A Passive Solar Panel Orientation Servomechanism

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This study presents the design of a servomechanism containing only passive elements designed to orient a solar power panel and maintain sun "lock" without the use of electronic or electromechanical devices or wiring. No expenditure of spacecraft power is required, while torques in the order of 30 in.-lb are readily obtainable with reasonable tracking resolution and pointing accuracy.

This proposed mechanism consists of two basic components: a thermal power piston and housing and a bimetallic sun sensor. These components are linked together to provide a unique closed-loop thermomechanical servomechanism.

I. Introduction

The trend of the modern spacecraft must be towards passive systems. Complex, sophisticated electromechanical systems, while they gladden the heart of the mechanical design engineer, suffer seriously when confronted with the reality of a reliability study parts count and failure mode analysis.

In an effort to find a unique solution to a problem usually solved by electromechanical subsystems requiring relatively heavy power drains, a servomechanism (Fig. 1) utilizing the direct conversion of solar thermal energy to mechanical effort was derived.

II. Mechanism Description

This mechanism[1] consists of two basic components:

(1) Thermal power piston and housing.

(2) Thermomechanical sun aspect sensor.

These components (see Fig. 2), linked together, provide a unique closed-loop thermomechanical servomechanism capable of the moderate positioning accuracies quite suitable for solar panel operation (typically within ±5 deg of sun normality).

[1]Subject of a TRW patent application.

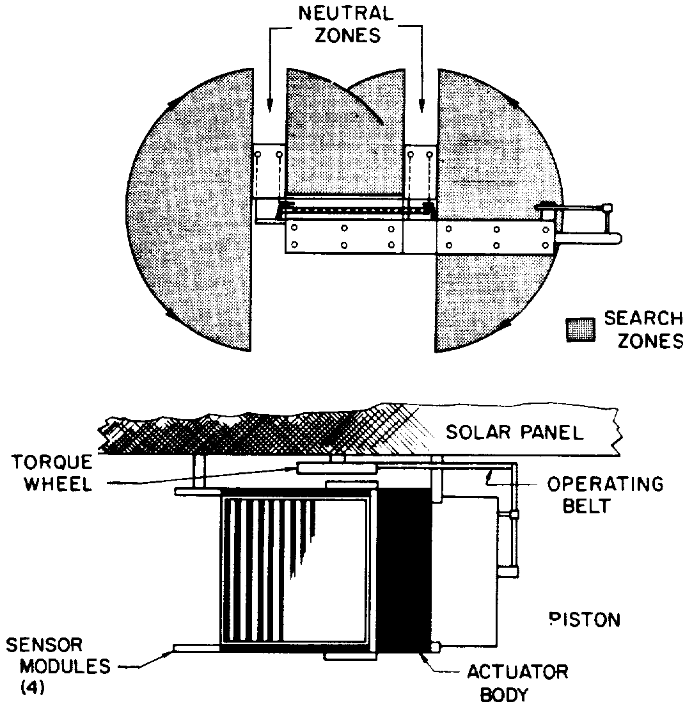

Fig. 1. Operational configuration of passive solar panel orientation system

A. Power Piston Assembly

The basic power piston operates in a cylinder machined in the center web of an H-section slab of aluminum alloy (Fig. 2, No. 1). The cylinder cavity is filled with a suitable fluid such that an increase in fluid temperature results in piston (No. 2) extension in a linear relationship to temperature rise. Similarly, a cooling of the fluid allows retraction of the piston by a torque spring (No. 13) with hysteresis errors of less than 0.5%.

The aluminum body is coated with a high-absorptivity finish on the upper surface and a highly emissive coating on the lower face. The cavities between the upper and lower fins (No. 21) are filled with a sandwich baffle of superinsulation to prevent radiation between surfaces X and Y. Thus any heat flow must take place through the central web containing the piston assembly and operating fluid. Attached to the piston rod is the cross-link (No. 17), which is connected to the torque pulley (No. 16) via a metal operating belt (No. 11).

Therefore, any extension of the power piston results in an increase in belt tension, thereby rotating the solar panel (to which the body assembly is rigidly attached)

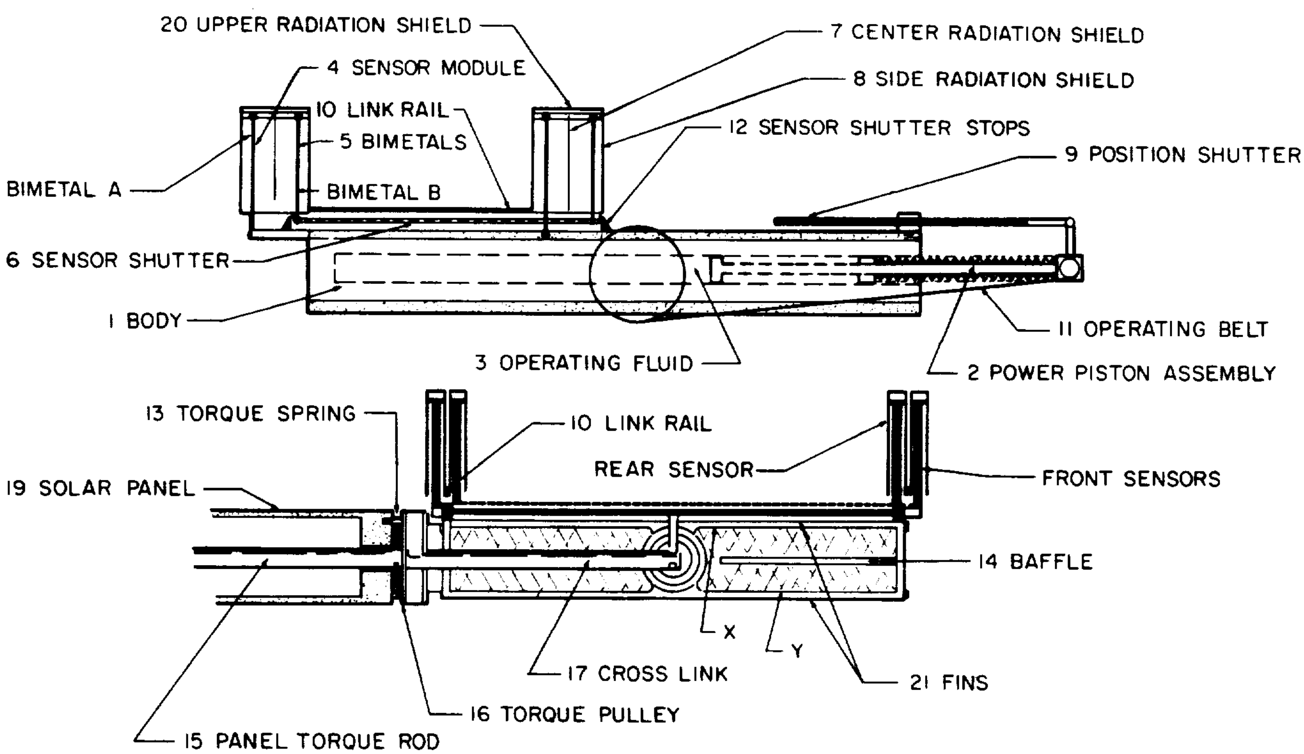

Fig. 2. Passive solar panel orientation servomechanism

around the panel torque rod, which is in turn bolted to the spacecraft structure.

Attached to the piston assembly (No. 2) is the position shutter, which rides in Teflon bushes on the upper surface of the aluminum body. Movement of the piston (following body heat-up or cool-down due to sensor action) will correct body heat balance to retain the new position by covering or uncovering the correct amount of absorptive upper surface. The sensor will of course return to neutral on sensing normal sunlight.

B. Sensor Assembly and Operation

The sensor assemblies control a shutter (No. 6) which, with "normal" sun radiation, covers a portion of the area of the absorptive body surface allotted to directional control of the system. Each sensor module consists of two bimetal strip elements A and B and radiation baffles (Nos. 7, 8, and 20). Bimetals A are attached solidly at their lower end to the body block but are thermally insulated from it, and the upper ends are pin-jointed to the two link rails (No. 10).

Bimetals B are rigidly attached to the sensor shutter (No. 6) at their lower extremities and pin-jointed to the link rails (No. 10).

Thus the sensor shutter (No. 6) is flexure-mounted above the body and restrained from excessive movement (during launch vibration, etc.) by the shutter stops (No. 12).

Solar radiation, when moving off normality towards the left of Fig. 2, will illuminate A bimetals, which will bow their tops towards the right of Fig. 2, thus carrying the link rails (No. 10), the unaffected B bimetals, and the sensor shutter to a position shutting off some solar radiation to the body. The resultant cooling of the body due to radiative heat loss will cause rotation of the whole assembly in a counterclockwise direction due to retraction of the piston assembly (No. 2). Since the piston assembly carries the position shutter (No. 9) to a position covering some of the absorptive upper surface of the body (No. 1), the cooler steady-state temperature will be retained when the sensor shutter returns to its neutral position due to a now "normal" sun (the upper radiation shields (No. 20) shadowing both bimetals at sun normality).

Illumination of the B bimetals by solar radiation from the right in Fig. 2 will cause them to attempt to bow to the right; however, the link rails, attached as they are via the A bimetals to the body, will enforce displacement of the sensor shutter (No. 6) to the left, thus uncovering some of the absorptive upper surface of the body, which will therefore heat up and extend the piston. Piston extension will rotate the whole assembly clockwise and also uncover some of the absorptive upper surface due to movement of the position shutter to the right in Fig. 1. This repositioning of the shutter (No. 9) will cause retention of the new piston/body position and allow return of the sensor shutter assembly to neutral.

III. Design Considerations

A. Power Piston and Body

The initial concept is based fundamentally on the Pyrodyne[2] actuator. This device consists of a fluid-filled cylinder and a piston that extends linearly with increase or decrease in fluid temperature.

These components have been qualified for use in space and, in fact, form part of the *Apollo* life-support control system.

Typically, extension ratios of 0.020 in./°F can be readily achieved with no theoretical limit on extension. In practice, however, the long heat-up time enforced by a large mass of fluid and very wide temperature extremes necessary for long extensions causes practical difficulties with sealing and heat-transfer arrangements.

In order to provide useful design criteria, an extension of 4.0 in. was selected, giving a total temperature excursion of 200°F.

Pyrodyne representatives indicated that such a device was practical and could be expected to deliver a 30-lb force over its range, utilizing a specially configured cylinder bore (to aid heat transfer) and a bellows hermetic seal to ensure that no fluid could be lost in space due to vacuum-enforced evaporation.

It was soon apparent that to assist in the all-important rapid heat transfer on which the time response of the device depended, the cylinder should become an integral part of the absorber/radiator system. From these considerations, the H section body was evolved.

[2]Pyrodyne Division, William Wahl Corporation, Santa Monica, California.

This configuration (see Fig. 2), was arrived at by the requirement to prevent any direct radiated heat flux from passing between the two fins and bypassing the piston assembly. As explained earlier, the volume between the two pairs of fins is filled with metallized Mylar. Aluminized fiber glass panels are used to prevent influx of radiant energy into the edges of the baffle matrix.

B. Orbital Considerations

The one constant necessary for good repeatability of panel position is a relatively consistent solar radiation flux. Variations in flux within earth orbits are unlikely to cause position errors of a magnitude to be measurable within normal operation. However, missions involving planetary flybys, etc., could cause variations in solar flux of sufficient magnitude as to require compensation to ensure maintenance of panel orientation. One method of obtaining adequate compensation is by the use of a "black body" sensor.

This sensor would take the form of a suitably coated spherical shell containing either a fluid thermal-type actuator or a bimetallic element linked to the position shutter so as to apply a bias relating to variations in thermal flux. Obviously, any variations in thermal flux would cause a variation in the steady-state temperature of the spherical housing, thus operating the enclosed actuator. This actuator could also operate a small separate trim shutter on the radiator or absorber surface of the main piston body, thereby producing the biasing action necessary for solar flux compensation. This type of bias would also help to compensate for any surface degradation that might occur in orbit.

It is worth noting that in the case of a spacecraft engaged on a mission involving relatively close sun proximity, this variation in solar flux could be arranged to deliberately allow the misorientation necessary to maintain solar panel temperatures at a reasonable level.

C. Earth Albedo and Thermal Input

Earth albedo and thermal radiation form significant inputs to this type of system at near-earth orbits (see Fig. 3); however, in view of the relatively rapid heat-up rates required at low altitudes, some assistance in response time can be gained from these inputs.

For operation at higher earth orbits, albedo and thermal radiations become insignificant within normal operating tolerances.

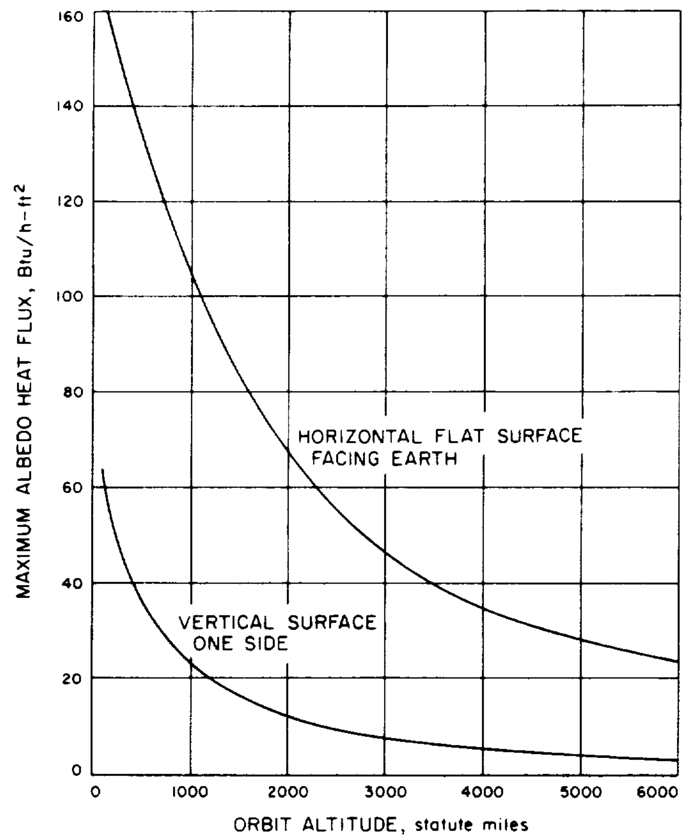

Fig. 3. Maximum albedo heat flux on one side of a flat surface

D. Actuator Slew Rate

About the fastest slew rate that the actuator will have to provide will be during a 90-min ecliptic orbit. Here the panel slew rates amount to about 4.0 deg/min.

Since the orbital height will be about 140 nmi, the time the spacecraft will be in eclipse is approximately 36 min (145 deg), assuming a simple ecliptic orbit.

Now if the solar panel drive system is arranged such that when the spacecraft is coming out of eclipse the actuator body is at its coldest position but with the panel oriented ready to receive "normal" sunlight, no rotation of the spacecraft will be necessary to "capture" the sun (see Fig. 4). It follows that the mechanism must be designed, therefore, for one of the two possible sets of conditions:

(1) When the spacecraft is in eclipse, the actuator plate cool-down rate must be such that when eclipse is completed the actuator body is at the

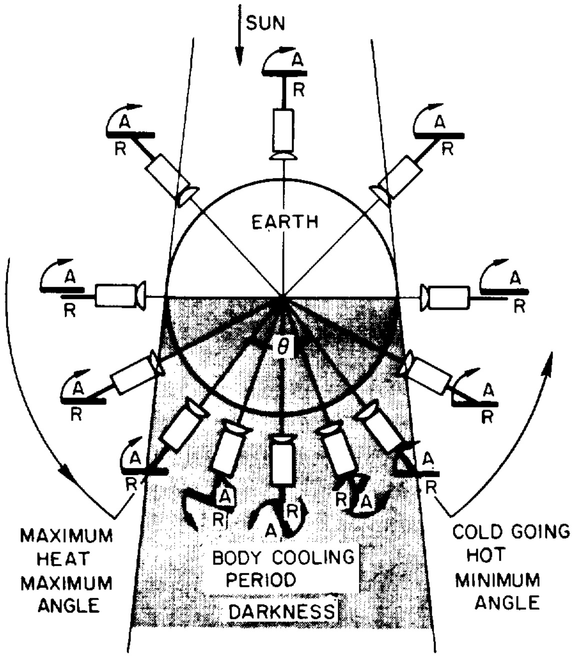

Fig. 4. Actuator body orientation cycle due to eclipse

temperature corresponding to correct sun normality, or

(2) When leaving eclipse, the actuator plate temperature is such that the sensor is so positioned as to acquire the sun within a very short time.

Since the plate is always heating up during operation, the sensor (for this particular orbit) is always demanding heat until eclipse is reached. At this point, the plate will commence cool-down. It can be seen, therefore, that no secondary systems need be applied for sun acquisition, so long as the spacecraft is three-axis stabilized.

It should be noted that the sensor described earlier has a nearly hemispherical view angle when misoriented (see Fig. 1), removing the necessity for wide and narrow angle sensors in order to achieve acquisition after maneuvering or when on a mission demanding this capability.

This effect is useful when the spacecraft is operated in orbits other than ecliptic (admittedly an ideal case), and, therefore, efficient orientation throughout the seasonal variations of orbital planes usually encountered in normal operation may be maintained.

E. Materials and Coatings

1. Piston and body. Aluminum alloy appears to be the logical choice of material for the body. Thermal conductivity is high for a relatively light weight coupled with straightforward producibility. For example, alloy 6101T6 gives very good machinability with a conductivity of 100 Btu h/ft^2/°F/ft (at 70°F) and quite adequate strength. The coating of absorber surface for maximum α/E ratio has been provisionally selected as copper plate oxidized in an Ebanol C solution, giving an α/E ratio of 14.0 (0.84/0.06).

This coating is, of course, compatible with an aluminum base by using electroless plating or copper cladding.

The radiative surface of the block is vacuum-deposited silver or silver plate having reflectances higher than 95%. However, in practice, protection of the surface from sulphide spoilage (tarnishing) is very difficult except by adding a fused silica coating. This combination yields an α/E ratio of 0.09 and an emissivity of 0.80 (α = 0.07).

F. Thermodynamic Considerations

We require a rod extension of 4 in., and, at 0.020 in./°F, a ΔT of 200°F becomes necessary. Selecting T_{max} as 700°R and T_{min} as 500°R and a fixed radiator area of 1 ft^2, the exposed maximum and minimum absorber areas can be computed assuming negligible temperature drop throughout the system and become approximately 0.3 ft^2 at 500°R and 0.9 ft^2 at 700°R. The linear position shutter travel can be arranged to deal with nonlinear heat input programs due, for example, to cosine law conditions of earth thermal radiation at low orbital altitudes, by arranging a suitable reflective pattern on the absorber surface, uncovered by the position shutter during its stroke.

These figures represent the area ratio based on a 1-ft^2 radiator; however, actual areas are really a function of desired time response and thermal mass.

Having reached the eclipse point in the ideal ecliptic orbit, the plate will be in the fully heated condition, that is, at 700°R. On entering eclipse, the plate will be exposed only to earth's thermal radiation.

However, the effect of earth's thermal radiation is negligible since the absorber surface emittance is only 0.06; thus, maximum absorbed energy at earth and plate coincidence (this radiation is subject to the cosine law) is 3.9 Btu/h/ft^2.

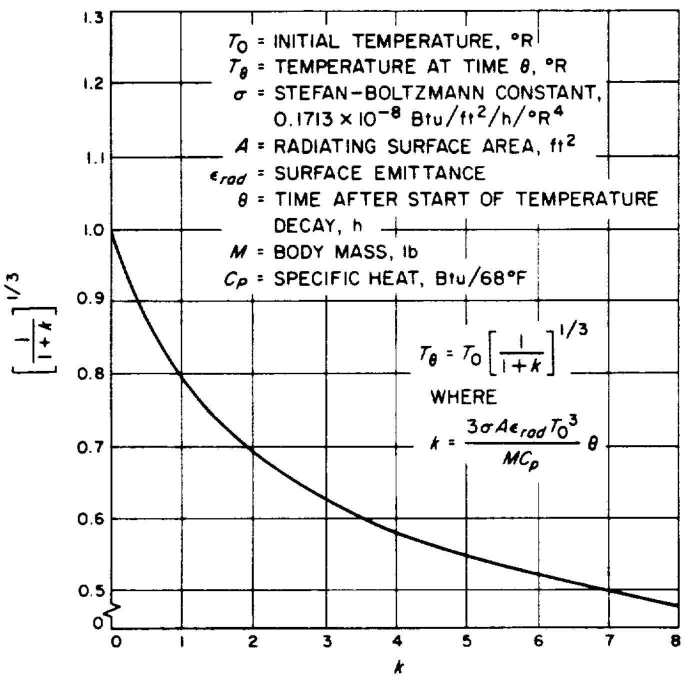

Fig. 5. Temperature decay of body with no internal or external heat input

The temperature decay (see Fig. 5) of a flat surface body with negligible heat input is expressed by

$$T_\theta = T_0\left(\frac{1}{1+k}\right)^{1/3} \qquad (1)$$

where

$$k = \frac{3\sigma A\,\epsilon_{rad}\,T_0}{MC_p}\,\theta \qquad (2)$$

and where

T_0 = 700°R = initial temperature

T_θ = unknown = temperature at time θ

σ = Stefan–Boltzmann constant, 0.1713 × 10^{-8} Btu/ft²/h/°R⁴

A = 1.0 ft² = radiating area

ϵ_{rad} = 0.8 = surface emittance

θ = 0.58 (time in eclipse) = time decay, h

M = mass of body
C_p = specific heat } MC_p = 0.445 (composite)

The term MC_p is a composite of the mass of heat expansive fluid and 2 lb of aluminum alloy and the appropriate specific heat constants.

Substituting the values noted above into Eqs. (1) and (2), T_θ becomes 495°R, which is very close to the 500°R design point of the mechanism; that is, the fully cold position.

G. Shutter Operation and Response

In order for the mechanism to operate correctly, a part of the front face (absorber) area should be sensory surface. Figure 6 shows a convenient sensor shutter configuration.

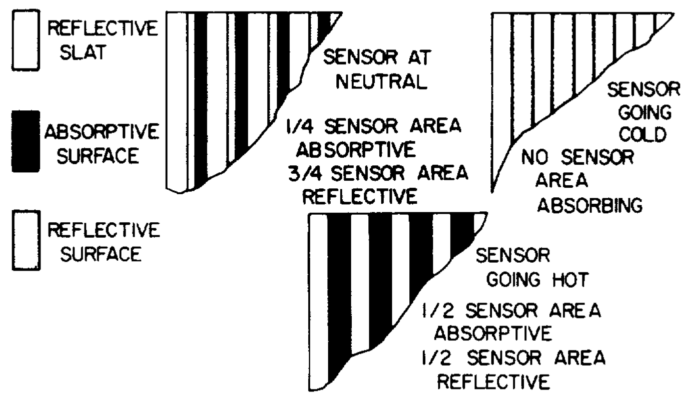

Fig. 6. Sensor area variations

This arrangement with ¼-in. spaces and ¼-in. slats adds or subtracts 93 Btu/h, depending on direction of misorientation, within 2–5 seconds of demand. This is sufficient energy to move the actuator and panel about 1 deg in about 30–40 seconds.

Obviously, to decrease this response time, more sensor area can be arranged by redesigning the absorber surface.

IV. Applications

The device discussed in this study appears to be quite practical for the worst-case orbit used as a model. Obviously, orbits requiring lower slew rates and requiring operation in both "going hot" and "going cold" modes are relatively easy to design for and will cause fewer albedo and reradiation problems than the near-earth orbits.

It is anticipated the device will weigh 4–5 lb and cover an area of 16 × 12 in. It is easily protected from launch shock and vibration by means of the overtravel stops shown in Fig. 2.

The power limitations at this time appear to be based on the 30-lb force actuator used, a trade-off between light weight, response time, stroke, and temperature range requirements. Practical limitations on the feasible maximum and minimum temperatures include such factors as surface treatment damage, excessive material evaporation, seal damage, and thermal distortion effects.

Utilization of a 1.0-in.-radius torque wheel and a 6.0-in. stroke will yield plate rotations of nearly 360 deg at a torque capability of 30 in.-lb.

Reduction of output force requirements would allow lower strokes, faster response, lower hysteresis, and more conservative operating temperatures.

These trade-off suggestions are offered in order to demonstrate the great flexibility of this design and should serve to stimulate persons engaged in the specifying of solar panel orientation systems to consider the possibility of passive thermomechanical operation.