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A Broadbased Actuator Concept for Spaceflight Application

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ABSTRACT

A recently developed electromechanical actuator has been found to be applicable to a variety of spaceflight requirements. Characterized by high torque and a small output step angle, the device is comprised of a coaxial, symmetrical arrangement in which a cup-type harmonic drive is directly coupled to a pancake configuration drive motor. The motor, with its dual stator driving a common rotor, is one illustration of the concept of Selective Redundancy.

Selective Redundancy promotes the idea that redundancy, to be effective, must not compromise inherent design simplicity nor introduce new failure modes.

The usefulness of the actuator is exemplified by its selection for a broad range of positioning and driving applications including TDRSS Gimbal Drives, Space Telescope deployment and latching machanisms, and Space Telescope secondary mirror drive, as well as others.

INTRODUCTION

A rotary actuator, broadly applicable to spaceflight service because of its high performance, adaptability, and high reliability, has been developed. The device, which is producible in a range of sizes, derives reliability from its inherent simplicity. Further increases in reliability are achieved by the inclusion of selected redundant features. However, redundancy is used only in those areas where the design is not compromised by the incorporation of those additional features.

Actuators of this type have been employed on a number of spaceflight programs. Details of some of these applications are briefly discussed.

THE ROTARY INCREMENTAL ACTUATOR

The rotary incremental actuator is based on an evolutionary design which was first produced more than ten years ago and has since grown into a family of standard actuators. These are currently being produced in various forms by Schaeffer Magnetics under the designation Rotary Incremental Actuator, Types 1 through 7.

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Concept

Figure 1 shows a sectional view of that first actuator as produced for the Pioneer 10 planetary probe in 1970. Viewed as state-of-the-art at the time, it illustrates the design thinking of that period.

The device, functioning as a telescope positioner, is required to have a small, accurate step and the ability to hold position with power off. A variable reluctance stepper motor (15 degree step) is used, and initial gear reduction is effected by means of spur gearing, thus minimizing inertia reflected to the motor. On the second shaft is a mechanical detenting device to provide position holding, since the VR motor lacks detent torque. Also fitted to this shaft are a shaft angle encoder and a mechanical damper to assist in controlling step-and-settle time.

This assembly illustrates an early application of the harmonic drive speed reducer to spaceflight hardware. (Harmonic drive is a proprietary product of the Harmonic Drive Division of USM Corp., Wakefield, Mass.) Its operating principle is shown in Figure 3. Briefly, the device uses a rotating elliptical element (the wave generator) to produce rhythmic deformation of a toothed elastic member (the flexspline) reacting against a toothed reaction member (the circular spline). Differing tooth numbers on the meshing elements produce reduced output motion with corresponding multiplication of torque. Ratios between about 60:1 and 200:1 can be achieved in a single pass with harmonic drive.

After a second pass of spur gearing, power flow in the device of Figure 1 is through a flexible coupling to the harmonic drive wave generator. The Harmonic drive, reflecting the thinking of that period, is hermetically sealed, in turn requiring its flexspline to be grounded against rotation. A large torsion spring provides bias torque to improve positioning accuracy.

After 11 years, these actuators continue to operate on board Pioneer 10 and 11, now near the orbit of Uranus almost two billion miles from earth. That early design embodies some attractive characteristics:

- Small output step
- Good positional accuracy
- High torsional stiffness
- Unpowered holding torque

But it also displays some not-so-attractive characteristics. First is complexity, with the attendant negative impact of high cost and reduced reliability.

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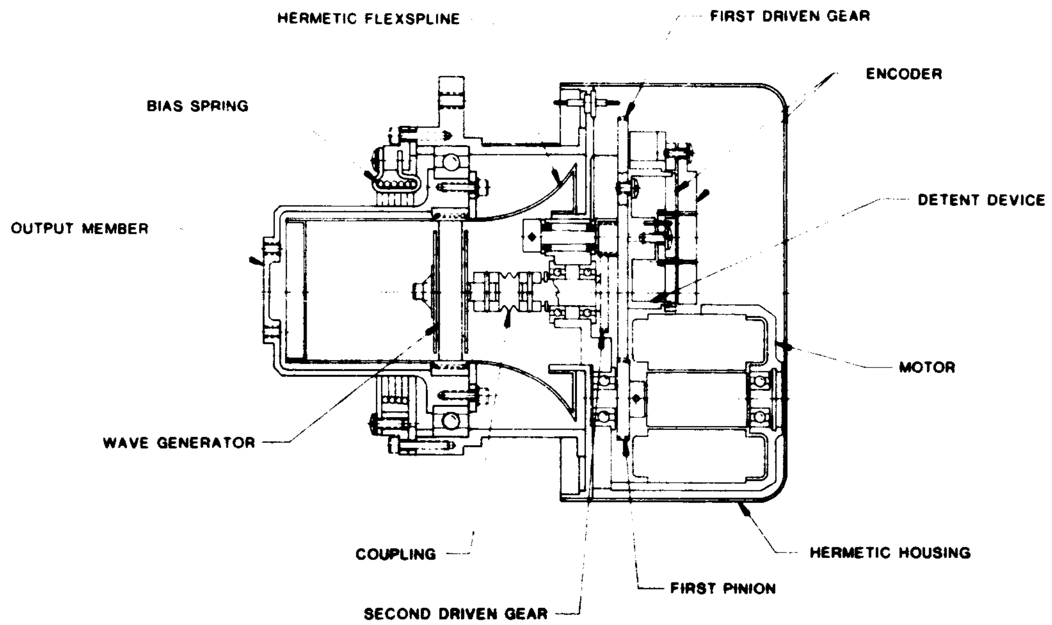
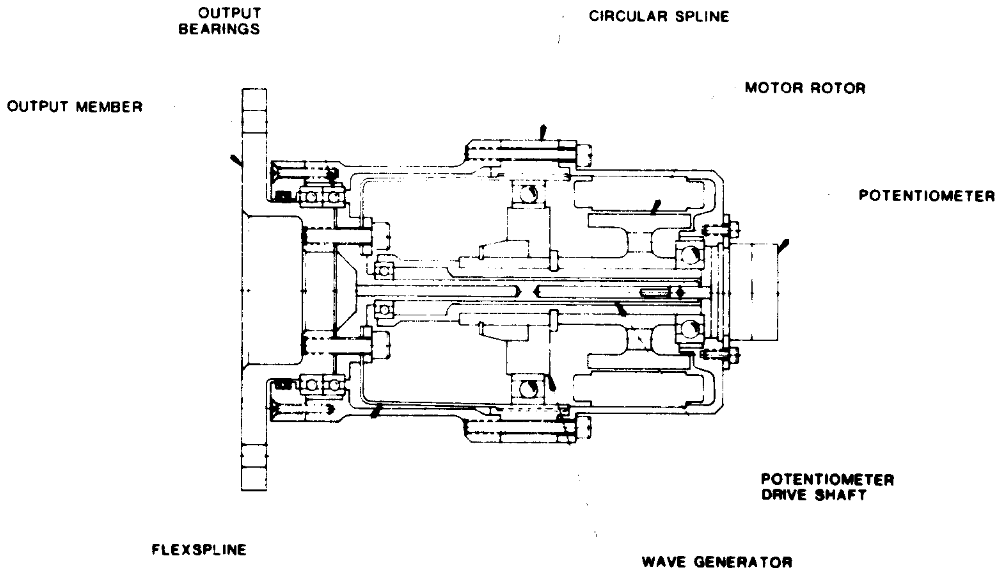


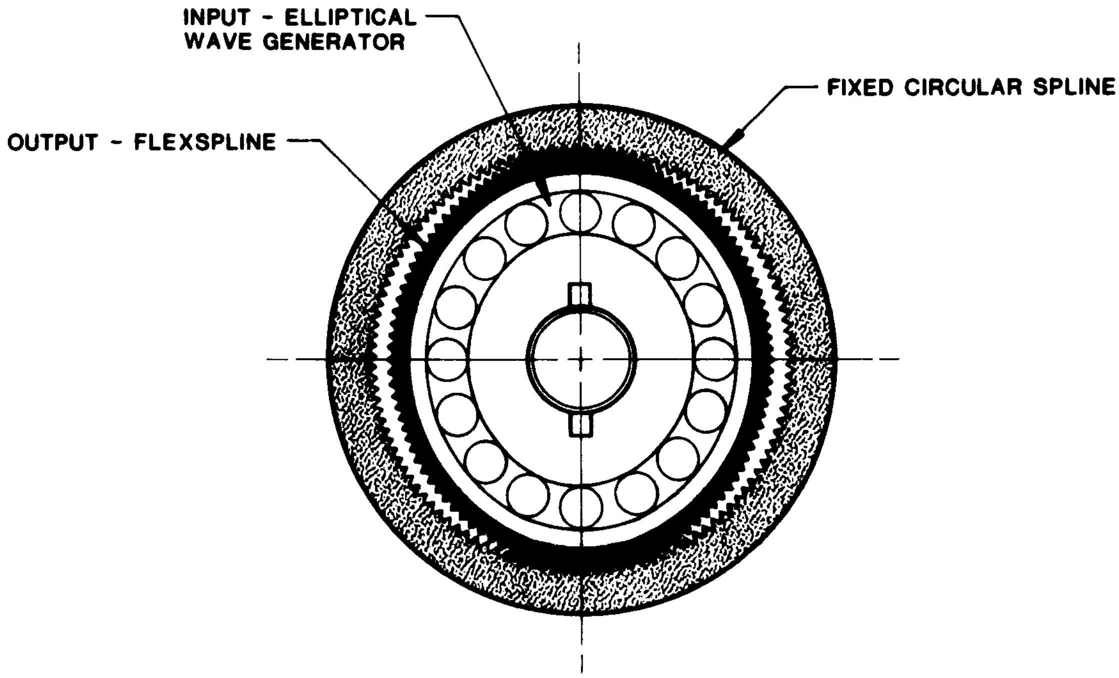
PIONEER II TELESCOPE DRIVE - 1970

FIG. 1



ANTENNA POSITIONER - 1977

FIG. 2



HARMONIC DRIVE PRINCIPLE

Rotation of the elliptical wave generator results in a greatly reduced motion at the toothed output members due to differential action between teeth on flexspline and circular spine.

FIG. 3

A more up-to-date design is depicted in Figure 2. Still based on harmonic drive, its function is the same as the early unit. But a number of changes are evident:

- o Spur gearing eliminated
- o No detent device or auxiliary damper required
- o Output self-supporting and load-capable
- o Non-hermetic

These changes are made possible by the use of a small-angle permanent magnet stepper motor to power the actuator, and by the availability of low-vapor pressure liquid lubricants. Parts count has been reduced sharply, with no loss of performance.

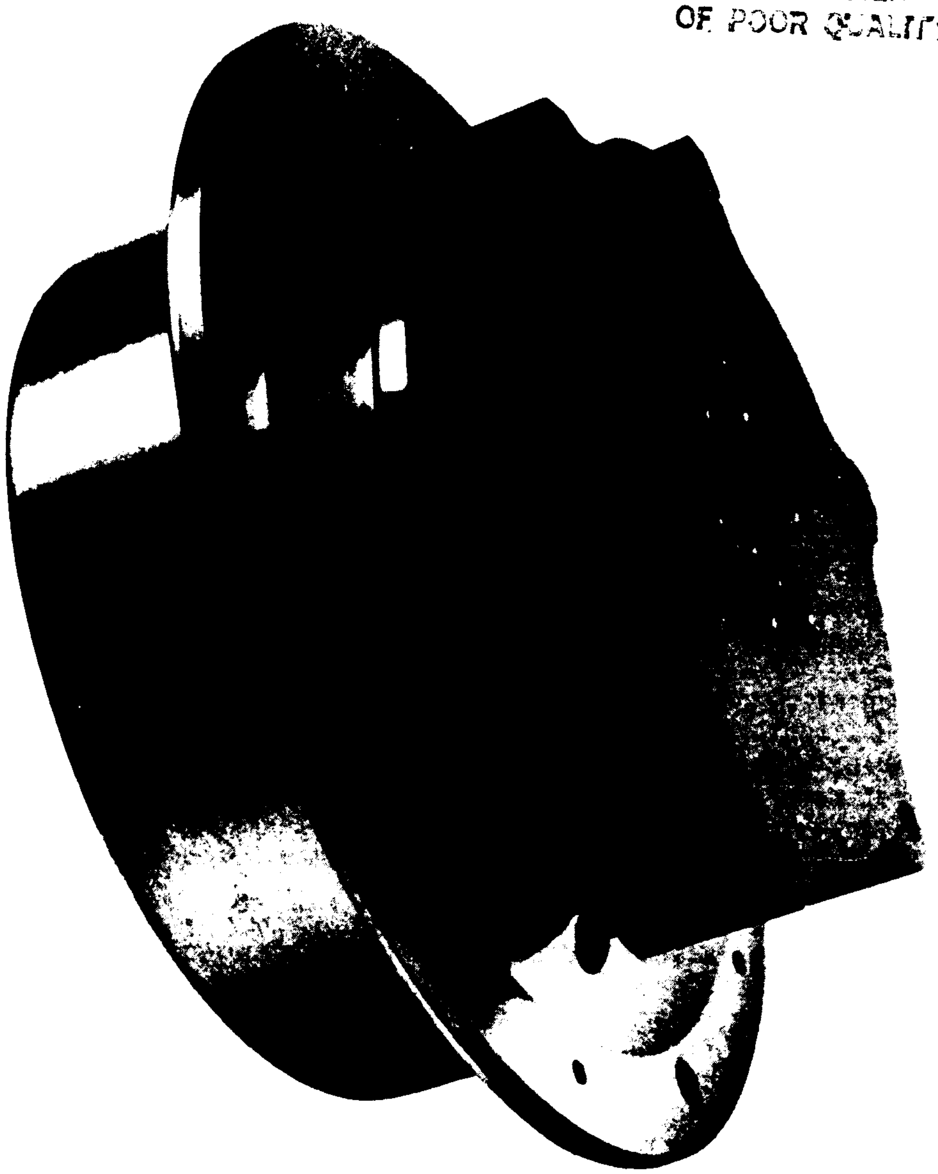
Quickly made obsolete by an even more advanced design, this unit never reached the 'production' stage. It is, however, viewed as the turning point in the design evolution of the product as it is known today. That rotary incremental actuator is seen in Figure 4.

The concept is detailed in the sectional view of Figure 5. It consists of a larger permanent magnet stepping motor, tightly integrated with the harmonic drive, and a larger rotating output flange.

The permanent magnet stepper motor is a unique design. It features a multi-toothed structure with a small step angle and a rotor magnetic structure that is inherently annular in configuration. Because of the small step angle and the use of samarium cobalt magnets, the motor is capable of directly driving considerable inertial loads. This characteristic is exploited by driving the rather large harmonic drive input member directly. Spur gear pre-reduction stages are not necessary.

The device employs a standard cup-type harmonic drive rather than a hermetic unit or a flat "pancake" type. The elliptical wave generator is driven directly by the motor rotor, and the flexspline output member is attached to the output flange of the actuator. The circular spline reaction member is attached to the frame of the unit. This is the most common speed reduction mode of harmonic drive -- a large reduction ratio and reversed rotation is achieved. The motor rotor is sized so that it envelops the circular spline at its outer periphery.

The motor drives the harmonic drive wave generator through a flexible coupling. The coupling now is of the Oldham type. It offers adequate radial accommodation, with much higher torsional stiffness than a bellows or similar type of coupling. The coupling allows for slight lateral movements of the rotor and wave generator, which are due to the slight but unavoidable eccentricities created by the wave generator. This feature enables the wave generator to be self-centering within the flexspline and the circular spline.



TYPE 5
ROTARY INCREMENTAL ACTUATOR - 1983

FIG. 4

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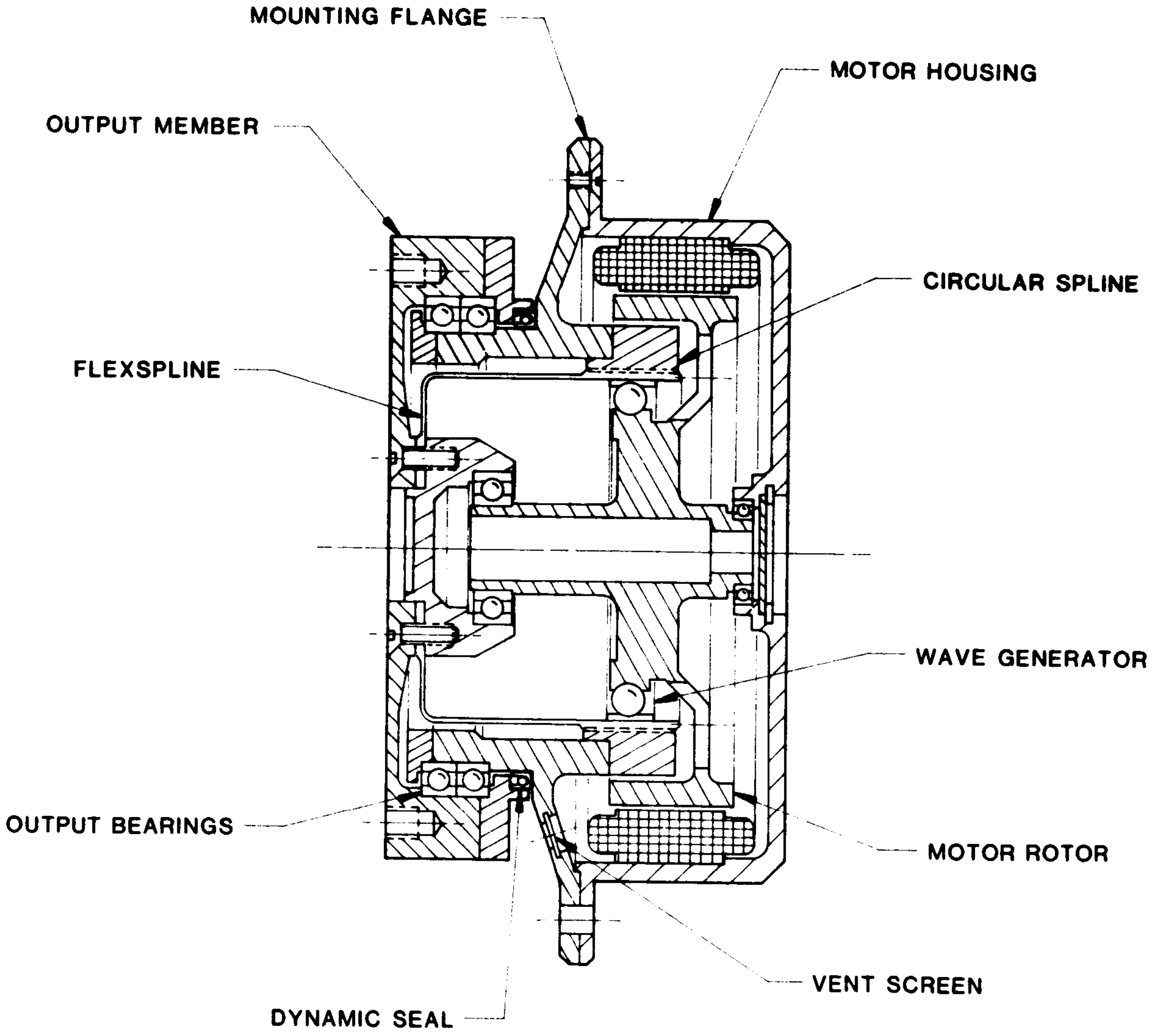

ROTARY INCREMENTAL ACTUATOR

FIG. 5

The output member is large, consistent with the performance capability of the device. The large, duplexed output bearings allow this part to be nested over the cup-type flexspline. The duplex bearing pair offers good rigidity as well as high load capability; so that large cross-axis moments can be resisted. A further benefit of this geometry is the high degree of structural integrity afforded to internal members of the device.

Key features offered by this arrangement can be cited as (a) a very low parts count, (b) relatively open internal structure having few tight clearances, and; (c) because of motor design, a device having no high speed shafts. Additionally, a short load path to ground is afforded for the moments imposed on the output member by overhung loads, and a similarly short thermal path to ground is provided for the flow of dissipated heat from the motor stator.

Although aerospace quality harmonic drive component sets are used, they are standard sizes. Figure 6 illustrates, in relative proportion, the size progession of devices from the Type 1 which uses a harmonic drive of 2.5 cm (1 in.) pitch diameter, to the Type 7 which uses the 2M harmonic drive component set.

The actuator described here is the most basic form of the device. A number of variations have been produced to meet different requirements. One common difference is in the size of the output bearings. Figure 7 shows a basic Type 5 unit, and Figure 8 shows the same unit adapted to withstand very large overhung loads. In this case, the outside diameter is increased at the frame to accommodate a larger pair of duplex bearings. The oversize bearings and seal are located on the output member where the torque level is very high. In Figure 9, a Type 2 unit with output bearings of reduced size is shown. Because this unit is designed for a pure torque output, the overhung load capability of the large duplex bearing pair is not needed. In this way, for a slight increase in the axial length of the unit, considerable weight is saved.

Figure 10 shows another embodiment, this one having an eccentric ball on the output flange, yielding rectilinear output motion. It also has feedback devices on the motor shaft as well as the output shaft.

A feature of the arrangement, of particular interest because of its impact on reliability, is the inclusion of redundant elements. The design in Figure 10 has redundant motor stators, redundant potentiometers, and redundant shaft angle encoders. Other components of the actuator assembly are not duplicated. They are of essentially the same size and design as in a similar basic device. Redundant design has a far reaching impact on performance as well as reliability of these units; and because of this, the philosophy of redundancy is given special attention.

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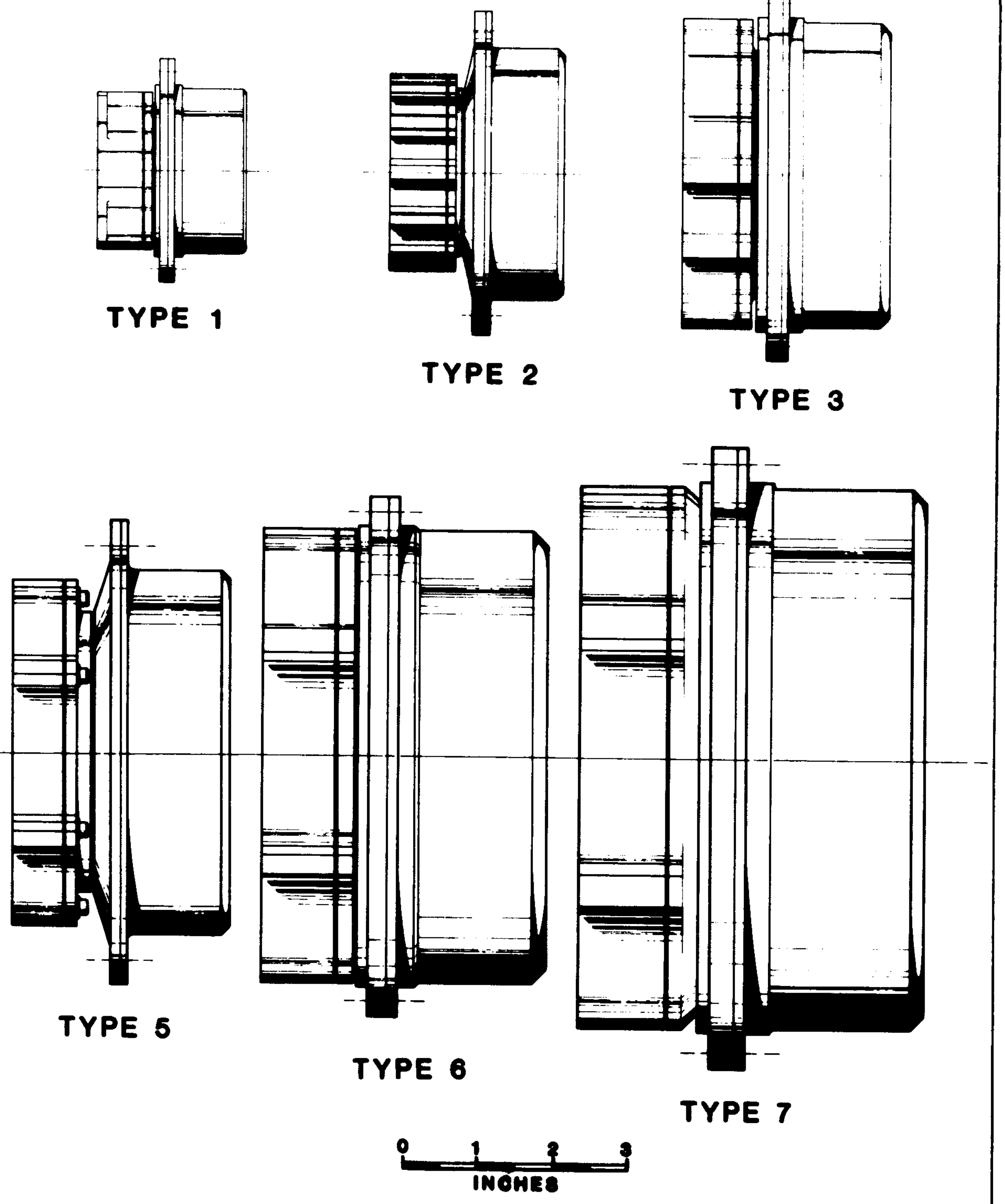

ROTARY INCREMENTAL ACTUATOR FAMILY

FIG. 6

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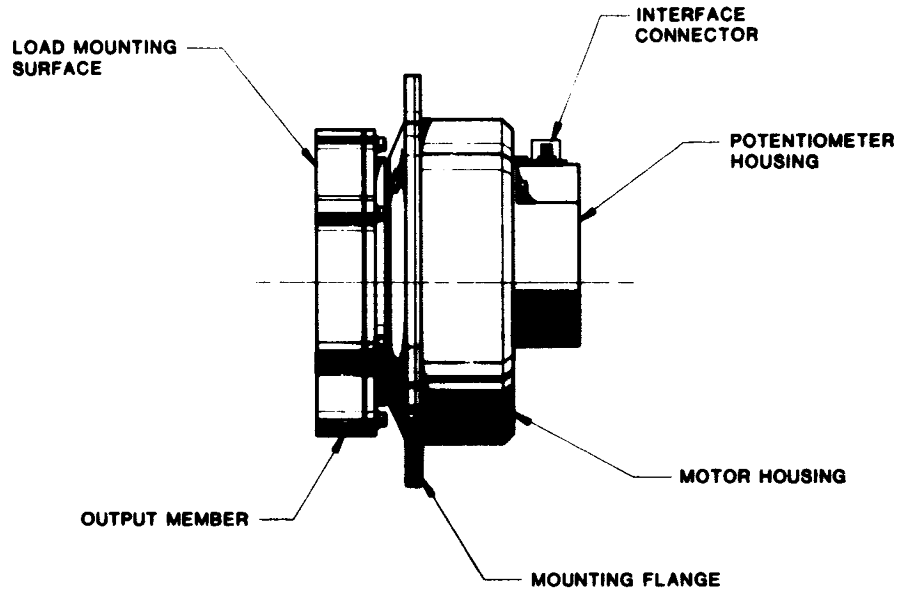
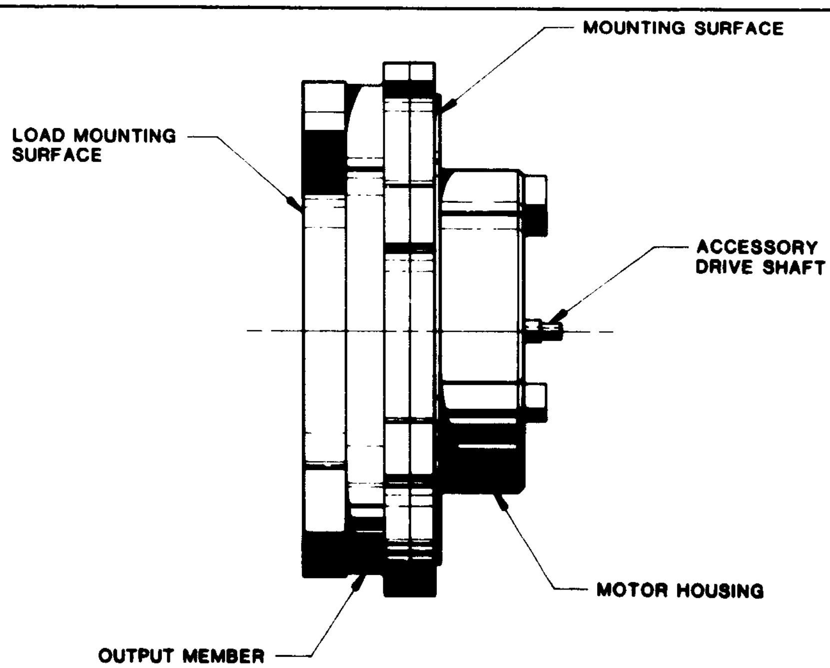


TYPE 5 ACTUATOR

FIG. 7



CONSTRUCTIONAL VARIATION

FIG. 8

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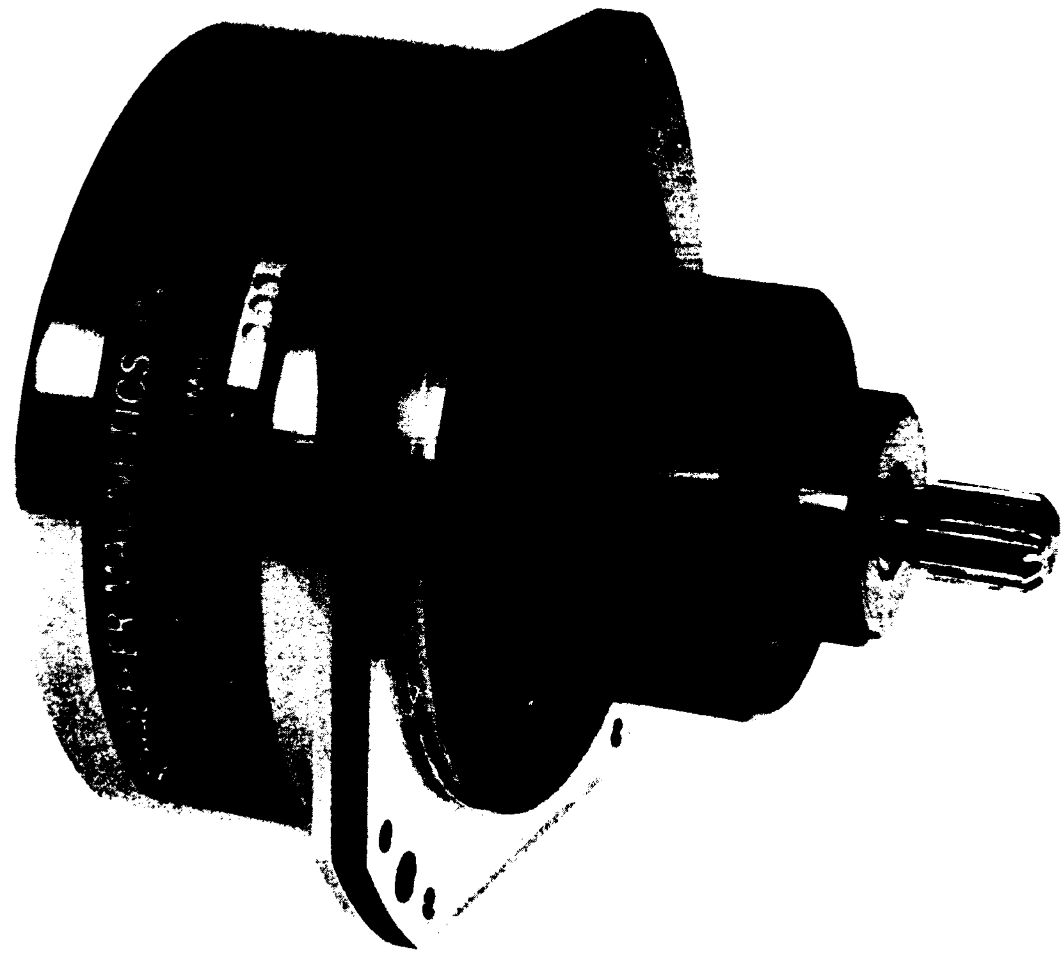


TYPE 2 UNIT WITH OUTPUT BEARINGS OF REDUCED SIZE

FIG. 9

TYPE 5 UNIT WITH ROTOR AND OUTPUT
ANGULAR POSITION FEEDBACK

FIG. 10

Selective Redundancy

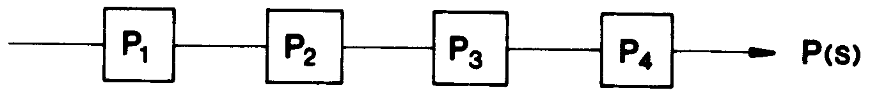
Selective Redundancy is a term aptly applied to the concept of redundancy as used in the design of this rotary incremental actuator family. Although the term may be new, the concept is not. One illustration can be seen in the frequent requirement for 'no system single point failure modes.' But, the attempt to totally avoid such failure modes can easily lead the designer to an arrangement of parts which in the end is distinguished more by its complexity than by its reliability. In devices where the design is aimed at full redundancy, there is almost always the tendency toward an increased parts count.

There are at least two provocative questions that should be asked before the concept of 'reliability via redundancy' is applied: (1) are the relative failure rates and the point of load convergence such that a worthwhile numerical reliability gain is realized? and (2) does the satisfaction of the 'no single point failure mode' requirement lead to the creation of a redundant load path that, in itself, is more prone to fail, thus further compounding the need for a back-up path?

A reliability block diagram of the basic elements of the actuator is shown in Figure 11. P1 represents the reliability of the motor stator, which is the only electrical part present. P2 represents the reliability of the motor rotor, P3 the reliability of the harmonic drive, and P4 the reliability of the output stage of the device. P4 is the output element through which the load is driven.

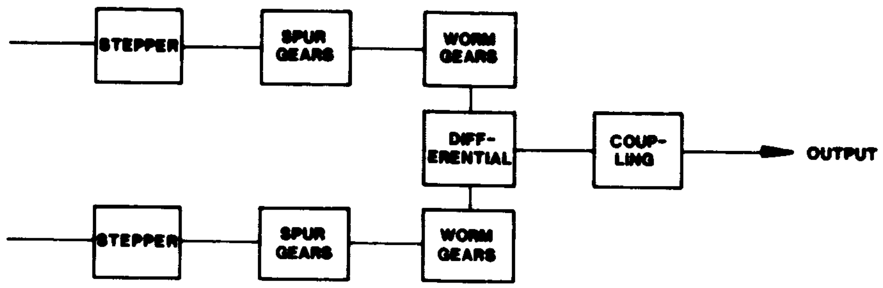
In contrast, a unit designed to be completely redundant is shown diagrammatically in Figure 12. This device was designed by Schaeffer; several have been flown. It uses independent large-angle steppers with spur pregearing and dual worm gear input to a differential, with output taken from the differential spider gear carrier. Actually, this design has many more parts than the newer rotary actuator; but for purposes of comparison it will be assumed that its parts count could be reduced. Here all of the elements P1 through P4 are duplicated in two parallel paths. P5 represents the reliability of the parts required to achieve the switching of mechanical power when a change from one parallel path to the other occurs (the differential spider gears). This branching element is not duplicated, because it appears in the output load path.

Actuators represented by both of these reliability diagrams have been successfully used in orbit, and neither has suffered failure. A further comparison on the basis of performance is as follows:

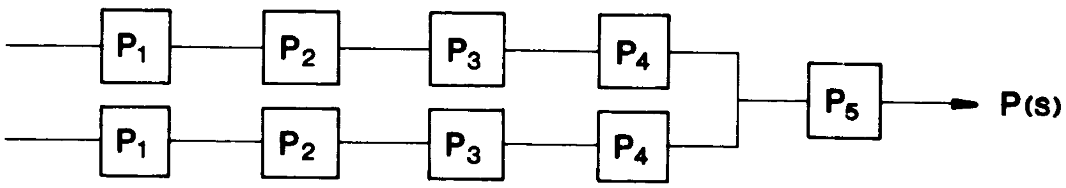


RELIABILITY BLOCK DIAGRAM - BASIC ACTUATOR

FIG. 11



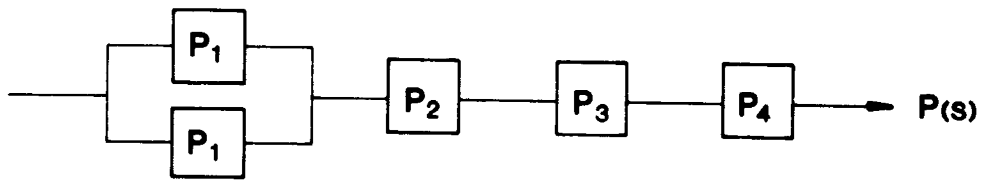
(A) MECHANICAL BLOCK DIAGRAM



(B) RELIABILITY DIAGRAM

REDUNDANT SYSTEM

FIG. 12



RELIABILITY BLOCK DIAGRAM - SELECTIVELY REDUNDANT

FIG. 13

	Redundant Device	Rotary Incremental Actuator
o Output Torque	5.1 nt.m (45 lb-in)	84.8 nt.m (50 lb-in)
o Weight	5 kg. (11 lb.)	1.8 Kg. (4 lb.)
o Output Step	.025 deg.	.0075 deg.
o Assembly Man Hours	T	T/3
o Backlash	30 arc min.	Nil

What this comparison appears to show is that redundant design can have a significant price. Its effect on predicted numerical reliability is powerful, however; and it would be desirable to reap the benefits of redundancy without compromising the inherent simplicity of a device like the rotary incremental actuator.

The reliability diagram of Figure 13 illustrates schematically how this has been done. Major components of the device have about the same failure rate. However, external drive circuitry is associated with the stator, and since electronic components in general have higher failure rates than mechanical components, there is good reason to want redundant motors (redundant motors allow redundant drivers). Although driver electronics are external to the actuator, reliability is ultimately a system concern; and system considerations make two independent electrical systems highly desirable. Therefore, provision of stator redundancy significantly increases system reliability, since additional mechanical elements are not required to effect the transfer of power from one path to the other. Figure 13 shows this concept applied to the actuator. Here only the motor stator is reproduced in a parallel path.

For purposes of illustration, it is assumed that failure rates for components 1, 2, 3 and 4 are identical while the failure rate of component 5 (mechanical switching means) is two times that failure rate. (If component 5 were an active electromechanical device such as a clutch, its failure rate might be higher than that of other components by as much as 7X). When system reliabilities are computed (all for the same mission time) the three approaches illustrated above can be compared. Figure 14 shows calculated reliabilities based on the reliability models (1). Here it can be seen that the fully redundant approach produces an increase in system reliability over that of the basic unit. But, Selective Redundancy is seen to produce a result nearly as good. This is largely an effect of the simplicity of the system. The hazard posed by the additional element P5 is l-rge compared to the gains that can be made by paralleling elements, because there are relatively few elements to begin with.

$\lambda = 20 \times 10^{-9}$ f per hr. (typical)

$t = 156$ hr. oper. time (typical)

Then $\lambda t = 3.12 \times 10^{-6}$

1. Basic System:

$$P(s) = e^{-\lambda t} \cdot e^{-\lambda t} \cdot e^{-\lambda t} \cdot e^{-\lambda t}$$
$$= e^{-4\lambda t}$$
$$= .9999875$$

2. Full Redundancy:

$$P(s) = (e^{-4\lambda t} + 4\lambda t\, e^{-4\lambda t})\, e^{-2\lambda t}$$
$$= (1 + 4\lambda t)\, e^{-6\lambda t}$$
$$= .9999938$$

3. Selective Redundancy

$$P(s) = (e^{-\lambda t} + \lambda t\, e^{-\lambda t})\, e^{-3\lambda t}$$
$$= (1 + \lambda t)\, e^{-4\lambda t}$$
$$= .9999906$$

CALCULATED NUMERICAL RELIABILITIES

FIG. 14

It should also be noted that those design compromises required to package redundant mechanical components within a given space and weight limit will in many cases result in the degradation of individual part reliabilities (P2, P3, P4). Like the addition of new failure modes, this is not demonstrably significant in terms of numerical prediction. The trend is in the wrong direction, however, and is a further argument in support of Selective Redundancy.

This analysis is intended to show numerically that the concept of Selective Redundancy is an effective way to achieve system reliability when applied to devices of the size and scope of these rotary incremental actuators. Selective Redundancy does not entail poorly defined risks and combinatorial failure modes, and is an especially effective approach when other requirements are considered together with reliability.

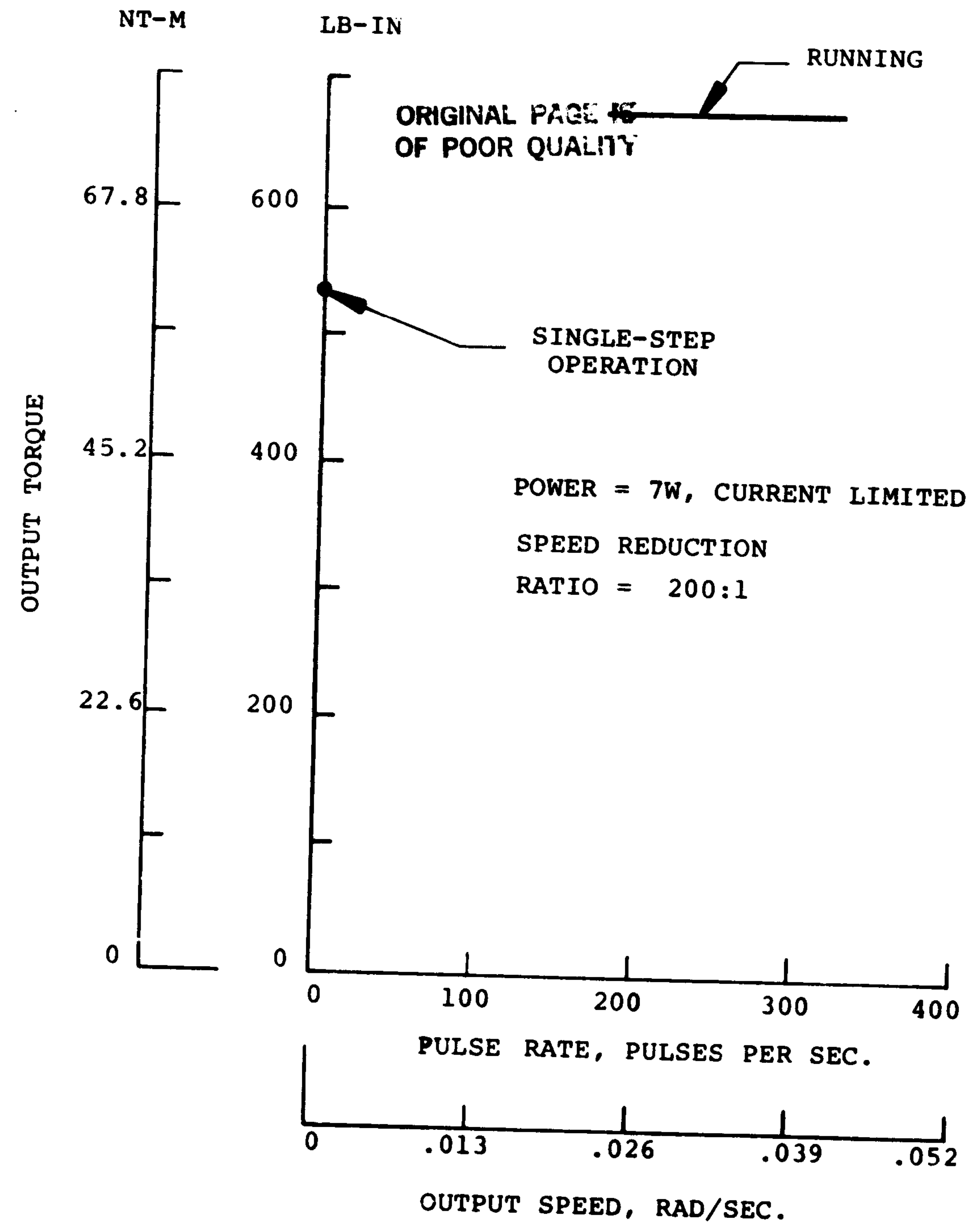
Performance and Testing

Applications of the Rotary Incremental Actuator fall into two broad categories: positioning and driving. Construction of the units and the provision of accessories and other design details varies accordingly.

Performance of a Type 5 unit in a driving application is shown in Figure 15. The torque-speed characteristic curve shown here is of typical shape. Since the devices have a characteristically small step angle at the motor rotor and a moderately high speed reduction ratio (100 to 200 to 1) the speeds achieved are not extremely high. Torque output is high, however. The curve shows torque available for start-stop operation. Higher angular rates can be achieved in slew mode operation in which the pulse rate is started low and ramped up to the operating rate. Not shown by the curve is the unpowered or passive detent torque of the unit which all such permanent magnet devices have. Unpowered and powered driving torque can be traded off to optimize the unit for specific applications, depending on the relative importance of holding torque.

Performance of a Type 5 unit in a positioning application is shown in Figure 16. In this test, groups of 400 steps were applied to a unit having an output step angle of .00013 rad (.0075 degrees), to produce .0524 rad, (3 degree) nominal displacements. Actual measured output positions of the unit are shown together with calculated errors. The typical error is on the order of 73×10^{-3} rad (15 arc seconds). Errors shown primarily reflect harmonic drive positioning accuracy, since motor positioning accuracy is greatly demagnified and the harmonic drive is essentially free of backlash.

Stepper motors as a class are sensitive to the inertia of the driven load. The permanent magnet stepper used in the Type 5 actuator, however, is somewhat less inertia-sensitive, due primarily to the large air gap radius and small step increment. Torque-to-inertia ratio at the motor rotor is greater than with a conventional large angle stepper, and peak kinetic energy of the rotor during stepping is less. Figure 17 shows a large inertia thermal vacuum load test facility. The shaft extending vertically from the vacuum chamber



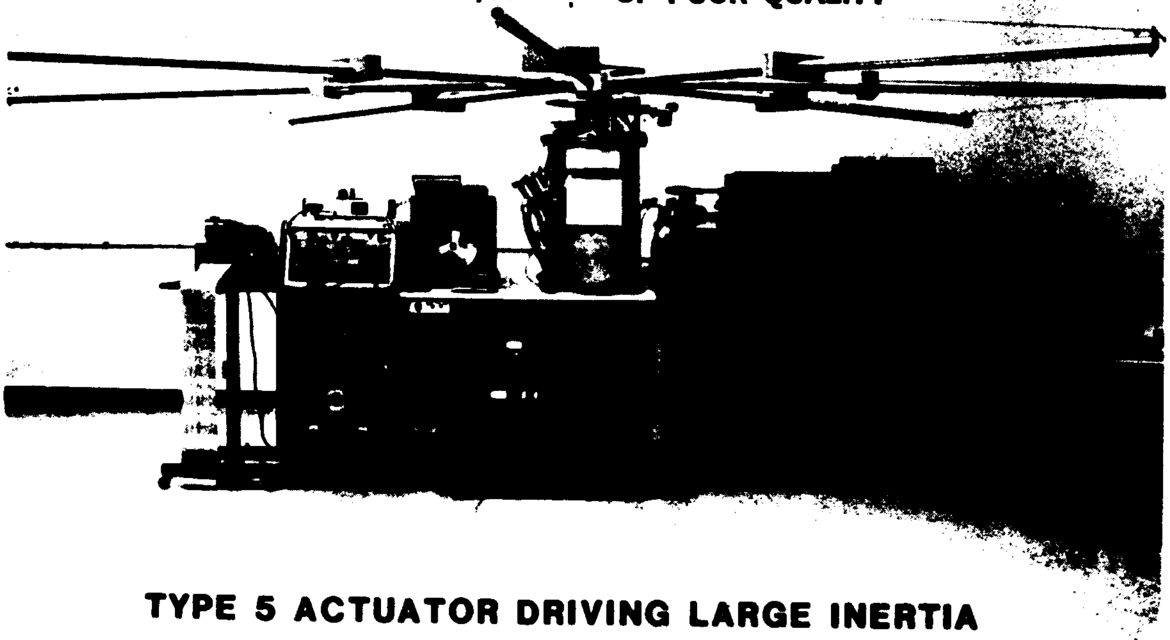
TYPE 5 ACTUATOR PERFORMANCE

FIG. 15

TOTAL STEPS	THEORETICAL POSITION DEGREES	TABLE POSITION DEG, MIN, SEC			POS. ERROR MIN, SEC
0	0	0			0
400	3.00	2	59	34	-26"
800	6.00	5	59	40	-20"
1200	9.00	9	0	16	+16"
1600	12.00	11	59	46	-14"
2000	15.00	14	59	50	-10"
2400	18.00	18	0	12	+12"
2800	21.00	20	59	30	-30"
3200	24.00	24	0	0	0
3600	27.00	27	0	14	+14"
4000	30.00	29	59	42	-18"
4400	33.00	33	0	0	0
4800	36.00	36	0	8	+8"
5200	39.00	38	59	50	-10"
5600	42.00	42	0	0	0
6000	45.00	45	0	10	+10"
6400	48.00	47	59	54	-6"
6800	51.00	51	0	0	0
7200	54.00	54	0	18	+18"
7600	57.00	56	59	46	-14"
8000	60.00	60	0	12	+12"
8400	63.00	63	0	12	+12"
8800	66.00	65	59	44	-16"
9200	69.00	69	0	4	+4"
9600	72.00	72	0	18	+18"

TYPE 5 ACTUATOR POSITIONING ACCURACY

FIG. 16



TYPE 5 ACTUATOR DRIVING LARGE INERTIA

FIG. 17

TYPE 1 ACTUATOR

FIG. 18

can be fitted with a number of inertial masses on the radial arms, to achieve inertias well in excess of 1356 kg.m.^{2} (1000 slug ft^2). The illustration shows an inertia of 474 kg.m.^{2} (350 slug ft^2) being driven by a Type 5 actuator under test mounted inside the chamber. The unit will reproducibly start and stop the inertia, at 0.039 rad per sec. (300 pulses per sec.), and with a ramped pulse rate can drive the inertia at angular rates up to 0.17 rad per sec (1300 pulses per second).

APPLICATIONS OF THE ROTARY INCREMENTAL ACTUATOR

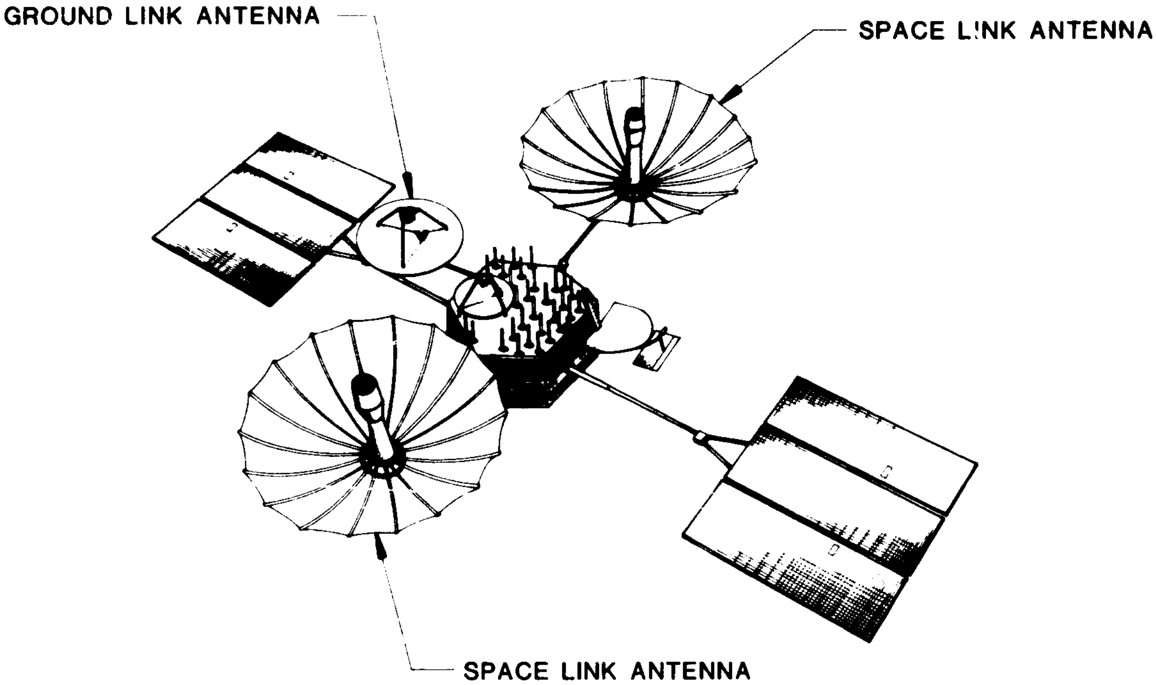
The actuators are used in a broad range of applications. Types 1, 2, and 5 have been built and delivered in numerous forms, and Types 3 and 6 have been proposed or are in development.

The low end of the size spectrum is represented by the Type 1 actuator shown in Figure 18. This unit is used for positioning a scan mirror on Dynamics Explorer. It weighs just over 0.45 kg. (1 lb.), including an integral potentiometer and position-sensing switch assembly. Step angle is 0.0022 rad. (.125 degrees), with worst-case positioning accuracy of about 3×10^{-4} rad, (1 minute of arc). Its unpowered detent torque is used to hold the output stable during power-off periods. This is a good example of Selective Redundancy. A single motor is incorporated, and a single potentiometer element is used. Position sensing switches, however, are deemed to have significantly higher failure potential, and are therefore duplicated.

A larger unit, used for both positioning and driving, is represented by the TDRSS Gimbal Drive Assembly. Figure 19 shows a view of the TDRSS spacecraft. These 1.8 kg. (4 lb.) Type 5 units are used in two-axis arrays to position the large umbrella-shaped high gain antennas and the ground link antenna. This application requires the actuators to drive an inertia load of 57 kg.m.^{2} (42 slug ft^2) at a speed of 0.005 rad. per sec. (35 pulses per sec). Required positioning accuracy is 7×10^{-4} rad (2 min 24 sec.). The unpowered holding torque of 11.3 nt.m. (100 inch-lbs) minimum is relied upon to maintain pointing of the antennas during actuator unpowered periods. These units are electrically redundant, and performance figures are based on operation of one motor. Position feedback is provided by integral redundant potentiometers.

A variation of the Type 5 actuator with oversized output bearings was depicted earlier (Figure 8). The application of this unit is on the ERBE program (TRW, under NASA contract NAS 1-15900). The entire ERBE instrument on the spacecraft is both supported and pointed in azimuth by the output member of this 4 kg. (9 lb.) actuator. The driven inertia represented by the instrument is 27 kg.m.^{2} (20 slug ft^2) and the mass of the instrument package is 11.3 kg. (25 lbs). No unloading latches are used at launch, so that the actuator output stage carries all inertial loads.

These actuators are used extensively on the Space Telescope mainframe for high gain antenna deployment, for operation of the main aperture door, and for latching of the high gain antennas, the main aperture door, and the solar



APPLICATION OF TYPE 5 ON TDRSS SPACECRAFT

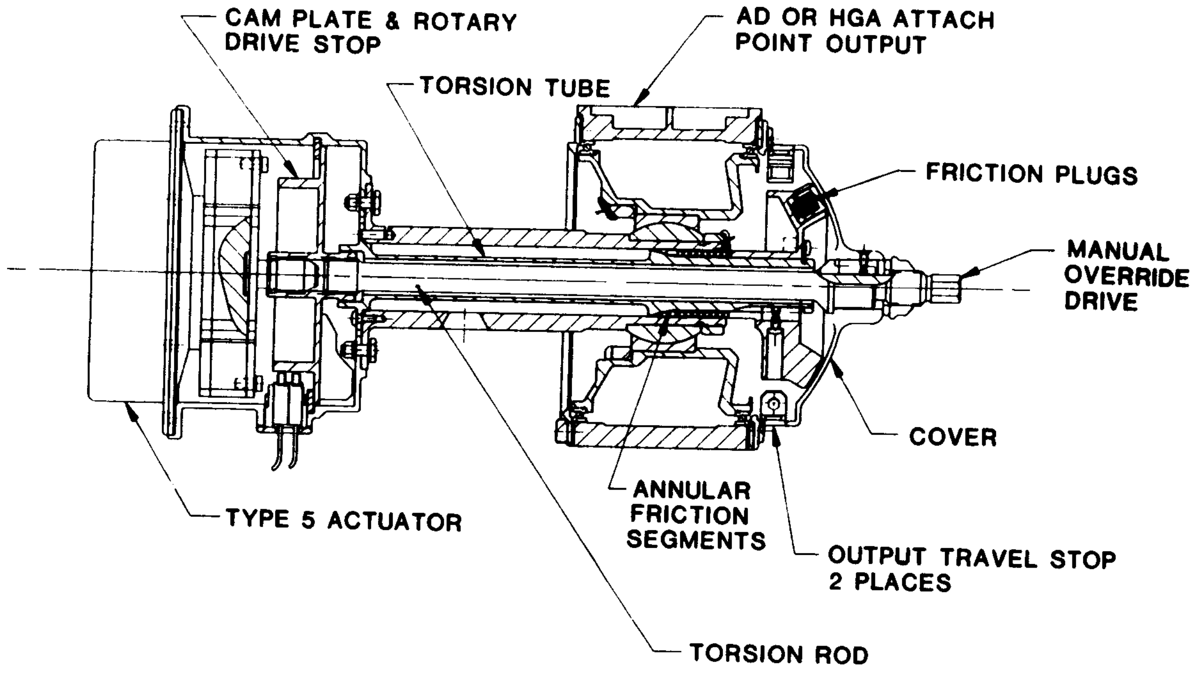
FIG. 19

array panels. The hinge and latch assemblies used for these tasks were developed by Lockheed Missiles and Space Company under NASA Contract NAS 8-32697 (2). Type 5 actuators to power these units are supplied to a common specification which is written to cover the worst case of this set of utility applications. Motors are redundant, and the devices are required, with the operation of one motor only, to meet the following specifications: torque 56.5 nt.m. (500 in-lbs) minimum, operating speed 0.039 rad. per sec. (300 pulses per second) maximum, driven inertia 474.5 kg.m^2 (350 slug ft^2), unpowered detent torque 11.3 nt.m. (100 in-lbs.) minimum/62.2 nt.m. (550 in-lbs.) maximum. (Maximum backdrive torque is limited in order to insure EVA manual re-stow capability). Figure 20 shows the actuator assembled in a typical hinge drive assembly, and Figure 21 shows a latch assembly.

Another Type 5 application on Space Telescope is found in the Optical Telescope Assembly (OTA), where an array of six Type 5 actuators are used to support and to position the secondary mirror. These units, referred to earlier, have an eccentric ball on the output flange in order to convert the output rotary motion into linear motion. Because of the very small angular output increment of the device and the small eccentricity of the ball relative to the center of rotation, an extremely fine rectilinear output step is achieved -- about 0.5 x 10^{-6}m (19 microinches) per step. Motors in this device are redundant, and the accessory devices (both potentiometers and optical position encoders) are also redundant. Potentiometers are special units located in the rear cover and are driven by a quill shaft which extends axially through the device. Optical encoders provide feedback of motor rotor position. Although the system control loop is closed through external devices, the combination of optical encoders and potentiometers provides unique position information for each of the six secondary mirror drives.

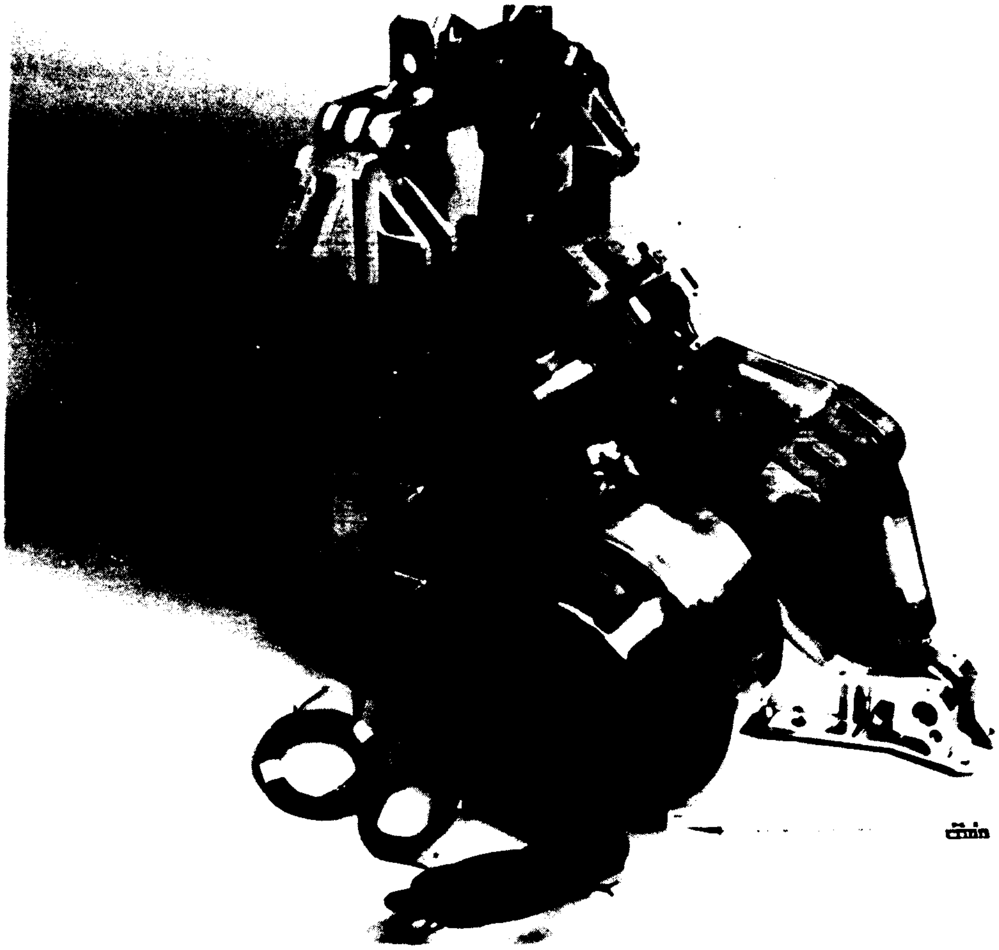
Including some other devices of a different generic type, the total count of Schaeffer Magnetics actuators on board Space Telescope reaches 58.

It appears that future applications of rotary incremental actuators will cover much the same spectrum as those of the recent past, with special interest in driving larger inertias and positioning loads in finer increments. Harmonic drives are available in sizes larger than the 2M size, and there is no inherent upper limit on the size in which the small-angle stepper motor can be built. Fine incremental positioning capability is implicit in the design, without pre-gearing or other auxiliary mechanisms, and without the need for added electronic complexities to effect micro-stepping. It is believed that these characteristics make this rotary actuator type as attractive a candidate for the increasingly demanding spaceflight requirements of tomorrow as it is for the applications of today.



SPACE TELESCOPE HINGE DRIVE ASSEMBLY

FIG. 20



SPACE TELESCOPE LATCH ASSEMBLY

FIG. 21

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