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Ultra-High Resolution, Modular Optical Angle Encoder for Space-Based Opto-Mechanical Applications

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Abstract

A 27-bit optical encoder using a novel patent pending technology has been developed by the MicroE Development Center of BEI Sensors & Systems Company and tested by the Sensor Systems Group (SSG) Inc., in a positioning and stabilization mirror assembly (PSMA) designed and constructed under a grant from the Marshall Space Flight Center. Test results verified performance within the specifications of the PSMA.

Introduction

The high cost of space-based scientific missions and the limited funds environment make it absolutely necessary to design space-based sensor hardware such that it is lighter, less costly, and outperforms the previous generation of space resident hardware. Thus there is a great emphasis on the development of new materials with greater specific strength, smart materials, and most importantly ultra-high resolution sensors that are small, lightweight, and robust. Whereas previous generation angle sensors featured resolutions on the order of microradians, sensors for future space missions must extend that capability by an order of magnitude and maintain that capability over an extended time in space.

In 1994, SSG received a Small Business Innovative Research grant from the Marshall Space Flight Center to design, construct, and test a single-axis PSMA. The purpose of the project was to demonstrate the feasibility of constructing large aperture, ultra-high resolution scanning and pointing mirror assemblies that have sufficient bandwidth to substantially attenuate satellite platform base motion errors affecting the line of sight (LOS) of optical remote sensors while also capable of pointing that LOS over a range on the order of ±30 degrees in object space. This precise angular positioning was achieved by employing an interferometric encoder from BEI MicroE. The PSMA requirements for the encoder performance are given in Table 1.

Encoder Design

The MicroE encoder utilizes diffraction from a radial grating to generate interference fringes which are detected and then processed yielding the high resolution electrical output. Its light source is a commercially available laser diode as used in CD players. The laser output is collimated by a miniature lens assembly and then apertured, before passing through a transmissive phase grating deposited on a 69.85 mm (2.75 in) diameter glass disk. Light diffracted from the grating falls into discrete orders, with the grating geometry chosen such that the zeroth and even orders are suppressed while energy in the first order beams is maximized. Without the zero order diffraction, there

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exists a region beyond the third orders in which the first orders overlap and create an interference pattern with a nearly sinusoidal spatial intensity distribution. This high fidelity/high resolution pattern is the basis from which the encoder output is derived. A photodiode array located in that region converts the optical signal into four current amplitudes, which correspond with the spatial distribution of the interference pattern. These four photodiode current channels have a sinusoidal time dependence in the presence of a constant rotation of the disk supporting the grating. This concept is equally applicable to transmissive and reflective gratings. Since the above region of interference is typically on the order of 2.5 mm deep, there is no critical requirement for alignment of the detector array with the encoder disk. Moreover, it is shown that the spatial wavelength of the interference is independent of the laser wavelength, thus making the encoder's metrological accuracy only a function of the grating constant of the phase grating on the encoder disk.

This encoder weighs ounces as opposed to many pounds typical of high resolution geometric encoders, and the encoder can be installed and aligned in a matter of minutes in comparison to the hours spent aligning conventional modular encoders with less than half of the resolution of the MicroE encoder.

PSMA Design

A prototype MicroE two read station encoder was fabricated and installed in the high resolution PSMA . The PSMA was designed to feature a silicon carbide lightweight mirror with an aperture of 15.24 cm x 22.86 cm (6 x 9 inches), an angular range on the order of ±2.5 shaft angle excursion and servo system bandwidth greater than 60 Hz. The mirror shaft of the PSMA is suspended on two Bendix flexures and is driven by a BEI-Kimco rotary actuator designed for SSG. The prototype PSMA, shown in Figure 1, contains a magnesium alloy mirror which has a moment of inertia that is comparable with the SiC mirror. The PSMA was integrated with the encoder at MicroE's facility and tested at SSG on a pneumatically suspended optical bench. Figure 2 shows the MicroE encoder on the PSMA drive shaft. The digital signal processor (DSP), which interpolates the angular position of the encoder disk using the sine and cosine quadrature signals from the encoder analog signal conditioning electronics, is embedded in the Motion Engineering, Inc. DSP-200 digital servo control board. The DSP-200 board is capable of supporting an 85 Hz servo loop bandwidth.

Performance Tests

Performance of the MicroE encoder technology was first measured prior to the integration of the PSMA. Accuracy of the interpolated bits are dependent on the fidelity of the sinusoidal signals within each cycle. To determine this interpolation accuracy, the output of a similar MicroE encoder was compared against a Hewlett Packard dual frequency laser michelson interferometer and a Heidenhain LIP 402 A interferometric grating based encoder. The michelson interferometer is far more sensitive to environmental fluctuations, such as minor beam path turbulence, than the grating-based interferometers; because of this, the MicroE accuracy was not successfully measured using the michelson as the standard. Comparisons of the Heidenhain and the MicroE were successful, and the results are shown in Figure 3.

Relative error in terms of linear motion was ±14 nm peak to peak. The error profile provides clues as to the source of the error, with some of it due to the Heidenhain and some due to the MicroE, as indicated by their characteristic error signatures. Accuracy can be improved significantly with tighter adjustments to the signal gains and offsets.

While the position output of the encoder provides important information on the PSMA performance, it is the motion of the mirror itself in the integrated system that in the final analysis is the primary object of interest. To that end the mirror deflection was measured with an electronic autocollimator— a Moeller-Wedel ELCOMAT 2000. This instrument has resolution of 0.24 μrad in both x and y axes, while its dynamic range is 0.56 degree.

Important to an optical sensor is the PSMA's ability to point the sensor's LOS repeatedly in any commanded orientation, and the PSMA's jitter amplitude as a function of that angular orientation. Accordingly, two test regimens were formulated. The first consisted of recording a number of samples of the position as reported by the servo system and the autocollimator at the mirror's home position, after which it was deflected by an incremental step of some 50,000 counts where again multiple position reports were sampled. This procedure was then repeated over the entire field of the autocollimator. Since that is small in comparison with the total deflection angle of which the PSMA is capable, the entire procedure was repeated at initial positions of ±2.5 degrees. The second test involved commanding the mirror to repeatedly execute a step on the order of 0.25 degree starting at a number of initial positions near the home position and at about ±2.5 degrees. After each step, the mirror position, as reported by the servo system and the autocollimator, was recorded.

Results and Conclusion

Table 2 summarizes the test results. The top five entries list the results of the first test. It is seen that both the servo system noise and the mirror point accuracy improved after the PSMA was installed on a pneumatically isolated optical bench. No evidence of a consistent bias error was found in these data sets. The last six entries list the results of the repeatability tests. It is seen that the optical accuracy is on the order of 1.5 times the ELCOMAT's LSB. It is therefore reasonable to conclude that the PSMA's pointing repeatability exceeds the resolution limit of the ELCOMAT. Again it is not possible to discern any substantial contribution to the repeatability error by the servo system at the ±2.5 degree mirror positions. Results confirm that the encoder met the PSMA system requirements including absolute accuracy.

Table 1. Performance Goals of the MicroE Encoder

Performance Parameter	Magnitude
Resolution [1]	0.047 μrad
Angular Range	±2.5 degree
Repeatability (over 10 min)	0.2 μrad
Accuracy	±2.0 μrad
Electrical Output	32 bit parallel word

[1] 12 DSP-based interpolation

Table 2. Summary of Marshall SFC PSMA Bench Tests

Date	Ang. Range (degree)	Noise/Jitter[2] (rad rms)	Accuracy (μrad rms)	Remarks
08/08/94	-0.26 to 0	0.126	1.164	Small Bench, Foam Rubber Pad
08/08/94	0 to +0.26	0.257	1.251	Same
8/18/94	-2.64 to -2.12	0.034	0.795	Large Bench, Air Support, Foam Rubber
8/18/94	-0.26 to + 0.26	0.034	0.679	Same
8/18/94	2.12 to 2.64	0.033	0.776	Same

Date	Ang. Range (degree)	Step Size (degree)	Repeatability (μrad rms)	Remarks
8/10/94	-0.26 to +0.26	0.13	0.340	Small Bench, Foam Rubber Pad
8/10/94	-0.26 to +0.26	0.26	0.291	Same
8/24/94	2.14 to 2.66	0.26	0.388	Large Bench, Air Support, Index Table, Foam Rubber
8/24/94	-2.4 to -1.88	0.26	0.388	Same
8/25/94	-2.4 to -1.88	0.26	0.437	Same
8/30/94	1.88 to 2.4	0.26	0.388	Same

[2] Accuracy Data: Moeller-Wedel Autocollimator ELCOMAT-2000 (LSB 0.243 μrad); Jitter noise limit of seismic environment ~ 0.034 μrad rms.

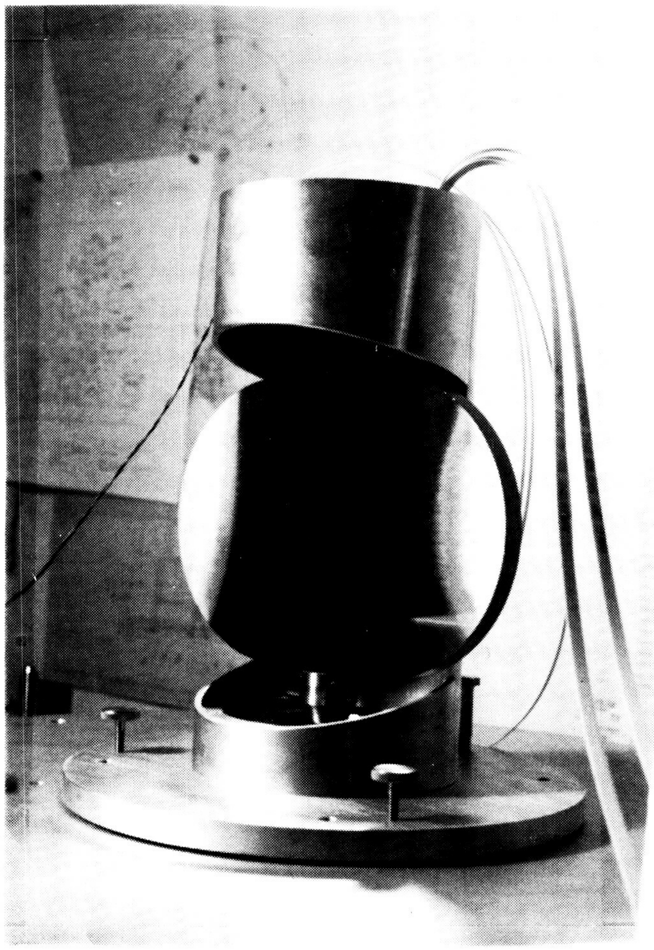

Figure 1. Marshall Pointing and Stabilization Mirror

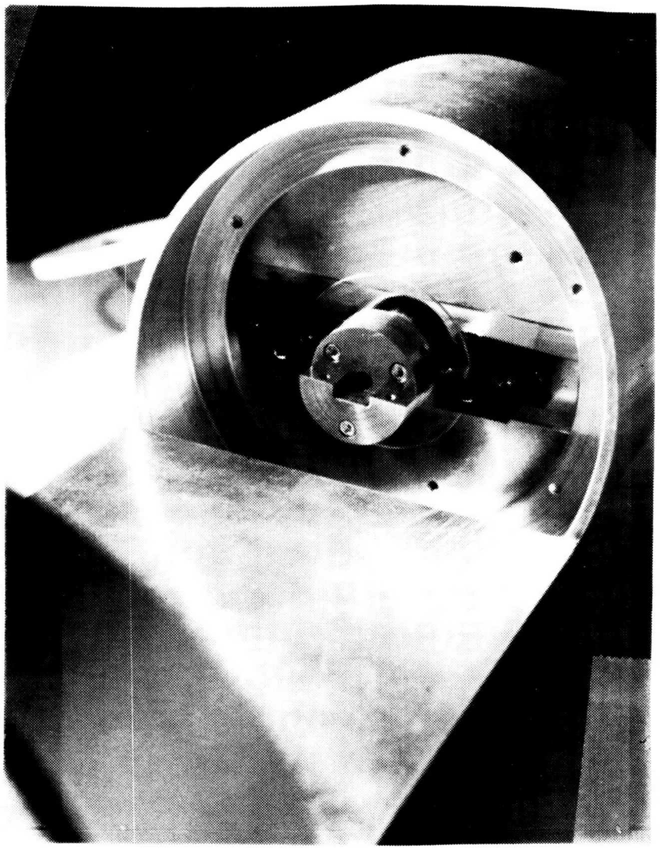

Figure 2. MicroE Encoder Installed in Marshall PSMA

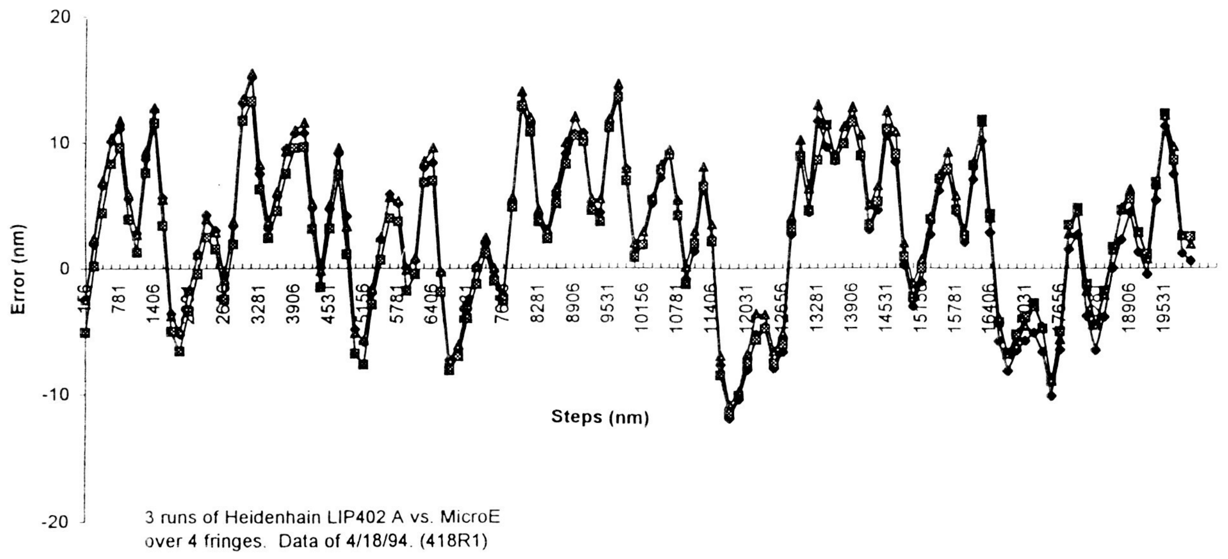

Figure 3. MicroE vs Heidenhain Encoder: Interpolated Error