NASA-CR-196138

Old Dominion University Research Foundation

DEPARTMENT OF AEROSPACE ENGINEERING
COLLEGE OF ENGINEERING & TECHNOLOGY
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529

LARGE ANGLE MAGNETIC SUSPENSION TEST FIXTURE

By

Colin P. Britcher, Principal Investigator

p. 21

Progress Report
For the period ended April 30, 1994

Prepared for
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-0001

Under
Research Grant NAG-1-1056
Nelson J. Groom, Technical Monitor
GCD-Spacecraft Controls Branch

July 1994

DEPARTMENT OF AEROSPACE ENGINEERING
COLLEGE OF ENGINEERING & TECHNOLOGY
OLD DOMINION UNIVERSITY
NORFOLK, VIRGINIA 23529

LARGE ANGLE MAGNETIC SUSPENSION TEST FIXTURE

By

Colin P. Britcher, Principal Investigator

Progress Report
For the period ended April 30, 1994

Prepared for
National Aeronautics and Space Administration
Langley Research Center
Hampton, VA 23681-0001

Under
Research Grant NAG-1-1056
Nelson J. Groom, Technical Monitor
GCD-Spacecraft Controls Branch

Submitted by the
Old Dominion University Research Foundation
P.O. Box 6369
Norfolk, VA 23508-0369

July 1994

ACKNOWLEDGMENTS

The attached paper entitled, "Annular Suspension and Pointing System and Mars Methane Engine Research was presented at the 1994 Universities Space Research Association, Advanced Design Program, Summer Conference." The paper entitled, "Current and Future Development of the Annular Suspension and Pointing System," will be presented at the Fourth International Symposium on Magnetic Bearings, Zurich, Switzerland, during August 1994. These papers are being submitted in lieu of a progress report for the project entitled, "Large Angle Magnetic Suspension Test Fixture," supported by the National Aeronautics and Space Administration, research grant NAG-1-1056, Nelson J. Groom, Guidance and Control Division is technical monitor.

ANNULAR SUSPENSION AND POINTING SYSTEM

and

MARS METHANE ENGINE RESEARCH

Old Dominion University

Departments of Aerospace Engineering,

Mechanical Engineering and

Electrical and Computer Engineering

ANNULAR SUSPENSION AND POINTING SYSTEM
and
MARS METHANE ENGINE RESEARCH

Old Dominion University
Departments of Aerospace Engineering, Mechanical Engineering and Electrical and Computer Engineering

Dr. Robert L. Ash & Dr. Colin P. Britcher
Daniel Neff, Teaching Assistant

ANNULAR SUSPENSION and POINTING SYSTEM

Thanh Quach, *Mechanical Design Engineer, Virginia Power, Surry, VA*
Wayne Thomas, *Hardware Design Engineer, Martin Marietta Control Systems, Johnson City, NY*
and Daniel Neff

Abstract

Over the past few decades, research has proven the feasibility of the concept of non-contacting magnetic bearing systems which operate with no wear or vibration. As a result, magnetic bearing systems are beginning to emerge as integral parts of modern industrial and aerospace systems. Further applications research is still required, however. NASA has loaned an existing magnetic bearing device, the Annular Suspension and Pointing System (ASPS), to ODU to permit student design teams the opportunity to pursue some of these studies. The ASPS is a protoype for a high-accuracy space payload pointing and vibration isolation system.

The project objectives are to carry out modifications and improvements to the ASPS hardware to permit recommissioning in a 1-g (ground-based) environment. Following recommissioning, new applications will be studied and demonstrated, including a rotary joint for solar panels. The first teams designed and manufactured pole shims to reduce the air-gaps and raise the vertical force capability as well as on control system studies. The most recent team concentrated on the operation of a single bearing station, which was successfully accomplished with a PC-based digital controller. The paper will review the history and technical background of the ASPS hardware, followed by presentation of the progress made and the current status of the project.

Introduction

The Annular Suspension and Pointing System (ASPS) is a high-accuracy end-mount pointing system for space experiments. Since the mid-1970's, NASA Langley Research Center funded the design and development of the ASPS Vernier System (AVS) for use on the Space Shuttle. The AVS is the non-contacting magnetic suspension module of the ASPS which provides fine pointing (up to 0.01 arc-second stability) of a payload and isolation from disturbances. An appreciation of the uniqueness of the ASPS sytem will be achieved by reviewing the history of its development and expounding on the technical background of the hardware.

Historical Overview

In the early 1970's, NASA's Earth-Orbital Systems Technology group established the need for a multi-purpose experiment pointing platform. To meet this need, the ASPS concept evolved. A prototype system [1-3] was designed and built for NASA Langley Research Center (LaRC) by Sperry Flight Systems (subsequently Honeywell Satellite Systems). Delivered to NASA in 1983, the ASPS program was terminated shortly afterwards due to shifting NASA priorities. However, in late 1992, the ASPS hardware was loaned to ODU, with a view to recommissioning and further development, as a result of renewed interest in the concept.

Four students, in two groups, from the Department of Electrical and Computer Engineering, worked on the project during the Spring semester 1993 (see Acknowledgements). The first group analyzed the performance of the axial magnetic bearings and carried out the modifications required to increase their force capability so as to enable the device to operate in a 1-g environment. The second group studied control system designs. During the Fall semester 1993, work was directed towards recommissioning the system. This work is the primary focus of this paper.

Hardware Technical Background

The ASPS consists of two major subassemblies, as illustrated in Figure 1. The two-axis, large-angle mechanical gimbal assembly is presently in use at Marshall Spaceflight Center, and is referred to as the Advanced Gimbal System (AGS). Normally attached to the AGS is the six degree-of-freedom magnetically suspended fine pointing and vibration isolation assembly referred to as the ASPS Vernier System (AVS). Only the AVS, presently at ODU, is utilized in this research effort.

The AVS, shown in Figure 2, consists of a 50/50 nickel-iron ring ("rotor"), approximately 0.65 meters in diameter, suspended by five Magnetic Bearing Actuators (MBAs). Two MBAs act on the cylindrical rim, in the radial direction, three others act on the radial flange, controlling vertical positioning, and a linear induction motor (LIM) acts on the rim providing motion about the rotor's axis. Using Kaman 6400-series inductive proximity sensors, the air-gaps at all MBAs are measured. The rotor position is monitored by these sensors with feedback to the magnetic actuators (MBAs). This configuration allows a payload, attached to the rotor, to be suspended and precisely positioned and oriented in the magnetic fields.

Hardware Recommissioning

Before designing a feedback controller, an in-depth understanding of the existing hardware was needed. Technical documentation was sparse, therefore a careful study of schematic diagrams and a signal flow analysis was necessary.

The hardware operates on 28V d.c. power, which is a common voltage for aerospace applications. A high-capacity Kepco 0-50V power supply was used in the laboratory.

From signal flow analysis, it was determined that the following subsystems were necessary for operation with the new digital controller :

1) Power supplies and distribution
2) Reference generator
3) Position sensor amplifiers
4) Wiring harness
5) Control electronics assembly
6) MBA drivers

Subsystem 1) consists of secondary power supplies and regulators, generating ± 5 and ± 15V power for the electronic systems. Power is distributed via bus-bars within the main equipment rack.

The position sensor system (2 and 3 above) was activated next. Readings were taken from front panel test points for bearing stations A, B and C. The following results correspond to the rotor at its upper and lower limits of travel :

Station:	A	B	C	Gap
Rotor up	1.47V	1.45V	1.44V	7.315mm
Rotor down	-1.48V	-1.42V	-1.46V	-7.315mm
Sensitivity	403.27	392.33	396.44	V/m

Figure 3 is a simplified schematic of one of the position sensor amplifiers. The input from the position sensors is a 25MHz sine-wave, that varies from 7-10V peak-to-peak depending on the position of the rotor. The position sensor amplifier acts as a demodulating amplifier with a gain less than unity.

The MBA driver assemblies are Pulse-Width Modulated (PWM) power amplifiers, which include compensation circuitry, represented by elements to the left of the PWM section in Figure 4. This circuitry includes bias current compensation, gap compensation, and bias current linearization, and thus represents an important part of the overall feedback control system.

The interfaces to the control system are now becoming clear - that is force commands from the controller should be applied directly to the MBA compensation cards. The feedback signal is gap width. The output of the compensation cards is a voltage signal fed directly to the MBA driver cards. These constitute dual high-efficiency voltage-to-current convertors. The waveforms shown in Figure 5 illustrate the operation. Input signals V1 and V2 from the compensation networks are used to determine the pulse width of the signals on the bases of the power transistors Q1 and Q4 respectively. The modulation applied is a 25kHz sawtooth waveform. As the pulse-width applied to the bases of Q1 or Q4 increases, the transistor is turned on for a longer periods of time, resulting in higher current flow to the associated electromagnet.

New Hardware Development

Much of the existing circuitry was not investigated and will not be required since it was designed to handle orientation of the payload in roll, pitch and yaw, under actual operating conditions. As many of these functions as possible will be incorporated into software in the new digital control system. The existing MBA drivers will be replaced with off-the-shelf power amplifiers since the compensation and linearization functions will also be incorporated into the digital controller.

Recommissioning Approach - Hardware

A Kepco BOP 20-20M programmable power supply was used as a linear power amplifier to activate the upper bank of one bearing station. Previous calculations and experiments have shown that a current of around 1.4A is sufficient to draw the rotor past its center position, in fact to "stick" to the top electromagnet. A one-ohm resistor was incorporated in the return lead from the power supply in order to dissipate additional energy during rapid changes in current. The time-constant of the circuit is reduced a result. The power supply was current-limited at 1.75A so as to avoid the possibility of overheating and damaging the magnets. A new wiring harness was developed that enabled activation of any chosen bearing station by replacing the original MBA driver card with anew connector. Figure 6 shows the final hardware configuration of the Magnetic Bearing Assembly. This configuration worked well and achieved stable magnetic levitation. The transfer functions for the plant, sensors and current amplifier are shown in the Figure.

Control System Development

The original ASPS control system was implemented in the late 1970's on an analog computer. The first objective in the recommissioning was to implement a digital controller for a single MBA station, usng the C language. Considerable time was spent learning the language, the compiler and the hardware employed.

The controller is implemented on a Gateway 2000, 486-class PC, with Data Translation DT2811-PGL data acquisiton card, programmed using LPCLAB subroutines. A DT2819 multi-function counter/timer board provides counting, sequencing and timing functions for data transfers between the host microcomputer system and peripheral devices. In order to program this board, Data Translation PACER software was employed. Microsoft QuickC V2.5 was used for the levitation program. Several problems associated with software incompatibilities were encountered, requiring updates to QuickC and LPCLAB. Incorporation of the timer interrupt function still proved troublesome, so early suspension tests were carried out with the timer function eliminated.

A complex but fairly user-friendly five degree-of-freedom magnetic suspension control program had previously been developed by Ghofrani [4]. This program sets up the controller functions in an interrupt service routine (ISR). The ISR uses DOS assembly level commands and certain matrix manipulations to achieve the PID controller algorithm.

Using the Ghofrani program as an outline, a program was developed for a one degree-of-freedom suspension system, according to the algorithm depicted in Figure 7. The main differences between the two programs are the screen interface options and the controller type. The PD control section of this program was modelled after the test program "LEVATE", shown in Figure 8.

Implementation of the Controller

The original ASPS hardware used simple PID compensators. The overall complexity of the control system arose from the integration of six degrees-of-freedom with extensive coupling, as shown in Figure 9. For the recommissioning, a PD controller was chosen. Figure 10 shows the single degree-of-freedom control structure. The plant physically consists of the Kaman proximity sensor, processing electronics, the control computer with data acquisition, the KEPCO power amplifier and finally the magnetic bearing assembly itself. A one ohm resistor is included in one of the current leads in order to reduce the system time-constant.

A simple mathematical model of this system was developed. In developing this model, the following assumptions were made : the bandwidth of the KEPCO power amplifier was effectively infinite, the power amplifier gain was two, the controller introduced negligible time lag, the position sensor could be modelled as a simple constant sensitivity (around 400 V/m). The mathematical model was developed from basic electromagnetic theories, incorporated with electronic relationships and resolved from the application of control theories. The model is depicted in Figure 11. MATLAB was used for analysis and simulation studies.

Once the controller was ready, a workable ratio of Proportional to Derivative gain (K_p/K_d) was identified. A value of 100 was chosen, with the resulting root locus as shown in Figure 12. The theoretical model analyzed for the selected gain ratio appears to be valid since the predicted stable operation was achieved.

Conclusions

The ASPS Vernier System has been partially recommissioned with a new digital controller. The simplified system provided good insight into the workings of the ASPS and will enable future design teams to concentrate on studies of possible applications for this technology.

Acknowledgements

The authors express their appreciation for the leadership of the third team member, Bill Smith. In addition, many thanks to Lori Skowronski, Anne Bisese, Josephine Vu and Kwok Hung Tam, all of the Department of Electrical and Computer Engineering, for their invaluable early work. All involved would like to thank NASA Langley Research Center for the loan of the ASPS hardware.

MARS METHANE ENGINE RESEARCH

Hung Bui, Daniel Neff

Abstract

Assuming that methane and oxygen can both be produced in their stoichimetric ratios, using in-situ Mars resources, it will be necessary to avoid using power plants which operate at any other oxidizer-fuel ratios. Unlike their terrestrial counterparts, the oxidizer is not available from the atmosphere and the "excess air" cannot be used to control combustion temperatures. However, since the Mars atmosphere contains in excess of 95% carbon dioxide, it is possible to utilize supercharged or compressed Mars atmosphere, to mix with stoichimetric amounts of methane and oxygen, as a diluent (like the nitrogen from air) and thus control the combustion temperature.

A 2.6kW Honda 4-cycle engine has been coverted to operate using controlled mixtures of oxygen, methane and carbon dioxide, in order to establish the performance of a generic internal combustion engine for Mars applications. The test stand was developed using digital/microcomputer based data acquisition and tests have been conducted to determine engine performance over a range of operating conditions. Supply pressure and the percentage of carbon dioxide were the primary control variables. Experimental results will be presented which will help future designers assess the use of internal combustion engines as prime movers on future missions to Mars.

Introduction

The Mars Methane Engine project has been underway for approximately 3 years. Previous teams have overcome many difficulties, but have been unable to gather a susbstantial set of test data. Last year's team procured a new engine - a single-cylinder, 4-cycle Honda GX120, added the necessary instrumentation and installed the engine into a test bed. Real-time data could then be obtained through a PC-based data acquisition system. The goal of this design team was to perform stoichimetric fuel-to-oxidizer calculations with carbon dioxide as a diluent, and to gather experimental data for varying dilutions. The data includes cylinder pressures, exhaust temperatures as well as power outputs.

Experimental Set-Up

In order to operate the engine on methane, oxygen and carbon dioxide, the existing air-fuel carburettor, throttle and fuel system were removed. The required fuel, oxidizer and diluent are supplied from pressurized tanks and controlled by regulators and flowmeters to a mixing chamber. The mixing chamber has eddy generators to promote mixing, however no provision is made for throttling. A pressure gage was connected to a tap in the mixing chamber to monitor inlet pressure. One end of the engine drive shaft was adapted for the dynamometer, the other for an incremental encoder to give shaft position information. The encoder shutters light from an LED light source, giving one pulse every 3.6 degrees of rotation, as well as a reference pulse once per revolution. The reference pulse is used to determine the Top-Dead-Center (TDC) position. A current-to-voltage conversion circuit had to be added to properly condition the output signal for A/D conversion. Exhaust gas samples can be taken from a tap in an exhaust extension. Cylinder pressures can be measured via a piezoelectric pressure tranducer mounted in the cylinder head. The output of this transducer is fed to a charge amplifier and then to A/D convertors in the data acquisition system. Intake and exhaust gas tempertatures are measured using thermocouples.

Data Acquisition System

The software used in conjunction with the data acquisition system is LPCLAB, by Data Translation Inc. The software consists of numerous subroutines that can be called from various languages, with FORTRAN being chosen for this application.

The program, called "DataReceive", written to acquire data consists of three main subroutines that allow for all required measurements to be made. The first subroutine involves sampling the temperature of the thermocouples. The next subroutine, for the pressure transducer, is slightly more complicated. A burst of A/D conversions is made at a specified high rate, with the program execution suspended until completion. The final subroutine, which represents a high-speed digital interface to the crank angle encoder, was the most difficult to construct. The encoder can operate in a two-channel mode. Channel A outputs a single pulse for every one revolution of the crank shaft. Channel B outputs 100 pulses per revolution. It was possible to align the single pulse from Channel A with the Top-Dead-Center (TDC) position of the piston stroke. The subroutine assigned a value of 1 to this position, which would be referred to as the designated "zero degrees" point. Depending upon sampling rate and the number of data points specified, it was possible for the program to determine the time elapsed between two Channel A pulses. Increments of this time were then used to determine the angular position of the crank. From this, a separate program was used to determine the instantaneous cylinder volume.

Engine Operation

The engine can be started using the dynamometer, which uses 12V d.c. power. The pressure transducer requires water-cooling when the engine is running. In order to determine the chemically correct mixture of methane, oxygen and carbon dioxide, many thermodynamic calculations had to be made. To begin with, the combustion process was assumed to be steady, ideal, complete, and to take place under adiabatic conditions. From these assumptions, a chemically correct combustion equation can be derived, and the appropriate flowrates of fuel, oxidizer and diluent can be selected to ensure complete combustion. The volumetric ratio of methane to oxygen is 2.33:1.

Following completion of the engine test-bed and programming of the data acquisition system, testing of base cases (methane and air) and test cases (methane, oxygen, carbon dioxide) was carried out. Many possibilites exist in order to establish comparable base and test cases. The team felt that an adequate preliminary test constraint was to hold the inlet (manifold) pressure constant in both cases. When operating the engine on methane-air, an aspiration plug is removed from the end of the mixing chanber to allow for airflow. This flow is not regulated by a flowmeter, therefore the inlet pressure for the base case is atmospheric. When operating the engine on methane, oxygen and carbon dioxide, the flowrates were adjusted to the same inlet pressure ($\simeq 1$ atmosphere) to avoid supercharging effects. With the inlet pressure held constant, similar R.P.M. and torque values could be set for each test. Temperature, pressure and crank angle position were then sampled by the data acquisition system.

Results

A set of results was obtained for both the base case and the test case. These results include exhaust temperatures, cylinder pressure as a function of volume, and flowrates of fuel, oxidizer and diluent, all as a function of r.p.m. and loading. One test was conducted where the manifold pressure was less than atmospheric to determine the effect on power produced.

A problem was encountered with the measurements of carbon dioxide flowrate. At high engine R.P.M., the flowmeter was over-range. However, the carbon dioxide flowrate could be estimated by subtracting the methane and oxygen flowrates from the estimated total at that R.P.M.

Figure 13, parts a-f, shows the pressure versus volume (pv) diagram for both the base case and the test case, with varying delivered torque. Particularly at the lower torque levels, there is a surprisingly large difference between the two cases. Methane+oxygen+carbon dioxide consistently yields a higher exhaust temperature, although usually a lower peak cylinder pressure. This may indicate different burning rates within the cylinder. However, the fact that the same torques are delivered at lower R.P.M. for the methane+oxygen+carbon dioxide case may also inidcate different effective dilutions. In fact, it is a matter of some debate as to the proper criteria for direct comparison between the two cases, in view of the unusually large number of variables involved. Significantly more data is available and more needs to be gathered to achieve a full understanding.

Figure 14, parts a and b, shows exhaust temperatures for the two cases as a function of diluent flowrate. Figure 15 gives a comparison of exhaust temperatures and gas flowrates as a function of R.P.M.. Figure 16 presents similar data as a function of torque. Figure 17 shows the test-bed.

Conclusions

The Mars Methane Engine test-bed is fully operational. Future design teams can concentrate on gathering data and understanding the performance characteristics of the engine.

Acknowledgements

The authors would like to express their gratitude to this Semester's other two team members, Chris Coletta and Alain Debois.

References

1. Anderson, W.W., Joshi, S.M., "The Annular Suspension and Pointing System for Space Experiments and Predicted Pointing Accuracies", NASA TR R-448, December 1975.

2. Anderson, W.W., Groom. N.J., Woolley, C.T., "Annular Suspension and Pointing System", Journal of Guidance and Control, September 1979.

3. Cunningham, D.C. et al. "Design of the Annular Suspension and Pointing System", NASA CR-3343, October 1980.

4. Ghofrani, M., "Approaches to Control of the Large-Angle Magnetic Suspension test Fixture", NASA CR-191890, December 1992.

5. Ramohalli, K.N., "Fueling a Revolution in Space Processing", Aerospace America, November 1993.

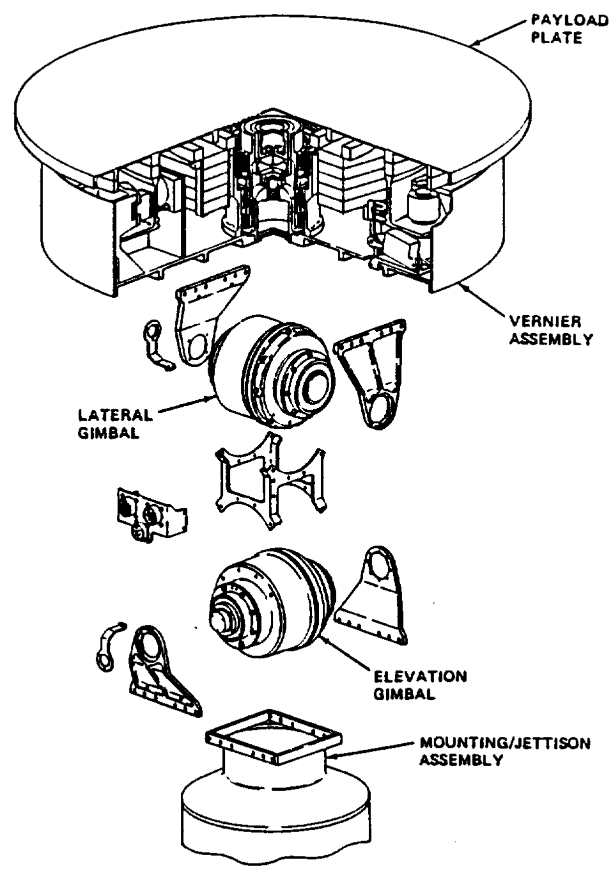


Figure 1 - The Annular Suspension and Pointing System

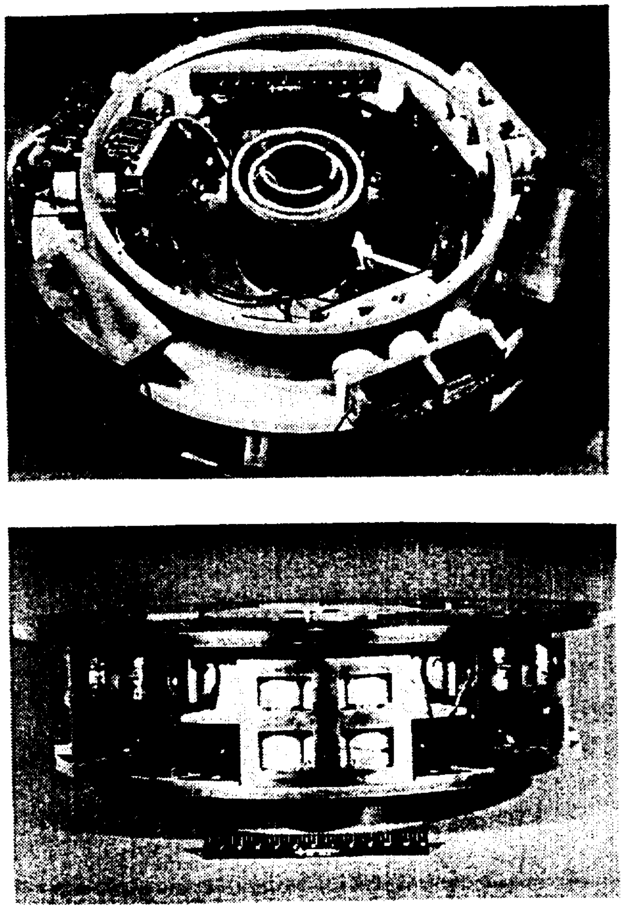


Figure 2 - The ASPS Vernier System

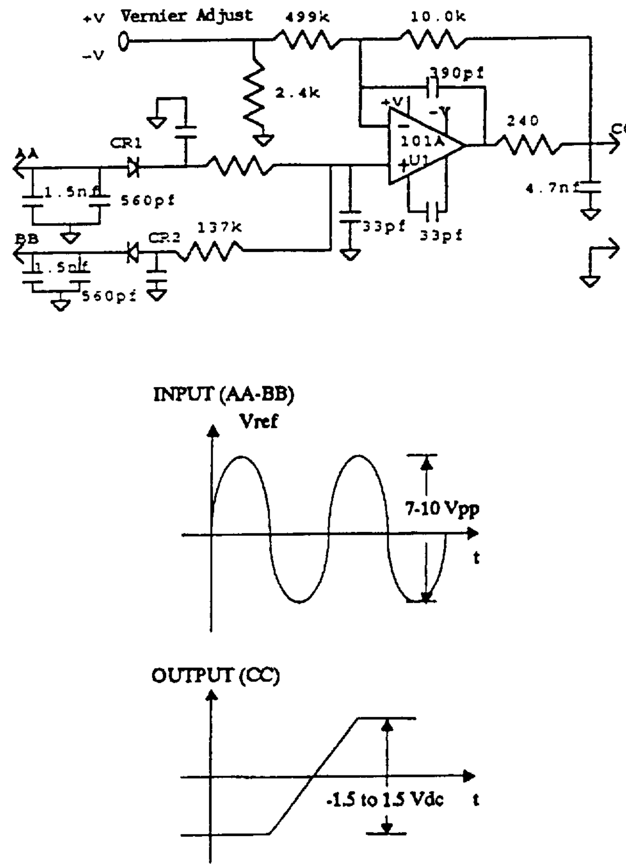


Figure 3 - Schematic of Position Sensor Amplifier

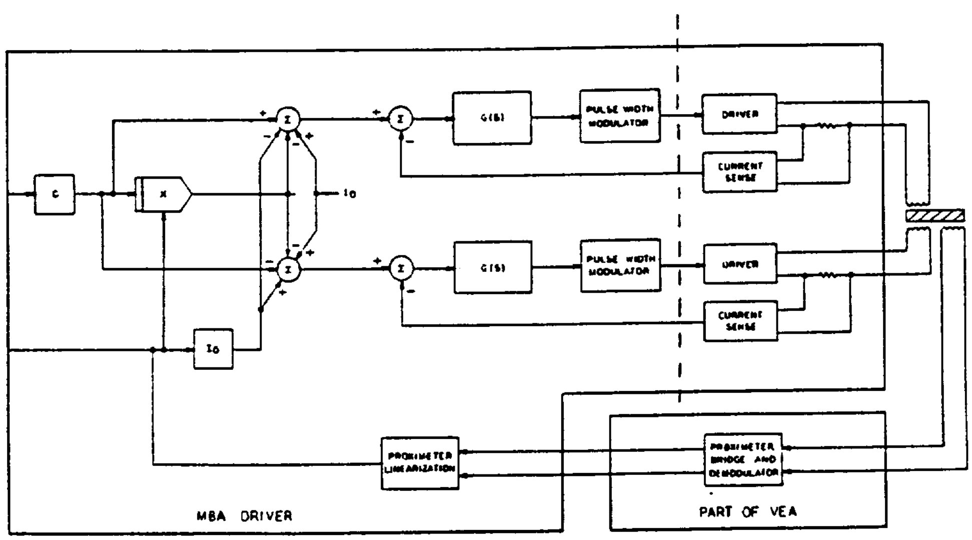


Figure 4 - MBA Driver Module Block Diagram

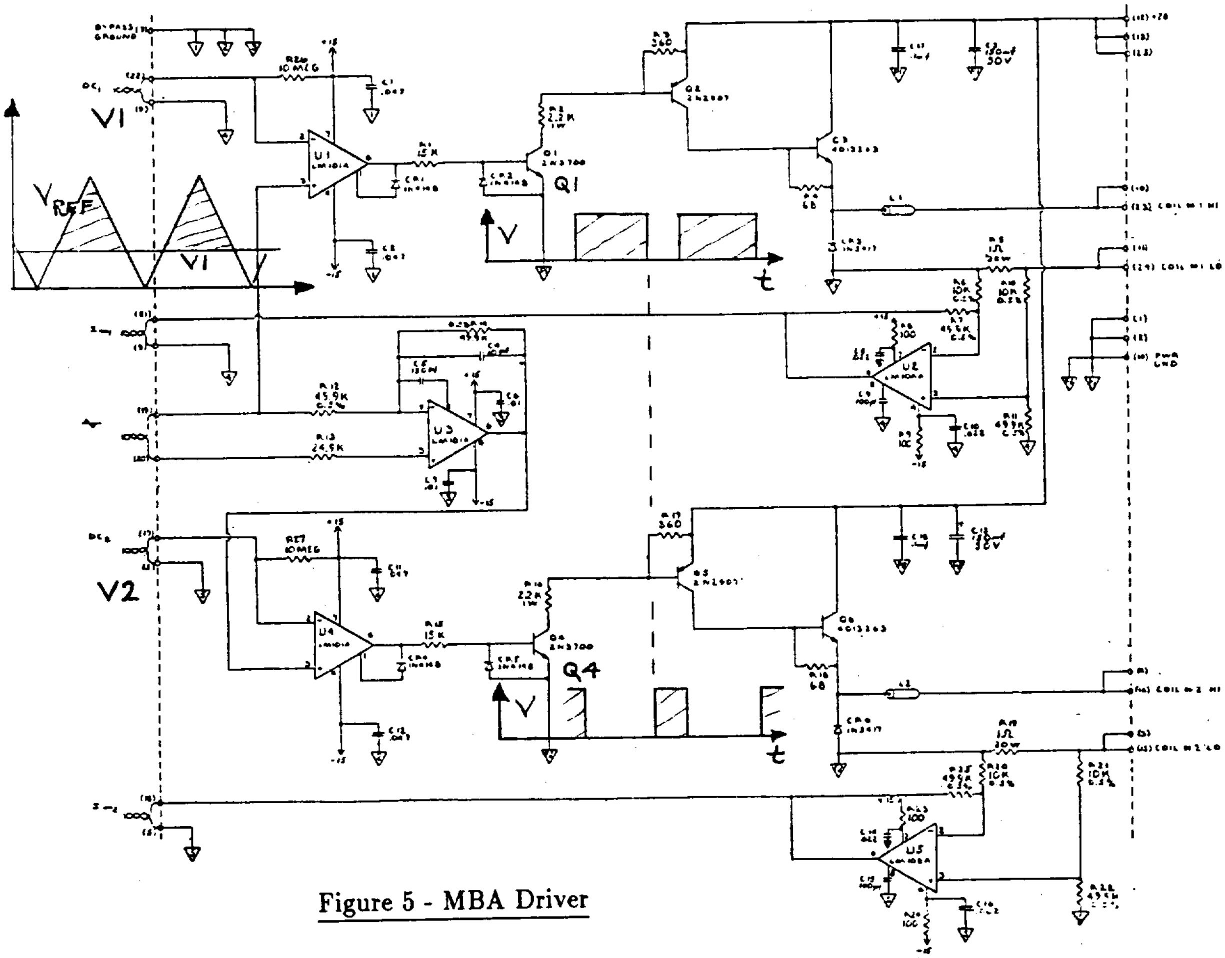


Figure 5 - MBA Driver

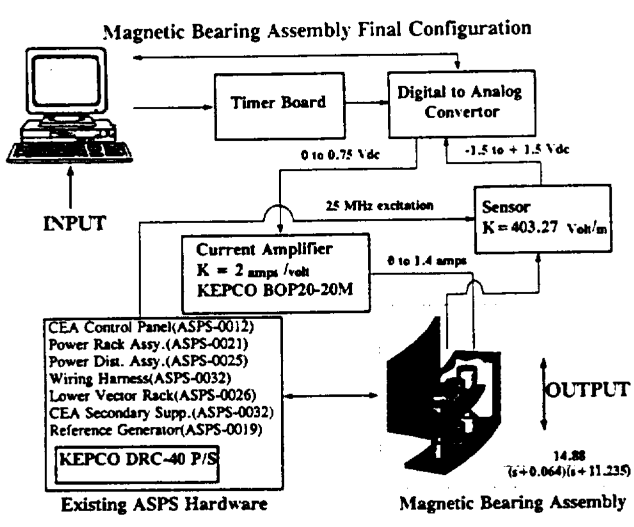


Figure 6 - Magnetic Bearing Assembly Final Configuration

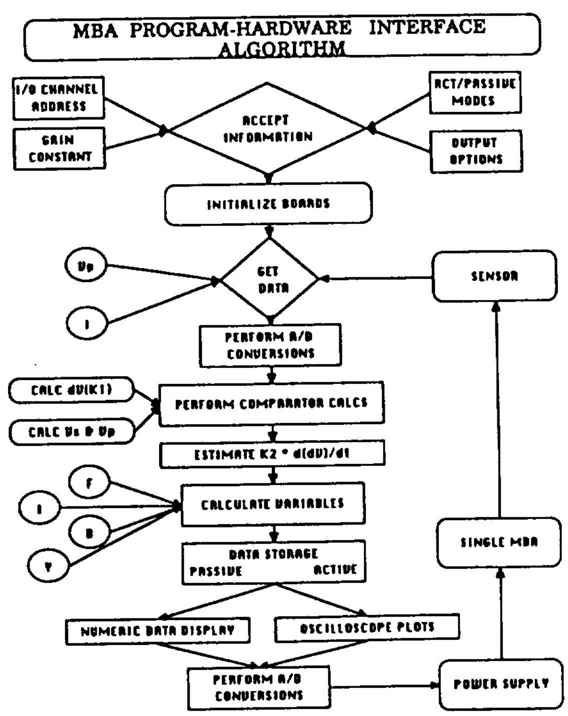


Figure 7 - Algorithm of Single D-O-F Program

LEVATE PROGRAM

```
#INCLUDE <STDIO.H>

VOID MAIN(VOID)
{
***** VARIABLE DEFINITIONS *****
FLOAT  INTEGRAL, YOLD,SPEED;
SHORT  VALUE,ACTCTRLS,CTRL;
INT B,N,M

***** INTIIALIZE DAC BOARD *****
LPINIT();
LPSB(1);

***** SET PARAMETER *****
INTEGRAL=0;
B=0;
YVALUE=0;
ACTCTRLS=0;
INTEGRAL=0;

***** PD CONTROL LOOP *****
WHILE (B<15000)    {
     YOLD=YVALUE;
     LPAV(1,1,&YVALUE);
     PRINTF("%I/N",YVALUE);
     YVALUE=YVALUE-2047;
     INTEGRAL=INTEGRAL+0.1*YVALUE;
     SPEED=(YVALUE-Y/0.00013);
     CTRL=0.5*YVALUE-0.005*SPEED-
          0*INTEGRAL;
     CTRL=CTRL+2314;
     LPDV(0,CTRL);
     B=B+1;}           ** INCREMENTAL COUNT

***** RETURN BEARING TO NON-SUSPENSION
CTRL=2047;
LPDV(0,CTRL);
}
```

Figure 8 - “Levate” Control Program

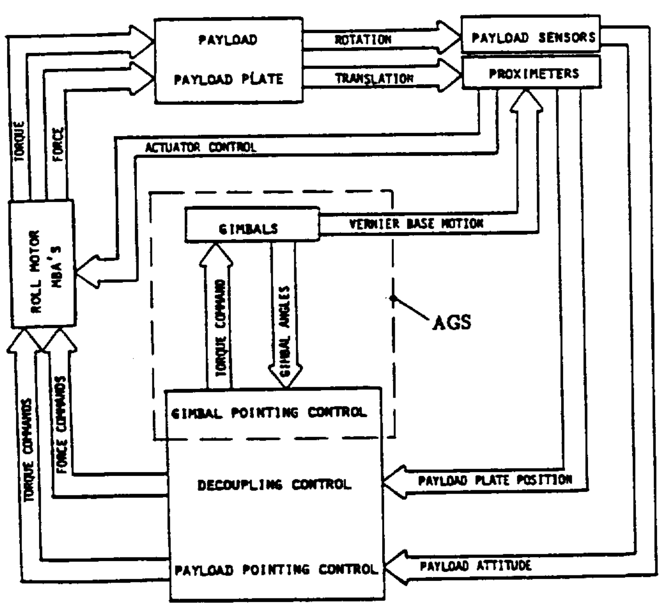


Figure 9 - Schematic Diagram of Original ASPS Controller

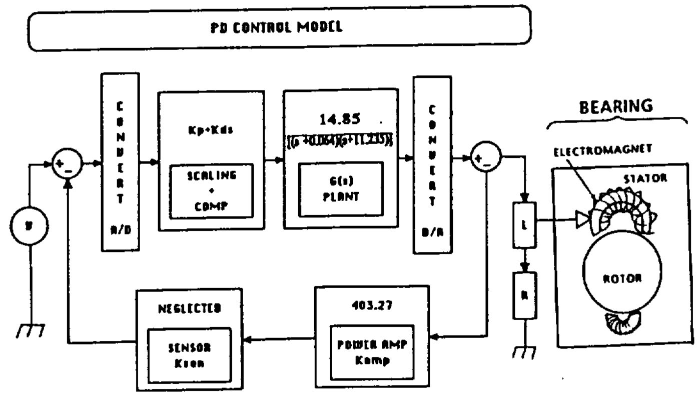


Figure 10 - PD Control Model

Use Bohr and Hyat's stored energy relation:

$$F = \frac{B^2 \times A_T}{2 \times \mu_o}$$

and the coil terminal voltage relationship:

$$V = R \times I + L\frac{dI}{dt} + I\frac{dL}{dy}\frac{dy}{dt}$$

Linearize about an operating gap, g_o and current, I_o :

$$\frac{Y(s)}{V(s)} = \frac{\dfrac{A\mu_o N^2 I_o}{2\, g_o^2 m\, (s + \frac{R}{L})}}{s^2 + \dfrac{A\mu_o N^2 I_o^2}{2\, g_o^2 m}}$$

Figure 11 - Mathematical Model

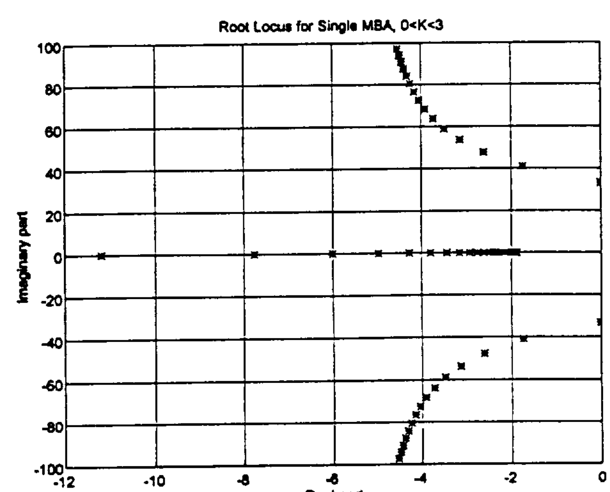
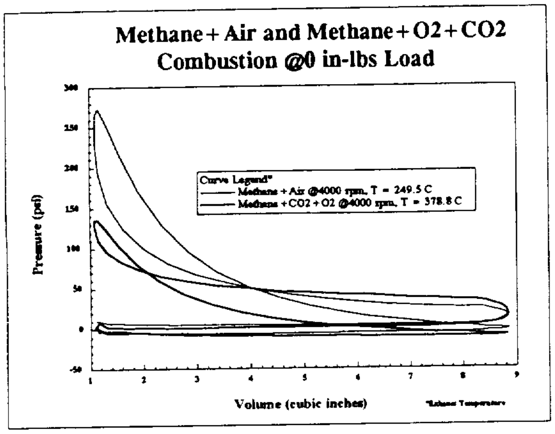
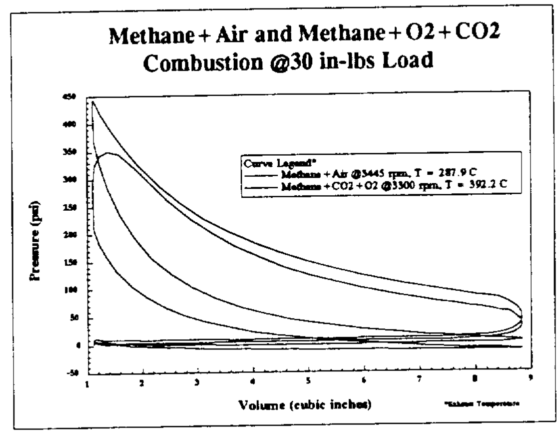
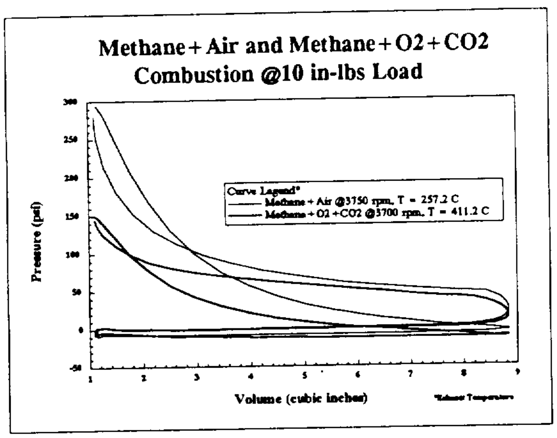
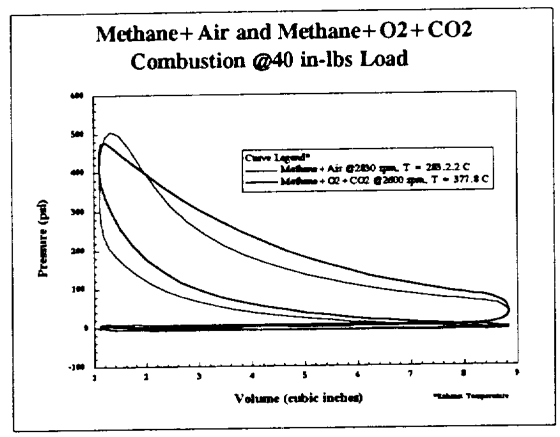


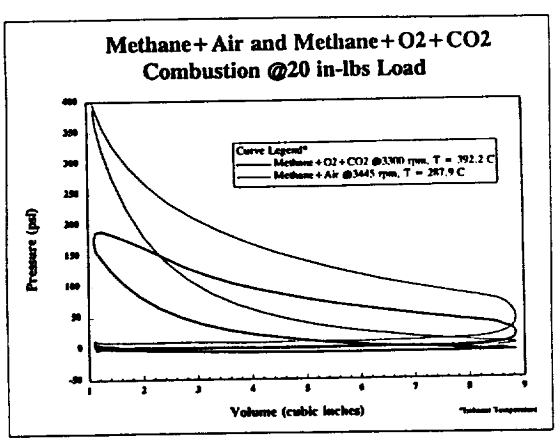
Figure 12 - MBA Root Locus Plot











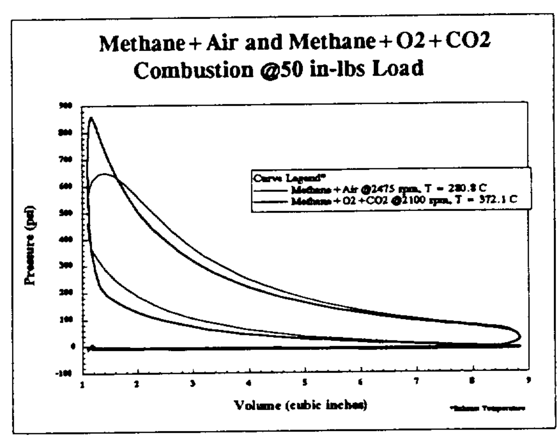


Figure 13 - PV Diagrams for Various Torque Level

Base Case (methane-air) and Test Case (methane-oxygen-carbon dioxide)

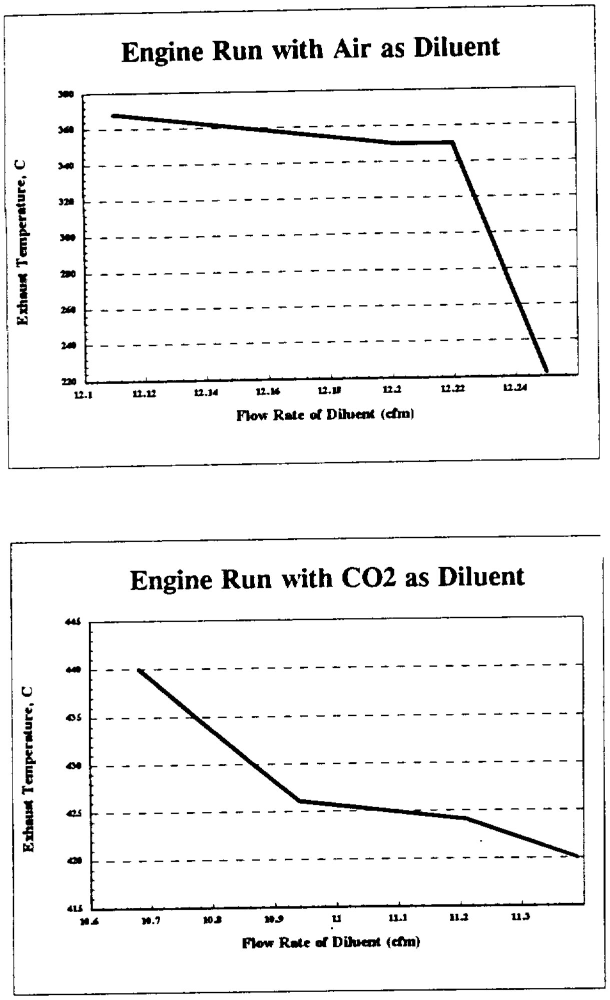


Figure 14 - Exhaust Temperatures versus Dilution

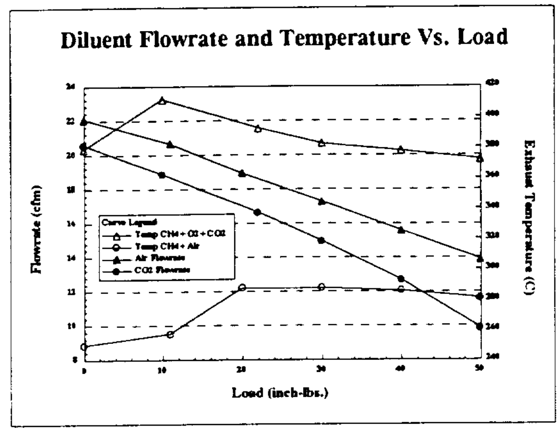


Figure 16 - Exhaust Temperature and Flowrates versus Torque

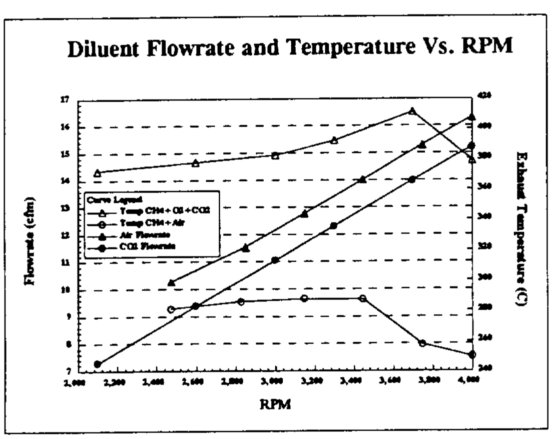


Figure 15 - Exhaust Temperature and Flowrates versus R.P.M.

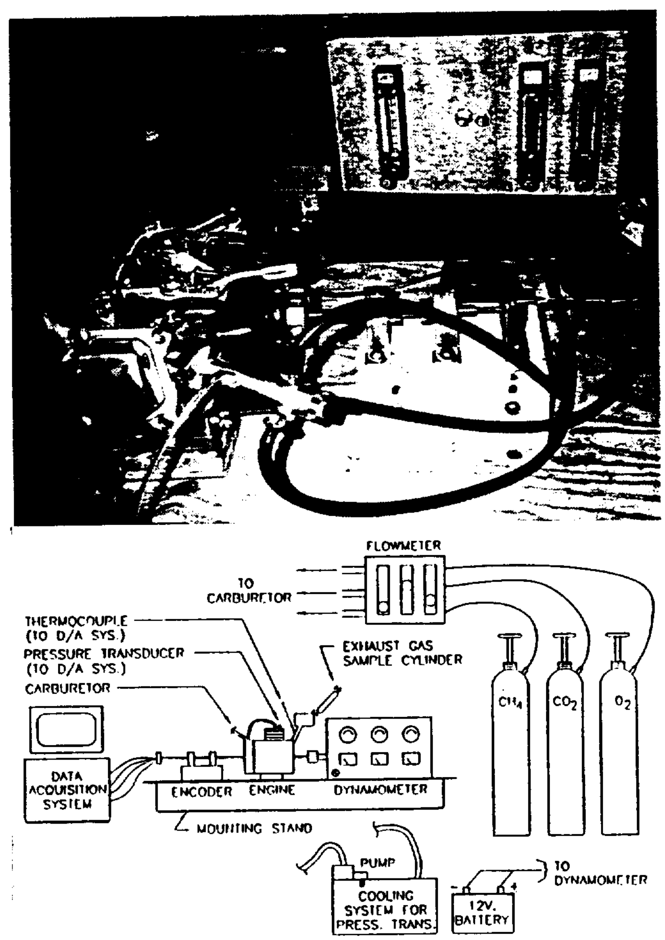


Figure 17 - The Mars Methane Engine Test-Bed

CURRENT AND FUTURE DEVELOPMENT OF THE ANNULAR SUSPENSION AND POINTING SYSTEM

Colin P. Britcher
Department of Aerospace Engineering, Old Dominion University
Norfolk, VA, U.S.A.
Nelson J. Groom
Guidance and Control Branch, NASA Langley Research Center,
Hampton, VA, U.S.A.

ABSTRACT

The Annular Suspension and Pointing System (ASPS) is a prototype space payload pointing and isolation mount, designed and built for NASA Langley Research Center (LaRC) by Sperry Flight Systems (subsequently Honeywell Satellite Systems). Over the recent decade, magnetic suspension technology has continued to advance, notably in the area of control system design, such that performance improvements from an ASPS-like design are likely to be acheivable. In addition, new applications for magnetic suspensions are being investigated, where the existing ASPS hardware can provide a useful technology demonstration tool. In this paper, the existing ASPS design and hardware will first be described in detail. Next, some of the potential applications currently of interest will be discussed. Finally, the hardware developments completed, underway, or planned will be reviewed.

INTRODUCTION

The Annular Suspension and Pointing System (ASPS) is a high-accuracy space payload pointing and isolation mount. A prototype system was designed and built for NASA Langley Research Center (LaRC) by Sperry Flight Systems (subsequently Honeywell Satellite Systems) during the latter part of the 1970's, with delivery to NASA in 1983. Shifting priorities at NASA and subsequent difficulties with the Shuttle program resulted in cessation of effort on the ASPS program. Continuing advances in magnetic suspension technology and continuing requirements for high-accuracy pointing and vibration isolation have resulted in renewed interest in the ASPS concept. In addition, new applications for magnetic suspensions are being investigated, where the ASPS hardware could provide a useful technology demonstration tool. Comprehensive descriptions of the ASPS hardware can be found in References 1-6. Summaries of ASPS and other related projects are given in References 7-9.

HARDWARE DESCRIPTION

The two major subassemblies of ASPS are a two-axis, large-angle mechanical gimbal, and a six degree-of-freedom magnetically suspended fine pointing and vibration isolation assembly, both illustrated in Figure 1. The mechanical gimbal system has been referred to as the Advanced Gimbal System (AGS) and the magnetic assembly as the ASPS Vernier System (AVS). Early in 1993, the ASPS Vernier System hardware was loaned to Old Dominion University and a recommissioning effort started. The AGS has been in use at the NASA Marshall Spaceflight Center. Only the AVS assembly is of interest in this paper.

The magnetic assembly, shown in Figure 2 and 3, consists of a large nickel-iron rotor, approximately

0.65 meters diameter and of L-shaped cross-section, suspended by five Magnetic Bearing Actuators (MBA's). Three MBA's act on the radial flange, parallel to the axis of the rotor, and two act on the cylindrical rim, in the radial direction. The design air-gaps were approximately ± 7.5 mm at all stations. These five MBA's control all three translations as well as two rotations, about the two axes in the plane of the rotor. The orientation of the rotor about its own axis is controlled using a linear induction motor acting on the rim. Air-gaps at all MBA's are measured using Kaman 6400-series inductive proximity sensors.

The original design payload was 600 kg, with payload moment of inertia perpendicular to the rotor axis of up to 500 kg-m^2. Both these values were raised in later design revisions [6]. The important specifications of the AVS are summarized in Table 1.

Table 1 - Original AVS Specifications

Pointing Axes	
Angular range	± 0.75 deg
Pointing accuracy	± 0.1 arc sec
Pointing stability	± 0.01 arc sec
Bandwidth	1.0 Hz
Payload mass	up to 600 kg
Payload inertia	up to 500 kg-m^2
C.G. offset	up to 1.5 m

Roll Axis	
Angular range	Unlimited
Pointing accuracy	± 1.0 arc sec
Pointing stability	same
Bandwidth	1.0 Hz
Payload inertia	up to 100 kg-m^2

APPLICATIONS

Fine Pointing and Isolation

The original fine pointing application is still of interest. The design performance goal corresponds to roughly 0.025 meter jitter at ground level from a 500 km (270 nautical mile) orbit. This level of performance was validated by laboratory testing of the AVS. Stability of this order tends to be limited as much by sensor and actuator noise as it is by controller performance. Therefore, conversion of the control system to digital form, permitting the implementation of more sophisticated algorithms would not be likely to result in a dramatic gain in absolute performance. Perhaps the most important opportunity, however, would be the ability to incorporate adaptive elements, such that the highest level of performance could be maintained over long time periods, even with hardware degradation and payload mass or inertia changes. Such changes might occur with deployment of solar arrays or instrument packages, or with the consumption of fuel or cryogenic fluids.

Solar Array Rotary Joint

One possible new application for a magnetic suspension of this general configuration is the attachment of solar panels on a space station. This corresponds to the "Alpha" joint on the Space Station Freedom (and the current International Space Station design), illustrated in Figure 3. The rotary joint could perform pointing of the arrays about one axis as well as isolate the station from array vibration. Existing mechanical bearing designs are difficult to lubricate in the space environment, offer no significant vibration isolation and would be difficult to repair or service in orbit. The AVS represents a candidate configuration for this application and will be used in a combined experimental and theoretical study. The concept is to employ the five magnetic bearings to support the rotor, to which the solar arrays would be mounted, with vibration isolation naturally provided by choice of control algorithm. The major pointing axis would be about the axis of the assembly, as shown in Figure 4, such that the rim-mounted linear induction motor could provide the torques required to maintain the desired orientation and rate of rotation. These required torques are, of course, quite small. Power transfer from the solar arrays could be accomplished with a non-contacting axial transformer. A transformer of this type was studied in the ASPS program and a preliminary design completed [10]. It was concluded that high efficiencies and power ratings could be acheived with this type of design. The only major difference for the new application would be the reversal of the direction of power transfer, since the ASPS design was intended to transfer power up to the rotor-mounted payload, rather than down from the payload, the solar arrays in this case, to the base.

HARDWARE UPGRADES

Axial Magnetic Bearing Assemblies

The original design could not be operated in a 1-g environment, since the MBA's were sized for on-orbit control forces, rather than suspension of the payload and rotor deadweight. During ground tests, a gravity offload system (a rather elaborate counterbalance arrangement [4,5]) was used. Rather than rely on the counterbalance system in the early phases of system recommissioning, it was decided to investigate the possibility of reducing the air-gaps at the three axial MBA's so as to raise the vertical force capability to the appropriate level. The original bearing design was double-acting, with bias current linearization, as shown in Figure 5. If the bearings are to be operated with a large steady-state force, the operating strategy requires modification. Typically, the top side of the bearing alone could be activated, with the bottom unused. Linearization can be carried out, if required, by input signal conditioning. This choice is illustrated in Figure 6.

The weight of the rotor is 212 N. An allowance of 70.6 N (30% of the rotor weight) was made for a top plate, payload and instrumentation. Therefore each axial MBA has to create a steady-state force of around 92 N. A further factor of 1.5 was used to set a design target for control force capability at 138 N (each station). It should be noted that the original design maximum force at each station was only 34 N (each station).

Two options are available for increasing the force capability of this type of MBA, increase the operating current or reduce the air-gap (or both). The maximum steady-state current for the bearings in the original design was, of course, equal to the bias current, i.e. 0.57 A. The design maximum current was around 1.5 A. It was experimentally determined that the MBA's could be operated (in an air environment) at the design maximum current for unlimited periods, without overheating. By classical magnetic circuit analysis, a design was developed where the air-gaps of the three axial MBA's would be reduced to roughly half their original value, then each MBA could be operated at well below the maximum tolerable steady-state current. The reduced air-gap was achieved by fabrication of new pole-pieces for the existing MBA's.

Control System

The original control system was all-analog, and included local linearization and control of each MBA, illustrated in Figure 7, as well as global control of payload position and orientation, illustrated in Figure 8. Several coordinate transformation (decoupling) stages were required to properly transition between bearing station displacements and forces, rotor position and orientation, and payload centered coordinates. Several feedforward loops were employed for various linearization and compensation tasks.

The entire controller, as well as some additional compensation functions previously built in to power amplifier hardware, will be replaced by a digital controller. The controller is based on a 486-class PC with standard commercial data acquisition boards. At the time of writing, individual MBA's have been made operational with simple local PD controllers [11]. Difficulties with some of the power amplifier hardware has so far prevented full (5-component) suspension.

CONCLUDING REMARKS

The ASPS Vernier System is in the process of being recommissioned and modified in order to facilitate future studies of payload pointing and vibration isolation, as well as a potential application for solar array attachment to a space station. Replacement of further controller functions and completion of the digital controller are the next major steps in this project.

ACKNOWLEDGEMENTS

This work has been supported by NASA Langley Research Center under Grant NAG-1-1056, Technical Monitor Nelson J. Groom, also the Universities Space Research Association under the Advanced Design Program. The authors would like to thank the following students for their assistance with the ASPS recommissioning - Daniel Neff and Lucas Foster of the Department of Aerospace Engineering, Bill Smith, Thanh Quach and Wayne Thomas of the Department of Mechanical Engineering and Lori Skowronski, Anne Bisese, Josephine Wu and Kwok Hung Tam of the Department of Electrical and Computer Engineering.

REFERENCES

1. Anderson, W.W., Joshi, S.M., The Annular Suspension and Pointing System for Space Experiments and Predicted Pointing Accuracies. NASA TR R-448, December 1975.

2. Cunningham, D.C., et al., System Design of the Annular Suspension and Pointing System. AIAA Paper 78-1311, August 1978.

3. Anderson, W.W., Groom, N.J., Woolley, C.T., Annular Suspension and Pointing System. Journal of Guidance and Control, Sept. 1979.

4. Hamilton, B.J., Labratory Evaluation of the Pointing Stability of the ASPS Vernier System. NASA CR-159307, June 1980.

5. Cunningham, D.C., et al., Design of the Annular Suspension and Pointing System. NASA CR-3343, October 1980.

6. Keckler, C.R., ASPS Performance with Large Payloads Onboard the Shuttle Orbiter. Journal of Guidance and Control, Jan-Feb 1982.

7. Wolke, P.J., Advanced Techniques for Active and Passive Vibration Isolation of Spaceborne Payloads. Workshop on Vibration Isolation for Microgravity Sciences, NASA Lewis Research Center, September 1988.

8. Havenhill, D.G., Wolke, P.J., Magnetic Suspension Systems for Space Applications. In Aerospace Applications of Magnetic Suspension Technology, NASA CP-10066, March 1991.

9. Groom, N.J., Overview of Magnetic Suspension System Research at Langley Research Center. In First International Symposium on Magnetic Suspension Technology, NASA CP-3152, May 1992.

10. Kroeger, J., et al, Conceptual Design of a Non-Contacting Power Transformer Design for the ASPS Vernier System. NASA CR-172238, April 1984.

11. Britcher, C.P., et al., Annular Suspension and Pointing System and Mars Methane Engine Research. Universities Space Research Association - Advanced Design Program, 10th Annual Summer Conference, June 1994.

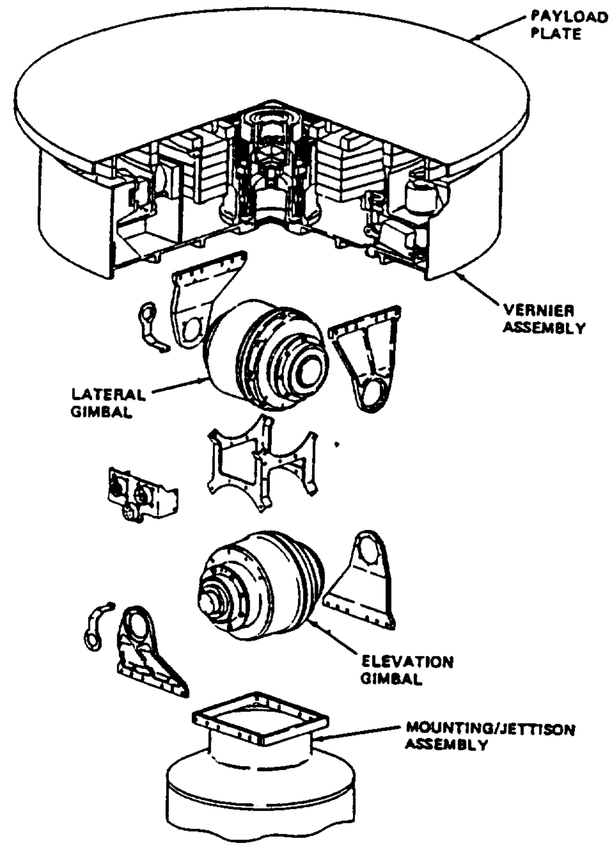


Figure 1 - The Annular Suspension and Pointing System (ASPS)

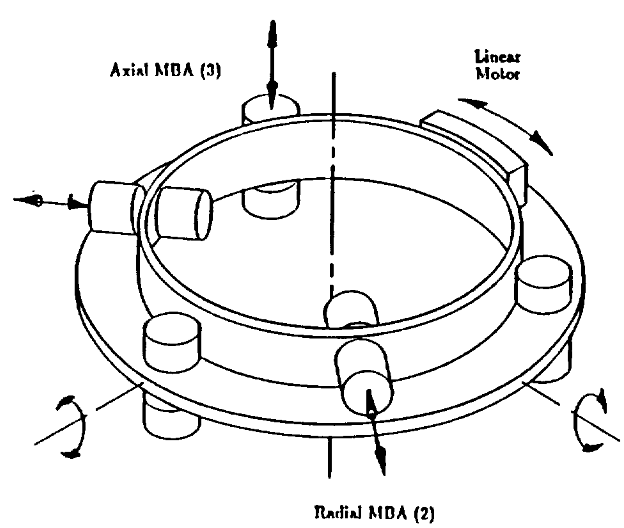
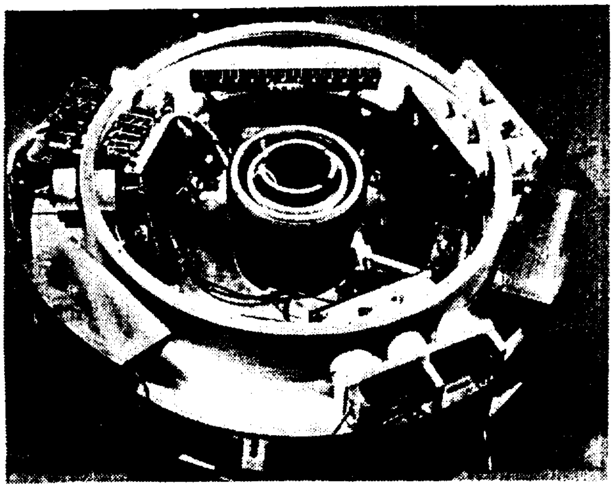


Figure 2 - Schematic Diagram of the AVS Magnetic Configuration



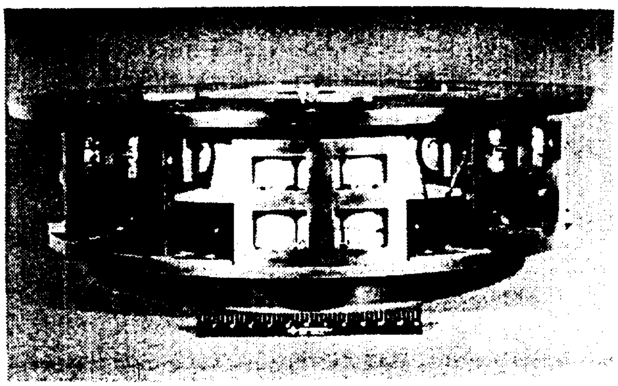


Figure 3 - The AVS Magnetic Assembly

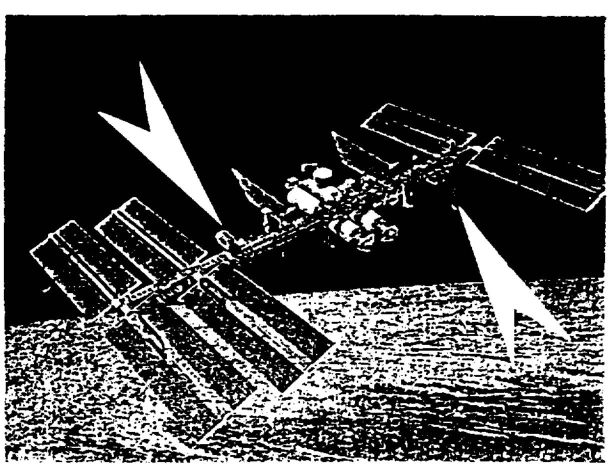


Figure 4 - Space Station Freedom (showing Alpha joint locations)

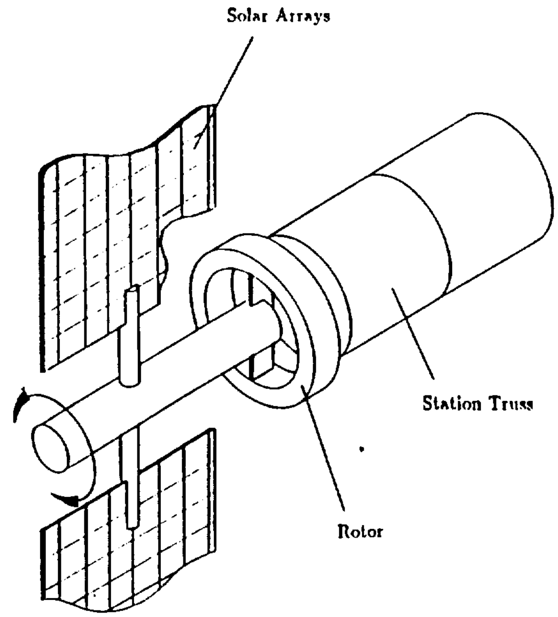
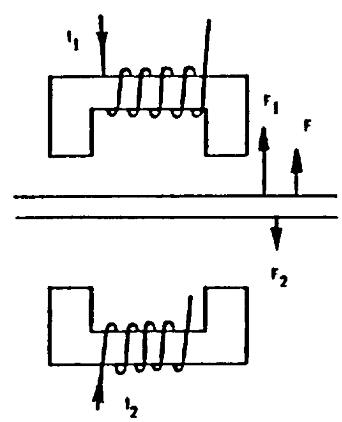


Figure 5 - Solar Array Rotary Joint Application



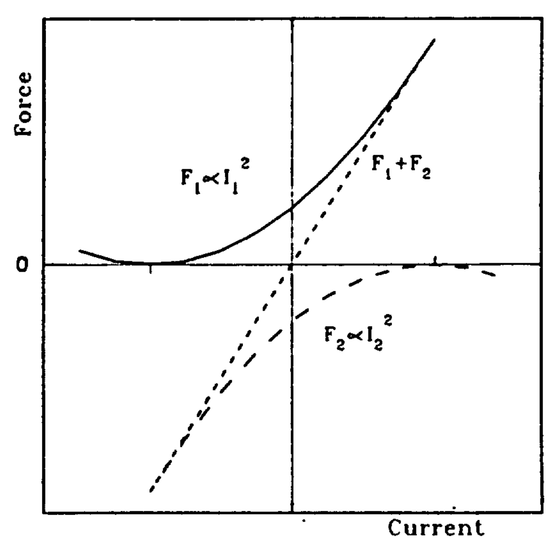


Figure 6 - Bias Current Linearization

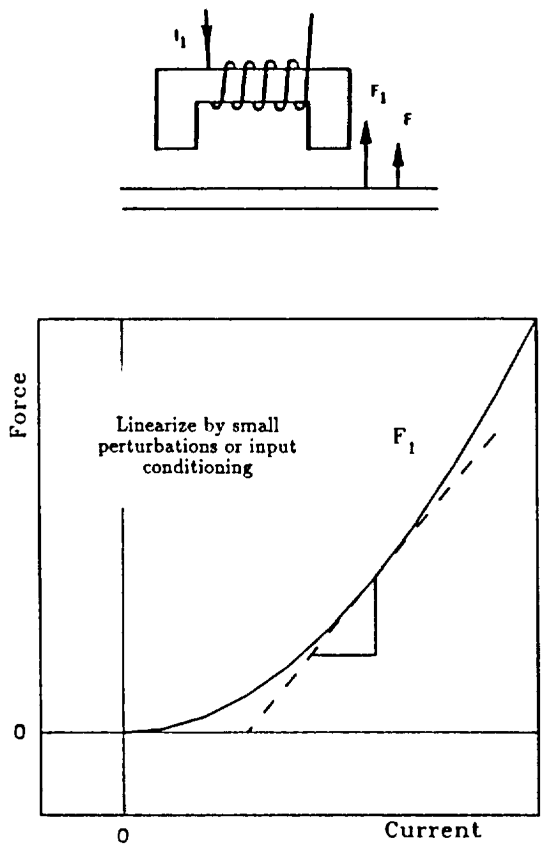


Figure 7 - Alternative Operational Scheme

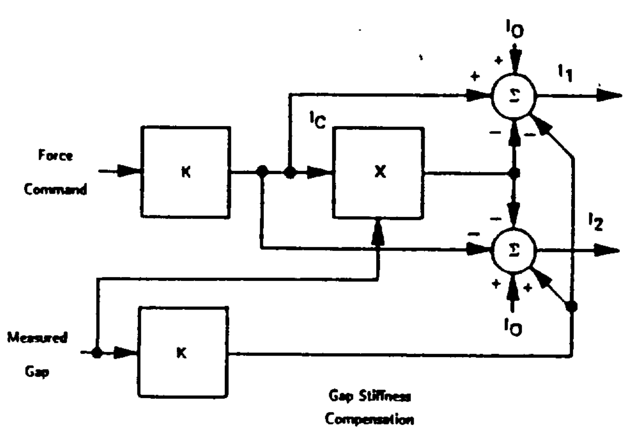


Figure 8 - Schematic Diagram of Existing MBA Local Controller

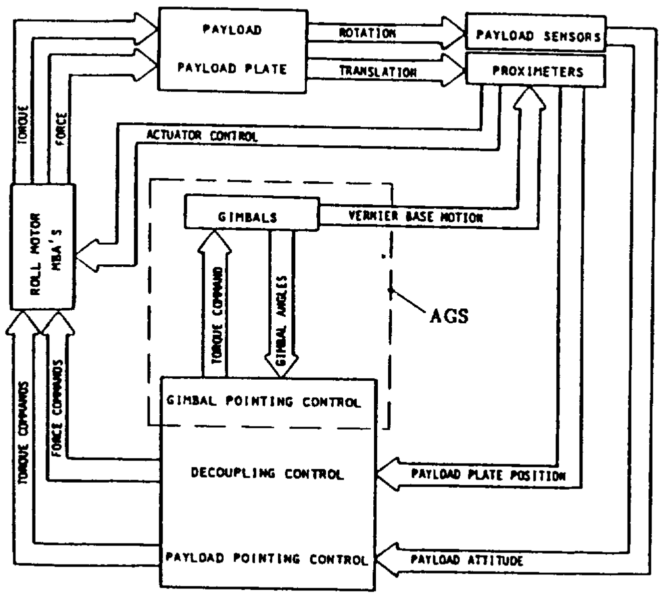


Figure 9 - Schematic Diagram of Global ASPS Controller