APPLICATIONS FOR INERTIAL SENSORS IN SPACE

Space missions are characterized by many possible trade-offs which provide options in how one uses and what is demanded of the inertial sensor. For example, in the space launch vehicle area, the Saturn is guided completely by an on-board inertial system while NASA versions of the Delta, Atlas and Titan II use radio or radio inertial systems. Although these radio systems were developed by the Department of Defense, it was inevitable, to meet military mission requirements, that the later generation ballistic missile systems would be all-inertial. For space applications, and I will be discussing non-military space applications, the options, in guiding launch vehicles by on-board or ground-based systems remain.

For many potential future missions, the inertial sensor requirements are not spelled out in firm numbers, either in terms of accuracy or operating lifetime requirements. Total mission life, much of which may be "shelf" life for the inertial sensors is easily determined. However, the operating life for future missions may depend on other factors. In Mariner IV, for example, a derived-rate passive attitude reference system was used in place of gyros during long period cruise. Similarly, a timer was used instead of an integrating accelerometer for controlling the midcourse correction rocket-thrust magnitude. Making a number of options available gives the system designer more latitude in configuring his system and providing redundan

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As I mentioned, current space launch vehicles use a variety of guidance configurations. The inertial sensor plays a role in all of the guided vehicles, either as part of an inertial guidance platform system as used in Saturn, or as a sensor for attitude reference and control from an on-board programmer or ground-based command. It seems safe to say that present inertial sensor accuracy, both gyro and accelerometer, is adequate for future launch vehicle missions. Considering other factors that affect interplanetary trajectory accuracy, it does not appear that working towards providing sufficient launch guidance accuracy to eliminate the midcourse corrections for advanced planetary missions would be a fruitful objective. The trend in injection launch vehicles is towards larger stages where achieving todays performance in smaller inertial packages is not a major consideration. However, such smaller sensors will certainly be used as they become available. Current sensor efforts for launch vehicle gimballed systems, however, are primarily aimed at achieving improved reliability margins.

As strapped-down inertial systems are now receiving attention for launch as well as other phases of space missions, new possibilities as well as problem areas arise. Among the possibilities, standardized subsystem packages for use in launch vehicles and many types of spacecraft can be considered. The relative ease of replacing an out-of-tolerance sensor during the launch countdown instead of substituting a complete platform is most attractive. Again, there is in the trade-off area, computer complexity versus platform complexity, and the relatively benign

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platform performance demands and environment, versus the increased torquing and rougher environment for the conventional sensor when mounted directly to the vehicle. As a compromise approach, consideration is being given at Marshall Space Flight Center to the single axis platform system which alleviates the strapped-down gyro performance problem while providing many of the advantages of the strapped-down system.

The use of one sensor package and computer for both guidance and autopilot functions has been considered for launch and cruise vehicles over the years. The strapped-down inertial package, operating directly in vehicle body axes, offers interesting possibilities for achieving this capability. A decision to implement this approach would favor sensors having good rate measuring capability as well as inertial quality drift rates. The laser gyro, which has the potential for meeting these requirements as well as the ability to withstand severe launch phase environments, could be of interest for such an application.

I would like to mention one final item in the launch vehicle area. The availability of very lost cost, small inertial guidance systems could improve the capability of relatively inexpensive rocket probe vehicles. It is fortunate that here as in other areas, military and NASA objectives tend to require similar capabilities and current military missile guidance programs may contribute to eventually achieving this capability.

Spacecraft navigation and guidance systems for manned and unmanned applications have understandably taken different paths in their development. Unmanned spacecraft have depended on ground-based radio navigation and guidance computation systems, with on-board inertial sensors used only to control thrust direction and magnitude for midcourse maneuvers. Manned spacecraft systems are being designed for a complete on-board capability under astronaut control, supplemented by the use of ground-based tracking information to improve accuracy and provide redundancy.

The lunar and planetary unmanned spacecraft flown to date, because of the short period of operation for inertial sensor drift rates to accumulate during midcourse correction, and need for simplicity and power saving, have used low viscosity flotation fluid in their gyros and eliminated temperature control. Gyro drift rates have been typically about 0.5°/hr. In Mariner IV, where the possibility of losing attitude reference existed during the picture taking portion of the mission, if the Canopus Tracker lost the star due to reflected light from Mars, lower drift rate gyros could have provided an attractive alternative to the celestial reference system during that phase of the mission.

Recognizing the desirablility of continually improving the lifetime and reliability of gyros, and need for providing a capability for on-board guidance for atmospheric planet entry and soft landing on the planets, efforts have proceeded at the Jet Propulsion Laboratory to develop gas bearing and electrostatic gyros for potential application to unmanned spacecraft missions.

The first slide illustrates typical requirements for gyros on unmanned spacecraft for future planetary missions. The requirements range from less than 1.5°/hour for acquisition and cruise, to less than 0.01°/hour for capsule maneuver guidance for planetary entry. The lifetime improvement requirement applies to all of the mission functions.

Earth satellite spacecraft are entering the era of long-term useful life requirements along with more demanding requirements for attitude reference accuracy. While solar, celestial and earth pointing techniques will be primary, gyros are required for short term memory during occultation of the sun or reference star, for acquisition of new target stars for pointing schientific instruments and for damping horizon scanners. The goal of five years of reliable operating life for many application satellite missions and the desire for low power consumption, provide challenging gyro technology requirements. Goddard Space Flight Center has initiate specific efforts towards achieving this five year lifetime capability, while general technology efforts on gas bearing, electrostatic and no-movin g part gyros should contribute to reaching this goal.

The navigation and guidance system concepts being implemented for Apollo, based on a complete on-board capability using a sextant-telescope, computer and inertial measurement unit, can be expected to set the pattern for manned spaceflight planetary missions. It is interesting to note that for Apollo, the IMU and computer have now become the primary attitude reference system. The computer derives attitude rates and sums these with the attitude error to develop control signals. Strapped-down inertial measurement units, presently used only in the LEM Abort system, can be expected to receive further consideration, taking into account the advantages and disadvantages mentioned earlier, as well as the new role of the guidance and navigation system as the primary attitude reference system. As mentioned earlier, the use of strapped-down systems having both rate and position measuring capability would be an asset in performing this dual function.

A typical set of requirements for inertial sensors for future manned missions is shown on the next slide. Keeping in mind the capability of frequent realignment from navigational sightings, the performance figures shown here may be somewhat stringent. However, the MTBF requirements will continue to increase as longer missions are planned.

The most critical phases for inertial sensor performance in manned planetary mission are planet entry and Earth reentry. Even, with reasonable uncertainty in knowledge of the planetary atmosphere for a Mars mission, the Earth capture maneuver phase is the most difficult for the navigation and guidance system because of the higher approach velocity. However, the use of a Venus swing-by return for such a mission reduces the Earth approach velocity to an acceptable level for automatic system and possibly pilot controlled guidance. Simulation studies at Ames Research Center have shown the need for velocity, acceleration and altitude rate information for the pilot to perform the critical capture maneuver. During reentry, where communications blackout may preclude the use of ground-based updating, there is need for an inertial system that will provide reasonable performance with high reliability at the end of a mission that may last two years or longer.

The development of the "true" free rotor gyro, typified by the electrostatic or electric vacuum gyro makes strapped-down systems particularly interesting for spacecraft application. Ability to drastically decrease the rotor suspension voltages during zero-g mission phases, reduces power consumption requirements and should improve performance. During maneuvering periods, the elimination of need for rapid precision torquing provides potential for an effective strapped-down system implementation. Present electrostatic gyros, however, do not have adequate rate measuring capability, and would probably require the use of derived rate as used in Apollo for attitude reference.

An interesting concept for an optical-inertial space sextant has been supported by Ames Research Center and is illustrated on the next slide. This concept uses two free rotor gyros, strapped to the sextant base, as protractors to read and furnish in digital form the measured sextant angles. The off-axis vidicon tracker which has been fabricated and demonstrated, is capable of narrow and wide-angle tracking modes. The tracker has not yet been integrated with the gyros. The gimbals shown serve only to facilitiate the celestial tracking function. Since the gyros provide the angle measuring capability, neither precision angle readout nor highly rigid gimbals are required. The self-stabilized device could, conceivably, be tethered outside the spacecraft, eliminating the need for even coarse attitude control of the spacecraft during sightings.

The subject of unique uses of inertial sensors in space for extremely low-level force measurements has been very well treated in a paper of a year ago, "Measurement of Small Specific Forces in Space" by Draper, Frey, Sapuppo, and Chapman, published in the Astronautics Acta Series. As noted in that paper, the use of accelerometers for measuring very small forces for a number of navigation and space experiment applications has been considered. These include guidance for spacecraft having low thrust level propulsion systems and the use of active gravity gradient attitude reference systems. Space experiments considered include detection of gravity waves and a pure gravitational orbit satellite to perform a gyro test of general relativity.

Measurement levels as low as 10^{-12}g are required for some of these applications. Assuming that it may be possible to measure such forces in space, the design and testing of the instruments on Earth is a formidable problem.

A number of novel low level accelerometers have been proposed and modifications of existing sensors have been considered. The electrostatically suspended accelerometer, whose support forces can be reduced in orbit to measure low accelerations, possibly as low as 10^{-12}g, is of interest for this application. A flight experiment using this type of accelerometer will be performed later this year on a Saturn as a joint undertaking between the Lewis Research and Marshall Space Flight Centers.

This will provide some insight into whether the accelerometer will suspend under near zero-g at low voltages and hopefully obtain some insight into the capability to measure very small forces. Other sensor concepts using cryomagnetic suspension along with optical means to detect proof mass displacement are being investigated.

The pure gravitational orbit satellite, proposed and under study by Stanford University through NASA sponsorship, would be used to perform a gyro test of General Relativity requiring the measurement of precession rates in the order of seven seconds of arc per year. A gyro drift rate of 0.01 seconds of arc per year is desired for the experiment. The approach being pursued utilizes a solid quartz sphere, electrostatically suspended at a superconductive temperature, in a zero magnetic field. London moment readout is used to track the angular momentum axis of the sphere.

The inertial sensor can be seen to play an important role in many space missions. The performance requirements vary greatly, depending upon the mission application. In addition, the unique environment of space has created interest in unusual inertial sensor applications that did not exist prior to the space era.

SPACECRAFT/CAPSULE ATTITUDE CONTROL & GUIDANCE
INERTIAL SENSORS

FUNCTION	SENSOR	PRESENT DRIFT PERFORMANCE	FUTURE DRIFT PERFORMANCE	REQUIRED IMPROVEMENTS
ACQUISITION	RATE	$< 1.5°/HR$	SAME	LIFE RELIABILITY
CRUISE	RATE	$< 1.5°/HR$	SAME	LIFE RELIABILITY
MANEUVERS	RATE & POSITION	$< 0.5°/HR$	$< .01°/HR$	LIFE PERFORMANCE STERILIZATION
ORBIT PLANE DETERMINATION	RATE	—	$< 0.1°/HR$	LIFE PERFORMANCE WEIGHT-POWER
INERTIAL HOLD	RATE & POSITION	—	$< 0.1°/HR$	LIFE PERFORMANCE WEIGHT-POWER

TYPICAL REQUIREMENTS FOR FUTURE MISSION MANNED SPACECRAFT INERTIAL SENSORS

Gyroscope:

Weight	0.5 to 1.0 lb
Randon drift rate	0.001 deg/hr
Mass unbalance stability/mo	0.001 deg/hr/g/mo
Anisoelastic drift	0.001 deg/hr/g^2
MTBF	10 to 50K hrs

Accelerometer:

Weight	0.5 lb
Threshold	10^{-6}g
Linearity	.001% at 15 to 20g
Scale factor stability	10^{-6}g/deg c
Null stability	10^{-6}g/mo
MTBF	10 to 50K hrs

OPTICAL INERTIAL SEXTANT
ELECTROSTATICALLY SUSPENDED GYROS

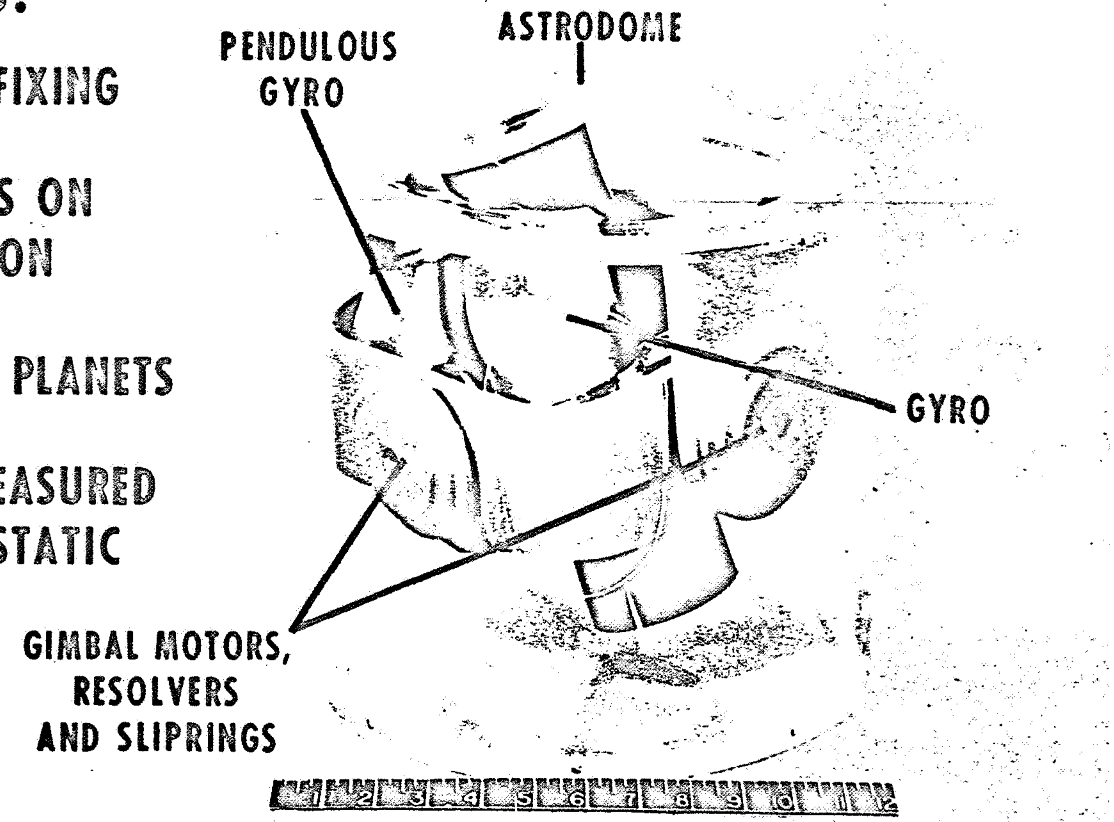
FEATURES:

MIDCOURSE POSITION FIXING

REDUCED REQUIREMENTS ON SPACECRAFT ORIENTATION

CLOSE IN TRACKING OF PLANETS

DIRECT READOUT OF MEASURED ANGLES FROM ELECTROSTATIC GYROS



NASA RE64–385

Fig 3