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Embedded, Real-Time DSP Control of an Electrostatically Suspended Gyroscope

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. *Abstract*—**The Electrostatically Suspended Gyroscope (ESG) is a rotating mass, high precision, two axis inertial angle sensor manufactured by Boeing. The ESG is currently the inertial angle sensor deployed on the Inertial Measurement Unit (IMU) of the Electrostatically Suspended Gyro Navigator (ESGN) on Strategic U.S. Navy submarines. The rotating mass, or rotor, is suspended in vacuo by controlled electrostatic fields inside a spherical capacitance actuation chamber. The existing ESG rotor suspension controls are aging 1970's analog electronics. This project mechanizes state-of-the-art, embedded Digital Signal Processor (DSP) technology as a prototype drop-in replacement of the old analog ESG rotor suspension control electronics. Embedded DSP software algorithms, for suspension and rotation control of the ESG rotor, provide improved performance, reliability, disturbance rejection, and continuous monitoring for sustainment of the ESG into the next generation.**

I. INTRODUCTION

Strategic submarine inertial navigation components, including the ESG instrument and ESGN IMU, depicted in Figure 1, are manufactured and maintained by Boeing Naval Electronics & Navigation (formerly of Rockwell). The ESG rotor suspension is mechanized with two analog suspension electronics boards, that plug directly into the ESG instrument. This project consisted of development of a prototype, embedded DSP hardware and software, that replaces the critical, real-time, rotor suspension control and monitoring functions of electronics board #1. ESG studies prior to this project were done at the Rockwell International Science Center [1].

The project development, begun officially in 1997, was the result of a collaboration with Caltech [2], [3], the Boeing Naval Electronics & Navigation group, and UCLA [4]. Within this group at Boeing, the project was known as the Caltech/Boeing/UCLA project.

To accomplish the aggressive goals of this project development, the tasks were split into three parts. The focus of Caltech was in nonlinear, dynamical ESG analysis and six degree of freedom (6 DOF) simulation, with emphasis on advanced ESG capabilities [2]. UCLA focused on linear, multivariable suspension control design and system identification of the ESG. Boeing worked on the development of state-of-the-art, embedded DSP hardware and software to replace the old analog ESG rotor suspension functions. This paper addresses, primarily, the embedded DSP suspension control hardware and software architecture, as mechanized in the digital ESG prototype by Boeing.

A.. ESG Rotor and ActuatorCavity Configuration

The heart of the ESG is a solid, one centimeter diameter, Beryllium ball, or "rotor", of one gram mass. It is suspended by dynamically controlled electrostatic fields created by placing voltages on four pairs of diametrically opposed electrodes, or "cavity plates", that form a spherical actuation chamber, or "cavity" closely surrounding the rotor. Figure 2 shows the ESG configuration, with rotor size and displacement relative to the cavity greatly exaggerated.

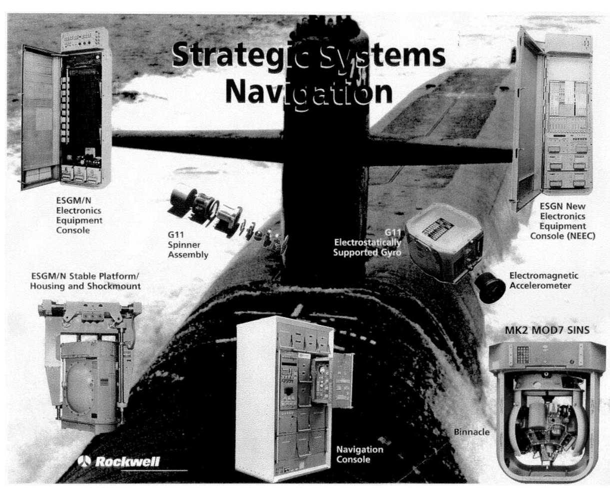

Fig.1 Strategic Inertial Navigation System Components

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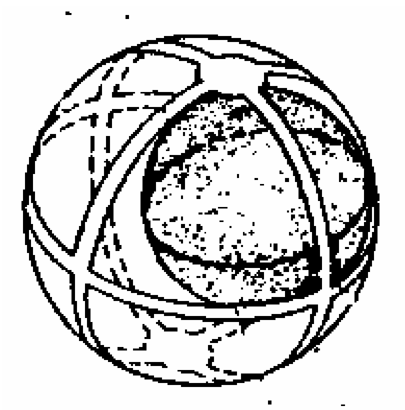

Fig. 2 ESG Plant – Rotor and Actuation Cavity

B. Rotor Suspension Control Overview

Fig. 3 shows a view of the rotor in three different displacement positions along a single suspension axis in the ESG cavity. The objective of the rotor suspension control is to perfectly center the rotor inside the cavity. Acceleration disturbances acting on the rotor are Earth's gravity, and submarine turn maneuver accelerations. Cavity position disturbances relative to the rotor come from vibration and shock inputs. A perfectly centered rotor has its Center of Geometry (CG) exactly at the Cavity Center (CC). Voltages placed on diametrically opposed cavity plates produce electric field forces within each plate-to-rotor capacitance gap, thereby creating a centering tug-of-war on the rotor. Electric field forces act through the CG of the rotor. Suspension controller input along an axis is a sensed plate-pair voltage differential, proportional to the rotor CG displacement from the CC. The controller output provides rebalancing plate voltages to pull the CG back to the CC.

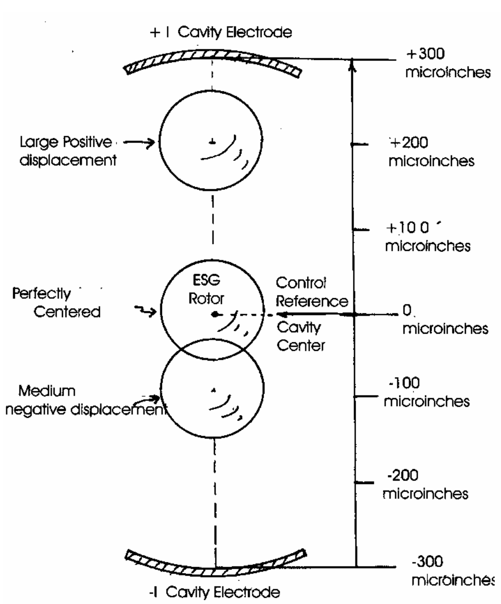

Fig. 3 Simplified Single-Axis ESG Plant

TABLE I
ESG SUSPENSION CONTROL PERFORMANCE OBJECTIVES

Magni-tude	Disturbance Acceleration	Required Attenuation (centering error < 0.1uinches)
1 g	Earth's Gravity (DC)	< -60 dB ref note (a)
100 mg	Boat Motion (<0.1Hz)	< -40 dB ref note(a)
10 mg	Vibration(50 -1000Hz)	< -20 dB ref note (a)
10 g	Shock (70 Hz)	< -30 dB ref note (b)

Disturbance Rejection Tasks/Modes
(a) High Performance Mode Rotor Centering – Normal mode of operation, ideally with 100% rejection of all rotor acceleration and cavity position disturbances, DC to 1000Hz frequency.
(b) Survival Mode Rotor Centering – Maximum rotor displacement for a "crash" into any cavity plate is 300 microinches. Shock disturbance rejection must be greater than 20% for time duration of 100 milliseconds to meet a conservative objective maximum rotor displacement of less than 200 microinches.

The entire cavity actuator space defines a four axis coordinate system. Fig. 3 defines a single axis of this cavity fixed coordinate system passing through the centers of the +1 and –1 cavity electrode plates. The origin is at the CC, and positive displacement of the rotor with respect to the cavity is measured toward the +1 cavity electrode plate. The same is true for the other cavity plate-pairs, giving a four axis, nonorthogonal, coordinate sytem (1,2,3,4).

II. ESG Control performance specifications

Precision rotor suspension and centering control is important for gyroscope performance, and is the focus of this work. Other ESG control tasks regulate rotor spin rate, temperature of the rotor/cavity, and cavity vacuum. ESG time varying, nonlinear dynamics, including parametric uncertainty analyses, are addressed in [2].

The design of the ESG rotor suspension control is driven primarily by the need to reject a wide frequency range of acceleration and displacement disturbances acting on the rotor or the cavity/rotor combination, as listed in Table 1. Disturbance input frequencies range from DC to 1000Hz. Frequencies higher than 1000Hz are assumed to be noise.

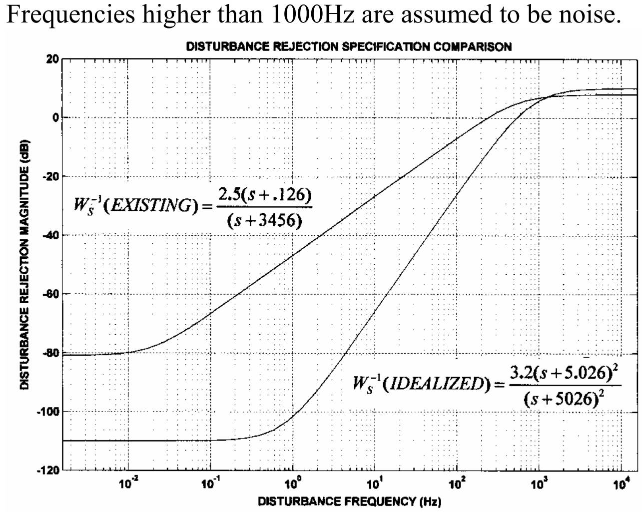

Fig. 4 Disturbance Rejection Specification Comparison

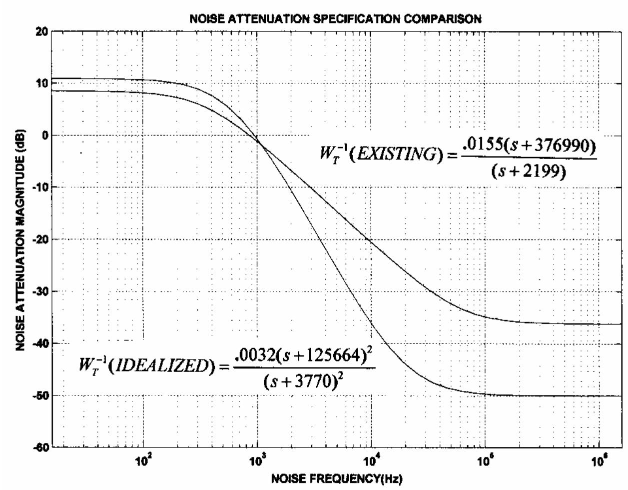

Fig. 5 Noise Attenuation Specification Comparison

Figures 4 and 5 show how performance objectives translate into disturbance rejection and noise attenuation specifications. The existing design does not perform well at some frequencies. The idealized design specifications increase the disturbance rejection and the noise attenuation.

III. ESG CONTROL MODELING AND DESIGN

Fig. 6 depicts a matrix block diagram model of the ESG rotor suspension control system. The upper row of blocks is here defined as the Plant, while the lower row of blocks is defined as the Controller. The Controller is depicted as it is mechanized for the embedded DSP. The existing analog Controller can easily be visualized by dropping the D/A converter, K0, the A/D converter, K2, and transformations T43 and T34. Note that rotor acceleration disturbances are D1, and cavity position disturbances are D2. The mathematical modeling presented here makes the following assumptions; (a) all linear blocks, (b) small rotor displacement of less than 10 microinches from Cavity Center (c) rotor Center of Mass, CM, and Center of Geometry, CG, are coincident, (d) rotor translational dynamics only,

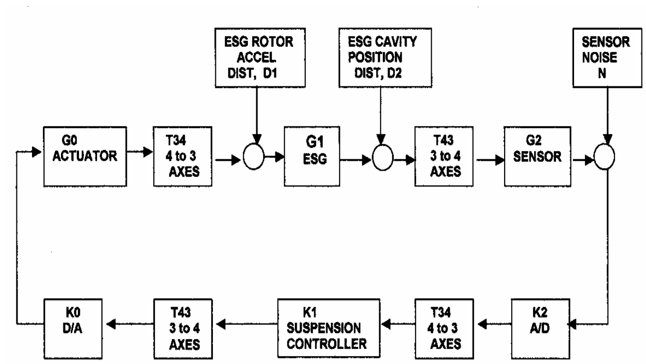

Fig. 6 ESG Suspension Control System Block Diagram

(e) exact matching of parameter gains on all rotor suspension control channels, and (f) actuators and sensors are assumed to be constant gains.

Referring to the digital ESG suspension control model block diagram of Fig, 5, we have the following definitions of the transfer function matrices.

$$G0 = g_0 I_4 \equiv Actuator\ (cm/\sec^2/Volt) \quad (1)$$

$$G1(s) = g_1(s) I_3 \equiv ESG\ (\mu inches/cm/\sec^2) \quad (2)$$

$$G2 = g_2 I_4 \equiv Sensor\ (Volts/\mu inch) \quad (3)$$

$$K0 = k_0 I_4 \equiv Converter\ D/A\ (Volts/count) \quad (4)$$

$$K1(z) = k_1(z) I_3 \equiv Dig.Control.(counts/count) \quad (5)$$

$$K1(s) = k_1(s) I_4 \equiv Ana.Control.(Volts/Volt) \quad (6)$$

$$K2 = k_2 I_4 \equiv Converter\ A/D\ (counts/Volt) \quad (7)$$

Identity matrices are 3x3 and 4x4 respectively. The Laplace tranform variable is "s", and "z", represents the Z-transform variable. $T34$ transforms a vector from the 4-axis (1,2,3,4) frame to a 3-axis, (X,Y,Z), cavity fixed frame.

$$T34 = (1/4)\begin{bmatrix} 0 & \sqrt{6} & 0 & -\sqrt{6} \\ 0 & -\sqrt{2} & 2\sqrt{2} & -\sqrt{2} \\ 3 & -1 & -1 & -1 \end{bmatrix} \quad (8)$$

$$T34 \equiv Pseudoinverse(T43) = T43^{\dagger} \quad (9)$$

where $T34 \cdot T43 = I_3$ (10)

The Plant, however, has a coupled architecture, since;

$$G(s) = G2 \cdot T43 \cdot G1(s) \cdot T34 \cdot G0 \quad (11)$$

$$T43 \cdot T34 = \frac{3}{4}\begin{bmatrix} 1 & -1/3 & -1/3 & -1/3 \\ -1/3 & 1 & -1/3 & -1/3 \\ -1/3 & -1/3 & 1 & -1/3 \\ -1/3 & -1/3 & -1/3 & 1 \end{bmatrix} \quad (12)$$

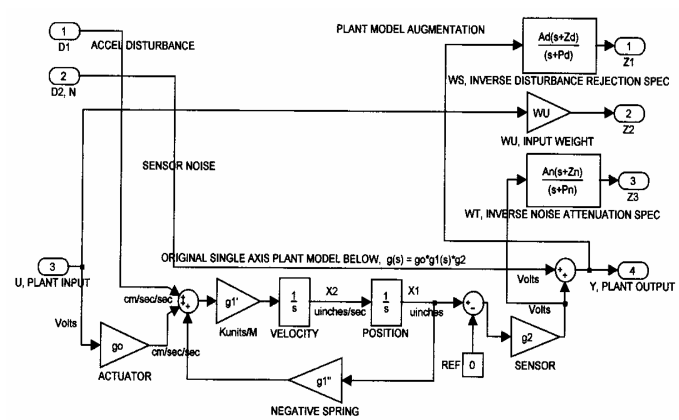

Fig. 7 Single Axis, Simple ESG Plant and Augmentation

Here arises the most important difference between the existing analog design and its digital controller counterpart. A fundamental controller design criteria for the Plant, (11), is to first decouple it by appropriate matrix pre/post multiplications [5]. These pre/post multiplications are mechanized in the digital controller as shown in the bottom row of blocks in Fig. 6, giving an uncoupled Plant.

$$G_u(s) = T34 \cdot G(s) \cdot T43 = g_0 g_1 g_2 I_3 \qquad (13)$$

The digital controller is mechanized via DSP as;

$$K(z) = K0 \cdot T43 \cdot K1(z) \cdot T34 \cdot K2 \qquad (14)$$

The existing analog controller is mechanized as;

$$K(s) = K0 \cdot K1(s) \cdot K2 \qquad (15)$$

By inspection, the digital controller, (14), when multiplied by the Plant, (11), decouples it on both the actuator and sensor sides. The analog controller, when multiplied by the Plant, leaves it coupled, per (12). This design difference has far-reaching consequences in regard to ESG performance. The most simple representation of the ESG Plant along an axis is given by the state space representation below.

$$\begin{pmatrix} \frac{dx_1}{dt} \\ \frac{dx_2}{dt} \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ g_1^{'} g_1^{''} & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ g_0 g_1^{'} \end{pmatrix} U + \begin{pmatrix} 0 \\ g_1^{'} \end{pmatrix} D1 \qquad (16)$$

$$Y = \begin{pmatrix} g_2 & 0 \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + N, where\ g_0, g_1^{'}, g_1^{''}, g_2 > 0$$

The Plant equations above describe a simple "negative spring" system with no friction, and having equal positive and negative real eigenvalues.

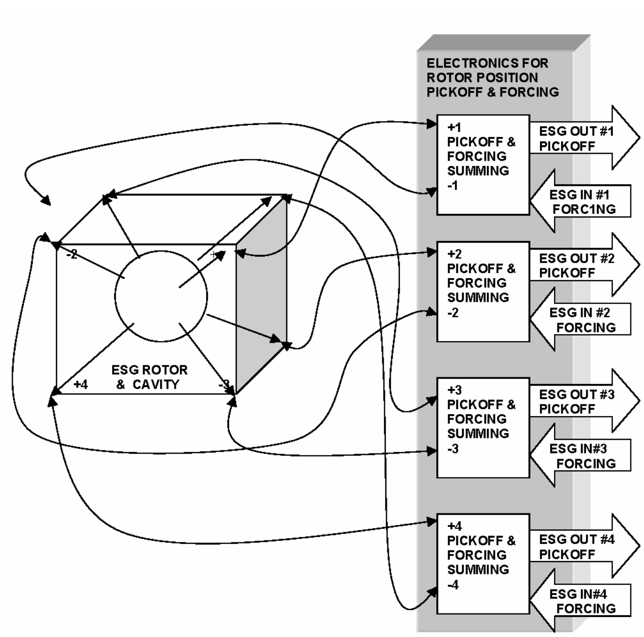

Fig. 8 ESG Plant block diagram

The simple Plant transfer function is therefore given by;

$$g(s) = \frac{Y(s)}{U(s)} = g_0 g_1(s) g_2 = g_0 \left(\frac{g_1^{'}}{s^2 - g_1^{'} g_1^{''}} \right) g_2 \qquad (17)$$

The simplest form of the existing analog control is given by;

$$k_1(s) = -2.5^{\backslash 8} \frac{(s+7.1^{\backslash 2})(s+3.9^{\backslash 3})(s+4.5^{\backslash 3})}{s(s+1.0^{\backslash 4})(s+1.53^{\backslash 4})(s+4.0^{\backslash 4})} \qquad (18)$$

The Plant of Figure 7 has been utilized to design robust controllers using Rho-Synthesis[1], H2-Hinfinity[6], etc., however they have not been mechanized due to a lack of time/budget on the project. Mechanized was the following;

$$k_1(z) = Z\{K_1(s)\} \ , Fs = 80kHz \qquad (19)$$

with the Plant decoupling of the T34, T43 transformations.

IV. EMBEDDED DSP MECHANIZATION

The existing analog ESG suspension control electronics has done its job well for 30 years, and is still mechanized and operational in the field with this publication. The ESG cavity/rotor physics are very expensive, but remain state-of-the-art electro-mechanics for the class of high angular momentum, low angle random walk, spinning mass gyroscopes. The analog suspension control electronics are not currently state-of-the-art. Why should we consider digital ESG rotor suspension controls? The answers to this are that the analog suspension control electronics (a) are aging components, giving rise to parameter degradation over time in any single ESG gyroscope, (b) are subject to parameter shift from one ESG gyroscope to another, (c) are not easily changed, and are literally frozen with the inherent design of the 1970's, thereby creating a barrier to performance improvements.

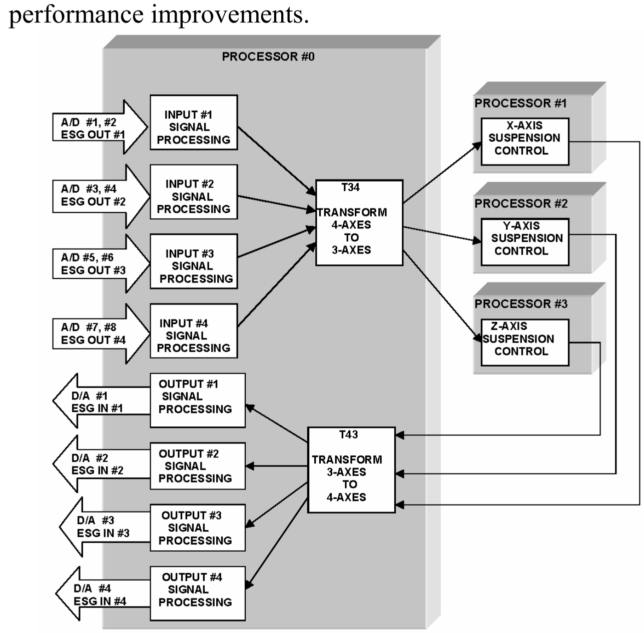

Fig. 9 ESG embedded DSP controller block diagram

Fig. 8 depicts a multi-axis, functional block diagram of the ESG Plant. The cube shown, with the rotor inside, is a geometrical representation of the cavity fixed electrode plates acting to suspend the ESG rotor. Each of the vertices of the cube coincide with the corresponding centers of the eight spherical cavity plates. This cube representation is inscribed inside the spherical cavity given in Fig. 2. The detailed mechanization in the Plant of the rotor forcing and position "pickoff" signal superposition on a 20 KHz reference carrier signal is beyond the scope of this paper. This is fully addressed in [2]. Adequate for this modeling description is the equivalent baseband representation for the Plant given previously. The 20KHz carrier system in the Plant is an important basis for the choice of sampling frequency for the digital controller at Fs=80KHz, or four times the carrier frequency. All of the forcing inputs and positional pickoff outputs of the Plant are riding on this 20KHz carrier signal. Fig. 9 depicts the functional blocks for the embedded DSP suspension controller. Each analog input from the ESG positional pickoff output is first run through some signal processing consisting of filtering with an anti-alias filter of corner frequency around 30KHz, then sampled at 80KHz.

Fig 10 shows the prototype DSP architecture embedded into the ESG, in a stand-alone mode, as a drop-in replacement of the analog suspension electronics board#1. The DSP "stack" consists of a BittWare Silvertip Quad processor board, with Sharc 21060 processors, and with a high speed BittWare Bitsi I/O mezzanine, called the Bitsi-DAQ (eight 12 bit A/D inputs and 14 bit four channel D/A outputs), [7], [8]. This stack conforms to the industry standard PC/104 interface and form factor. The DSP stack is mounted on an interface carrier board, which provides I/O signal conditioning and interface in the form of anti-alias filters for the A/D inputs, and smoothing for the D/A outputs, as well as all I/O connections to the gyroscope.

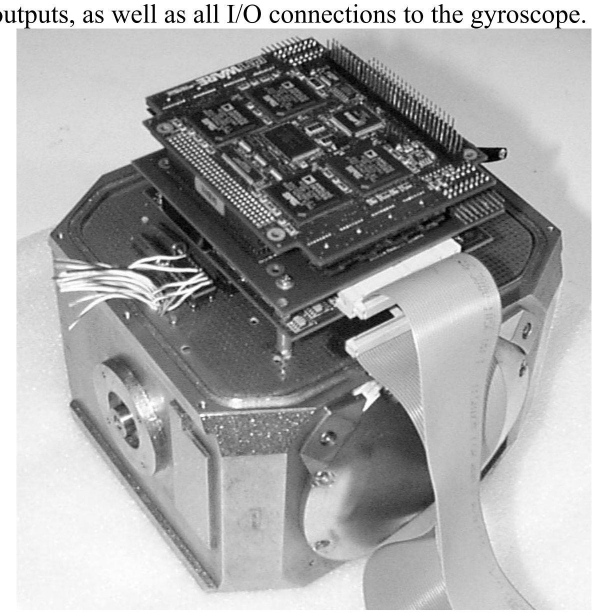

Fig. 10 ESG Embedded DSP Controller Mechanization

V. RESULTS

The digital ESG suspension mechanization results are first compared to that of the analog suspension in the "open loop", or inverse Sensitivity, frequency domain responses of Fig. 11. The digital response compares well with that of the analog, with the exception of slightly lower gain by 7.5dB. Adding this gain adjustment, and also a simple first order digital lead/lag compensator for increased stability margins, to the digital controller will bring the digital controller into coincidence with the original analog ESG controller. However, as previously explained, both time and budget caused the project to be closed before doing this fine tuning of the digital controller. Fig. 12 shows a digital controller levitation of the ESG rotor, showing rotor miscentering, in micro-inches, in X,Y,Z suspension coordinate axes (note that +Z corresponds to the +1 axis). Because the digital controller was not tuned, the time domain responses are significantly slower than the analog. These are not compared here for that reason.

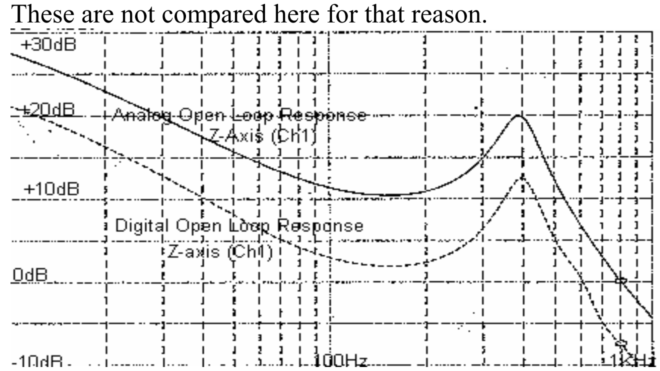

Fig. 11 Inverse Sensitivity Comparison, Analog vs. Digital

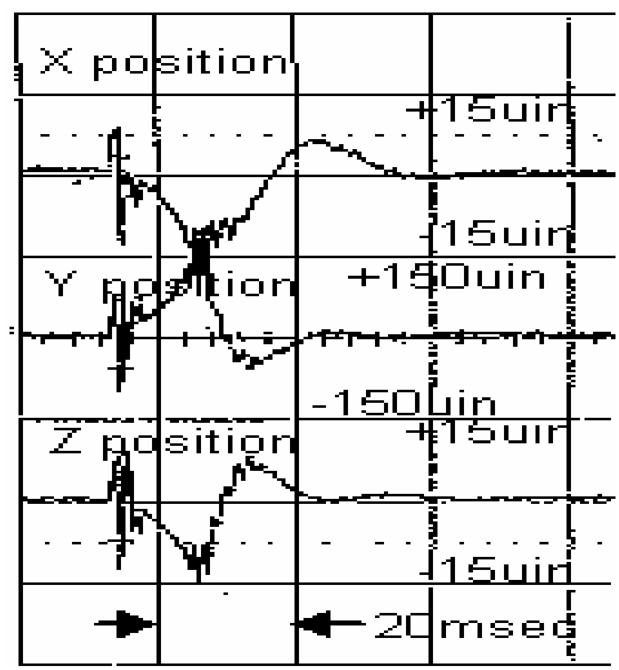

Figure 12 Digitally Controlled Levitation of ESG Rotor

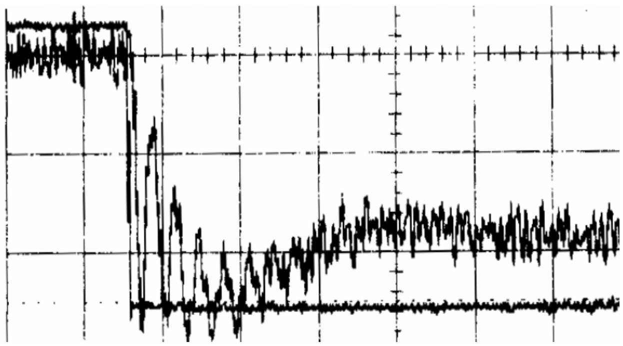

Figure 13 Step Response of Digital Control System

The peak rotor position values of X,Y, and Z (-15, +150, -15 micro-inches respectively) represent the first time instant that the rotor position is actually resolved after rotor liftoff, since the levitation command was initiated. The initial transient on the left, for each curve, represents the time instant when the levitation command was issued. In this case, the rotor initially rested somewhere on the +3 axis actuation cavity electrode, which is nearly coincident with the +Y coordinate of the X,Y,Z- frame. Fig. 13 gives an example of a step input response of the digital suspension control (vertical scale 50mV/cm, horizontal scale 5ms/cm). Since the digital controller was not fine-tuned, some high frequency noise/oscillations are clearly present.

VI. Conclusion

A revolution in high speed microprocessor development has enabled embedding processors and digital control algorithms directly into precision instruments. Embedded DSP suspension controls for the ESG gyroscope are the answer to each and every drawback posed above by the aging analog suspension control electronics. Digital ESG suspension controls are (a) fixed in software and give parameters that never change with time on any single ESG gyroscope, (b) exactly the same and do not shift from one ESG gyroscope to another, thereby improving instrument reliability and repeatability, (c) minimal cost and can be updated to accommodate new control strategies for performance improvements, and can be readily downloaded to the embedded processors for immediate testing, (d) inherently easy to mechanize matrix calculations of modern MIMO control, and (e) state-of-the-art, and the obvious choice for an upgrade of the ESG gyroscope. This work accomplished the first step toward accomplishing the above, mechanizing the first embedded DSP suspension controller prototype into the ESG instrument. Further work will include fine tuning the digital controller equivalent of the existing analog controller. After dynamic testing of this is accomplished, more advanced digital robust controllers can then be implemented.

Acknowledgment

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