A Mechanism for Three-Axis Control of an Ion Thruster Array

G. S. PERKINS,* K. G. JOHNSON,* J. D. FERRERA,† AND T. D. MASEK§

Jet Propulsion Laboratory, Pasadena, Calif.

Introduction

THE JPL (Jet Propulsion Laboratory) solar electric propulsion system technology hardware program (SEPST III) is directed toward developing the SEP technology required for several advanced missions.[1] The SEP system has two principal functions: 1) to convert solar energy into spacecraft acceleration and 2) to provide control torques for spacecraft attitude control. The first function is performed by use of power conditioners, a thruster, a controller for power management and failure detection, and, if needed for reliability, a thruster power-conditioner switching matrix. The second function is performed by the thrust vector control (TVC) subsystem. This paper describes the mechanical portion of the TVC subsystem under development in the SEPST III program.

Translation and gimballing requirements were based on the Jupiter mission study.[2] A life requirement of 5000–10,000 hr places a significant constraint on actuator design. Stepper motors typically used to drive the actuators are believed to have life expectancies in the 10^8–10^9 step range.‡ For the expected limit-cycle operation with a period of about 1 min (Refs. 3 and 4), 10,000 hr of operation would require about 10^6 corrections, with the assumption of a single-step deadband width and no backlash between input and output. Including the capability to correct for a few large disturbances requiring full translation of gimballing and to perform ground testing, the life requirements are in the 10^7 step range. However, the step requirements increase substantially if the limit-cycle deadband width is greater than one step.

The uncertainty in stepper motor life at the present time has led to a conservative actuator design, i.e., a design with low backlash to conserve steps in the limit-cycle operating mode. Such a design, in near flight-ready form, is described in the following sections. The design includes consideration of launch loads, high-vacuum operation, positioning accuracy, reliability, weight, thermal loads, wiring and propellant line flexibility, contamination by ion-beam sputtered material, and testing in a 1-*g* environment. Results of vacuum endurance testing are presented.

Design Requirements

The portion of the TVC subsystem described in this Note includes gimbal actuators (one per vectored engine), translation actuators (one for each of two perpendicular axes), propellant lines, electrical cabling, and a thruster array structure to support these and the thruster array itself.

The array maximum travel for both actuators was based on a five-thruster (20-cm-diam) array. The translation axes are aligned with the sides of an imaginary square formed by the four outside thrusters. The output travel of ± 33 cm allows any thruster to translate about half a thruster diameter past center. Two gimbal axes are provided along the diagonals. The spacecraft configuration used required $\pm 10°$ thruster gimballing.

The slewing rate, stepping rate, and step size (resolution) are determined jointly. To first order, the required time response of the spacecraft to a large disturbance determines the maximum slewing rate. The values chosen (0.63 cm/sec and 10 mrad/sec) appear to be consistent with the requirements for spacecraft in the 5- to 20-kw power range.[5,6] The step resolution must consider limit-cycle operation as well as the maximum stepping rate available. The torque output of the stepper motor is dependent on stepping rate. For a given torque at the actuator output, with the output resolution and slewing rate specified and with the friction losses in bearings and seals estimated, the motor size can be determined. In order to apply small stepper motors and yet provided a design margin, the maximum stepping rate was limited to about 100 steps/sec. Slewing rate and motor stepping rate determine the gear train reduction required.

Detail Design

Gimbal actuator

In actuator design, a tradeoff must be made between friction losses, wear, torque, power, and backlash. With a straight spur gear reduction system, the low amount of backlash must be accepted in the last gear stage (1–2 mrad) for low wear (long life) and reasonable power. This minimum backlash represents 10–20 steps with required resolution of 1×10^{-4} rad. To reduce this value to less than one step requires the last reduction stage to have a backlash of less than 0.1 mrad. This minimization of backlash is accomplished for the gimbal actuator by use of a high-tolerance lead screw (6.3 threads/cm) and saddle nut configuration. The saddle nut is attached to the output sector by means of a split strap. The strap can be tensioned to provide a zero backlash coupling. The bearings supporting the lead screw are preloaded to remove backlash.

The three spur gear stages from the motor to the lead screw provide 50 to 1 reduction. Thus, one step of the 90° (1.57 rad), size 11 stepper motor produces about 31.4 mrad of lead screw rotation or about 0.8×10^{-4} cm of saddle nut translation. This step results in the output shaft rotation of about 0.1 mrad/step. Thus the lead screw and saddle nut stage provides a reduction of about 314 to 1, which reduces (by this ratio) the total spur gear backlash. The backlash remaining results from clearance between the lead screw and saddle nut. This clearance must be less than 0.8×10^{-4} cm for the output to move on the first step. Clearances of less than this value can be obtained without substantial friction losses by lap matching the lead screw and saddle nut combination during assembly.

The position pickoff is a linear variable differential transformer (LVDT) that senses lead screw position. Because there is essentially zero backlash between the pickoff and the output, testing of the actuator is simplified. The output shaft, vacuum-sealed with two O-rings, is clamped to the thruster gimbal shaft. An insulating spacer is used in the coupling to reduce heat transfer from the thruster. Spherical, self-aligning bearings in pillow blocks are used for mounting the thrusters to the array structure. The actuator case is an O-ring sealed unit and is pressurized to 5 psig with a 90% nitrogen, 10% helium mixture. Hermetic sealing is required for lubricant protection during long-term operation in space vacuum. All metal parts of the actuator, except the split strap, are aluminum to minimize thermal expansion differences. The lead screw is a hollow shaft, hard anodized after machining. The present actuator mass is 1.7 kg with an expected flight mass of about 1.5 kg.

Presented as Paper 70-1156 at the AIAA 8th Electric Propulsion Conference, Stanford, Calif., August 31–September 2, 1970; submitted June 16, 1971, revision received September 20, 1971. This work presents the result of one phase of research carried out in the Propulsion Research and Advanced Concepts Section of the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS 7-100, sponsored by NASA.

Index categories: Electric and Advanced Space Propulsion; Spacecraft Attitude Dynamics and Control; Spacecraft Navigation, Guidance, and Flight-Path Control Systems.

* Member Technical Staff

† Senior Engineer. Associate Member AIAA.

§ Member Technical Staff. Member AIAA.

‡ Life data from Kearfott Division, Singer-General Precision Inc.

Translator actuator

To obtain low backlash in the translator actuator, a harmonic drive unit was used as the final reduction stage (100 to 1). The basic characteristic of the harmonic drive, with minimum gear tooth friction, allows low backlash (less than 2.5×10^{-5} rad) without high friction or wear. The reduction between the stepper motor and the harmonic drive is 28.3 to 1. The total 2830 to 1 reduction produces a rotation of the output drum of 0.55 mrad per step (6.3×10^{-3} cm translation per step for a 23 cm drum).

A size 15, 90° stepper motor is used for the actuator drive. A rotary, infinite resolution potentiometer is connected to the output by means of a spring-loaded gear for position readout. The present unit has a mass of 2.7 kg with an expected flight mass of about 2.5 kg.

A beryllium-copper split flat strap converts the actuator output drum rotary motion into linear motion of the structure. The strap loops the drum and is attached to eliminate slippage. Rotation of the drum causes the strap loop to move relative to the strap ends, which results in the translation of the array.

Thruster array structure and translators

The thrusters, gimbal actuators, cabling, feedline, and rails for one translator axis are attached to the thruster array structure. The translator actuators and the bearings for both axes are housed in an intermediate carriage (Fig. 1). Thus, the carriage and array structure together translate along one axis, while the array alone translates along the second axis. Two translator rails per axis are used. These rails are solid 3.2-cm-diam stainless-steel rods in the present assembly. However, beryllium tubes are proposed for flight application. The translator bearings, which are linear recirculating ball bushings, are press-fitted into the carriage structure. The completed assembly is shown in Fig. 1. For laboratory tests, the vertical axis is counter-balanced because, in space, the translator actuator is not required to lift the array weight. The lead counterweights fit within the vacuum header-array support structure (inside square tubing). The array structure is constructed primarily of aluminum sheet with riveted joints. The array could support five thrusters, although fewer are presently used for simplicity. A third thruster will be added as a spare for system testing. It was determined analytically that caging will be required during the launch environment.

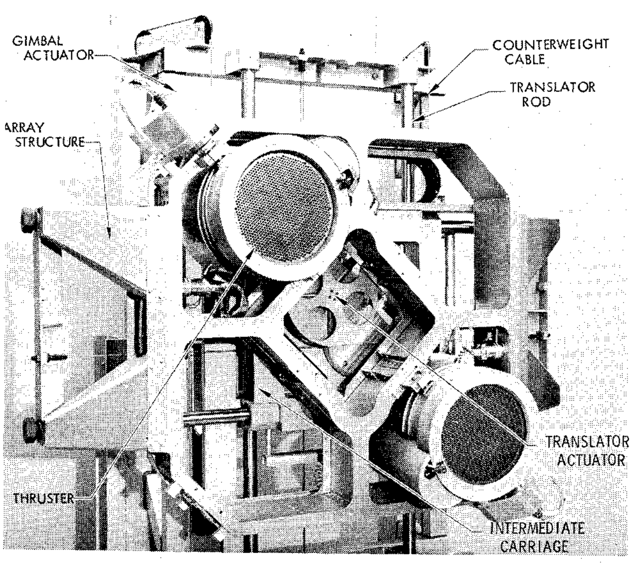

Fig. 1 Complete TVC mechanism.

Cabling and propellant lines

Cabling, which includes requirements for high voltage (a few kv), high current (up to 10 amp), and low-noise pickup, must span the two-axis translator as well as the gimbal interface. To meet these requirements with proven spacecraft-compatible materials, Teflon (TFE) insulated ribbon cable was selected. A total of four cables are used with two for the actuators. The thruster high-current requirements are met with four 19-strand 20-AWG conductors in parallel. The four conductors are insulated together. Nine of these sets are bonded into ribbon form with another layer of Teflon. The remaining nine thruster low-current requirements are met with 19-strand 20-AWG single conductors bonded in ribbon form. The actuators require twisted-shielded pairs and triads for minimum electromagnetic interference. A cable each of pairs and triads, with braided shielding and 28-AWG conductors, is used. Each ribbon is about 6-cm wide.

The four ribbon cables are stacked and formed into an open loop. Beginning at an attachment point on the array, the first loop lies in a horizontal tray attached to the carriage. Thus, the loop "rolls" in this tray as the arrays moves relative to the carriage. The cables are then bent 90° to form a second loop along the vertical axis. Supported by trays on the carriage and mounting structure, this loop crosses the second axis. This design results in a low total loop (4 cables) rolling force of about 5–6 N. On the carriage, the actuator cables are split for operation of the translator actuators. On the array, all of the cables are split and distributed as required. The combined mass of the four ribbons is about 4 kg (1.12 kg/m).

The propellant feedline crosses the translator in a rolling loop design similar to that for the cabling. Single lines are run for each thruster from the distribution point on the array. The cabling and feedline configuration is designed so that minimum redesign would be required for flight application.

Mass Summary

The masses of the present TVC system components, which include actuators, thruster array and actuator, electronics, flexible cabling, flexible feedlines, and caging for launch, total 77.2 kg for a three-thruster array. The reductions for the same components expected with redesign would be to 37.1 kg for a three-thruster array and 48.5 kg for a five-thruster array.

Conclusion

A thrust vector control mechanism, which meets electrically propelled spacecraft requirements, is presently in the final stages of development. The actuators have been evaluated singly in bench tests and in the complete thrust vector control subsystem tests in vacuum. The output torque, stepping rates, and life characteristics were found to exceed the expected requirements. In addition, the actuators have demonstrated near-zero backlash (about 0.5 steps for the translator and 2 steps, correctable to 0.5 steps, for the gimbal). The minor problems encountered in testing were highly beneficial in evaluating the design and in understanding actuator assembly requirements.

The flexible cabling and feedlines were found to be problem-free. Contamination by sputtered material did not affect the mechanism or the cabling. Additional testing will be performed to evaluate long-term reliability of the flexing elements.

The present thrust vector control subsystem was designed conservatively to meet any expected future requirements. Additional stepper-motor life data as well as more detailed control system analyses will be required before the present design requirements can be modified. The impact of the allowance of substantial backlash in the mechanism, which might allow an actuator mass reduction, must be fully considered. Notwithstanding these possible future actuator refinements and associated minor system tradeoffs, the present mechanism will adequately and reliably perform the thrust vector control function.

References

[1] Masek, T. D., "Solar Electric Propulsion System Technology," Paper 70-1153, Stanford, Calif., 1970.

[2] Reader, P. D. and Mankovitz, R. J., "Attitude Control of an Electrically Propelled Spacecraft Utilizing the Primary Thrust System," paper presented at Annual Aviation and Space Conference, Beverly Hills, Calif., June 1968.

[3] Crawford, W. E. and Fleischer, G. E., "Solar Electric Spacecraft Thrust Vector Control System Mechanization," *Supporting Research and Advanced Development, JPL Space Programs Summary 37-62*, Vol. III Jet Propulsion Lab., Pasadena, Calif., April 30, 1970, pp. 164–166.

[4] Crawford, W. E., "Solar Electric Propulsion System Technology Project Thrust Vector Control Electronics," *Supporting Research and Advanced Development, JPL Space Programs Summary 27-64*, Vol. III, Jet Propulsion Lab., Pasadena, Calif., Aug. 31, 1970.

[5] *Solar Electric Propulsion Asteroid Belt Mission Study*, Final Report SD-70-21, JPL Contract 952566, Jan. 1970, North American Rockwell Corp., El Segundo, Calif.

[6] *Study of a Solar Electric Multi-Mission Spacecraft*, Final Report 09451-6001-R0-02, JPL Contract 952394, Jan. 1970, TRW Space Technology Lab., Redondo Beach, Calif.

Experimental Studies with a Liquid-Filled Gyroscope

B. G. KARPOV,* J. T. FRASIER,† AND W. P. D'AMICO‡
Ballistic Research Laboratories, Aberdeen Proving Ground, Md.

Nomenclature

$a, b, 2c, d$ = cavity radius, radius of cylindrical air core, cavity length, and radius of a central rigid rod, respectively
Re = $a^2\Omega/\nu$ = Reynolds number, where ν is kinematic viscosity
t = time
α = exponential growth rate factor for the gyro's motion; yaw amplitude $\propto e^{\alpha\Omega t}$
τ_{NU}, τ_{nj} = nutational frequency of the gyro, and the eigenfrequency of the nth radial and jth longitudinal mode of liquid vibration, respectively, both nondimensionalized by Ω
Ω = spin of the gyro

Introduction

THE behavior of rotating liquids is a field of active interest.[1] A part of this field studied by the authors is the flight stability of liquid-filled spinning projectiles and earth satellites.[2,3] Poor flights can result from interactions between the liquid and the solid casing. Our investigations include theoretical and experimental efforts. The theoretical aspects center about an analysis by Stewartson of the stability of a gyroscope containing an inviscid, incompressible liquid in a right circular cylindrical cavity of its rotor.[4] The experimental part centers about a gyroscope designed to study the stability of systems containing rapidly spinning liquids. Reduced to their fundamentals, the mechanisms of interaction between a rotating liquid and its container are the same for the gyro as for a projectile or satellite. The gyro has been productive as it has provided: 1) critical tests of theory, 2) observations of phenomena to guide further analysis, and 3) solutions to theoretically intractable problems. In as much as the gyro has not been generally reported upon, it is the purpose here to describe this rather novel device and briefly give some results obtained with it. Experiments pertinent to Stewartson's theory will illustrate the first two functions listed above, while tests with a gyro container having a rigid central rod illustrate the third function. Relevant theory is given by Refs. 3 and 4. The terminology and nomenclature of Ref. 3 will be used herein.

Received April 12, 1971; revision received September 27, 1971. The authors are pleased to acknowledge the assistance of B. McKay of the BRL for his efforts in performing the experiments reported here.

Index category: Uncontrolled Rocket and Missile Dynamics.

* Tryon, North Carolina, formerly with the Exterior Ballistics Laboratory.

† Chief, Terminal Ballistics Laboratory.

‡ Mechanical Engineer, Exterior Ballistics Laboratory.

Description of the Apparatus

The gyro is shown schematically in Fig. 1. Two design constraints were that the entire system have a ratio of axial to transverse moments of inertia of less than 0.04 and that the c.g. of the system be at the gimbal axes. These conditions give nutational frequencies pertinent to our interests and suppress the precessional motion. The latter is desirable since theory indicates the liquid causes the nutational mode to become unstable. The rotor is 33.0-cm long by 7.6 cm in diameter and can be spun to as high as 7,000 rpm by the low inertia motor. The spin is measured to within one per cent by a calibrated stroboscope. The hollow aluminum rotor accepts containers having desired cavity geometries (maximum length: 28 cm, maximum diameter: 6.5 cm). Usually, the containers are transparent so that the fluid flow can be observed. The rotor and upper end caps of the containers are centrally ported to allow liquid to be added while the gyro is spinning.

The nominal axial and transverse moments of inertia of the gyro (2×10^5 gm-cm^2, 35×10^5 gm-cm^2) can be altered by addition of brass rings to the rotor. The rings are attached so as to maintain the c.g. at the gimbal axes. By this scheme the nutational frequency can be varied in increments of 0.001 over a range of 0.020–0.120.

The gimbal supports are crossed spring leaves, "Bendix Flexural Pivots," arranged so that halves of the unit rotate relative to each other about a common axis. Rotation is virtually frictionless and is linear (within 2.5%) with applied

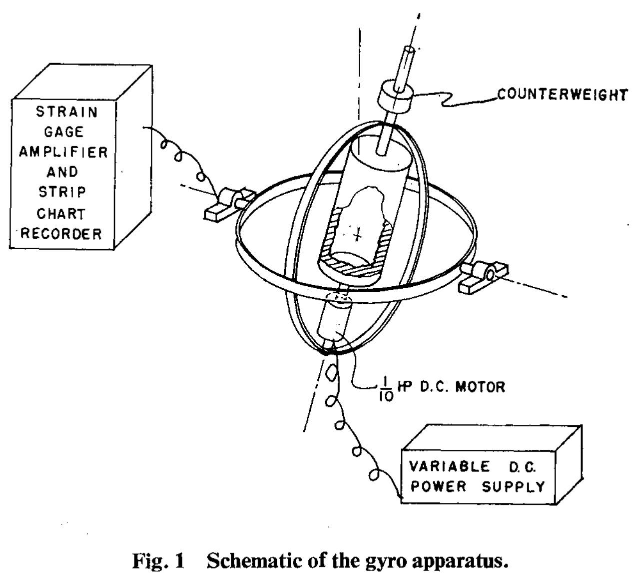

Fig. 1 Schematic of the gyro apparatus.