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SOLAR ARRAY DRIVE SYSTEM

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ABSTRACT

A solar array drive system consisting of a solar array drive mechanism and the corresponding solar array drive electronics is being developed by the Lewis Research Center of NASA. The principal feature of the solar array drive mechanism is its bidirectional capability which enables its use in mechanical redundancy. The solar array drive system is of a widely applicable design. This configuration will be tested to determine its acceptability for generic mission sets. Foremost of the testing to be performed is the testing for extended duration.

INTRODUCTION

A Solar Array Drive System (SADS) consisting of two elements, a Solar Array Drive Mechanism (SADM) and the corresponding Solar Array Drive Electronics (SADE), is being developed by the Lewis Research Center of NASA (NASA-LeRC). The design of the SADS and the status of the test program are the subject of this paper.

Requirements for the SADS arose from the NASA-LeRC studies of future spacecraft missions (ref. 1, 2, and 3). During conceptual design of spacecraft to fulfill these missions it became apparent that available solar array drive system design and performance data were meager. Also, existing designs did not fulfill the full range of mission requirements. Consequently, specifications for a solar array drive system were formulated from the NASA-LeRC studies and other potential applications (ref. 4 and 5). A set of SADM and SADE hardware was built to these specifications. This hardware is of a quality consistent with its intended use: performance testing, environmental testing, and extended duration testing.

Extended duration testing is perhaps the most meaningful testing to be done. Experience has shown that subsystem and component level testing is essential for detection of defects (ref. 6) and that components must be tested in their correct configuration to minimize flight failures (ref. 7). Specifically, however, motor gear-reduction systems are prone to failures that are not predictable but are unique to a particular design. The only method of determining actual failure modes is by performing an extended duration test of units of flight configuration (ref. 8).

This paper presents a summary of the SADS specifications and descriptions of the design of the SADM and the SADE that were produced to meet these specifications. The status of the SADS test program is presented.

DESIGN REQUIREMENTS

The SADS design requirements were formulated from missions that range from low earth orbit to geosynchronous orbit to planetary missions. Corresponding rotation rates of the spacecraft solar arrays range from 14 revolutions per day (rpd) to 1 rpd to several revolutions per two or three year mission. The rigid-body mass moments of inertia for these solar arrays, about the axis of rotation, are as high as 270 kg-m^2 (200 slug-ft^2) for one wing of a two wing system. Missions are up to six years in length. Mission characteristics thus determine the required life, rate of rotation, and minimum torque for the SADS. Additional requirements for the SADS include bidirectional operation capability, use in parallel for redundancy and/or increased output, and the ability to be completely operated by ground command or by an autonomous spacecraft system.

The SADS specifications are given in Tables 1 through 5. There are several design constraints that should be emphasized so that these specifications are clearly understood. First, some SADM design specifications are based on past test experience with a specific design. Second, it is intended that there be a final 6:1 gear reduction between the SADM output and the solar array; this is noted in the specification. Third, the SADE for each SADM is contained on one 12.7 by 17.7 cm (5 by 7 in.) printed circuit card. This should facilitate use in any spacecraft electronics assembly (attitude control electronics, on-board processor, or housekeeping electronics). The current effort, however, includes packaging two cards in a separate box with conventional connector interfaces.

Principal aspects of the SADS, SADM, and SADE require emphasis. Operation of the SADS is bidirectional. The SADS design permits use of two or more SADM/SADE in parallel for block redundancy and/or increased output. The SADS is operable completely from the ground or completely by an autonomous spacecraft system; thus, the widest range of applications and contingencies is bracketed. The SADM configuration permits single-ended or double-ended output; specifically, the SADM output can be coupled anywhere along the shaft of the driven unit. Loads to the SADM are thus reduced. This also allows more flexibility in the end use of the SADM. The SADE is self-contained on one printed circuit card. The SADE is electrically and mechanically compatible with current spacecraft systems.

SADM DESIGN DESCRIPTION

Background

The SADM developed for the Solar Array Drive System is founded in the General Electric Co. "Long Life" solar array drives extensively life tested in 1972-1974 (ref. 9). Counter-wound wrap springs have been added to the output of this compact step motor-harmonic drive subassembly to provide bidirectional clutching action. This permits direct coupling of two or more drives to a common solar array shaft gear resulting in a bidirectional block redundant drive assembly.

The two "Long Life" drives were removed from the vacuum chamber in May, 1974 with a total of 60,180 output shaft revolutions and a total time in 1.3×10^{-6} N/m^2 (10^{-8} torr) pressure of 28 months accumulated on both units. The drives were disassembled and thoroughly inspected for evidence of wear or degradation. The condition of the bearings and gears was excellent. Since one of these mechanisms was dry lubricated, the actual cycle life is some measure of "mission life." For a 600-nautical-mile orbit the 60,180 cycles is equivalent to 11.7 years of orbit operation, and for a geosynchronous satellite this is equivalent to 164 years of operation in orbit.

Mechanism Description

The drive mechanism is patterned directly after the General Electric "Long Life" drive mentioned above. The step motor and harmonic drive assembly is identical, using a small angle step motor (1.8° per step), and a 100:1 ratio harmonic speed reducer. A cross-sectional view of the drive is shown in Figure 1. The harmonic drive flex spline is connected to the output pinion shaft through two wrap spring clutches which are counter wound to provide bidirectional overriding clutch action. The clutch energizing torque, which is a requirement for all wrap spring clutches, is provided by a friction drag disc. The friction torque level is adjustable on the exterior of the unit through the action of a wave spring washer and wedge. The smaller wrap spring is wound left-hand and drives when the input shaft rotates clockwise looking at the motor end of the unit, and the larger spring is wound right-hand, making the drive connection when the input shaft is driven counterclockwise.

The net characteristic of the SADM is one of free wheeling at the output in either direction while still maintaining drive capability in either direction from the input side. When driving, a rigid mechanical coupling is established by the spring clutches so that large torques can be transmitted. Hence, two or more units can be directly geared to a common shaft. Clutching from one unit to the other results from switching input power from one drive motor to the other. The interface between the SADM and the driven unit is a keyed output shaft on which a pinion can be mounted to interface with the ring gear of a solar array system.

Design Considerations

The DC step motor is inherently adaptable to space since it does not require mechanical commutation. The small 1.8° steps help to reduce the output step size and to smooth the velocity profile of the driven load. The discrete steps of the motor make the drive readily adaptable to open loop control. A high reserve torque of 8.1 N-m (6.0 ft-lb) can be realized from the drive because of the size 23 motor and the 100:1 gear ratio in the harmonic drive (chosen for its compactness, simplicity, and reliability).

Since the SADM is modular in construction it can be connected to the drive member with a further gear reduction providing any desired output torque up to 40 ft-lb. A preloaded pair of bearings support the clutch input shaft and in turn hold the flex spline in proper alignment. The wrap spring clutches are positioned next in line at an intermediate torque level. At this location the springs can be relatively small and lightweight. Clearances between the shaft and spring are sized to provide the desired overriding clutch action

Adjustments for the clutch energizing torque are placed radially on the outside of the output housing assembly for easy access. A low gradient wave washer provides an insensitive method of changing the normal force on the friction ring pad. The energizing torque is on the order of 0.1 N-m (3.0 in.-lb) or 4% of the output torque capability.

The mechanism is completely lubricated with dry lubricant throughout for a long life potential. The only exception is the presence of a small quantity of fluorocarbon grease in the harmonic drive. This grease protects the silver plated raceway of the wave generator ball bearing during assembly and run-in. A thin film of grease on the outside diameter of the bearing aids in its insertion into the flex spline. A listing of the types of dry lubrication used in the mechanism is given in Table 6. The lubricants were all chosen on the basis of their performance in the 28-month life test on the "Long Life" drive.

Discussion

A total of six units was fabricated. Following fabrication, all six drives were functionally tested. The drives were mounted on a test stand and flexibly coupled to a hysteresis brake used as a load. The motor was driven with a commercial two-phase, bipolar driver. Measurements were made on rotation rate, output step size, input power, torque output, and clutch performance.

Rotation rate was made to be linear with respect to the input pulse rate for all loads by adjusting the energizing torque level of the clutch (0.2 N-m (2 to 4 in.-lb)) so that full motor torque could be realized without slip. When a no-slip condition exists the output step size is nominally .018° per step. This value was verified to the required accuracy by interpretation of oscillograph data provided by a potentiometer on the test stand output shaft. Power measurements were made on the voltage-current product at the motor input reflecting a 100% duty cycle. This value was typically 6.6 watts. (If the motor driver is designed to remove power after the step has occurred, average power input can be less than 0.5 watt for low orbit rates.)

Temperature tests were performed to determine the drive operating characteristics at low temperature. The drive is operable down to -29° C (-20° F). Below this point the redundant heaters are activated to accommodate the low interface temperature range of -29° C (-20° F) to -46° C (-50° F). The necessity for heaters is the result of the viscous drag of the grease in the harmonic drive wave generator bearing.

The SADM demonstrated the feature of bidirectional drive capability with mechanically coupled redundancy. The SADM were manufactured with flight-type quality controls on critical materials and processes and are considered representative hardware capable of providing long life.

SADE DESIGN DESCRIPTION

Design Considerations

Primary considerations in the design of the SADE were the minimization of circuit complexity and power consumption consistent with maximum operational flexibility. The SADE has command capability sufficient for convenient ground control and the ability to be completely operated from an on-board computer or programmer. This latter mode requires only two inputs. One sets the direction of rotation, the other steps the motor once for each input pulse. Step rate in this mode is independent of any internally set rate.

Three things were done to minimize SADE power consumption. First, drive power is applied to the motor for only 125 milliseconds for each step. This allows sufficient time for any oscillations of the motor armature to damp out completely. Second, the step motor is driven in the bipolar mode with only one winding excited at any time. This doubles the number of output transistors required but provides the best torque to power rating for the motor. A primary advantage of single winding drive is that it reduces the tendency of the motor to make a partial step when power is removed. Third, all internal logic circuits are C/MOS. Low power TTL is used to interface all input and output lines. This provides low impedance interface and transient protection.

Circuit Description

The SADE electronics can be roughly divided into two sections: one section generates and gates a selectable rate pulse train for the 3° step and slew modes, and one section contains decoding and power circuits that drive the step motor. Figure 2 shows a block diagram of this whole system.

Design of the step rate portion was based on the requirement that the step rate be selectable over a wide range to match the dynamic requirements of potential applications. Basic timing is derived from either an internal or external clock. An internal clock of 1024 pulses per second and about 3% stability is provided. If higher accuracy or synchronization between several SADS units is desired, an external clock can be used. The clock signal is divided to provide the required step rate. This is done in a four stage divide-by-N counter, which is programmed by soldered jumpers on the circuit board. It can divide the input by any integer from 1 to 16. For a clock rate of 1024 pulses per second this provides a selectable output from 34 to 512 pulses per second.

For operation in the slew mode, this output is merely gated on or off by a flip-flop that stores the command. In the 3° step mode, an 11 stage counter is used to gate out 1024 pulses each time it is commanded. This corresponds very closely to 3° for the 6:1 gearing expected in most SADM applications. In the single step mode, the clock derived output is bypassed, and the external pulse is passed directly to the next stage. This way, there is no rate limitation in the single step mode. The motor step rate equals the single pulse command rate. After being gated, the pulse train drives a 2 bit up/down counter. Its output is decoded to provide the drive signal to the step motor. A convenient means of reversing the direction of the motor is the count up/down mode of the counter, which is controlled by a flip-flop that stores the direction command. The decoder gating circuit is also used to limit the drive pulse to 125 milliseconds. A retriggerable one-shot multivibrator controls this feature, holding the drive output on for pulse rates above eight per second. At lower pulse rates the one-shot multivibrator times out on each pulse, turning off the drive after 125 milliseconds.

One circuit not shown in the block diagram has been incorporated as a diagnostic measure. It monitors the drive current drawn by the motor on each step. If this current either increases or decreases beyond set limits, a flag output is set for telemetry.

SADE Package Description

SADE packaging was considerably simplified by its low power dissipation. Conventional printed circuit card construction was used. Only the eight output transistors and one transistor in the switching regulator had enough dissipation to require heat sinking. This was accomplished by leaving a band of copper along one edge of the card which makes thermal contact with a BeCu spring card retainer.

The completed package houses two circuit boards, one for each SADM. Each circuit board is 12.7 by 17.7 cm (5 by 7 in.). The package contains three MIL-C-38999 type connectors, one for the package input and one for output from each SADE.

Development Testing

A breadboard version of the SADE was operated in air at temperatures from -45° C (-49° F) to 65° C (149° F) for a total time of 1800 hours without failure. Measured power consumption at 26 V dc was 75 milliwatts in standby. Maximum power of 4.55 watts occurs at 8 pulses per second step rate. Above this rate power decreases because the inductance of the step motor never allows it to draw dc current. At 60 pulses per second, a typical slew rate, power is 3.6 watts. Below 8 pulses per second the power to the motor is turned off after each pulse and total power therefore decreases linearly to the standby power of 75 milliwatts at zero rate.

TESTING

Current plans for the SADS are outlined in Table 7. This series of tests will serve to verify that the SADM and the SADE will perform as specified. The component characteristics of the SADM (damping, output torque profile, and other characteristics) will be determined; this will enable complete documentation of the SADM characteristics. The SADM will be tested with simulations of the rigid-body and flexible-body inertias expected in typical applications. Environmental testing of the SADM and the SADE will be performed to specifications that envelope the environments expected in typical applications. Extended duration testing will be performed in a thermal vacuum environment. This testing will consist of SADS operation profiles and thermal profiles that are representative of generic mission sets.

CONCLUDING REMARKS

The SADS has been approached in its design as an integral spacecraft subsystem. Sufficient flexibility has been incorporated into the design of the SADM and the SADE to encourage widespread adoption. The basic elements of the system, the SADM and the SADE, contain the bulk of the complexities that would exist in any given application. Testing, then, of the SADS as it now exists should increase confidence in its applications.

Engineering model units of the SADM and packaged SADE have been completed. These units are of a flight configuration and were manufactured with sufficient quality control to allow engineering and environmental testing of maximum validity consistent with reasonable cost. Performance testing, environmental testing, and extended duration testing are being performed at the NASA-LeRC.

Further optimization of the design of the SADM that reduces weight and volume without compromising the basic drive train has been identified.

Tests to determine the acceptability of the design for generic mission sets have been formulated. Tests currently planned are performance tests, component characterization, applications testing, environmental testing, and extended duration testing.

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TABLE 1. - SADS PERFORMANCE SPECIFICATIONS

Life	2 years storage; 6 years space operation
Operation	bidirectional
Rotation rate[a]	0 to 150 rpd
Torque output[b]	8.1 N-m (6.0 ft-lbs)
Step size[a]	0.018 degree
Motor input power	0.5 watt average at 10 watts peak at 6 rpd, 10 watts average at 150 rpd
Electronics input power	1 watt without motor drive

[a] A further reduction by 6:1 would be typical in application
[b] An increase by 6:1 would be typical in application

TABLE 2. - SADS DESIGN SPECIFICATIONS

Modes of operation	operation by ground command, input available for operation by an autonomous spacecraft system
Commands available	1 System on 2 System off 3 Slew rate on 4 Slew rate off 5 3° step 6 Single step 7 Forward 8 Reverse 9 Heater on 10 Heater off

TABLE 3. - SADM DESIGN SPECIFICATIONS

Elements	consist of: permanent magnet step motor, harmonic drive, wrap-spring clutch, output interface, motor rotation sensor
Configuration	provisions for single or double ended output
Output interface loads	500 pounds radial, 50 pounds axial
Lubrication	predominantly MoS_2: harmonic drive: ion plated silver: bearing parts; gold plate: bearing, mesh; fluorocarbon grease: bearings, mesh motor: Ag + WS_2
Output interface	keyed shaft
Clutch	engage and disengage output interface
Motor rotation sensor	sense 1/4 motor revolution, direction
Mass	4.6 kg (10.1 lb) maximum
Envelope	11 cm dia. by 27 cm long (4.3 in. dia. by 10.7 in. long) maximum
Mounting interface	Flanged, 4 holes of 0.64 cm dia. (0.25 in. dia.)

TABLE 4. - SADE DESIGN SPECIFICATIONS

Communications interface	all signals TTL compatible
Electrical interface	input voltage 26 to 30 vdc
Signals processed	SADM motor current flag, 5 (SADM plus SADE) temperatures, SADM heater current flag
Size	one 12.7 by 17.7 cm (5 by 7 in.) printed circuit card per SADM
Package (option)	two cards per box, MIL-C-38999 type connectors, bolted flange mounting

TABLE 5. - SADS ENVIRONMENTAL SPECIFICATIONS

Temperature

Radiative and conductive heat sinks at the SADM and SADE radiative and conductive interfaces will range from -46° C (-50° F) to 66° C (150° F).

Acceleration

The following qualification acceleration is to be applied 5 minutes:
16.0 g thrust with +3 g lateral applied simultaneously

Sinusoidal Vibration

The following is qualification sinusoidal vibration to be applied to each axis at a sweep rate of 2 octaves per minute:

Frequency	Amplitude
5 to 15 Hz	0.75 in. double amplitude
15 to 100 Hz	9.0 g 0 to peak
100 to 200 Hz	6.4 g 0 to peak
200 to 2000 Hz	5.0 g 0 to peak

Random Vibration

The following is qualification random vibration to be applied to each axis for 4 minutes:

Frequency	Amplitude
20 to 100 Hz	+3db/octave to 0.10 g^2/Hz
100 to 200 Hz	0.10 g^2/Hz
200 to 300 Hz	slope to 0.16 g^2/Hz
300 to 700 Hz	0.16 g^2/Hz
700 to 2000 Hz	-3db/octave from 0.16 g^2/Hz

TABLE 6. - BEARINGS AND LUBRICATION

Location	Type	Lubricant
Motor	Deep Groove Crown Retainer	Feuralon AW ($Ag + WS_2$)
Harmonic Drive	Ball Bearing (Braze Machined Retainer) Flex Spline	Silver plated race (Gold plated retainer) stn. stl., gold plated
Input Shaft	Ball Bearing (Angular Contact)	Ceramic Bonded MoS_2
Output Shaft	Ball Bearing Deep Groove Bronze Retainers	Ceramic Bonded MoS_2

TABLE 7. - SADS TESTS

Performance	Performance testing of the SADM and the SADE to verify conformance to performance and design specifications.
Characterization	Determine the component characteristics of the SADM and the SADE that are necessary for complete documentation of component performance.
Applications	Testing with simulations of rigid-body and flexible-body inertia
Environment	Testing consists of the following environmental exposures: 1. Temperature testing 2. Sinusoidal and random vibration testing 3. Acceleration testing 4. Thermal vacuum testing
Extended duration	Thermal vacuum testing for an extended duration; testing consists of operation and temperature profiles representative of generic mission sets

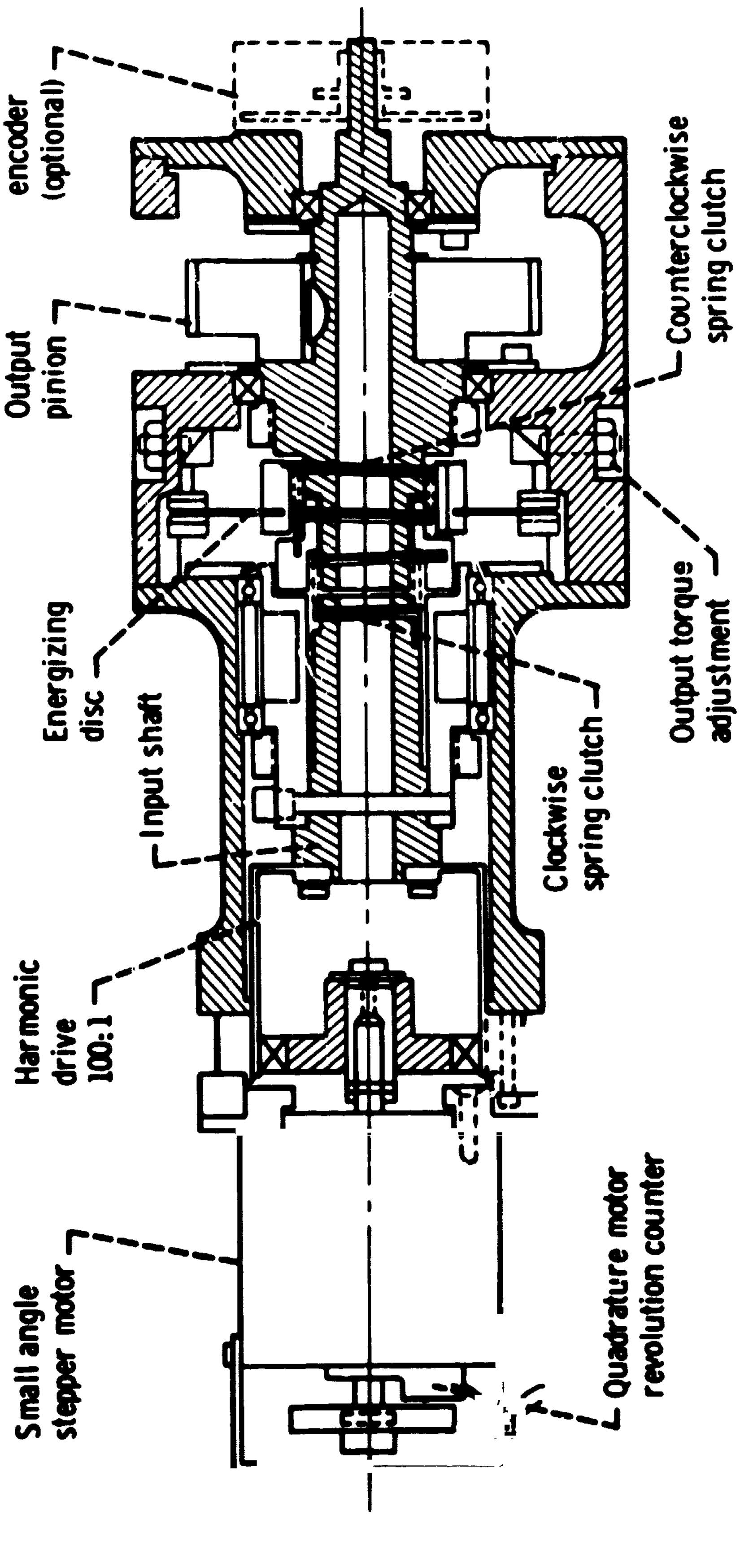

Figure 1. - Solar Array Drive Mechanisn

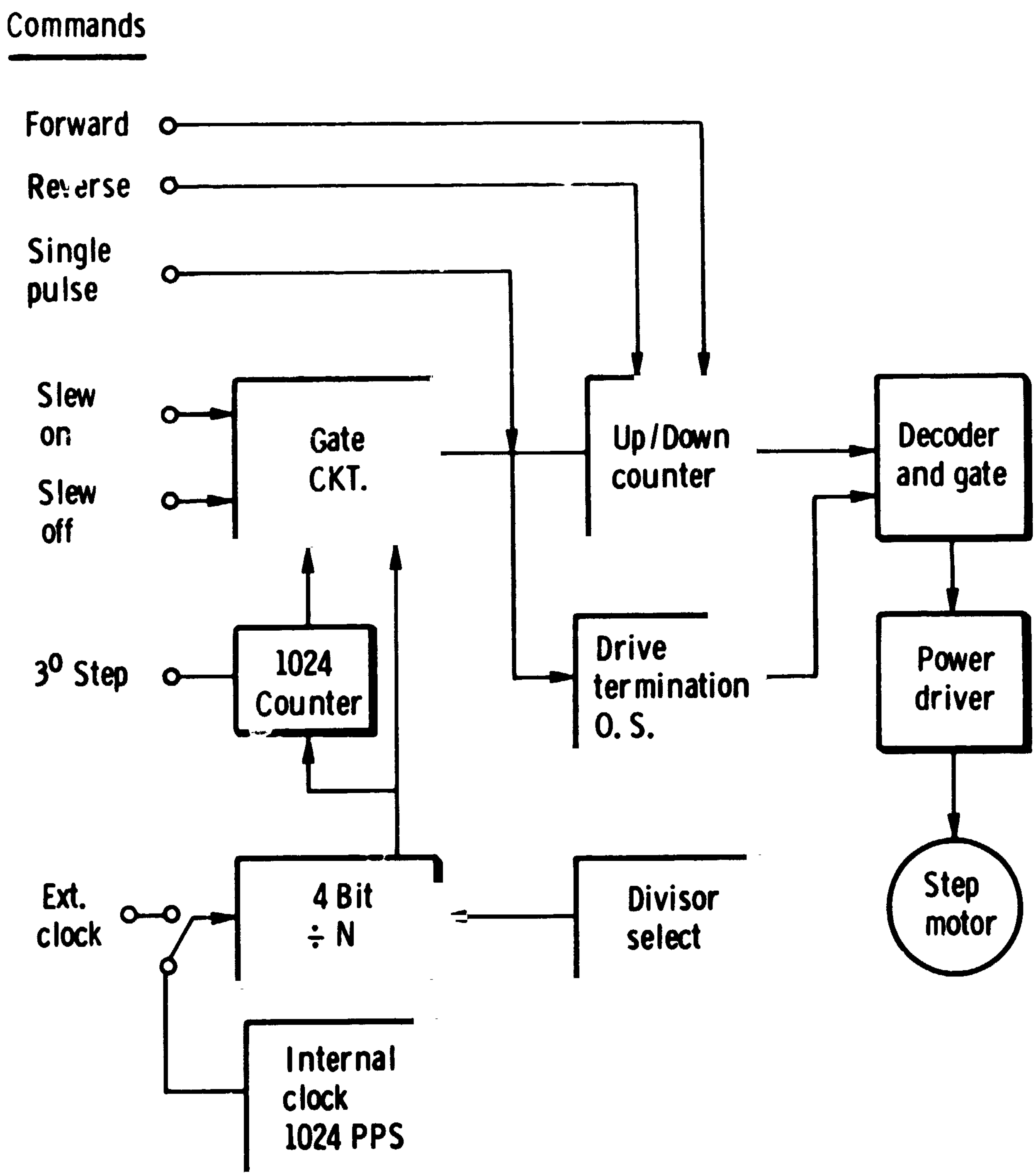

Figure 2. - Solar Array Drive Electronics