A New Architecture for Absolute Optical Encoders

Timothy Malcolm*, John Beasley* and Mike Jumper*

Abstract

BEI Precision Systems & Space has developed an encoder technology, nanoSeries, that can calibrate itself in-situ and correct most of the common causes of error in typical encoders. The new nanoSeries ARA design has detailed health and status readouts that can definitively indicate when a re-calibration is in order. The re-calibration process can be done on-orbit if desired. The units can accommodate either full revolutions or limited angle sweeps, and the principles are also applicable to linear encoders.

Introduction

Optical encoders manufactured by BEI Precision Systems & Space (BEI) have been used in space since the earliest days of space flight. The combination of low weight and high resolution relative to electromagnetic resolvers made them an obvious choice for many applications. Optical encoders have typically been of only a few types.

The primary type of optical encoder selected for commercial and industrial applications has been the incremental encoder. This type of encoder requires a return to an index or home pulse to index a counter, which then counts the number of ‘incremental’ pulses or bits that pass by. This is a very simple and robust concept but it has some disadvantages for space, primarily that if power should go off or the counter upsets, even for a very short time, the encoder does not ‘know’ where it is until the system moves it back to the home position and it re-acquires the index pulse. A further concern with this type of encoder in space is that Single Event Effects can cause the number of recorded pulses to be in error, or cause a spurious index pulse to reset the counter, and the count will not be corrected until the index is reacquired. Other issues with this type of encoder are that the light source must remain turned on at all times, increasing the power consumption and limiting the lifetime of the source, and that the data rates for high resolution devices can be very high, often resulting in Electromagnetic Interference (EMI) issues.

A second type of encoder could be called pseudo-absolute or chain code. This type of encoder includes a set of tracks encoded with a non-repeating digital code, similar to an endless bar code, plus a set of incremental tracks for timing. This style of encoder does not need to return to zero to reset itself; instead it just needs to read a certain number of sequential bits to know where it is. This design mitigates some of the issues inherent in the typical incremental encoder. However, the Light-Emitting Diode (LED) still must remain on all the time. This sort of encoder has not been used much in space to date.

A third type of optical encoder is the absolute encoder. This style of encoder actually generates a discrete digital code for each of a number of discrete locations encoded on a code disk or scale, and these bits are read simultaneously. Thus, even if power flickers, the encoder recovers immediately and there is no need to return to a home position. Moreover in this type of encoder it is common to pulse the LED to take readings, which has the effect of maximizing the life of the encoder. Of course it is still possible for readings to be in error due to Single Event Effects, but for this type of encoder, the very next sample will correct the error. The simplest versions of this device directly encode the digital patterns on the code disk, but higher resolution types derive the digital data from sine and cosine patterns on the disk.

* BEI Precision Systems & Space Company, Maumelle, AR

nanoSeries Design

It is important when discussing the relative merits of these various encoding techniques to make a distinction between 'wide angle errors' and 'narrow angle errors', since they arise from different sources.

Wide Angle Error is a term used to encompass all of the low spatial frequency errors that arise as a result of optical pattern alignment to the axis of rotation, i.e., perpendicularity and concentricity, and the repeatable and non-repeatable runout of the spindle bearings. From a kinematic point of view, wide angle errors are those that result from translation of the code pattern relative to the readhead rather than pure rotation. None of the methods discussed above address these geometry- induced errors. Over the years, the primary method of mitigation for these wide angle errors has been the use of multiple read stations. Clearly the use of multiple read stations can cancel the most damaging harmonics of the error at the expense of increasing other less harmful error components. In extreme cases, some larger encoders have had 8, 12, or 16 readheads which dramatically reduce the effects of these geometric errors. As a specific example, consider an encoder with a Total Indicated Runout (TIR) of 2.54 micrometers (μm). For a code disk with a radius of 50 mm, the peak once-per-turn error component due to spindle runout would be:

$$Error_{peak} = tan^{-1}\left(\frac{TIR/_2}{R_{Track}}\right) = tan^{-1}\left(\frac{2.54 \cdot 10^{-6}/_2}{50 \cdot 10^{-3}}\right) = 25.4\ \mu rad$$

Adding a second read station located at π radians relative to the first station, properly calibrated, will reduce the error resulting from this particular harmonic to less than 1.3 μrad (95% reduction typically). However, mechanical ball bearing errors are rarely purely sinusoidal. They usually contain many harmonics of the fundamental. In this example, if the twice-per-turn error is 10% of the fundamental (i.e., 2.5 μrad), the addition of two readheads can actually double that particular component of the error to 5.0 μrad, as well as doubling every other even harmonic of the error. Adding still more pairs of readheads will reduce other harmonics, at the expense of increasing the higher order residual errors. Clearly this solution to wide angle error is a diminishing returns game, as well as being a distinct cost adder, since each new readhead adds associated circuitry.

In recent times, with the advent of digital signal processors to encoders, it has been found that even without multiple read heads it is possible to remove many of these geometry-induced errors algorithmically. This can be accomplished by adding optical features which make it possible to discriminate which errors arise from wide angle causes and which from narrow angle causes. Since wide angle errors result from translations of the code pattern instead of the expected pure rotation, this change in approach allows mechanical repeatability to be 'finessed' into accuracy. However, it should be apparent that any sort of algorithmic correction can only be as repeatable as the hardware.

The multiple read station approach, although expensive in terms of hardware, is very fast and can usually remove 95+% of the wide angle errors for a high quality spindle. A software approach takes additional processing time, and generally removes somewhat less of the wide angle error. However, there is a large cost advantage to using the software approach. Moreover, as technology advances, the correction algorithms have become more capable, processing hardware is faster, and the disadvantages of the software approach are diminishing. In addition, the software approach does not prefer any harmonic relative to another. In the traditional multiple read head approach the harmonic doubling described above has sometimes resulted in exciting mechanism resonances with servo systems. That sort of problem is very unlikely with the software correction method.

As can be seen in Figure 1, the nanoSeries correction scheme reduces the large once-per-turn harmonic more than 99% while still not doubling the 2nd harmonic, and reducing higher order errors. The same raw curve compared to a typical two-head reduction scheme would have indeed reduced the once-per-turn, but the 2nd harmonic would have doubled. In this specific case, that would have doubled the residual error!

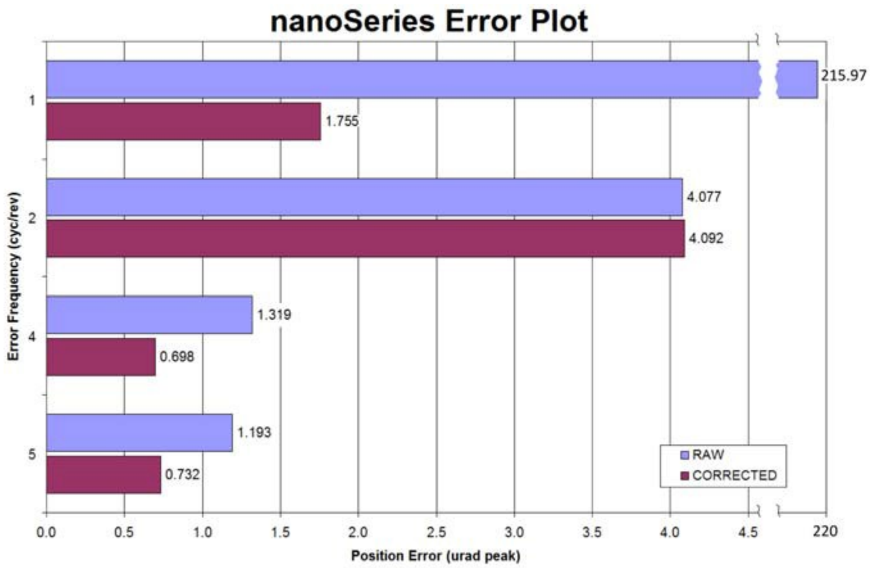

Figure 1. NanoSeries Error Plot

Narrow Angle Errors are those which arise from code pattern distortion, interpolation non-linearities, intermodulation, and other sources of noise. These errors are most common at the spatial frequencies of the higher order tiers of data. A few manufacturers have developed test equipment to quantify these harmonics at beginning of life. A properly designed encoder should be capable of measuring and eliminating most of these sorts of harmonics, assuming the mechanical system is robust and repeatable. Of course the patterns printed on the code disk must inherently have a high degree of consistency; otherwise the number of errors that can be removed is limited by the memory available. Modern high-resolution encoders very quickly can outrun the available memory, which is another reason why an algorithmic method of error correction is desirable. In addition, although a static memory map could be made to correct every bit to some ideal number, assuming that an accuracy tester was available, yet the resulting correction would generally not be stable with time, temperature, or life. In fact, the more precise the correction, the more likely it is that subsequent environmental shifts of the axis of rotation will 'break' it. In some cases this can result in much higher error than otherwise would have been observed.

All of these techniques have validity in some area of application. Ideally one would like the simplicity and cost of a single-tier incremental encoder with the resolution and reliability of the multi-tier absolute encoder, and of course all of this achieved in a very small, lightweight, and low power design. Perhaps surprisingly, these goals are all achieved to a large extent in modern space encoders such as the BEI ARA nanoSeries encoders. These absolute optical encoders use a multi-tier design with sine-cosine tracks at several different spatial frequencies to generate all of the code. To minimize the electronic failure rate and reduce the cost, BEI has developed a rad-hard front-end Application-Specific Integrated Circuit (ASIC) which performs all of the chores of managing the LED and photodiode array, and includes simultaneous analog-to-digital conversion of all of the code tracks. This digital data is transmitted to a remote processor in high-speed serial format which includes Error Detection and Correction codes for high reliability. All of the data transmission is done with Low Voltage Differential Signaling (LVDS) drivers and receivers to minimize EMI emission and susceptibility. The remote processor contains the required digital circuitry to correct, merge and assemble the final data words, coordinate multiple readheads (if used), and format and output the final data words to the customer.

All of the circuitry in the BEI Front-End ASIC is silicon gate CMOS, and is rad-hard to more than100krad (Si). The ASIC also is Single Event Latchup hard (75 MeV-cm^2/mg), and has a low Single Event Upset hit rate (2.4 x 10^{-14} errors/bit-day). The circuitry is all based on switched capacitor CMOS design, so that any sort of upset or error that does occur will rapidly be flushed out. The switched capacitor transimpedance amplifiers used to convert the small currents from the photodetectors to voltages have programmable gain and other parameters that allow them to be configured ideally for nearly any geometry or technology detector.

The analog-to-digital (A/D) converters in the ASIC are a proprietary design, and provide both fast response and improved DC fidelity for the signals as compared to conventional discrete A/D converters. Since the amplifiers are used primarily for sine-cosine signals that are intended to be ratiometrically compared, common voltage references are used for all of the A/D converters. This assures that the signals all continue to track over time, temperature, and common mode disturbances.

The ASIC also includes the LED pulsing circuitry which is fully selectable for current level, pulse width, repetition rate, and other parameters. Circuitry is also included for monitoring and controlling the LED current. In normal operation, an external transistor is used to switch the LED current, and a small external current sense resistor is also provided to allow for constant current drive. The current drive level is controlled using internal D/A devices to keep the light levels at the detectors at a constant level to end-of-life. Thus at beginning-of-life, the system is set up for robust operation under nominal conditions, and the current through the LED is then varied as required to keep the system margins in place in spite of variations in temperature, radiation, and ageing of components. This sort of scheme nearly doubles the useable life of the LED as it degrades. Moreover, since the LED is pulsed, there is a linear reduction of current-induced degradation of the LED proportional to the duty cycle, allowing very long on-orbit lifetime. The ASIC is procured to a government- controlled SMD at V-quality level which eliminates a lot of concerns about quality and reliability.

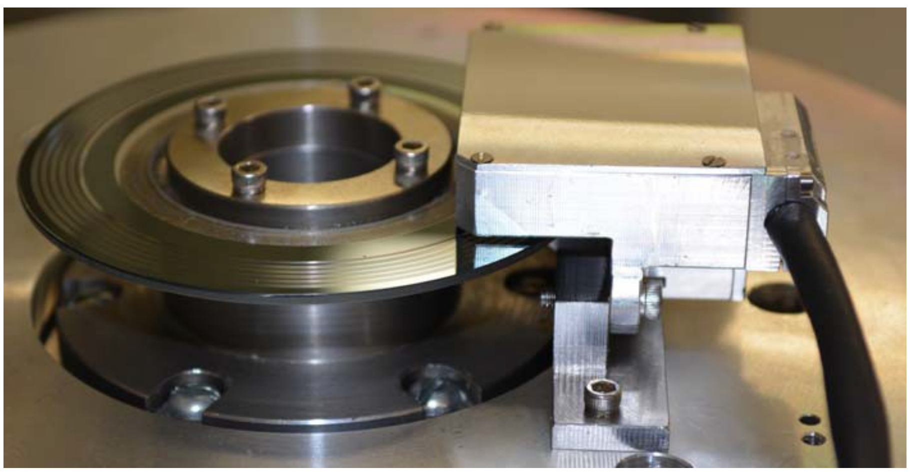

Figure 2. ARA Space nanoSeries Encoder Readhead

The new readhead mechanical design is shown in Figure 2. The small readhead (25 x 50 x 46 mm) contains the ASIC, the LED and driver transistor, the photodiode detector with a precision grating, and the optic to collimate and fold the light. The readhead and the code disk hub can be fabricated from titanium, aluminum or stainless steel, depending on the application. The precision code disk (chrome pattern printed on glass) is pre-mounted at the factory to the hub.

The readhead is powered from the remote electronics through a shielded cable with a MicroD connector. All of the signaling wires are using LVDS drivers and receivers and are twisted pairs for low EMI susceptibility and emission.

This design also requires a remote electronics assembly that can process data from 1 to 4 readheads. The small 125 x 125 x 40 mm remote box (not shown) or 3U size remote card (Figure 3) contains a powerful data processor implemented in a rad hard Field Programmable Gate Array with critical portions of the design implemented as a pipelined processor. This processor applies the mathematical algorithms that correct the encoder signals for optimal performance. The details of the algorithms are proprietary to BEI, but the end result is easily demonstrated using BEI test and diagnostic equipment. Research continues to improve the correction algorithms still further. At some future date, a rad-hard digital ASIC will be obtained with the algorithms internally coded, improving the power consumption, performance, and hardness of the resulting systems.

The system is designed to be relatively straightforward to implement in a customer design. The readhead and code disk/hub are first mounted, usually with pinned or piloted interfaces. Usually it is not necessary to electrically or optically center the code disk. Then the system is connected and powered on and four relatively slow revolutions of the disk are made while the encoder measures the signals. For limited angle systems, such as Az-El gimbal systems often are, four sweeps of the arc to be used performs the same function. Exact rotational speed and/or speed stability are not critical for these sweeps. The preliminary data is then processed and the encoder is calibrated automatically. The processor also provides outputs that verify that the data streams are properly adjusted and merged into one contiguous data word. At this point, the encoder is placed in the normal operational mode and no further calibrations will normally be required. The software corrects for most alignment issues, as well as future component degradation issues on earth or in orbit, including degradation of components with radiation, temperature shifts and most other common issues.

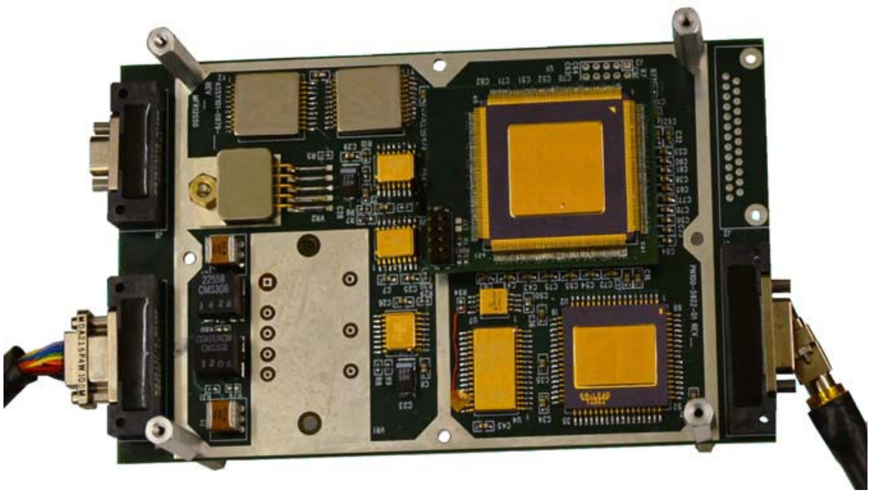

Figure 3. ARA Space nanoSeries Remote 3U Electronics Card

The encoder can be queried at any time to verify proper operational margins. The encoder can even be re-calibrated on-orbit if required to compensate for unexpected degradation due to either natural or strategic environments.

The standard customer interface to the remote card or assembly is by means of a synchronous serial protocol in which the customer supplies a strobe to initiate a reading and a data clock to shift data out. The primary reason for this non-standard protocol, instead of the more common Synchronous Serial Interface with no strobe, is that many servo systems are sensitive to the delay from the time position data is actually captured to time of receipt of data. A second consideration is that the LED primarily degrades only when current is flowing through it, so reducing the strobe rate to a minimum, consistent with system objectives, is a very good design practice. The standard design also provides a shift clock from the encoder at the same frequency as the clock provided by the customer. In systems with long cable runs or other delays, this provision assures robust capture of the serial data by the customer electronics, even with lengthy cable runs.

There are many advantages to the BEI ARA nanoSeries approach. First is that since most encoders will be very similar in basic design there is a lot of commonality of design and analysis, minimizing the program-specific engineering work required. Second, this design has a minimal number of integrated circuits, none of which are likely to become obsolete. Third is that critical parts like LEDs, photodiode arrays, and ASICs are stocked at BEI to minimize lead time.

The BEI ARA nanoSeries encoders have demonstrated resolutions up to 25 bits and absolute position accuracy less than 5 µrad rms over a full revolution at data rates of up to 8 kHz. The power dissipation for the readhead at that rate is just 0.6 watt, while the remote electronics will consume about 3.0 watts with a 5-volt supply and a single readhead, and a little more if the 24-volt option is used. The remote electronics has been designed to handle up to four readheads with no reduction.

BEI can also supply engineering prototype units. Our AIME nanoSeries encoders are industrial temp range encoders that mimic the readhead size of the ARA nanoSeries encoders. These much less expensive units are form, fit and function equivalent to the ARA space encoder readheads, even to using the same test box design. The AIME encoders do not require a remote electronics assembly however, since the complete electronics package can be fit inside the space of the ARA readhead envelope. This allows for cost-effective prototypes and risk reduction units to make system checkout much easier and with much higher fidelity. The AIME encoders are not rad-hard, but are a logical choice for any application that is less demanding. The same code disk sizes and hub/readhead materials are used for both designs.

It is important to know how well a kit encoder is mounted and calibrated and the effects of spindle runout and environments on the encoder during operation. Standard interface and test boxes are available for power, communications and evaluation of the health/status of the ARA and AIME encoders. These test boxes provide the ability to command auto-calibration, normal operation, set output parameters, and evaluate and view in real time the quality and status of each tier of position information and the alignment of all other position tiers internal to the encoder. This information is output in part through health and status bits with each position output word and is valuable in determining if and when re-calibration in-situ may be needed. In-situ calibration can compensate for changes in gravitational loads, component drifts and degradation due to extreme environmental conditions such as radiation, although generally adjustments will not be necessary. The test box software is written in LabVIEW and can support position reporting, analysis, control, and data logging.

For the future, it should be clear that the new ARA nanoSeries space encoder has the potential to dramatically improve performance of space systems, especially when paired with a servo system designed by BEI. BEI has primarily been involved in precision servo systems for only the most demanding applications, such as the pointing systems in the Hubble Space Telescope, or for the Microwave Limb Sounder, one of four instruments on the NASA's EOS AURA satellite. Today's space systems are smaller, lighter, and higher performance than in the past, and BEI can bring our experience in designing space systems to assist you in meeting and exceeding your most stringent program performance requirements.