulse width to keep the sensor response constant. This, in fact, is easy to do. It is accomplished by checking the lowest pixel value recorded in each scan (exposure). If it is below a certain level, the strobe width will be incremented a notch, if above, decremented. If the value falls outside a window of

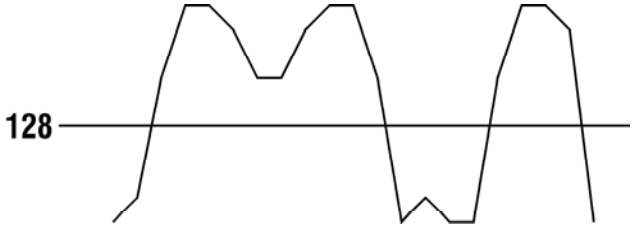
acceptability, the encoder goes into a "not ready" state, the pulse is adjusted, and another attempt is made. This should only happen at power up.

Limiter and FIR Filter

The code wheel-modulated output waveform from the sensor is not an ideal square wave, as one might like it to be. Because the ends of the sensor get slightly less light than the center, the amplitude is slightly "crowned" in the middle. And because of minor scratches, smudges, and the like, the waveform for the clear portion of the film is rather bumpy. So we have both low frequency and high-frequency noise present. Thus simply thresholding the output at a fixed level to extract the binary code data is not an option. The ideal way to get rid of the noise would be to use a band-pass filter. A symmetric finite-impulse-response (FIR) filter is preferable here, because it won't affect the relative positions (phase) of the features we're trying to preserve and measure. But, especially to filter out the high-frequency noise, an adequate FIR filter would require many taps and be computationally burdensome. So we resort to a little chicanery. To get rid of the highest frequency noise, we simply lop it off. In other words, we pass the waveform through a *limiter*. Since the high frequency variation in the pixel output is due primarily to minor blemishes in the clear areas of the disk and normal pixel light-signal variation, limiting the values of the light pixels removes most of the high frequency noise. Now it is possible to use a simpler FIR filter. But we need to simplify even more. In order to avoid software multiplication, each filter coefficient will be limited to a power of two. After considerable experimentation, the following set of filter coefficients was obtained:



This is essentially a high-pass filter that removes the low-frequency "crowning" noise from the waveform. In practice the result is added to a constant value of 128 to get the final analog waveform. Due to the simplifications, however, this filter is sub-optimal, as the resulting waveform now contains some filter artifacts consisting of dips in the wider peaks and bumps in the wider troughs, as shown below:

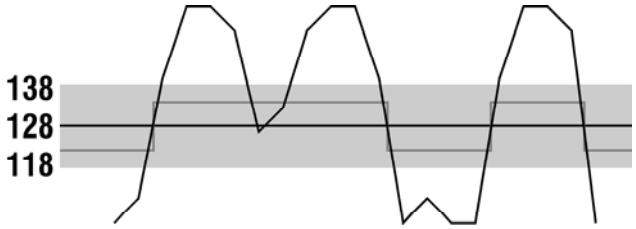


Now, it would be nice if we could use 128 as a threshold to delimit the bright pixels from the dark ones. But sometimes those artifacts come dangerously close to – or even cross – the threshold line. Therefore, more work needs to be done, as the next section describes.

Sub-Pixel Interpolation and Thresholding

Once we've determined the eight-bit code we're looking at, we need to interpolate its position *within one bit frame* to another four bits, to get a total of 12-bits of circumferential resolution. But a bit frame is only 9 pixels wide, and we need at least 16 to get the extra precision. To accomplish this, we resort to *sub-pixel interpolation*. This means that between each pair of real pixels, we create a virtual pixel whose value is the average of the two real ones surrounding it. This gives us a total of 255 pixels – 18 for each bit frame. Moreover, because the center position of each dark bar is calculated by averaging the positions of *two* edges, we actually have 36 possible center positions from which to compute a four-bit extension to the eight-bit code. The sub-pixeling is actually done during the thresholding process. We look at a pixel to see if it is over or under a threshold value, then we look at the average of that pixel and the next one, then

the next pixel by itself, and so forth. To accommodate the filter artifacts discussed in the previous section, we include some hysteresis in the thresholding operation. This means that to transition from light-to-dark or dark-to-light, the waveform has to cross not only the centerline, but also that and a little more: the hysteresis value. This creates a hysteresis band, which the waveform transition must pass *all the way through* to be considered a change of state. The following illustration, with a twenty-point hysteresis band, demonstrates this principle:



Notice, however, that for maximum accuracy, we need to keep track of where the waveform crosses the centerline – *not where it exits the hysteresis band* – to locate the edges of the bars. The hysteresis band exists simply to determine whether a given centerline crossing is real or not.

Decoding and Position Interpolation

Once the gray-level pixel waveform has been converted to 255 black/white bits, we can begin decoding the resultant wide and narrow bars into a meaningful position. (Actually, the thresholding and measuring are done in the program concurrently with the limiting and filtering. But it is more useful, for pedagogical purposes, to discuss them as if they were separate steps.) We begin by measuring the widths of all the dark areas in the scan. Each of these widths is compared to a threshold to determine whether it is a wide bar or a narrow bar. Wide bars are shifted into a shift register as "one" bits; narrow bars, as "zero" bits. There will be about fourteen bits shifted in altogether. The centroids of the two bars straddling the center pixel are also recorded. These are computed as the *sum* of the two edge positions, so can range from 0 to 510. Then the four shift register bits left of center and the four bits right of center are combined to form an eight-bit binary value. This value is an eight-bit sub-string of the 256-bit maximal-length sequence code. It is used to poll a lookup table, which returns the unique position (0 – 255) of that sub-string on the code wheel. Next, the two centroid positions (call them **L** and **R**) are used to calculate the last four bits, as follows:

$$\textbf{Four-bit-value} = \text{int}[16 * (R - 256) / (R - L)]$$

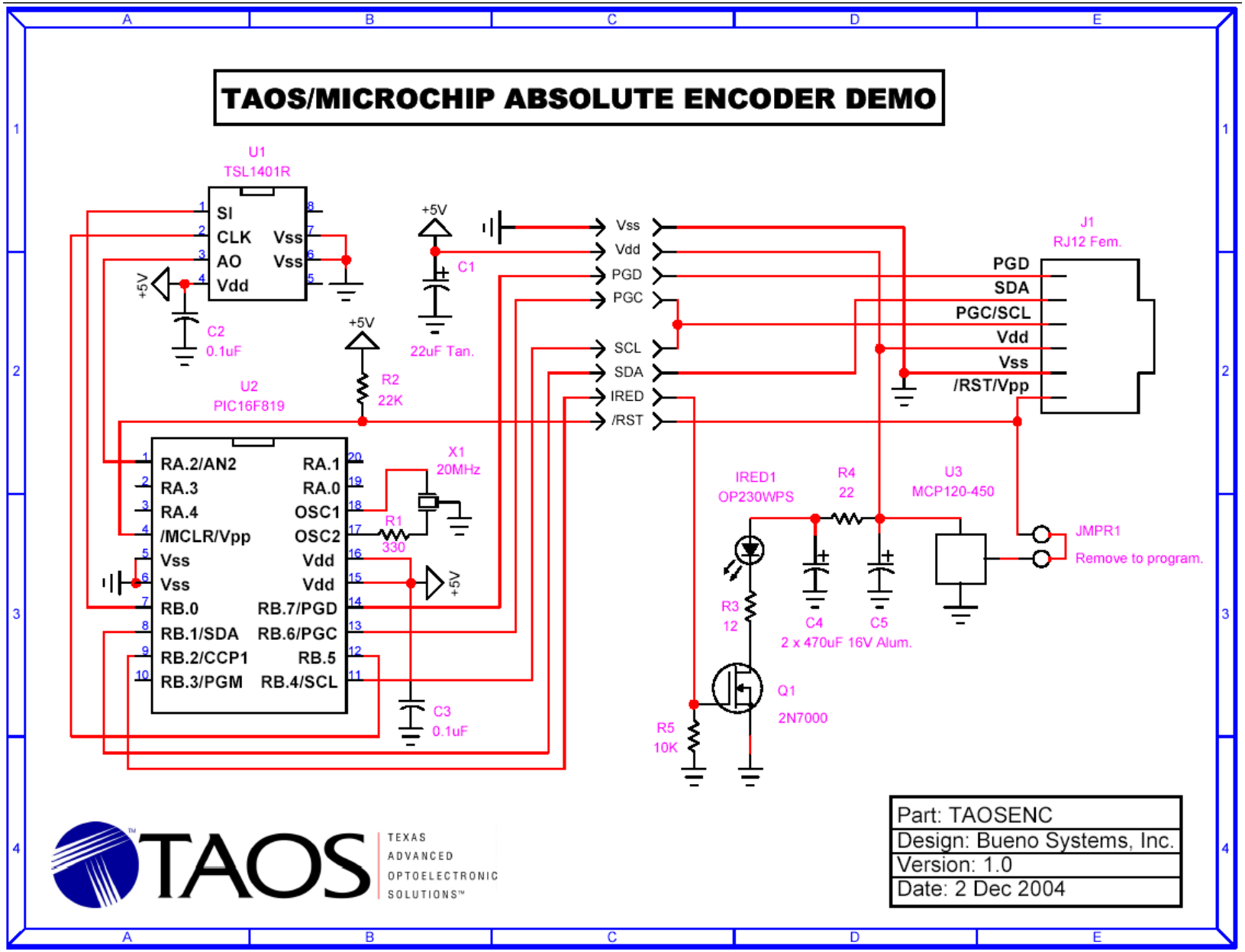
This is then tacked onto the end of the eight-bit decoded value to form a 12-bit result.

Looking Forward

What has been described to this point is enough to make a working demonstration encoder. Each scan, with all its computations, can be completed in well under 10ms, thus meeting the 100 samples-per-second requirement. But to make this into a product suitable for use as a production steering-angle encoder, much more needs to be done. This includes:

- **Better filtering of the sensor waveform.** This will probably require an advanced microcontroller such as Microchip's dsPIC® digital signal controller (DSC). The dsPIC DSC incorporates signal-processing functions such as a hardware MAC. This would allow a precisely-tailored FIR filter to be constructed and optimized to filter the encoder bars from both low- and high-frequency noise.
- **Finer position interpolation.** To get those last four bits, we have relied on a number that can take on no more than 36 values. This is pretty coarse and can lead to non-linearities in the encoder output. By extending the sub-pixel interpolation to four values per pixel, instead of two, we could theoretically double this to 72. A larger code wheel would also prove helpful here, as it would increase the number of pixels per bit frame.

- **Error detection for failsafe operation.** Even with better filtering, one cannot discount the possibility of a misread code. Fortunately, the proper choice of a maximal-length sequence gives us the opportunity to do some error checking. Remember that each bit is some function of the eight that came before it. We used a formula that XORed bits 2, 4, 5, 6, 7, and 8, to get a new bit 0. The only bits not entering the computation were bits 1 and 3. But after the first computation, followed by a shift, these are now bits 2 and 4 and enter into the next computation. What this says is that if we can examine ten sequential bits, the two latest bits must result from some function that combines the values of *all eight* preceding bits. That is, they form a checksum of sorts for the other eight bits. If the computed and observed checksums disagree, we know we've misread the code wheel and can take corrective action.
- **Calibration.** Even though the maximal-length sequence code is forgiving of minor mechanical misalignment, such misalignment can still lead to errors. By creating fifteen bits of raw output, for example, instead of twelve, we could obtain enough extra headroom to calibrate out these errors post-production. This would be done by recording the encoder's output at equally spaced, known mechanical positions. Thus, for each of these output values, we would obtain a known, desired value. From these samples it would be possible to derive an interpolation function by which to compute a desired value from any measured value. The coefficients for this function could then be stored in the dsPIC DSC's EEPROM. (The demo encoder, in fact, employed a small bit of calibration, allowing the position offset and code direction to be determined and recorded in its EEPROM.)
- **External interface.** The demo unit used an I^2C interface. As auto manufacturers are standardizing on the CAN bus for interfacing, this will have to be incorporated into the encoder as well. Again, the DSC could help in this regard.
- **Environmental hardening.** The demo encoder used a plastic housing that is marginally light-tight and certainly not hermetically sealed. Moreover, no consideration was given to the temperature characteristics of the components used to build it, and the circuit required a regulated five volts to operate. The enemies of ultimate success here are temperature extremes, voltage fluctuations, dust, vibration, moisture, and condensation. Each of these must be dealt with effectively to yield a unit rugged enough to survive the automotive environment.
- **Disclaimer.** This demo nor any of the documentation is intended for use for a production intent design but is a guide only for those individuals using it. The user specifically holds harmless and indemnifies TAOS INC. and all associated parties from any type of liability that results from improper use of this design.


TAOS/MICROCHIP ABSOLUTE ENCODER DEMO
U1
TSL1401R
SI
CLK
AO
Vdd
Vss
Vss
+5V
C2
0.1uF
+5V
C1
22uF Tan.
+5V
R2
22K
U2
PIC16F819
RA.2/AN2
RA.3
RA.4
/MCLR/Vpp
Vss
Vss
RB.0
RB.1/SDA
RB.2/CCP1
RB.3/PGM
RA.1
RA.0
OSC1
OSC2
Vdd
Vdd
RB.7/PGD
RB.6/PGC
RB.5
RB.4/SCL
X1
20MHz
R1
330
+5V
C3
0.1uF
Vss
Vdd
PGD
PGC
SCL
SDA
IRED
/RST
J1
RJ12 Fem.
PGD
SDA
PGC/SCL
Vdd
Vss
/RST/Vpp
IRED1
OP230WPS
R4
22
U3
MCP120-450
JMPR1
Remove to program.
R3
12
C4
C5
2 x 470uF 16V Alum.
Q1
2N7000
R5
10K
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Design: Bueno Systems, Inc.
Version: 1.0
Date: 2 Dec 2004