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**ALIGNMENT TRANSFER IN A  
MODULAR GUIDANCE SYSTEM**

**by  
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# Alignment Transfer in a Modular Guidance System

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## Abstract

One of the requirements for a modular, integrated guidance system, is to determine and maintain the angular alignment between and among some of its various subsystems. Whether the purpose of the modularity is to permit substitutions of the units, or to permit a distributed placement of the units on the vehicle, the relative angular alignments among the sensors can have an impact on the accuracy of the guidance system. These angular alignments have traditionally been maintained by rigid structure, but this can place severe constraints on the overall design. An alternative is to measure these alignments and use the measurements in a compensation scheme.

## Introduction

In a company-sponsored demonstration of an advanced modular guidance system at the Draper Laboratory, we plan to incorporate an alignment device to measure the misalignment between an Inertial Measurement Unit (mounted on shock mounts) and a Stellar Sensor. This device is based on a concept known by the acronym AXIS, which is taken from Alignment Transfer by Integrated Strain. The alignments are sensed by measuring the integrated strains on the surface of a connecting rod. The device, which has been under development for two years, will measure all three degrees of freedom to a resolution of 0.4 arc second and over a range of 25.6 arc seconds. It has a total length of about 6 inches and is "L" shaped with a right-angle bend. The measurements are made with optical fibers. The concept of the device is described in this paper.

In general, the angular or positional orientation of one subsystem with respect to another is determined by a structure. One subsystem, for example a sensor, is usually located with respect to another measurement subsystem by the structural frame of the vehicle supporting it. Of course, at installation (and perhaps periodically afterward) various tools may be used to adjust or check this rigid alignment. In cases where this alignment is critical, this may be an "expensive" way to do it. For example, in the Apollo Command Module the critical alignment between the IMU, the telescope and the sextant was maintained by mounting all these elements on a navigation base which was a large structure machined out of a solid piece of beryllium.

When the structure is not sufficiently stable, alignment is frequently transferred by optical means, usually with

mirrors, lenses, etc. An example of this is the Optical Alignment Group on a ballistic missile carrying submarine where azimuth information is transferred from the SINS to the missile guidance system by a system of mirrors and a traveling optical cart. In these cases, the alignment transfer is usually done on an occasional or periodic basis, where the orientation is sampled and either presumed to remain constant between samplings or else the subsequent misalignment is not important.

Described in this paper is a method of monitoring the alignment between two or more units continually and with high bandwidth. This can be done with high resolution (nanoradians) using optical fibers, or less expensively using resistive wires although with resistive wires the measurement resolution will be reduced. The method requires that the units be connected with a flexible member (a thin rod or pole) on which the fibers or wires are attached. (In some circumstances the supporting structure itself can be used for attaching the fibers or wires.) In many aspects, this approach is much more tolerant of the environment than mirrors and lenses, e.g. fog and vibration. Also, it has much flexibility in that it can be placed around corners, pass through bulkheads, etc.

The concept is called AXIS which is an acronym for "Alignment Transfer by Integrated Strain". This device is being investigated at the Draper Lab., and has been for several years (Ref. 1). We have several designs under development currently. The objective of one of these efforts is to demonstrate the transfer of alignment on a Patriot or ERINT Launcher for the U. S. Army Missile Command. We will transfer the orientation of the Gunner's Quadrant, on the base of the launcher, to a reference near the guidance systems of the erected missiles, transferring all three angles continually with a sub-milliradian accuracy.

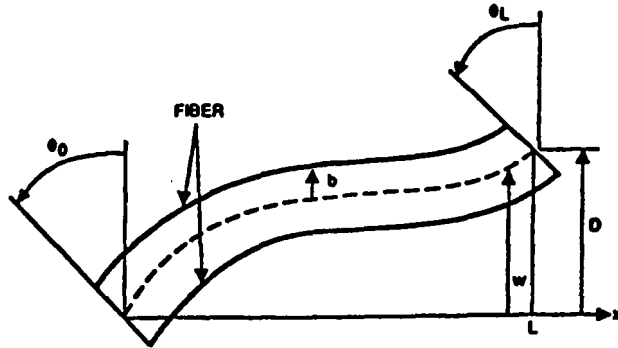
I believe that this concept and its development has many applications; in the civilian as well as the military market. I characterize it as a solution looking for more problems.

## Alignment Transfer by Integrated Strain (AXIS)

If one considers the strains on the surface of a long thin uniform rod, one comes to the heuristic conclusion that the change in length of a longitudinal surface line is directly proportional to change in angle of one end of the rod with respect to the other. Specifically, the change in length is equal to the change in angle times the distance of the line from the neutral axis. (Here, the bending, the neutral axis and the

surface line all lie in the same plane). A more rigorous examination, as shown in Figure 1 supports this conclusion and also indicates how a displacement measurement of one end with respect to the other can be instrumented.

**P** = sensor weighting (uniform)  
**b(x)** = half diameter  
**w''(x)** = rod curvature  
**x** = distance along rod



OUTPUT OF INTEGRATING STRAIN SENSOR  
 WITH WEIGHTINGS FUNCTION  $p(x)$

$$-\Delta L \equiv \varepsilon = \int_0^L P b(x) w''(x) dx$$

$$= P b(x) w'(x) \Big|_0^L - P b'(x) w(x) \Big|_0^L + \int_0^L P b''(x) w(x) dx$$

If  $b(x) = B$

$$\varepsilon = P B [w'(L) - w'(0)] = P B (\theta_L - \theta_0) \text{ (ANGLE OUTPUT)}$$

If  $b(x) = K (1 - x/L)$

$$S = -K P w'(0) + K P/L [w(L) - w(0)]$$

$$= -K P (\theta_0 - D/L) \text{ (DISPLACEMENT OUTPUT)}$$

Figure 1. AXIS Analysis.

If the line element is at a constant distance (B) from the neutral axis, the change in length is given directly by:

$$\Delta l = B (\theta_L - \theta_0) \quad (1)$$

(Figure 1 also shows how the line element can be selected to provide a displacement indication, but that is not the subject of this paper.) Note that in the analysis shown on Figure 1, the change in length of the line element is **independent of the length and shape of the rod**.

This concept provides the basis for a very powerful method of transferring angular orientation (and displacement) of one end of the rod to the other end, where the line element is represented by a physical fiber whose length, or change in length, can be measured.

This change in length can be troublesome to measure directly, and, as is frequently the case, the differential length

between two fibers, providing common mode rejection, is a substantially better method. These ideas can be utilized to effectively implement the transfer of all three rotation angles between units. Figure 2 below shows a three-axis AXIS arrangement to accomplish this.

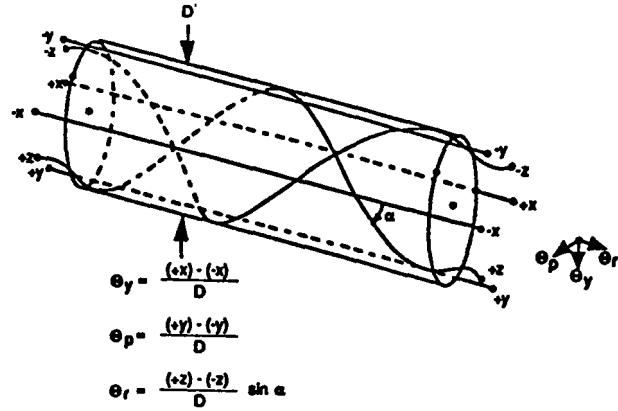


Figure 2. Three-Axis Angular Transfer Arrangement.

As shown in Figure 2, a pair of fibers in the (nominally) y z plane will provide a measure of the relative rotation about the x axis (e.g. the pitch angle):

$$\Theta_p = \Delta L_y / D \quad (2)$$

The pair of fibers in the (nominally) x z plane provide the yaw angle,

$$\Theta_y = \Delta L_x / D \quad (3)$$

while a clockwise helical fiber compared to a counterclockwise helical fiber provides the roll (twist) angle,

$$\Theta_r = \Delta L_z \sin \alpha / D \quad (4)$$

where  $\alpha$  is the helix angle, D is the diameter separating the pairs of fibers, and  $\Delta L$  is the difference in length between the fibers of a pair.

Some topological comments are in order. (1) The above configuration will provide the three angles independently given that the magnitude of the angles does not get too large (of order 30 degrees). (2) Bending and twisting that is constrained to one plane can be accommodated to large angles without topological limit. (3) Several rods can be joined in series: if the rods are joined at fixed right angles in cardinal directions, then the fiber pairs, rod to rod, can be joined so as to provide the proper angular transformations; if the rods are constrained to lie in cardinal planes, but at (fixed) arbitrary angles in these planes, and a double set of fibers implemented, the double pairs of fibers can be proportionally combined for proper transformations; with a triple set of fibers, the rods can be at any arbitrary fixed angles, and proportional combinations among the fiber pairs will provide the correct transformations. Further analytical work remains to be done to fully understand the limitations of three

dimensional large angle bending. One further topological comment: the characterization of the rod as long and thin is meant to denote that the rod does not have any significant transverse shear.

### Implementation

The primary implementation question is how to measure the change in length between the pairs of line elements. At Draper we have pursued two main directions; optical and electrical. The optical approach utilizes optical fibers which are bonded to the rod and the difference in length is sensed interferometrically. The electrical approach utilizes conductive wires bonded to the rod and the difference in length is sensed by measuring the resistance change. Both of these methods have been successfully demonstrated and each has its own unique characteristics. Other approaches, and variations from those described below, are under development at the Draper Laboratory.

#### Optical

The interferometric fiber-optic approach provides great sensitivity, wide bandwidth and a large dynamic range. The fundamental configuration is shown in Figure 3 below. The output from narrow line width laser is split by a 50/50 coupler. This provides coherent light to the two optical fibers which are bonded to the rod. The output light from these two fibers is caused to form an interference pattern which is sensed as described below. The sensed fringe pattern is digitized and summed into a register. The accumulated net sum from the time that the process is started then represents the net angular change of one end of the rod from the other.

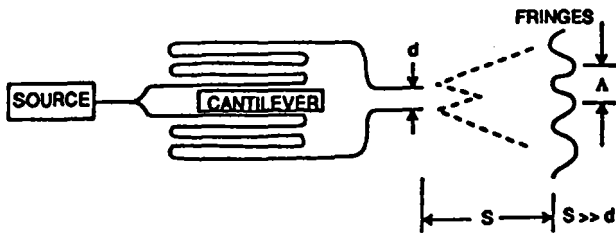


Figure 3. Interferometer Scheme.

This optical approach can be designed to be extremely sensitive – both by the nature of the basic interferometer scheme itself and also by virtue of the fact that the length of fiber bonded to the rod can be very great. By laying multiple traverses, back and forth, each traverse will measure the surface integrated strain. The basic sensitivity is given by:

$$\Delta \Theta / \Delta \Phi = N \lambda / 2 \pi D \eta \quad (5)$$

where

- $\Delta \Theta$  = Angle change (radians)
- $\Delta \Phi$  = Fringe angle (radians)
- $N$  = Number of traverses of optical fiber
- $\lambda$  = Free space wavelength of light
- $D$  = Diameter between fibers of a pair
- $\eta$  = Strained index of refraction of fiber (includes photo elastic effect)

For an experimental measurement, partial results are shown in Figure 4 below, the calculated scale factor is 1.5043 arc sec/fringe-count. The measured scale factor shown in Figure 4 is 1.235 arc sec/fringe-count.

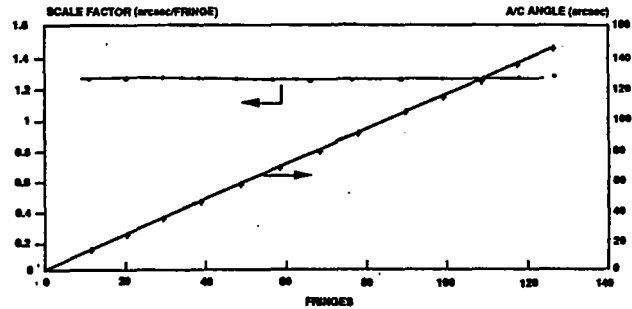
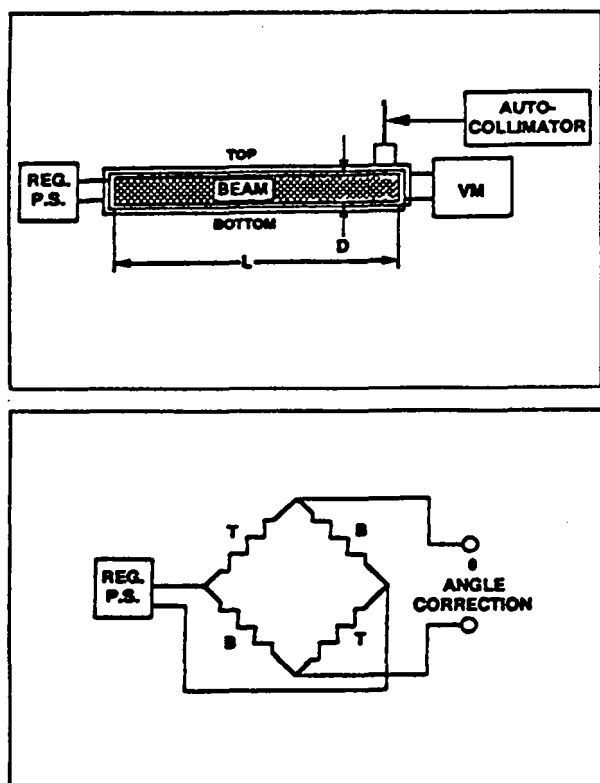


Figure 4. Test Configuration 2 Results.

#### Electrical

An alternative method of measuring the integrated strain is to use resistive wires bonded on the rod. As the wires are stretched or compressed, the change in resistance is measured and the change is a measure of the strain. Typically, multiple wires are used so that they can be placed in a full Wheatstone bridge configuration. This technique is similar to strain gage technology, although instead of discrete sensing at a small area, the wires are laid along the length of the rod. Although this approach is not nearly as sensitive as the optical method, it has some significant advantages. The two main advantages are: (1) it is considerably less expensive; and (2) it provides a whole angle readout during all operation. One of the major differences with the optical approach is that the sensitivity is now inversely proportional to length. This is due to the properties of the Wheatstone bridge configuration, whose sensitivity is proportional to  $\Delta R/R$ . Adding more turns of wire does not change this ratio. This approach is indicated in Figure 5.



$$\delta\theta = \frac{\Delta L}{D} = \frac{\Delta L/L}{D/L} \propto \frac{\delta R/R}{D/L}$$

Figure 5. Resistive AXIS Concept.

The sensitivity of the configuration is given by:

$$\Theta / \Delta E = 2L / fDE \quad (6)$$

where;

- $\Theta$  = Angle of one end of the rod with respect to the other (referenced to an initially calibrated value)
- $\Delta E$  = Voltage output from bridge
- $L$  = Length of rod
- $f$  = Strain gage factor of wire
- $D$  = Diameter separating wires of a pair
- $E$  = Excitation voltage applied to bridge

In Figure 6 we show some early experimental results. With 30 volts applied to the Wheatstone bridge, we achieved a sensitivity of 1.46 millivolt / milliradian.

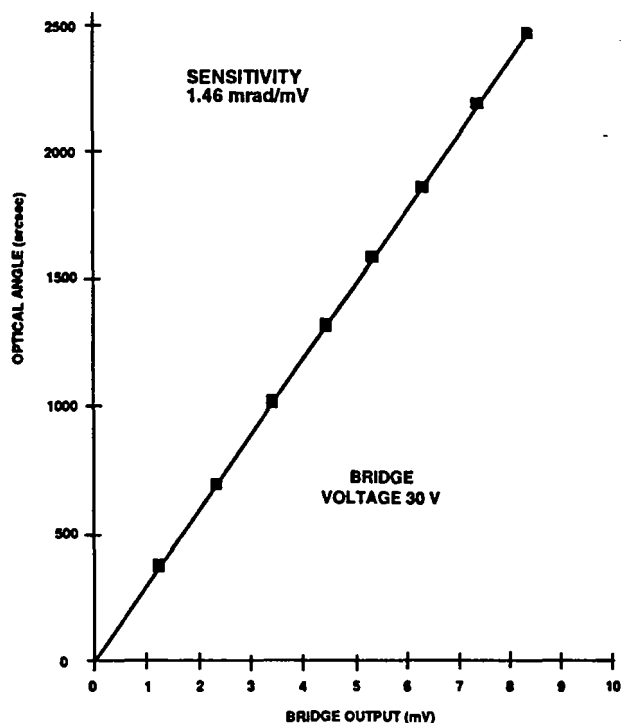


Figure 6. Resistive AXIS Test Results.

#### Strapdown System Demonstration AXIS Subsystem

The Draper program to demonstrate the operation of a Stellar-Inertial Strapdown System is described elsewhere. In this paper is outlined the design parameters of the AXIS alignment transfer subsystem.

The AXIS subsystem to provide the alignments between the AIMU and the Stellar Sensor is based on the technology described above. In this case the integrated strains are measured only by the photonic method. In particular, all three degrees of freedom are measured twice, each with a different scale factor. This technique is analogous the two speed resolver method of achieving a large dynamic range along with fine resolution.

The scale factors are chosen to provide one of the speeds with a sensitivity of 3.200 arc seconds per fringe, while the other has a sensitivity of 3.657 arc seconds per fringe. By interpolating fringes to 1/8 of a fringe, we achieve a resolution of 0.4 arc second over a dynamic range of 25.6 arc seconds.

Each speed is implemented by a 1.3  $\mu\text{m}$  5 mW dfb laser feeding a 60 dB optical isolator, driving a 1 x 8 splitter (only 6 outputs used). Each pair provides one channel of measurement on the AXIS substrate, and then connected to a fringe

generator, which is described in Ref. (2). These fringe generators, however will incorporate 4 in-line element detectors in place of the dual detectors. By properly summing and differencing the outputs of the four detector elements, the fringe pattern can be resolved to 1/8 by sensing the sign of these signals only.

The AXIS substrate is basically made in three sections, which will be bolted together. Two of the sections are spool-like arms with machined grooves to guide the laying of the optical fibers. The central section is a precision cube, which serves to position the arms at precisely 90 degrees.

### References

- (1) U. S. Patent No. 4,788,868: 1988.
- (2) "Wide Dynamic Range Fiber-Optic Alignment Transfer Device," L. S. Wilk, R. P. Dahlgren, SOLID STATE OPTICAL MATERIALS SYMPOSIUM, AMERICAN CERAMIC SOCIETY, MAY 1991.
- (3) "Dynamic Missile Reference Alignment," L. S. Wilk, AIAA MISSILE SCIENCES CONFERENCE, FEB. 1993.