Future Payload Isolation and Pointing System Technology

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Pointing requirements for spaceborne scientific instuments are getting progressively more stringent. At the same time, many of these instruments are likely to fly in an increasingly disturbance-rich environment characterized by large basebody and instrument-to-instrument dynamic interactions. It is not clear that current state-of-the-art pointing technology will be able to adequately address the needs of articulated instruments in a multipayload environment. Design options to meet these needs are suggested herein, including a soft-mounted, inertially reacting concept.

Introduction

THROUGHOUT the remainder of the current decade and through the 1990s, the pointing requirements of spaceborne scientific payloads (both planetary and Earth orbiting) will grow increasingly more stringent. It is further likely, for reasons of cost effectiveness, that the trend will be away from single payload, dedicated free flyers and toward multipayload space vehicles. These contingencies drive the need for the development of advanced pointing mount technology that can simultaneously provide a high degree of precision while isolating a payload from a disturbance-rich host vehicle.

Traditionally, the pointing of space-based scientific instruments has been implemented via a custom-designed scan platform/pointing mount (e.g., Voyager and Galileo). The costliness of such an approach motivated the recent development of so-called "generic" pointing mounts, designed to accommodate a wide variety of Space Shuttle-based experiments.[1-7] Although a number of these mounts passed the conceptual stage and some were even prototyped, the European Instrument Pointing Subsystem (IPS) is currently the sole survivor of this development effort. IPS and the recently cancelled Advanced Gimbal System (AGS) would appear to be logical candidate payload pointing systems for future space platforms/stations. The problem is that it is unlikely that such systems (which consist of precision gimbal assemblies), even with major modifications, will be able to meet the most stringent scientific pointing requirements of the mid 1990s. These requirements will likely be in the sub 0.1 arcsec range (for pointing stability) which is more than an order of magnitude improvement over current IPS and AGS capabilites.

This is not to say that such pointing is beyond the current (or near-term) state of the art. The Space Telescope promises to do considerably better than 0.1 arcsec but will do so with an expensive custom-designed pointing system that relies upon an extremely quiet host vehicle.[8] The challenge is to develop a modular, multimission mount that can deliver the necessary pointing at a reasonable price and in the presence of significant disturbances and other environmental constraints (e.g., basebody flexibility). Our ultimate objective is to set forth technology options which would enable such a system. This paper represents a first step in that direction.

Future military precision pointing systems (e.g., for ballistic missile defense) may have some similarities to civilian systems, and may in fact use some of the technology described below. Military requirements will likely be tighter than those given here, and will have to be achieved during high rate slewing and tracking. Although the discussion below is appropriate for military systems also, they will not be addressed explicitly.

We will begin by considering the high-level architectural options that characterize the precision pointing problem. Attention then shifts to a compilation of a representative NASA mission set for the decade of the 1990s. Pointing accuracy and stability (jitter) requirements are extracted from mission requirements, with the sub 0.1 arcsec stability requirement emerging as the primary driver. Next, the state of the art of current technology is assessed. This survey includes an evaluation of gimbal systems, suspension systems, and actuator and sensor component technologies. Military systems will be given only brief mention, however. Areas where the technology needs to be pushed to satisfy future requirements are identified, and some promising design options are proposed. Some of these designs represent alternatives to gimbal-based systems. A common thread among the alternative systems is the use of a very "soft" interface between the basebody and the payload. A planar stability and disturbance response analysis reveals that the softmount approach enjoys several advantages over a simple gimbal mount, especially in light of the likely pointing environment of the next decade.

Architectural Options

Before a set of design options is formulated, it is useful to identify the top level architectural options for the precision pointing problem. Architectural considerations can be cast into three categories: actuation options, sensing options, and control methodology options. Pointing actuation will be accomplished via a multilevel system topology. There could be just one level, as is the case for a free-flying spacecraft dedicated to the pointing of its payload. We will refer to such systems as having zero-level actuation, since there are no articulating elements. The Space Telescope is an example. Extremely high precision is achieved by making the telescope an integral part of the spacecraft, constraining disturbances to a very low level, and pointing the whole assemblage using a set of very quiet reaction wheels. Multimission vehicles are our primary interest here. These generally require at least a single-level pointing architecture (i.e., one level of articulation), if only to satisfy competing pointing objectives. Articulation is also necessary to provide compensation if the spacecraft basebody is excessively noisy. More than one level of articulation allows for a vernier approach, with each level successively more precise. SIRTF, the Space Infrared Telescope Facility (which may ultimately fly on the space station), plans to use a

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two-level actuation architecture with "coarse" articulation provided by a gimbal system, on top of which an articulating secondary mirror fine-tunes the line of sight. A three-level system is pictured in Fig. 1. Note that the various levels of actuation can serve distinctly different functions. In the figure, the "dynamic isolation" block serves mainly as a disturbance decoupling stage, while "image motion compensation" typically provides high bandwidth jitter rejection. This scheme is used in the military Talon Gold Experiment (now ground based), designed to demonstrate precision pointing for space-based laser systems, which employs a two-stage actuation system consisting of magnetic suspension and fast steering mirrors. A multilevel actuation architecture presents the designer with options as to the number of levels, the arrangement of levels, and the component makeup at each level.

Sensing options are driven by the pointed payload's attitude determination scheme. Such schemes fall into three categories: basebody referenced, inertially referenced, and target referenced. Basebody referencing leaves the bulk of the work to the vehicle basebody. The payload is only responsible for determining its position relative to the basebody, typically through a set of potentiometers, resolvers, or angle encoders. Such an approach has fundamental limitations: The payload attitude knowledge can never be as good as that of the basebody, since the sensing of relative position introduces errors; it is difficult and expensive to sense relative position to high precision; and structural deformations between the basebody attitude sensors and the payload line of sight are unsensed and can take on significant values. For all these reasons, basebody-referenced pointing is not the indicated approach for high-precision applications. An inertially referenced scheme allows for much higher accuracy. IPS and AGS both take this approach. They mount star trackers and gyros on the payload side of the gimbals, which allows them to measure payload attitude directly with respect to the "fixed" stars. The absolute accuracy of this approach, given the state of near-term star tracker capability, will soon be limited only by the accuracy of current star catalogs (about 1 arcsec). By the mid 1990s the Space Telescope should have improved star catalog accuracy by at least an order of magnitude. Hence, by the middle of the next decade, 0.1 arcsec inertially referenced attitude determination should be possible. Target referenced tracking is capable of providing the ultimate accuracy. As the name implies, here the pointing loop is closed around the target so that issues of interposed flexible structure and alignment calibration are effectively bypassed. However, a price must be paid: The pointing control system must have access to an error signal provided by the payload's focal plane sensors. This can be done, but it makes for complex, instrument-specific interfacing problems and sorely compromises the pointing system's prospects for modularity and multimission capability. If these are goals, it is better to implement target-referenced tracking on the payload, where it can be utilized as part of an image motion compensation system.

The third facet of any control system, besides sensing and actuation, is the manner in which the loop is closed, i.e., the control methodology. The top-level options are classical methods vs modern control. Either approach will have to address the need and applicability of several important techniques: disturbance rejection, flexible body modeling and compensation, feedforward and preview control, system identification, and adaptive control. Underlying all is a fundamental trade between isolation and compensation, i.e., to what extent should a pointed payload be dynamically isolated (passively or actively) from basebody disturbances, and to what extent should active control be used compensate for these disturbances? Finding the proper mix will be a major driver in the choice of both sensing and actuation options.

Mission Set

In order to assess the readiness of current and near-term pointing technology, it is essential to know the requirements and constraints against which the technology will be applied. Hence, we have assembled a representative set of science missions of the next decade which require precision pointing. The missions can be classified according to whether they are Earth-orbiting free flyers, attached to the space station/space platform, or carried on planetary probes. We will treat each in turn.

Earth-Orbiting Free Flyers

A wide variety of Earth-orbiting free-flying missions are planned from 1986 to 2000 (see Table 1 for those requiring precision pointing). The most precise pointing is required by the Space Telescope. The Large Deployable Reflector (LDR) also is a challenging problem, not only because of its pointing requirements but because it consists of an array of individual mirrors, perhaps 20 m in diameter, requiring precision shape control. The rest of the missions are within current technology. Both the Space Telescope and LDR will be custom-designed systems, and so will not be considered in detail here. Since the other missions do not require articulation, nor do they push the state of the art, they are not of central interest to this survey. They are included primarily for the sake of completeness. It is conceivable, however, that some of the instruments [e.g., the advanced X-Ray Astrophysics Facility (AXAF)] could actually fly as payloads on the space station or on co-orbiting platforms together with other

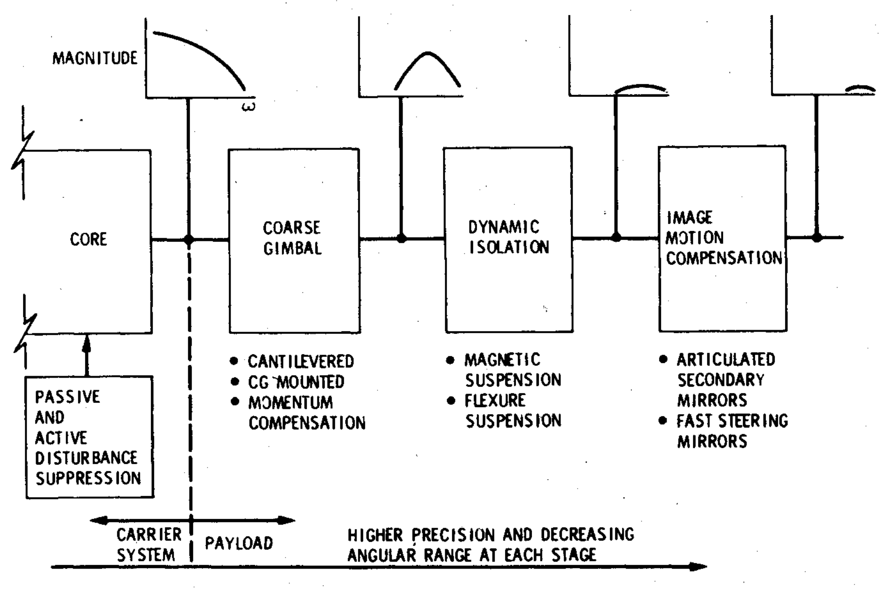

Fig. 1 Multilevel actuation architecture.

payloads, rather than as free flyers. As attached payloads, their pointing would be more challenging and would fall into the domain of interest of this study.

Space Station/Space Platform Attached Payloads

Several Earth-orbiting space platforms are currently planned for 1990-2000 under the aegis of the space station program. These may include[9] a) space station: a low-inclination, manned station; b) Earth Observing System (EOS): a set of polar-orbiting, unmanned platforms, each with its own complement of predominantly Earth-observing instruments; c) Co-orbiting platforms: a set of unmanned platforms in the same orbit as the space station, mainly including large solar and astrophysics payloads; and d) Geosynchronous platform: a proposed high-altitude, unmanned platform.

NASA has sponsored several independent studies of space station needs, attributes, and architectural options undertaken by various private corporations. The pointing requirements for attached payloads listed in the more complete of these studies[10-12] are plotted in Fig. 2 along with the latest data in the NASA Langley space station data base.[13] Some near- and far-future free flyers, such as the Thinned Aperture Telescope (TAT), are included for comparison. The pointing requirements (from the Langley data base) of some instruments that are candidates for attachment to the space station are given in Table 2.

The pointing capabilities required by the various scientific instruments varies considerably, even over the more limited set of instruments in the Langley data base. The tightest requirements in the Langley data base are for SIRTF, STARLAB, Advanced Solar Observatory (ASO), Large Imager (LI), High Resolution Imaging Spectrometer (HRIS), Multilinear Array Stereo (MLAS), Stereo Synthetic Aperture Radar, Multilinear Array, and Coastal Zone Color Scanner (SSMC), and Pinhole Occulter Facility (P/OF). Detailed descriptions of these payloads are given in Refs. 10 to 14. They all require sub arcsecond stability and accuracies better than 10 arcsec. The payloads that need precision pointing are also

Table 1 Earth-orbiting, free-flying missions

Mission	Launch year	Pointing Requirements: Accuracy, arcsec	Pointing Requirements: Stability, arcsec
Solar Coronal Diagnostic Mission (SCDM)	1995	10	2
Space Telescope (ST)	1986	0.01	0.007
Gamma Ray Observatory (GRO)	1988	1800	60
X-Ray Timing Explorer (XTE)	1991	360	36
Advanced X-ray Astrophysics Facility (AXAF)	1991	30	0.2
Far Ultraviolet Spectroscopy Explorer (FUSE)	1993	2	1
Solar Seismology Mission (SSM)	1993	2	1
Ocean Circulation Mission (TOPEX)	1989	720	N/A
Orbiting Very Long Baseline Interferometer (OVLBI)	1995	30	1
Large Deployable Reflector (LDR)	1997	1	0.03

Table 2 Candidate space station attached payloads, from NASA/Langely database

	Orientation	Pointing accuracy, arcsec	Field of view, deg	Pointing stability rate, arcsec/sec	Pointing stability, arcsec	Launch nominal	Mass (kg) maximum
Multilinear Array Stereo (MLAS)	Earth	8.700	80.000	0.800		92.000	
Stereo Synthetic Aperture Radar, Multi-Linear Array, and Coastal Zone Color Scanner	Earth	8.700		0.800		1500.000	
Spectra of Cosmic Ray Nuclei (SCRN)	Other	36000.000	140.000	100.000	36000.000	3082.000	
Shuttle Infrared Telescope Facility (SIRTF)	Inertial	0.150	60.000		0.100	4000.000	
Transition Radiation and Ionization Calorimeter (TRIC)	Other	36000.000	120.000	100.000	36000.000	5750.000	
STARLAB	Inertial	2.000	180.000		0.020	3200.000	
High Throughput Mission (HTM)	Inertial	180.000	200.000		10.000	10000.000	
High Energy Isotope Experiment (HEIE)	Other						
Pinhole/Occulter Facility (P/OF)	Solar	10.000	3.000		1.000	3600.000	
Advanced Solar Observatory (ASO)	Solar	1.000	0.500		0.100	12500.000	
Lidar Facility (LF)	Earth/Other	3600.000	60.000		3000.000	1900.000	
Geosynchronous Platform	Solar/Earth	6.000	20.000	0.30	0.300	7000.000	15000.000
Space Plasma Physics PL/Advanced (SPPP/A)	Solar/Earth	3600.000	360.000		3600.000	3200.000	
Moderate Resolution Imaging Spectrometer (MODIS)	Earth	30.000	90.000		30.000	360.000	
High Resolution Imaging Spectrometer (HIRIS)	Earth	1.000	60.000		1.000	2100.000	
High Resolution Multifrequency MW Radiometer (HMMR)	Earth	60.000	150.000		60.000	320.000	
Laser Atmospheric Sounder (LASA)	Earth	30.000	80.000		30.000	1300.000	
Synthetic Aperture Radar (SAR)	Earth	15.000	50.000		360.000	1000.000	
Radar Altimeter (ALT)	Earth	180.000	1.600		100.000	150.000	
Scatterometer (SCATT)	Earth	360.000	90.000		360.000	150.000	
Tropospheric Composition Monitor (TCM)	Earth	300.000	60.000		300.000	1400.000	
Direct Tropospheric Wind Sensing	Earth	10.000	104.000		10.000		
Upper Atmospheric Composition (UAC)	Earth/Other	30.000	140.000	10.000	30.000	1430.000	
Upper Atmospheric Wind Sounding (UAWS)	Other	180.000	140.000	10.000	180.000	200.000	
Environmental Monitors (EM)	Solar/Earth Other	300.000	360.000		300.000	300.000	
Automated Data Collection/Location System	Earth	36.000	140.000			300.000	
Large Microwave Antenna (LMA)	Earth				3.000	2000.000	5000.000
Infrared Sounding (IS)	Earth	6.000	20.000		3.000	500.000	1000.000
Large Imager (LI)	Earth	6.000	20.000	0.030	0.300	2500.000	5000.000

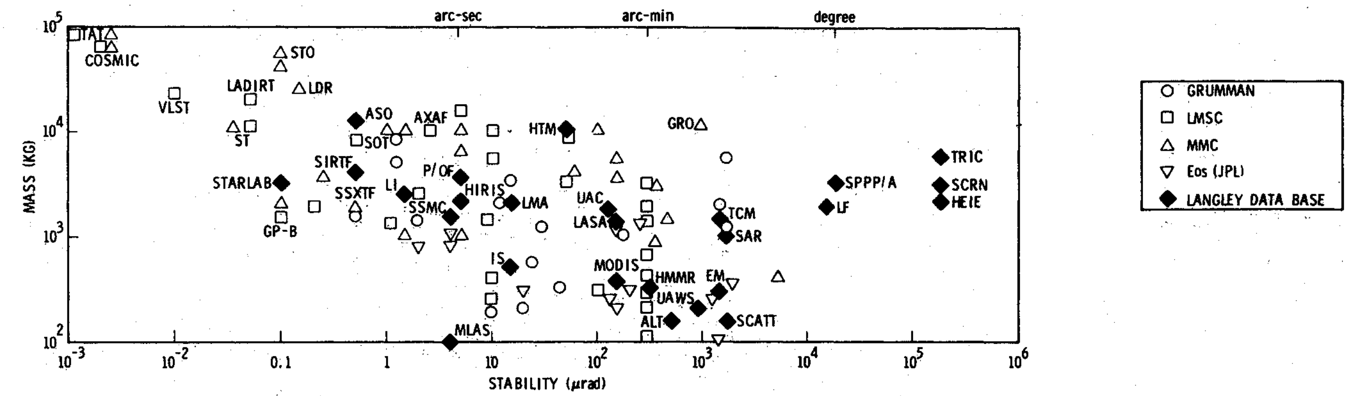

Fig. 2 Earth-orbiting space station/platform attached missions.

relatively massive, ranging from 2500-4000 kg. Note that some of the payloads that require less precise pointing are also massive, notably High Throughput Mission (HTM) at 10,000 kg, Transition Radiation and Ionization Calorimeter (TRIC) at nearly 6000 kg, and Spectra of Cosmic Ray Nuclei (SCRN) and High Energy Isotope Facility (HEIE) at 3000 kg. These may require advances in pointing mount technology driven not by precision but by the need to slew large inertias at relatively high rates.

While some of the accuracy and stability requirements in the Langley data base only approach Space Telescope in precision, the environment that attached payloads must compensate for will be much more noisy and complex. This is indicated to some extent by Fig. 3, which plots basebody and payload stability vs the fundamental basebody core structural frequency for the Space Telescope, a representative interplanetary spacecraft (Galileo), the Space Shuttle, and the space station. The basebody structural frequencies that must be considered in the pointing controller design of space station/space platform attached payloads will be significantly lower than those for previous missions. Man motion and machine vibration disturbances, as well as less frequent docking and thruster disturbances, will likely limit the base space station attitude control to 2-5 deg with jitter at approximately 0.1-0.2 deg,[15] more coarse than the other systems. On the other hand, the payload pointing requirements for the space station are the most challenging. The enclosed area for each system in Fig. 3 thus indicates the degree of difficulty of the pointing problem, showing that the space station environment is significantly more challenging. The multipayload nature of the platforms will make for numerous articulating elements with the potential for large-scale dynamic interaction problems. Futhermore, the configurations of the space station and the platforms will be changing over time as instruments and modules are changed out, as Shuttles, Orbital Transfer Vehicles (OTVs), or Orbital Maneuvering Vehicles (OMVs) are docked, and MV as free flyers and planetary explorers are serviced or assembled. This drives the need for pointing-system design that is either insensitive to basebody parameter variations or able to adapt autonomously and in real time.

The space station and associated platforms present the would-be designer of a generic pointing mount with unprecedented challenges through a combination of tight pointing requirements, rigorous environmental constraints, and the need for multipayload accommodation.

Interplanetary Spacecraft

The proposed interplanetary exploration missions through the year 2000, the NASA Core Planetary Program, are listed together with their pointing requirements in Table 3.[16-19] Most of the requirements are not drivers of pointing technology, the tightest requirement being 1.0 arcsec stability during flybys of

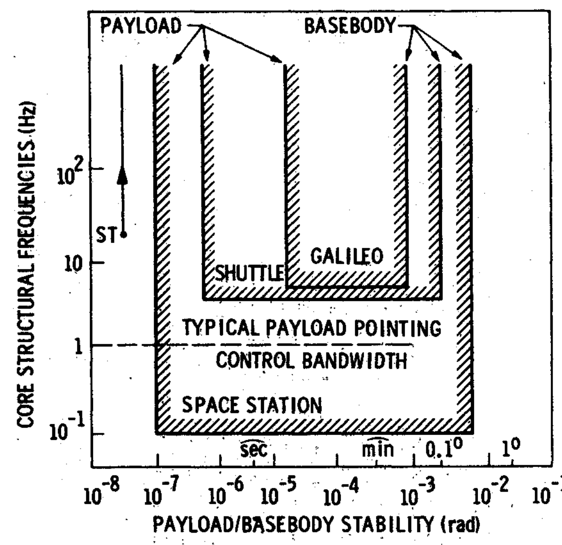

Fig. 3 Pointing environment characterization.

small bodies. Further, the disturbance environment will be benign, compared to that of the space station/space platforms. An exception would involve the use of nuclear electric propulsion (NEP) for outer planet missions. NEP would entail the attachment of a disturbance-rich nuclear reactor to the planetary spacecraft, probably at the end of a long flexible boom. The result would be environmental constraints similar to those of the space station.

Although planetary science payloads are not likely drivers of pointing technology (unless NEP is utilized), there is a development associated with planetary missions that could play such a role. Optical communication is being considered for near-Earth applications.[20,21] Optical Deep Space Communication (ODSC) has received attention at the Jet Propulsion Laboratory (JPL) recently as a means of vastly improving telecommunications with planetary spacecraft.[22,23] The concept calls for a relay station in Earth orbit which links the ground station with the deep space vehicle. The most stringent tracking and pointing requirements are most likely to be on the deep space vehicle itself, as it must direct a high data rate laser to intercept the relay station in Earth orbit. The pointing system on the deep-space vehicle must be capable of keeping the total pointing error below approximately 0.4 arcsec. It is also likely that provisions for disturbance isolation and autonomy similar to those necessary for the space station will have to be provided.

A chart summarizing the pointing requirements associated with space station/space platforms attached payloads, planetary science payloads, and ODSC appears in Table 4.

Table 3 NASA core planetary program

Mission		Pointing requirement	
Initial core missions	Launch year	Accuracy, deg	Stability
Venus Radar Mapper	1888	0.12	0.12 deg
Mars Geoscience/ Climatology Orbiter	1990	0.57	0.06 deg
Comet rendezvous/asteroid flyby	1993	0.11	2 arcsec
Titan Probe/Radar Mapper	1989-94	0.05	2 arcsec
Subsequent core missions			
Mars Aeronomy Orbiter		0.1	
Venus Atmospheric Probe	1994-99		
Lunar Geoscience Orbiter	1993-96	0.5	0.1 deg
Mars Surface Probe	1994-99		
Comet Atomized Sample Return	1997-2000	0.1	1 arcsec
Mainbelt Asteroid Rendezvous	1994-2000	0.11	2 arcsec
Earth-Approaching Asteroid Rendezvous	1999-2000	0.2	1 arcsec
Saturn Orbiter/Titan Probe	1989-94	0.05	2 arcsec
Saturn Flyby/Probe	1989-94	0.05	2 arcsec
Uranus Flyby/Probe	1994	0.05	2 arcsec
Neptune Flyby/Neptune Probe		0.05	2 arcsec

Table 4 Pointing requirements summary

	Space station platform	Planetary science	Optical Deep Space Communications
Accuracy	0.15 arcsec→10 deg	0.01 deg→0.5 deg	0.1 →0.4 arcsec
Stability	0.02 arcsec→10 deg	1 arcsec; s→0.1 deg	0.1→0.4 arcsec
Mass	92→10^4 kg	10→100 kg	30 kg
Dynamic isolation	Needed	Desired	Desired
Autonomy	High	High	High
Reliability	Short (serviced)	Long	Long
Special features	Variable Configuration accommodation		Look ahead 68 arcsec

Technology Assessment

The purpose of this section is to survey the state of the art of current pointing technology in order to assess its readiness to satisfy the requirements and constraints imposed by the reference mission set. The survey covers gimbal systems and suspension systems as well as actuators and sensors. An attempt is made to address the issue of cost of the various components, but only in a qualitative sense. Cost is ranked as either high (more than $10 million), moderate (from $2-10 million), or low (less than $2 million). No attempt is made to separate recurring from nonrecurring costs in the qualitative estimates. These qualitative costs may also be thought of as representing system complexity.

Gimbal Systems

Table 5 lists the capabilities of several near-term gimbal systems[1-7,24] together with the Space Telescope for comparison. Most of the gimbal systems are currently under development; only two, the Apollo Telescope Mount (ATM) and IPS, have flown to date.

The Annular Suspension and Pointing System (ASPS) is not a simple gimbal system but an AGS with a magnetic suspension stage added for isolation and vernier control. The pointing and stability numbers in the table assume a Space Shuttle disturbance environment since the Shuttle is the target basebody for most of the gimbal systems. The space station can be assumed to be a somewhat noiser environment and also to present more difficult problems of interaction of flexible structure with gimbal system control bandwidth. The small payload mounts (those capable of handling less than 600 kg) are seen to do somewhat better, largely because they tend to incorporate payload center of mass mounting in their designs. Center of mass mounting automatically uncouples basebody translational motion from payload rotation, greatly reducing the sensitivity of line-of-sight pointing to basebody disturbances. However, it also levies payload configurational constraints that become unwieldy for large payloads and tends to limit system modularity even for small payloads.

It is clear from Table 5 that without a vernier stage, near-term gimbal systems will not be able to meet the more taxing requirements of the reference mission set. There are further generic problems with applying gimbal mounts to the positing of the large science instruments expected to fly in the next decade. Gimbals generate torques by reacting against the spacecraft basebody. Large torques applied by a relatively high bandwidth controller will be necessary to provide slewing and disturbance rejection for future large payloads. However, such torques will be potentially destabilizing to the structural modes of a large flexible basebody such as the space station. Furthermore, gimbal reaction torques will be seen as disturbances by neighboring payloads on a multimission platform.

Table 5 Gimbal system capabilities

	IPPACS[a]	IPS[b]	MPM[c]	SIPS[d]	ASPS[e]	AGS[f]	ATM[g]	ST[h]
Pointing, μrad	10	30	TBD	5	0.05	40	12	0.05
Stability, μrad, s	10, 400	18, TBD[i]	10, TBD	2.5, TBD	0.05, TBD	12, TBD	4.8, 900	0.035
Slew rate, mrad/s	105	56	TBD	TBD	52	70	TBD	1.3
Acceleration, torque, mrad/s^2, Nm	6, 0.7	1.8, 23	1.5,0.6	TBD	10, 34	14, 34	5, 19	TBD, 0.8
Field of view, deg	270	130	TBD	180/10/90	200/120	140	4	Full
Servo bandwidth, Hz	1.0	0.5	1.0	1.0	1.0	1.0	2	1.0
Payload mass, kg	104	200-2000	85-456	85-600	60-7200	60-7200	11,000	11,000
Payload inertia, kg-m^2	31	~2000	85-400	85-400	TBD	TBD	TBD	N/A
Readiness level	3	4	3	4	4	4	Flew, 1973	4
Cost	Moderate	High	TBD	TBD	High	High	TBD	High

Note: [a]IPPACS-Integrated Platform Pointing and Attitude Control Subsystem; currently being developed for the Mariner Mark II interplanetary exploration spacecraft. [b]IPS-Instrument Pointing System, designed for the Shuttle Spacelab. [c]MPM – Minature Pointing Mount (a modified ATM star tracker). [d]SIPS-Small Instrument Pointing System. [e]ASPS-Annular Suspension and Pointing System. [f]AGS-Advanced Gimbal System. [g]ATM-Apollo Telescope Mount (flown on Skylab). [h]ST-Space Telescope.

Table 6 Pointing actuators state of art

Component	State of art	Problem areas
Control moment gyro	Single degree of freedom >1000 N-m-s torque = 1000 N – m Two degree of freedom >2000 N – m – s Torque = 1000 N – m	Noise reduction gimbal cogging vibration Bearing reliability Life Use of mag suspension Inadvertent touchdown
Reaction wheel	100 N-m-s 1.0 N-m	Mag spin bearing Inadvertent touchdown
Fast steering mirror	High bandwidth reactionless	Low throw
Piezoelectric	High bandwidth 100-500 Hz	Low throw ±0.005 in. typical
D. C. torque motors	1-30 N-m 1-5% ripple and cogging torque redundant windings brushless	Ripple and cogging torque reduction
Stepper motors	1.8 deg quantization 1.0 N-m	Lack of damping small quantization drive inertia impacts

Adding an isolation stage (as ASPS does) will not necessarily alleviate the problem since following a given slew pattern will require the same torque profile (and result in the same reaction torques), regardless of the number of stages used. Two other issues are worth raising with regard to gimbal systems: They are intrinsically "hard" mechanically and will pass, with virtually no attenuation, disturbance frequencies beyond their control bandwidth, thus necessitating a follow-on isolation stage; they are also costly, especially the large payload systems such as IPS and AGS. Several large gimbal systems similar to AGS and IPS have also been proposed or partially developed for the military Talon Gold original flight experiment.

Suspension Systems

There are two suspension (or isolation) systems currently in advanced development that are meant to serve as vernier stages on top of gimbal systems. These are Gimbalflex,[25] a flexure-based system, and the Vibration Isolation and Pointting System (VIPS), a system based on magnetic bearings and virtually identical to the vernier stage on ASPS.[6] Both claim to be able to supply pointing stability down to approximately 0.01 arcsec (assuming perfect sensing) in the Shuttle environment by introducing a mechanically soft interface through which high frequency disturbances, which are transmitted by the gimbal system, do not pass. They can also be operated in a "stiff" mode so that they can follow the gimbal during fast slews and for quick settling. During such operations, however, they do nothing to alleviate the gimbal's tendency to excite structural vibrations.

There are currently a few areas in which these systems experience problems.[26] Magnetic suspensions are limited in the amount of load that they can handle, and limited as well to relatively small magnetic gap dimensions. They also require high power. Reliability is also a problem area. Flexure suspensions are based on simple, high reliability components. However, as is true for magnetic suspensions as well, they are useful only for small angular displacements. Both systems fall into the moderate price category with flexures on the low end and magnetic bearings somewhat higher.

Actuators and Sensors

The state of the art for precision pointing actuators is shown in Table 6. Control moment gyros (CMGs) have very high torque capabilities and are thus candidates for providing high slew rates for large payloads. However, currently they are too noisy for high precision pointing application.[26,27] The application of magnetic bearing technology could produce advances in this area and lead to longer lifetime as well. Reaction wheels are capable of high precision (e.g., the Space Telescope) but are torque limited.[26,27] CMGs and reaction wheels are in the moderate price range. Fast steering mirrors using electromagnetic or piezoelectric actuation can supply jitter rejection out to very high bandwidths. They should find applications as vernier stages in inertially referenced pointing systems or as elements of image motion compensation systems. However, they are currently limited in angular range and mirror size. To make use of the high bandwidth capability, they also have to be used with an extremely fast control processor. Piezoelectric polymers offer potential for distributed flexible structure damping and for tuning interface stiffness to enable adaptive disturbance isolation.[28]

See Table 7 for the state of the art in sensor technology for precision pointing. This area is well developed now, and significant improvements are expected by the early 1990s. Current spun-mass gyros approach 0.001 deg/h in random drift with low noise equivalent angles. Near future spun-mass gyros may improve on this significantly. Fiber optic gyros promise to have high performance while greatly reducing mass, power, and cost with significantly increased lifetime and reliability. They should be flight ready early in the next decade.[29] The Advanced Star and Target Reference Optical Sensor (ASTROS) project at JPL, slated to fly in 1986, represents the state-of-the-art star tracker with 0.8 arcsec accuracy, 8.2 visual magnitude sensitivity, and a 3.5 deg field of view.[30,31] Accuracy of 0.1 arcsec is expected by 1991.[32] Target body tracking capability, both centroid and correlation type, is currently under development and should find application in the most stringent pointing problems, both military and civilian.

Design Options and Technology Development Needs

Given the above technology, we now consider architectural design options that will meet the performance requirements.

Single-Stage Gimbal Systems

With the possible exception of NEP missions and ODSC, the pointing needs of 1990s planetary payloads should be adequately provided for by a center of mass mounted precision gimbal system such as the Integrated Platform Pointing and Attitude Control Subsystem (IPPACS). The IPPACS gimbal is momentum compensated in order to avoid dynamic interaction problems. Uncompensated gimbal systems, such as used on previous interplanetary spacecraft or the IPS, apply a torque on the payload by reacting (applying a torque) on the basebody. To determine the pointing system peformance or even stability, the basebody must be included as well. Rigorous analysis[33] of a simplified gimbaled pointing system model (single axis, center of mass mounted, viscous friction, proportional and derivative control) attached to a basebody with a flexible appendage indicates that there may be a frequency region, which includes the appendage natural frequency, in which the gimbal control natural frequency must not lie. This allows the control bandwidth to be either lower or somewhat higher (the amount depends on the damping details) than the appendage natural frequency. In practice, since any structure will have many natural frequencies and not just one, the control bandwidth is set below the lowest of these. This can have a major impact on performance, since the ability of a control system to reject disturbances and track input signals increases with its bandwidth. In addition, fast gimbal slews may excite lightly damped structural modes, even though the system remains stable. The IPPACS is designed so that the gimbal system becomes essentially a reaction wheel-control system. Since reaction torques are carried by the compensation wheel rather than the basebody, the structural natural frequencies no longer determine the control bandwidth, which may be set to handle the expected tracking requirements and disturbance environment.

Comparing the pointing and stability requirements of the SIRTF/STARLAB class large platform-attached payloads with the capability of state-of-the-art large gimbal systems such as AGS and IPS (even in the Shuttle environment) indicates about an order of magnitude shortfall in capability. Even if these single-level systems could meet the pointing requirements, there would remain serious questions of torque margin and control/structure and payload/payload interactions that would have to be addressed if these systems are to be used for the space station. It is very difficult to gimbal such large payloads about their mass centers, especially if one mount is to be used for a variety of payloads. Note that this also rules out momentum-compensated systems, such as a large version of IPPACS.

Table 7 Pointing sensors state of art

Component	State of art	Problem areas
Gyro	Inertial angle reference drift = 0.001 deg/h	Low noise (0.01 arcsec) over 100 Hz BW, tolerate fast slews, rapid settling
Star tracker	0.6 arcsec accuracy at 3.5 deg FOV	Limited dynamic capability
Accelerometer	0.1 μg resolution 100 Hz BW Angle-sensing applications	
Optical encoder	3.0 μ rad resolution 75 kHz BW	High cost

Two-Stage, Gimbal-Based Systems

Two-level actuation systems such as ASPS (or VIPS or Gimbalflex on top of a gimbal) have the potential to meet the stringent pointing requirements and should be considered as serious design options for the pointing of space station and platform-attached payloads. A system like ASPS does not escape all of the problems associated with single-stage gimbals, however. The ASPS isolation stage *is* able to filter out high-frequency disturbance components that pass through the gimbal (provided they are of sufficiently small amplitude) and this alleviates the need for high bandwidth compensation that is potentially destabilizing to the surrounding structure. However, when operating in a slew or raster scan mode (as opposed to the inertially pointed disturbance-isolation mode just mentioned), the suspension stage must be capable of "following up" the gimbal and hence will transmit all the torques necessary for slewing (rastering) and subsequent settling. Such operations will thus be accompanied by the same basebody reaction torques as would be exerted by a single-stage gimbal. To this extent, the issues of control/structure and payload/payload interaction, critical issues for future large platforms, remain. With the application of emerging multi-input, multi-output control techniques, these are probably not insurmountable problems. However, they may constrain the controller design to the point that it will have to be essentially custom designed, not only to the payload it is pointing but to the overall platform configuration (which will vary with time) as well. The major drawbacks of a gimbal system with an isolation stage are as follows:

1) Control-structure interactions (discussed above).

2) Limited disturbance rejection capability. Disturbance isolation capability is the hallmark of the ASPS approach. However, practical design limitations (e.g., magnetic bearing gap size, currently about 1 cm) place an upper bound on the amplitude of disturbances that can be effectively rejected. The isolation capabilities of systems like ASPS, vis-a-vis future high-disturbance environments, have yet to be evaluated.

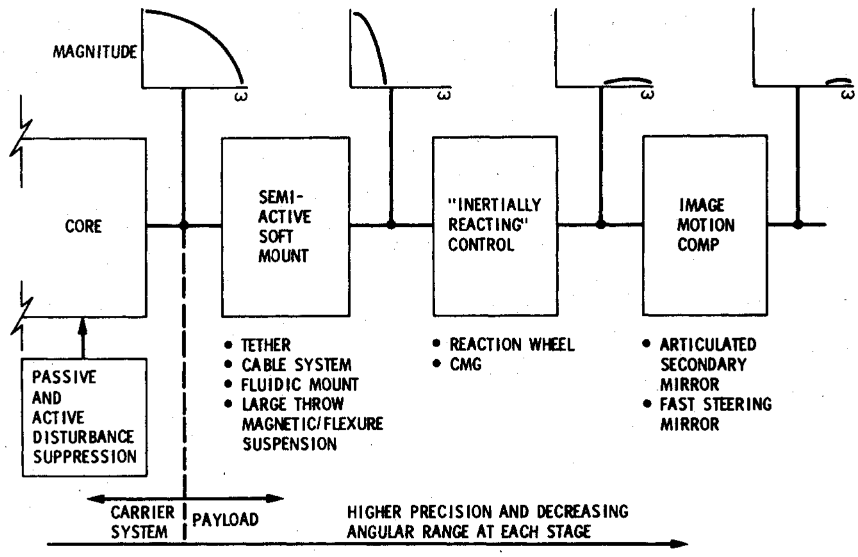

Fig. 4 Softmount architecture.

3) Low torque margin. Multistage gimbal system torque capability is bounded by the torque output of the gimbal stage. The peak torque of AGS and IPS (about 30 N-m) is judged by some to be low by a factor of two to five when compared to the needs of SIRTF-class payloads.

4) High cost. Large gimbal systems are very costly items (more than $10 million). The addition of an isolation stage can be expected to increase this cost substantially.

There are no ready solutions to the last two drawbacks. However, these drawback, by themselves are not sufficient to disqualify the two-stage gimbal approach. The critical question is whether or not the application of advanced control methodologies can adequately address the first two issues.

Another two-level, gimbal-based design option is the SIRTF or Solar Optical Telescope (SOT) approach of using a large gimbal system on top of which sits a high bandwidth articulated optics system (which may itself consist of multiple stages). The philosophy of such a system is to compensate actively for high-frequency disturbances, rather than to isolate the payload from them architecturally. Assuming that the high-frequency articulation of the optics does not disturb the payload (near-term, fast-steering mirror technology claims to be "reactionless"), the results at the line of sight should be the same. However, this approach suffers from the same generic drawbacks as does the ASPS approach: potentially destabilizing or disturbance generating (for other payloads) gimbal reaction torques during slews, rasters, and settling; low torque margin for large payloads; relatively high cost; and hardware-based disturbance-rejection limitations. The optical compensation stage must be custom designed for each instrument.

The input/output characteristics of the two options just discussed can be discerned with the help of Fig. 1. Refer to the small magnitude vs frequency plots in the figure that depict the disturbance state on either side of each system interface; the "coarse gimbal" is seen to act as a high-pass filter, removing disturbance components that fall within its bandwidth but passing the higher frequencies without attenuation. In a two-stage system, the higher frequency components are removed by the second stage. This can be accomplished by a mechanically soft "dynamic isolation" stage that acts as a low-pass filter (the ASPS approach) or by a mechanically hard "image motion compensation" stage that behaves qualitatively in the same manner as does the coarse gimbal: It high-pass-filters disturbances but does so out to a much higher cutoff frequency, and over a far more limited angular range, than the gimbal. Both generic two-stage gimbal options are capable of producing a flat, well attenuated disturbance spectrum at the line of sight.

Soft-Mounted Inertially Reacting Systems

An alternate approach to the problem arises from the following question: Why not substitute a low-pass filter for the high-pass filter (gimbal) at the first articulation stage? Consider the system architecture depicted in Fig. 4. the mechanically "hard" gimbal is replaced by a very "soft" interface that is largely passive but must have at least an intermittent active mode which allows it to reposition the payload in a gross fashion and latch it up to the base vehicle if necessary. During normal operations, the "softmount" acts as a low-pass filter that sets the cutoff frequency as low as is practically possible. In the limit, mount stiffness goes to zero, and the payload is free flying in tandem with the base vehicle. The pointing control resides onboard the payload side of the mount where inertially reacting actuators such as reaction wheels or CMGs implement the high-pass (i.e., low-bandwidth) disturbance filtering and tracking/slewing control. In actuality, the controller onboard the payload is not bandwidth limited (unless by payload considerations), since control torques are not generated by reaction against a relatively flexible base vehicle, but rather against a relatively rigid spinning wheel. The softmount architecture precisely inverts the ASPS approach by interchanging the high- and low-pass filters in the system topology. Notice that this concept is fundamentally different than an isolation system between the base vehicle and a gimbal, which is sometimes referred to as a softmount. Such a system must still pass the basebody reaction torques that allow the payload to be articulated. The stiffness of such a system is tightly constrained by the competing interests of disturbance isolation and slew response. This softmount architecture offers the following advantages over the more traditional gimbal-based, two-level design options discussed above:

1) Potential for high performance. Since in the limit the payload becomes a free flyer, accuracy and stability can theoretically approach that of the Space Telescope. Also, CMGs are capable of providing much higher torques than gimbal systems for fast slews and quick settling.

2) Minimal basebody and payload/payload interactions. The soft interface and lack of basebody reaction torques mitigate the issues of basebody flexible structure excitation and payload-to-payload interference. For simple proportional, derivative (PD) payload controls, the system stability no longer depends on the basebody (provided the basebody is stable by itself).[33]

3) Supports modular design and multipayload accommodation. Since the basebody and payloads are mutually isolated from each other, the pointing needs of individual payloads can be met independent of the overall system configuration.

4) Potentially low cost. Expensive gimbals and magnetic or active flexure bearings are replaced by moderate cost reaction wheels or CMGs and a mechanically simple soft interface.

Conclusion

An overview of the technology issues associated with the precision pointing of future spaceborne science instruments has been presented above. Although current technology will be adequate to point many of these instruments, the class of large, high-precision space station/space platform attached payloads appears to present substantial problems for near-term, gimbal-based pointing mounts. The pointing of payloads on planetary probes using nuclear electric propulsion will also be problematic and for the same reasons: the structurally flexible and disturbance-rich basebody to which the payloads are attached. These problems may find a solution in the "softmount" concept proposed above. The softmount circumvents the problems of basebody and payload-to-payload interactions through its mechanically soft, disturbance isolating interface. Feasibility studies are currently under way to address the practicality of this innovative approach.

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