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DRAG-FREE SATELLITE CONTROL

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A drag-free satellite cancels the effect of external disturbances. Although the forces may be small, a satellite is disturbed by residual air drag, radiation pressure, micrometeorite impact, and other small forces that act on its surface disturbing its orbit, which is principally determined by the gravity field. In some missions, these small perturbations that make the satellite deviate from its purely gravitational orbit are limiting. An internal unsupported proof mass is shielded by the satellite from the external disturbances. The position of the shield (or the main part of the satellite) is measured with respect to the internal proof mass, and this information is used to actuate a propulsion system which moves the satellite to follow the proof mass. Fig. 1 illustrates a drag-free control system. Since the proof mass is shielded it follows a purely gravitational orbit — as does the satellite following it — hence the name drag-free satellite. The idea was conceived by Lange (1964) and has been applied to many mission studies since.

In some cases, it is not necessary to cancel the disturbances, only to measure them so they may be taken into account. In such a case, an accelerometer may be a more suitable solution (for example, using the ONERA Cactus or the Bell Aerosystems MESA).

I. MISSIONS

In developing the concept of the drag-free satellite, Lange considered a number of applications. An obvious choice is when the gravitational path itself is an indicator of the gravity field, and thus disturbances decrease the accuracy with which geodesy can be studied from artificial satellites.

By observing the control effort applied to make the satellite drag-free, the disturbing forces can be measured. At low altitudes, these are predominantly atmospheric drag, so atmospheric density can be determined with unusually good spatial resolution.

A third application of the drag-free principle is to provide a uniquely weightless environment for instruments. If an instrument is used as the proof mass of the drag-free satellite, there are no support forces at all, and thus errors introduced by supports are completely removed. This feature is absolutely essential to the success of the Stanford gyro test of Relativity in which the gyros must be scrupulously free of any disturbances, so that changes in orientation they may undergo, due to their interaction with the gravity field, can be determined unambiguously.

Fourth, in a test of the principle of equivalence (proposed by Everitt and Worden 1974), the dynamic range of the measurements is greatly reduced if performed on-orbit and one of the two test masses is taken as the drag-free reference.

Fifth, when drag is cancelled, there is no uncertainty due to external disturbances, and an orbit can be predicted much farther into the future. This is useful for navigation satellites which must store and report their ephemerides (Space Department 1974).

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II. SENSORS

The position of the satellite, with respect to the proof mass, must be detected without disturbing the proof mass. Capacitive sensors have proved successful, such as those developed at Stanford (Space Department 1974) and at the Office National d'Etudes et de Recherches Aerospatiales (ONERA) (Juillerat 1970). Optical sensors may produce even smaller disturbances, but are slightly less reliable by analytical comparison, though they offer the major advantage of providing a means of detecting a small proof mass inside a large cavity — a desirable feature for some missions. A shadowing technique, developed at the Johns Hopkins University Applied Physics Laboratory (APL) (Mobley *et al.* 1975), is similar to the small motion detector proposed by MATRA in a spinning satellite, in which the large detection was performed digitally by interrupting a series of pencil beams of light. A novel technique, developed by DeHoff (1975) at Stanford, excites fluorescence in a coating on the proof mass with ultraviolet light; the re-emission occurs in the infrared. Large motions can be detected using Schottky-barrier diodes without a serious internal reflection problem. The intensity of Beta emission has also been considered at APL, and a number of other novel schemes have been proposed.

III. ACTUATION

Any propulsion system is possible, from the use of the simplest compressed gas, such as nitrogen or Freon 14 (CF_4), to the exotic pulsed plasma Teflon engine, which has many advantages for extended missions. These systems are usually pulsed to provide the most efficient use of the propellant. Cryogens, which are needed to maintain a low-temperature environment, may also be used as a propellant for drag-free control as well as for attitude control. For example, liquid helium produces an effective propellant once the gas has warmed up to satellite body temperature. Since the flow must be continuous to provide cooling, differential proportional thrusting is employed, as the efficient use of propellant is not a consideration. On the Stanford gyro test of Relativity the He gas is at very low pressure (3 torr), but the specific impulse has been measured at 137 sec. The continuous thrust makes it possible to track the proof mass smoothly without significant error. This experiment is planned to carry a Global Positioning System (GPS) receiver. With negligible proof mass error signal, the GPS signal is a direct measure of the proof mass position, enabling the satellite to perform some very useful and important geodesy.

IV. CONTROL LAWS

If the satellite's angular velocity is slow compared with the bandwidth of the control system, the control can be considered for each axis separately. Simple lead compensation is a sufficient way of providing the rate information needed to damp the closed-loop behavior. As a result of mission requirements, or to obtain averaging of some of the disturbances between the satellite and the proof mass, the vehicle may spin at an angular velocity that is significant compared with the control bandwidth. Since the measurements are made in body axes, lead compensation will be applied incorrectly as viewed from inertial space. Lange (1964) provided a correction for this by including the necessary Coriolis terms due to the rotating coordinate frame in calculating the required velocity information. At ONERA, the position of the satellite, with respect to the proof mass, was measured each quarter of a revolution and the sensors were interpreted according to their orientation in space, so that the information was actually gathered as an inertial measurement by indexing the information around to sequential sensors. Thus, even in a rotating satellite, the velocity information could be derived by a simple single-axis mechanization.

It is not always possible to place the proof mass at the mass center of the satellite. There is no interest in forcing the satellite housing to stay exactly centered on the proof mass, particularly if some of the relative motion is simply due to mutation of spin rather than a relative movement of the two mass centers that must be corrected. Sanz (1975) developed an estimator with which to subtract the part of the relative motion signal due to attitude motion in a spinning satellite. It was then possible to proceed with the control as if the proof mass was at the satellite mass center.

Most control laws, as originally conceived, are motivated by ideas of continual actuation. However, most propellants are not easily throttled, and for their effective use the thrusters are operated on-off. A dead zone is introduced into the control and this nonlinearity can cause some very interesting effects in a rotating satellite. Specifically, equilibria can exist beyond the edge of the dead zone when dead zones are established for each axis of the control. These equilibria are locations where the error signal produces a thrust equal to the centripetal acceleration of the mass center moving about the center of spin. Powell (1972) discovered these equilibria and developed circular dead bands and the techniques for mass center estimation to locate the pickoff null to coincide with the center of spin. With his techniques, spinning satellites, even with nonlinear control, can be made to operate as efficiently in their use of propellant as nonspinning satellites.

Some disturbances between the proof mass and the satellite have a gradient. Thus, if an external disturbance requires an error signal which will be correlated with the direction of the disturbance in space, averaging may not be obtained in a spinning satellite. Integral control is the solution to this problem; however, the calculations must be performed in a rotating coordinate frame. An inertially fixed external disturbance, which appears to rotate in the satellite coordinate frame, can be modelled as an oscillator and the benefits of integral control in inertial space are obtained (Tashker 1974).

V. ERROR SOURCES

For missions in which the path of the satellite must be as nearly gravitational as possible, it is important that disturbances between the satellite and the proof mass are made quite small. Solar radiation pressure acting on a typical satellite with an area-to-mass ratio of 0.01 m^2-kg^{-1} produces an acceleration of the order of 10^{-7} m-s^{-2}, thus the proof mass acceleration from internal disturbances must be kept several orders of magnitude smaller than that if improvements are to be realized. Disturbances from electric charge, gradients in magnetic fields, the radiometer effect due to temperature differences, radiation pressure due to temperature differences, and many other effects can be calculated and must be taken into account. With careful design these can all be kept below 10^{-11} m-s^{-2} using a proof mass of 20 mm diameter made of a heavy metal. The density must be high to reduce the area to mass ratio. An alloy of gold and platinum can also minimize magnetic susceptance (Space Department 1974).

the mass attraction between the satellite itself and the proof mass. The vehicle must be symmetrical, the location and the mass of the parts, especially those close to the proof mass, must be determined and compensating masses must be placed nearby to offset the mass attraction.

VI. FLIGHT EXPERIENCE

In 1972, the first drag-free satellite was launched. It provided a prediction capability for navigation satellites of 2 weeks, compared with the 12-hour limitation caused by the uncertainty in estimating atmospheric drag and radiation pressure. This three-axis control system demonstrated the principles and achieved a performance level of 5×10^{-11} m–s^{-2} (Space Department 1974) (see Fig. 1). Subsequent flights have been made with single-axis, drag-free satellites providing the drag-free performance in the in-track direction, which is most sensitive to error buildup, and using a passive eddy current repulsion suspension technique for the proof mass in the vertical direction and normal to the orbit plane. Pulse plasma thrusters provide lifetime potential of 7 years or more. With proper modelling of the attitude behavior, the equivalent prediction capability of 10^{-10} m–s^{-2} was achieved in 1982 with the NOVA navigation satellite (Eisner and Yionoulis 1982).

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DISCUSSION

SHAPIRO: Have you considered the placement of optical corner reflectors on the GPB satellite to allow 'cross-checking', as part of the geodesy uses of the GPB flight?

DeBRA: Yes. It may not provide more or better information than the GPB continuous, but it is important to have a comparison of radio and optical data. It is our intention to add corner reflectors for whoever may wish to use them.

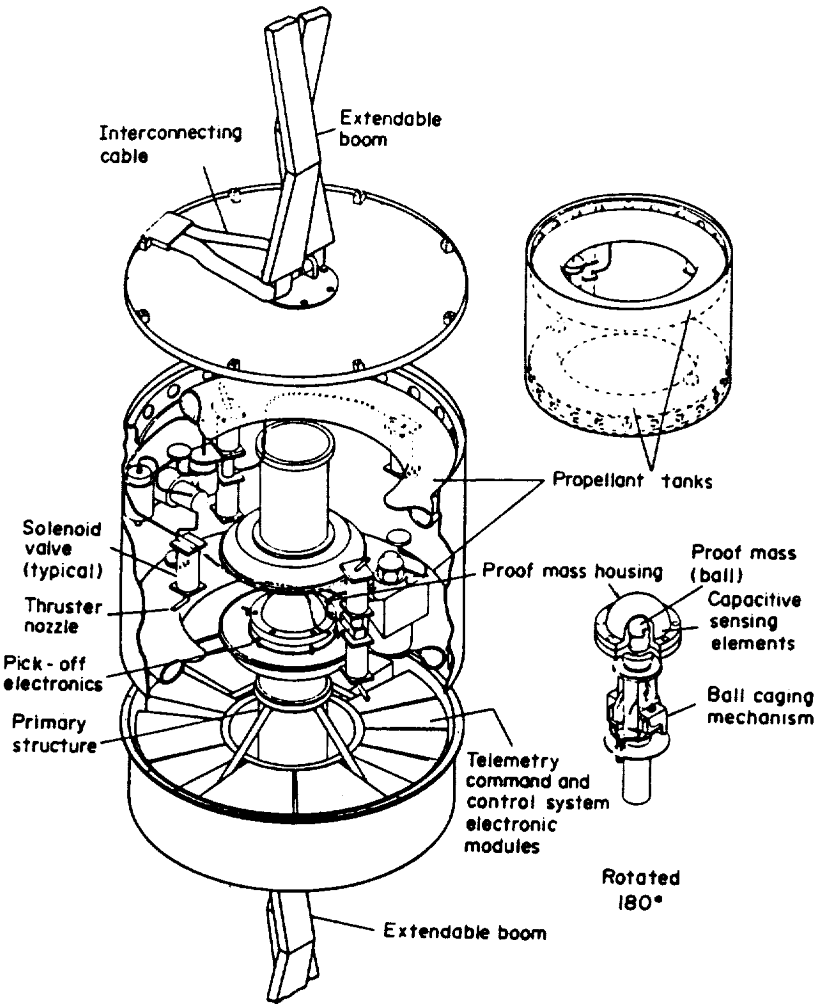

Figure 1
Cutaway drawing of the Stanford disturbance compensation system (DISCOS)