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# Space mechanisms and tribology challenges of future space missions☆

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## Abstract

The future space mission scenario of scientific and commercial/application missions impose very challenging requirements on the design and performance of space mechanisms and the tribology of their moving surfaces in contact. Taking as example the scenarios and preliminary design concepts of possible future ESA science missions, critical technological advancements of their mechanisms are being identified. The challenges of competitive mechanical product development for commercial/application missions and the role of equipment suppliers in the rapid development cycle are highlighted in selected examples of mechanism-related space equipment.

## 1. Introduction

Experience with space missions has shown that space mechanisms and their related tribological performance play a major role in the overall success of the mission. This is due to the fact that mechanisms are frequently employed in mission critical single point failure locations. The use of mechanisms is often imposed by the envelope constraints under the fairing of the different launch vehicles. As a result, deployable features for solar arrays, booms, antennas, optical reflectors, etc. are often implemented on spacecraft.

However, mechanisms also involved in the operation of main payload instruments are often critical for the success of the mission and require extreme reliability in design implementation. Considering future mission plans and the related advanced mission feasibility assessments, many critical features and performance requirements can be identified. They call for substantially extending the performance capabilities of mechanisms and their related tribological solutions beyond the presently known space experience.

Examples of the challenging requirements and critical enabling technology items for space mechanisms and tribology are discussed here.

## 2. Science mission scenarios

### 2.1. Future science mission overview

As part of the ESA-identified candidate future missions under the Horizon 2000 Plus Science

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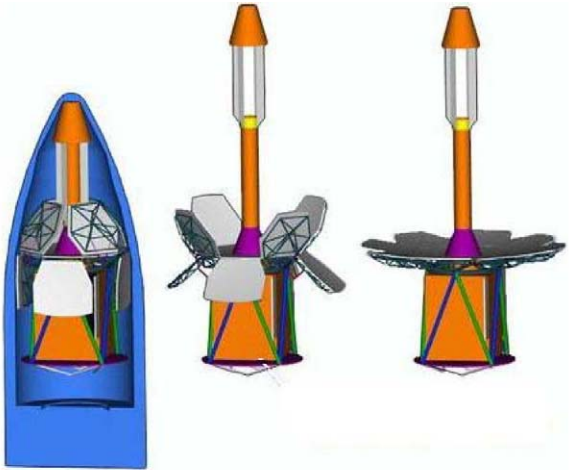

Fig. 1. NGST in launch and deployed configuration (sunshield not shown) [4].

Programme, the following mission scenarios have been assessed with respect to their technological challenges related to mechanisms and tribology:

- NGST (Next Generation Space Telescope)
- MERCURY mission
- GAIA (Global Astrometric Interferometer for Astrophysics)
- LISA (Laser Interferometer Space Antenna)
- DARWIN (Infra-Red Space Interferometer)
- XEUS (X-ray Evolving Universe Spectroscopy).

The critical mechanism applications and their challenging requirements are described in the following mission examples.

### 2.2. NGST

The NGST (Fig. 1) is currently under investigation for future replacement of the Hubble Space Telescope (HST) after 2007. The satellite comprising the telescope will be even larger than the orbiting HST. The telescope will be optimized for the near to mid-infrared wavelength range (0.6–30 μm) to enable the exploration of the most remote, highly red-shifted universe.

In order to identify areas for ESA contribution to this joint programme with NASA, feasibility studies are presently being performed in industry. These studies highlight the possible contributions European industry and scientific institutions might provide to NGST and identify the critical technology issues attributed to the established design concepts.

#### 2.2.1. Technological challenges

Challenges in the field of mechanisms and tribology arise from a number of constraints.

Mechanisms have to operate at cryogenic temperatures (20–60 K). In order to avoid adverse effects on scientific measurements, the power dissipation of mechanisms has to be minimised and operational phases with the power completely switched off, while stable positions need to be maintained, are being considered. To achieve this, mechanisms need to be designed with a repeatedly unpowered clamping or holding feature, which should provide a good position repeatability and ensure constant clamping/holding force. Wear of moving surfaces in contact has to be avoided over the entire operational lifetime, and ideally an identical tribological performance operated at both cryogenic and ambient temperatures should be facilitated. Since liquid-lubricated systems cannot be used at these temperatures and because the known low-friction solid lubricants such as molybdenum disulphide ($MoS_2$) show substantial performance differences between ambient and cryogenic conditions, novel solutions have to be explored.

With an envisaged telescope aperture of 8 m and a distance of about 10 m between the primary and secondary mirror, numerous deployment mechanisms are needed to fit the spacecraft under the fairing of current launchers. The deployment mechanisms for the primary mirror petals need to provide a positioning accuracy of a few nanometers in order to be compatible with the high optical quality envisaged for the telescope.

To correct any telescope wave front error in orbit and to control the optical path difference in interferometric payloads, mechanisms have to achieve positioning accuracies in the order of nanometers, even when strokes in the order of millimeters are required. Such requirements are equivalent to at least 20-bit resolution of the sensors and electronics controlling the mechanisms.

Lifetime requirements for the different mechanisms vary from a moderate 10,000 cycles up to a challenging $10^{10}$ cycles for a fast steering mirror. Apart from the lifetime issues, it will also be challenging to design the latter device such that it produces only minimum disturbances, despite moving a mirror of 350 mm diameter at amplitudes up to 250μrad and at a frequency of more than 10 Hz.

Also the control of the various mechanisms is a challenge. A number of mechanisms have to be controlled in several degrees of freedom with the extreme of an actively controlled deformable mirror utilizing about 150 actuators in a coherent simultaneous fashion.

### 2.3. Mercury mission

After the fly-by observations by Mariner-10 in the 1970s, a new mission to Mercury will be a major leap to improving our knowledge and understanding of the innermost planet and its surroundings. The mission feasibility and overall concept is presently studied under ESA contract. Carrying a large complement of scientific instruments, three separate spacecraft elements shall be sent to Mercury, attached during orbit transfer to a common cruise carrier stage:

- a three-axis stabilised *Orbiter* primarily for remote sensing observations;
- a spinning *Magnetospheric Satellite* for investigations of particles and fields, and;
- a small *Surface Probe* for in-situ geochemical analysis.

By using solar-electric propulsion combined with multiple gravity assist manoeuvres at Venus and Mercury, the cruise phase is expected to last for only about 2 years compared to typically 6 to 8 years using direct transfer. Final orbit insertion around Mercury will be accomplished by chemical propulsion.

The Orbiter element requires a Mercury polar orbit and Nadir pointing attitude for efficient remote sensing by narrow/wide angle cameras and a set of spectrometers (infrared and ultraviolet light, X-ray, gamma ray and neutron radiation). Furthermore, it will be equipped with a solar X-ray flux and energy monitor, an accelerometer to map the planet's gravity field, and a radio science package. Fig. 2 shows the Orbiter's conceptual configuration with a high gain antenna (HGA) and a deployable infrared shield to block reflected radiation from the planet.

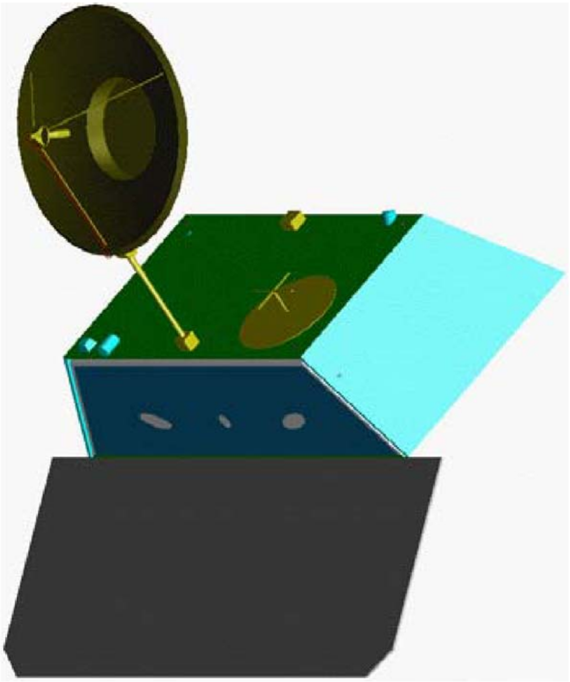

Fig. 2. Mercury Orbiter [1].

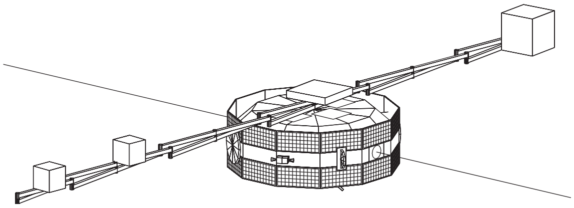

Fig. 3. Mercury Magnetospheric Satellite [1].

The Magnetospheric Satellite (see Fig. 3) will be inserted in a highly elliptical orbit, which will cover the entire magnetosphere including the distant tail once per Mercury year. The concept of a spinning satellite is best suited to field and particle science experiments. The payload will comprise a magnetometer, an ion spectrometer, ion/electron analysers, E- and H-wave analysers as well as detectors for cold plasma and energetic particles. Some of these sensors will have to be mounted on deployable booms. Furthermore, the satellite will feature two long wire antennas.

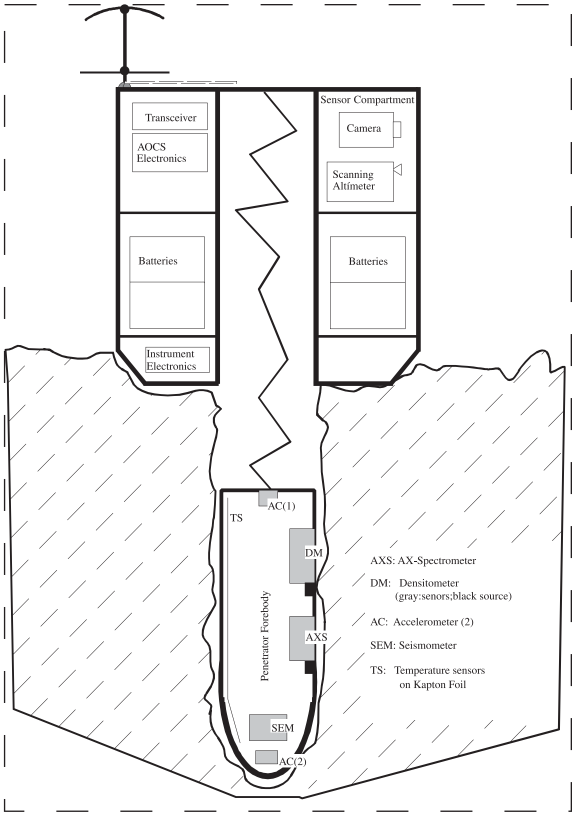

Fig. 4. Mercury Surface Probe [1].

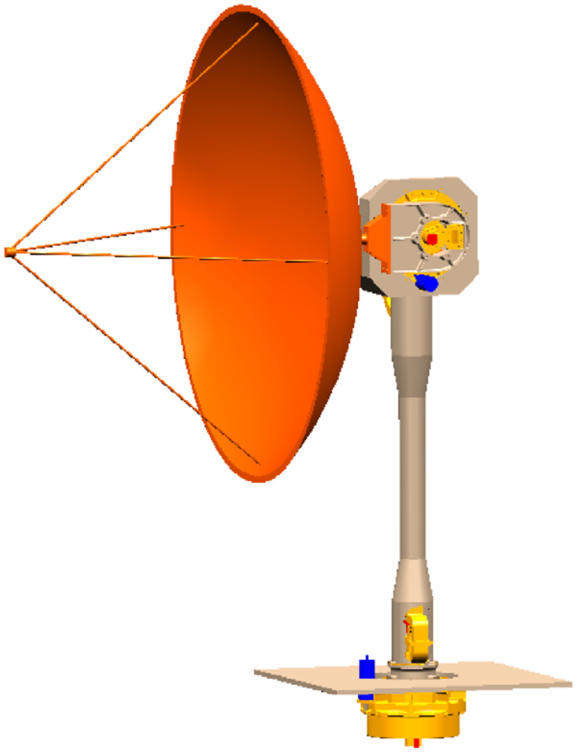

Fig. 5. HGA pointing mechanism [2].

The Surface Probe (see Fig. 4) is conceived as a "hard" lander with a short lifetime. It will be deployed from the Orbiter and impact the planet at high latitude where the environmental conditions are more benign than in the equatorial region. The front module of the lander will penetrate the ground to approximately 1 m depth, whereas the aft module will remain on the surface, with a cable link between the two modules. In the front module, a miniature instrument package will be accommodated, e.g. for measuring the composition and physical properties of the soil.

### 2.3.1. Technological challenges

A mission to Mercury will comprise many innovative and challenging aspects at the level of the entire spacecraft as well as for the key equipment to perform scientific investigations. The high return of scientific data can only be satisfied using a HGA, which has been baselined to use X and Ka-band communication. The deployable, two-axis articulated antenna forms the most dominant item protruding the exterior surface of the Orbiter spacecraft.

The antenna reflector and pointing mechanism will be exposed to the extremely harsh environment of 10 solar constants and high radiation input at only about 1/3 of the Earth's distance from the Sun while also being exposed to the albedo from Mercury. Even using high-temperature insulation materials, the temperatures of exposed equipment are subject to very large cyclic variations, in some cases from around 0°C in eclipse up to more than 250°C when the Sun illuminated. Fig. 5 shows a conceptual HGA configuration [2].

The design of active components like motors and sensors as well as the lubrication of moving parts will be very much driven by the severe environmental conditions. Functionally critical dimensions, e.g. inside RF rotary joints, must be controlled over the full temperature range as the HGA system shall be continuously operating for at least one year in Mercury orbit.

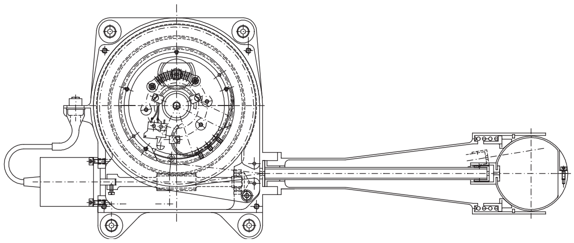

Fig. 6. Wire antenna mechanism [3].

Another example of enabling technology can be found with the wire antenna mechanism of the Magnetospheric Satellite. While the satellite will be spinning at about 15 rpm, a wire dipole of 2 × 30 m will be radially deployed for radio and plasma wave detection.

A preliminary design of the wire antenna mechanism is shown in Fig. 6. Again, the thermal and radiation environment imposes stringent requirements on the selection of the wire material and other design features. Furthermore, special provisions for the damping of wire oscillations have to be added because the attitude stability of the relatively small satellite will be sensitive to induced oscillations.

Further mechanisms items requiring specific attention regarding application on a Mercury mission include:

- Cruise stage large deployable solar array (20 kW at 0.6 AU) and its drive mechanisms.
- Magnetospheric Satellite deployable booms and its mechanisms operated at high temperature.
- Smooth separation devices for propulsion stage ejection and high-temperature separation devices for the Magnetospheric Satellite and the Surface Probe.
- High temperature thermal louver technology.
- High-temperature Surface Probe landing and instrument deployment devices.
- Miniaturisation of mechanisms and electronics compatible with high temperature.

### 2.4. GAIA

As follow-up of the successful HIPPARCOS mission, the GAIA mission objectives are essentially to build a catalogue of more than 1 billion stars (about 1% of our galaxy) with accurate three-dimensional positions, space velocities, and related information. Performing global or wide-field astrometry using two separate telescopes on the spinning spacecraft from the L2 libration point, the stellar observations will be obtained by a fully autonomous on-board object detection system.

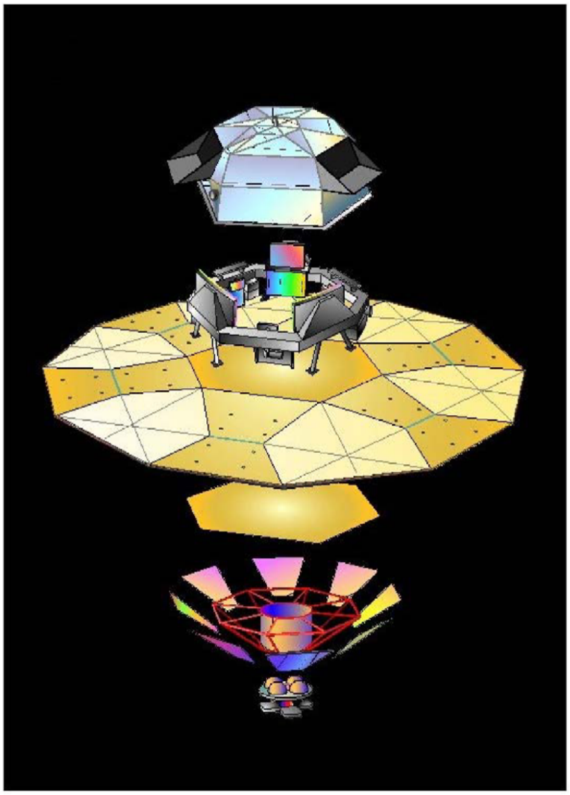

Fig. 7. GAIA spacecraft configuration [4] (exploded view).

The spacecraft (Fig. 7) is protected against direct illumination from Sun, Earth or Moon by a large deployable sunshield, which also comprises the six deployable solar panels used for providing power to the satellite.

The payload instruments are covered by a thermal cover with deployable baffles. Stringent accuracy requirements are imposed on the optical assembly in order to achieve high-precision positional measurement accuracy.

#### 2.4.1. Technological challenges

The driving requirements for the payload mechanisms on GAIA are derived from the stringent pointing and alignment accuracy better than 1 μm to be achieved by the telescope. This has led to the implementation of a five degrees-of-freedom (two tilts and three translations) position alignment mechanism for one of the mirrors on each telescope. Using a hexapod configuration for the alignment mechanism, linear actuators with positional accuracy in the nanometer range, and compatibility/stability in the cryogenic temperature range are required.

Inchworm actuators available for on-ground applications need substantial adaptation for potential space use and technology improvements to achieve the high stability at low temperature. High stiffness in unpowered mode during launch is another key requirement if a launch-locking device is to be avoided.

On the spacecraft side, the large diameter (9 m) deployable sunshield combined with solar array panels is the key critical technology driver. To achieve the compact launch stowage envelope required to facilitate a cost-efficient dual launch opportunity on Ariane-5, a novel deployment concept needs to be validated. Stray-light avoidance calls for particular emphasis on the panel deployment hinges and adequate panel edge overlapping for the complete planar surface area.

### 2.5. LISA

The primary objective of the LISA mission is the detection and observation of gravitational waves from massive black holes and galactic binary stars in the frequency range $10^{-4}$–$10^{-1}$ Hz.

Consisting of six identical spacecraft forming an equilateral triangle in space (see Fig. 8), the positional shift due to gravitational waves of “free-floating” proof masses contained in each spacecraft will be measured by optical interferometry.

When a gravity wave passes through the system, measurements of the fluctuations in the positions of the proof masses will allow the determination of the gravitational wave.

#### 2.5.1. Technological challenges

In this mission, mechanism challenges lay in the establishment of the ultra-sensitive acceleration measurement package. Particularly, the caging for launch and the in-orbit release mechanism for the movable proof masses are critical since they have to be realised without affecting the proof mass shape and surface state.

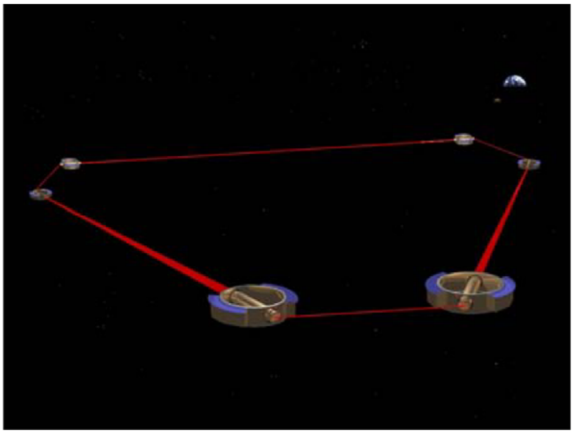

Fig. 8. LISA spacecraft configuration [4].

The design of an active acceleration calibration mechanism, which should expose the proof mass to a defined extremely low acceleration in the order of $10^{-15}$ m/s$^2$ constitutes a further critical element.

### 2.6. DARWIN

Employing infrared space interferometry, the DARWIN mission will search for planets that are about the same size as the Earth, with similar atmospheres.

Applying a so-called nulling interferometry method to cancel out the light from a nearby star, the detection of Earth-like planets is envisaged using a set of free-flying satellites (see Fig. 9) controlled in distances to each other with about a billionth of a meter accuracy. Each spacecraft is protected from disturbing illumination by a large sun and stray-light shield keeping the telescope at 30–50 K.

#### 2.6.1. Technological challenges

Critical mechanisms of the proposed spacecraft configuration are comprised in the lightweight, large deployable sun and stray-light shield with a diameter of 7 m.

In order to comply with a minimum size envelope under the launcher fairing, the deployable concept has to aim for minimum stowage volume and provide a large in-plane deployed surface with adequate insulation capability to maintain the telescope at cryogenic

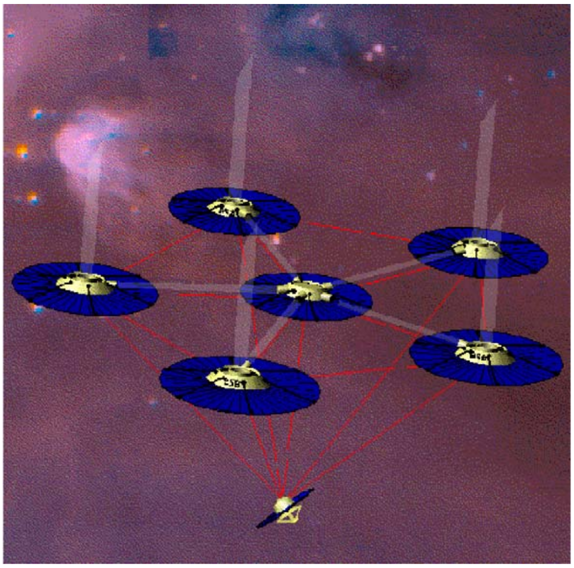

Fig. 9. DARWIN free-flyer concept [4].

Fig. 10. XEUS spacecraft configuration [4].

temperature and avoid stray-light effects on the measurements.

## 2.7. XEUS

As follow-up to the ESA XMM mission, the XEUS mission is being proposed as a permanent X-ray observatory composed of two free-flying spacecraft in low Earth orbit (Fig. 10). Initially, a single module "mirror spacecraft" flying in formation at 50 m distance to the "detector spacecraft" will ensure a perfect focus within $+/-1$ mm$^3$. Subsequent rendezvous operations with the International Space Station (ISS) should allow the addition of a 10 m diameter ring of mirror petals and the increase of collecting area to 30 m$^2$.

### 2.7.1. Technological challenges

Critical issues are the establishment of a large area of X-ray mirrors, which are to be assembled in the orbit by robotic operations from the space station ISS. In order to avoid many individual mirror module doors, contamination-free rendezvous and docking mechanisms as well as robotic assembly devices are required. The associated mechanisms have to provide high-accuracy positioning and attachment devices for assembly of the various mirror shell modules. In order to compensate for misalignments of the individual modules, high-precision active position adjustment devices might be required on each module.

## 3. Commercial/application missions

Commercial and application missions impose the most demanding challenge for the next generation of space mechanisms. For mechanism suppliers, a timely development and competitive availability of mechanisms becomes mandatory in order to play an adequate role in the future provisions of mechanism products for prime contractors.

The extremely rapid growth of planned commercial applications based on space systems with global coverage explains why the commercial applications will be the most significant driver for future equipment development. This predominance of commercial missions is being reinforced by the overall slow-down of institutional programmes as result of governmental pressure for reducing the public budget deficits.

This market evolution leads to an important restructuring of the space sector. Prime contractors already experience this situation at system level on the market for geostationary spacecraft, while equipment suppliers are being exposed to this as a second step. Low cost, reduced schedule and adaptability to market needs are now much more important than the capability of achieving ultimate technical performances as it is often the case for scientific missions.

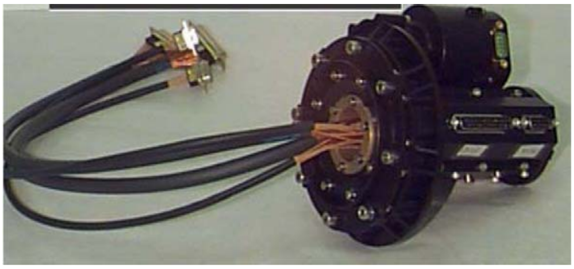

Fig. 11. Solar array drive mechanism (courtesy of ALCATEL SPACE).

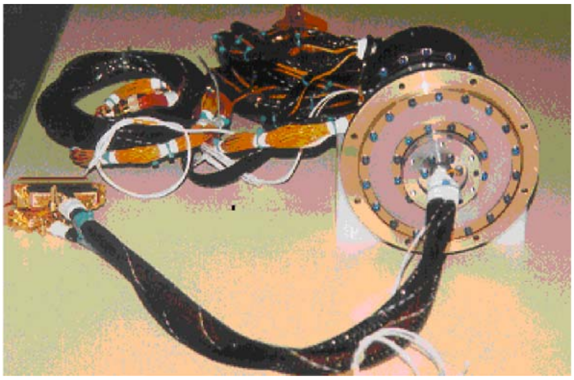

Fig. 12. Solar array drive mechanism (courtesy of SNECMA).

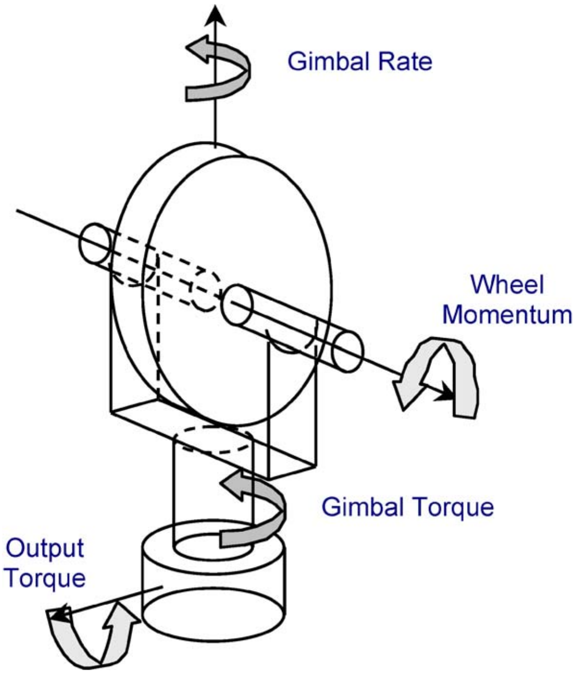

Fig. 13. CMG basic principle [5].

Satellite providers have reinforced their position by proposing standard/recurrent platforms and by increasing the commonalities between equipment for all programmes as much as possible. Spacecraft architecture adaptability, modularity and reduced assembly, integration and testing efforts now appear more important than system budget optimisation.

This trend is also observed at equipment level. New generations of solar array drive mechanisms (see Figs. 11 and 12), or components like new low-cost optical encoders can be highlighted as examples.

Whatever the predominant commercial missions, it will not significantly change the challenge for future mechanisms. The Earth observation market may grow significantly for responding to the public demand, real-time event monitoring, or the control of the increasing global traffic.

Growing markets may also be experienced in the domain of fully digital communication, global information, navigation or advanced mobile services. In such applications, reaction wheels for 3-axis stabilised spacecraft may be replaced by Control Moment Gyros (CMG) for future agile spacecraft where pointing is performed by the whole spacecraft. In this context, improved mechanism technologies will be required with respect to improved bearing assemblies, advanced motor and compact control electronics, high stiffness, low friction, hysteresis-free joint concepts and further areas.

The basic working principle of a single gimbal Control Moment Gyro for future agile spacecraft is indicated in Fig. 13, and a possible CMG design implementation is given in Fig. 14. A flywheel with constant momentum is accommodated on a gimbal structure. The gimbal motor rotates the spin axis and the resulting gyroscopic output torque is created.

By analysing the prime contractor approaches and evolution for the constellation market (e.g. for Globalstar and Skybridge), it is possible to extrapolate what will be the most likely scenario at the level of equipment suppliers, and more specifically for the mechanism products. A future world-class satellite supplier will involve partnership between companies,

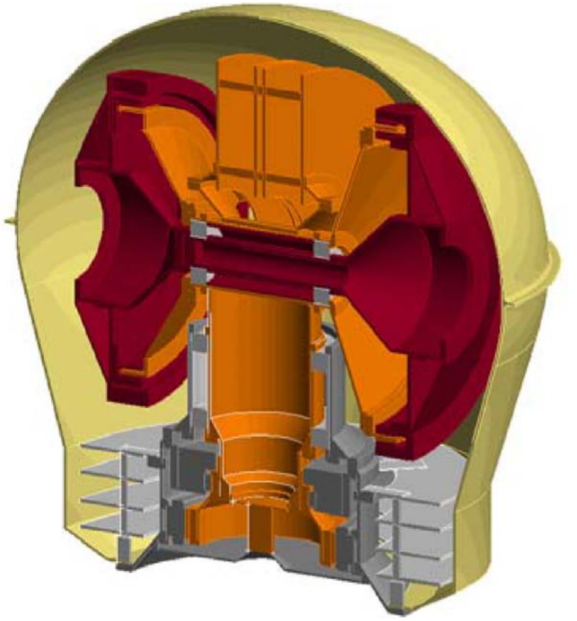

Fig. 14. CMG concept for agile spacecraft [5] (courtesy of ASTRIUM).

recognised for their leadership in a specific technology and having full control of the associated manufacturing processes. Each company shall be responsible for maintaining and developing their domain of excellence by its own technology and process strategies.

This approach will require process optimisation, industrialisation and standardisation, development of a product family, and business position consolidation with several customers, on top of achieving reliable performances and adequate delivery time at competitive prices. "Make-or-buy" decisions by prime contractors will depend on the competitiveness of the equipment supplier versus prime contractor in-house development and production capabilities. Taking this approach into account will enable mechanism suppliers to identify enlarged opportunities for increased volume production, coupled with the related cost efficiency on the developed product, and it should enable further access to the global market.

## 4. Conclusions

The challenging requirements and mechanism performances of future space missions are highlighted. Examples indicate that novel mechanism designs and tribological solutions have to be found to facilitate the success of the scientific missions proposed. In the field of commercial missions, mechanism providers have to closely interact with system engineering at satellite level while complying with substantially reduced development cycles and stringent cost targets.

Benefits of these developments will lead to further increase in batch production of mechanism products, which might subsequently find their implementation also in scientific satellite components and lead to related cost reductions.

## Acknowledgements

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