Actuators for Space Applications: State of the Art and New Technologies

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Abstract:
Actuators in space are broadly used to operate satellites' platform and payload devices. Despite their common utilisation, actuators still represent critical subsystems as their failure might often lead to severe, when not catastrophic, effects on the spacecraft operations. Environmental conditions to which actuators are exposed in space are generally not favourable: operating temperature ranges and deep vacuum are certainly the most critical ones. On the other end, performance requirements are instead becoming more and more challenging. In this context, consolidated technologies, like electric motors, are undergoing further design optimisations and progressing in terms of performances and reliability. Furthermore, new material and smart devices are progressively considered to best fulfil the wide range of applications and requirements of future spacecraft. The paper is intended to provide an overview of the state of the art of actuators technologies currently used in space and to highlight new trends and challenges that are characterising next generation of actuators.

Keywords: actuators, space, mechanisms, ESA, smart materials

Introduction

Actuators for space application shall satisfy requirement covering a wide variety of applications. Most spacecraft have appendages, like solar arrays or antennas or payloads, to be deployed and in some cases these appendages need to be continuously rotated or repointed during the mission. Furthermore, a vast majority of spacecraft embark instruments as payloads, where actuation is needed either for pointing purposes, like scanning mechanisms, or refocusing of mirrors, or optical path adjustment (optical wheels, shutters, choppers, etc …) or many others mechanical activities up to soil drilling in case of exploration missions. Due to this reason, requirement specification can also vary quite substantially, with the commonality of launch vibration environment, which is applicable for all applications.
In this context, very broad usage of DC electric motors and actuators has to be considered, thanks to their heritage, performances and reliability.
Despite applications of smart materials and structures technology to aerospace and other systems are expanding rapidly, when talking about current space missions, they are still rather limited. This indicates that a widespread technology transfer from smart materials to space has not quite yet occurred. This is easily justified when one considers the life cycle cost and complexity of an advanced space system. However, where extremely high precision are requested in combination with low mass and long operational life, smart materials have been seen as an approach which could make the mission viable.

Space actuators state of the art: electric motors

Mechanisms are single point failures, which play a major role in assessing the global risk of premature degradation or even loss of the mission: the European standards (ECSS [1]) recommend appropriate mechanical design margins and internal redundancy over the equipment mass and volume.

Fig. 1: *GAIA sunshield deployment test at ESA*

In a summary, mechanisms actuators shall be designed to be robust against hostile environment, whilst providing the requested performances. Space environment is in most cases a challenge for actuators: wide range of temperatures, vacuum, outgassing, radiations, long life mission with, of course, no maintenance possibility, just to mention the most significant concerns. Due to the above mentioned reasons, most common selection goes toward electric motors, and particularly to stepper motors thanks to their inherent capability of exhibiting unpowered holding torque and their simplicity in terms of electronics command and drivability in open loop. A very common configuration for actuator is composed by a combination of stepper motor with harmonic drive, typically monitored by a position sensor. A recent example of usage of this kind of actuator is the successful deployment in orbit of the 10.2m diameter GAIA sunshield last December 2013 (fig. 1), thanks to the European Harmonic Drive Rotary Actuator developed and qualified by Sener in Spain, with the support of ESA [2]. A picture of this device is reported in figure 2.

Fig. 2: *Harmonic Drive Rotary Actuator (HDTA), courtesy of Sener (E)*

Another example of similar actuator configuration is represented by the Satellite Antenna Rotary Actuator (SARA 21) developed by RUAG (CH), which finds its application in several scientific and telecom commercial satellites (fig. 3).

Fig. 3: *Satellite Antenna Rotary Actuator (SARA21), courtesy of RUAG (CH)*

Alternatively, brushless motor are also quite commonly used, despite more demanding electronics effort for commutation, especially where high speed are needed as per robotic applications. They are in standard use for reaction wheels actuation. Brushed motor are also a possible solution if pressurized environment could be guarantee, e.g. for Mars exploration or within sealed housing, in order to mitigate risk of brush arching and accelerated wear out. Regarding gears, beside harmonic drives, planetary and spur gears are also frequently used as well as worm gears, with some constraints coming from choice of lubricants in case of extreme temperatures.

Space actuators state of the art: smart materials

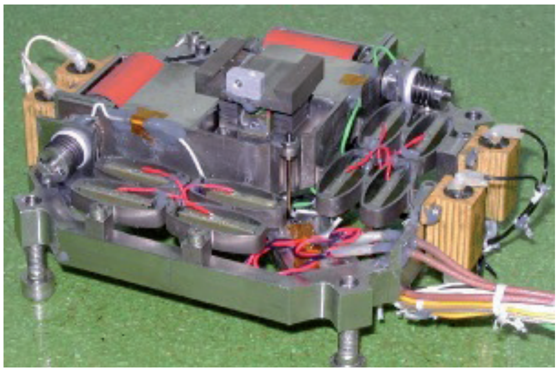

Fig. 4: *ROSETTA MIDAS instrument scanning mechanism, FM, courtesy of C-Tech (F)*

When moving from traditional electric motors to application of smart material technology into space mechanisms, one has to keep in mind many different aspects, including the size of space market. Whilst smart materials could be thought as being advantageous in terms of mass, volume and tribological aspects with respect to traditional actuators and sensors, they suffer of compatibility limitations toward typical platforms power and signal interfaces, and EMC problems due to the high voltage often required for their actuation. They also have compatibility limitations with some critical space requirements, often leading to complicated and/or jeopardised applicability on-board satellites. However, significant improvements have been recently achieved in these relatively young technologies, which make systems based on smart materials more and more interesting and mature for a near future breakthrough as space sensors and actuators.

It is impossible to single out few reasons why traditional solutions are often favored by spacecraft manufacturers against smart materials technologies, because it very often depends on the specific application: satellites are not mass produced objects. In general, areas that need attention are: product assurance, process quality controllability and reliability, functional and process reproducibility and repeatability, simpler design for interfaces (mechanical, thermal, electrical,…), redundancy approach, compatibility to radiation and contamination requirements. Most of these topics are currently addressed case-by-case for each

individual device, with a considerable impact on the final cost and risk for the projects, which could be significantly mitigated by converging toward an agreed European Standard, setting the basic rules and procedures to achieve standard space qualified items. Work in this direction is fostered by ESA.
What is often overlooked by academic technology trade-off is the additional mass and engineering complexity due to the essential ancillary equipment (electrical power units, controller hardware, electronics, software logic and algorithms,...), which shall be space qualified equipment as well.

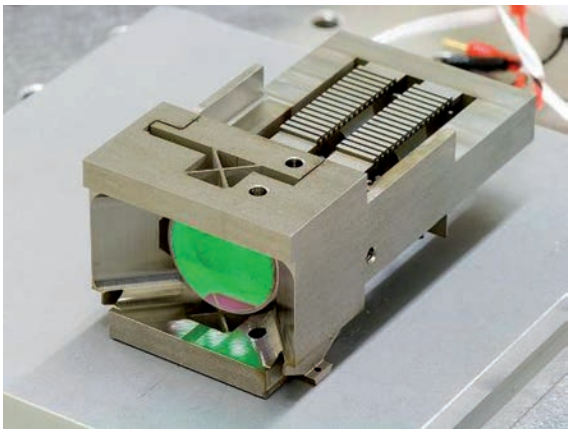

***Fig. 5:** The breadboard model of the Pointing Ahead Angle Mechanism, courtesy of RUAG(CH) and CSEM (CH)*

Embedding smart materials has higher impact on system architecture than passive systems. One example: passive dampers are placed at the critical interface and only require minor local redesign; therefore, they can be retrofitted on already built hardware at the last minute with minor impact at system level. Conversely, smart active techniques require dedicated multidisciplinary design effort, which cannot be easily modified a posteriori. Therefore, they are most effective when they are included as part of the baseline design since the preliminary phases of the project, and all involved disciplines are kept informed on the evolution.
Finally, aspects such as the on-ground integration, qualification and testing policies, set to preserve adequate mechanical margins (motorization, resistance characterization, life,…), shall not be underestimated.
Far from the presumption to be exhaustive, few encouraging examples of past, current and expected developments have been selected hereafter, with the intention to highlight the most promising categories of smart materials today.

Piezoelectric actuators

Among all smart materials, piezoelectric components certainly represent the most mature and consolidated technology for space mechanisms and structures applications. Many devices relying on piezo actuators have been successfully flown or have been qualified for flight within the following projects:

- Pointing mechanisms (ARTEMIS, PHARAO, EARTHCARE, SOHO)
- Point Ahead Angle Mechanisms (LISA)
- Laser control (AEOLUS, PHARAO, EARTHCARE, SWARM)
- Optical delay line (LISA-PF)
- Microvibration cancellation (PICARD, Solar Orbiter)
- Instrumentation (ROSETTA [3], MISSE7, CURIOSITY)
- Free-floating object handling (LISA-PF [4], FOTON M3)
- Propulsion (GAIA, LISA-PF)
- Scanning mechanism (Solar Orbiter)

Few examples are reported in figures 4 and 5.
Major advantages of piezo actuators are their magnetic cleanliness, high operating frequency, easiness of control, high accuracy and repeatability. In most cases, multi-layer configurations are preferred, in order to achieve higher strokes or produced forces; amplification of displacement is often realized via mechanical means. One major disadvantage of this technology is represented instead by the need for piezoelectric actuators of being continuously powered to maintain a certain position, which for many space applications could be not acceptable (especially where few operations during the mission are foreseen). Another drawback consists in the current absence of applicable dedicated standards for space oriented Product Assurance, but a lot of work has been done in this sense and this concern is considered almost covered.
Piezoelectric actuators can be also of interest for cryogenic applications due to their low power consumption. Preliminary work to assess their behavior and reliability in cryogenic conditions are on-going. An example of this kind of application is reported in figure 6: the Cryogenic Fine Steering tip/tilt Mechanism for EChO mission, which has been recently developed by Cedrat Technologies (F) and is intended to operate at 30K.

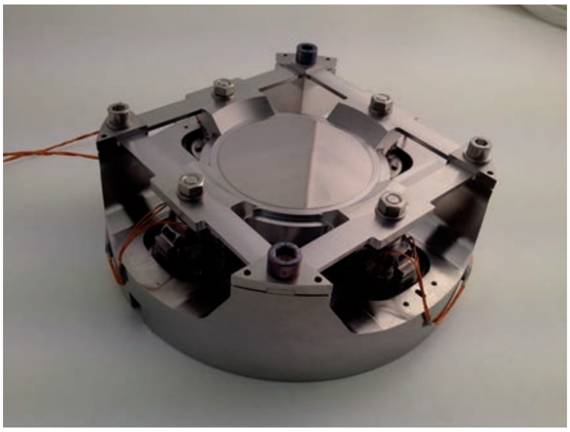

Fig. 6: *Cryogenic Fine Steering Mechanism, courtesy of C-Tech (F)*

Shape memory alloys

Shape memory alloys are broadly used in space applications since many years. SMA pin pullers are baseline for many deployment systems and the achieved flight heritage on these components is wide.

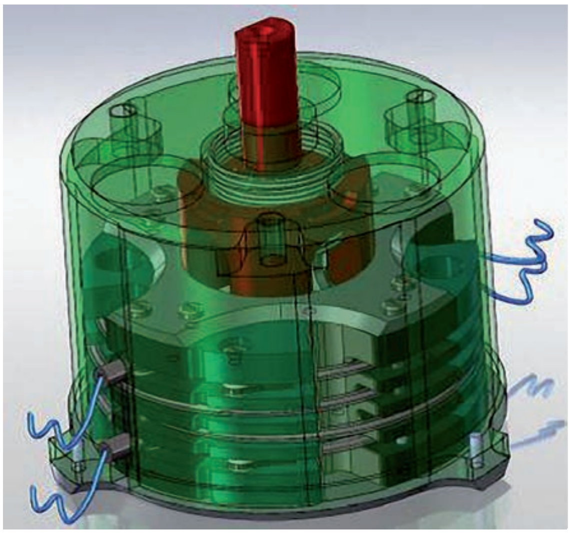

Fig. 7: *Transparency of SMA pin puller, courtesy of Arquimea (E)*

One of the limits of this technology has been the number of actuations capability and the typical thermal transition temperature (commonly about 70degC), which may not be fully compliant with some launchers specified environment. Currently, a new class of alloys have been studied and characterized by Arquimea in Spain, with European Space Agency contribution, which allow for successfully increasing the operating temperature range of a European SMA based actuators above 125degC. This novel, fully European, SMA technology has already been tested in space environment and demonstrator models for several space applications based on SMARQ have been successfully probed:
• Non-explosive actuators for Hold-Down and Release Mechanisms (HDRM), e.g. Pin Puller and REACT (non-explosive release nut) [7].
• Actuators for Deployment Mechanisms (DM), e.g. Rotary Actuators for Inter-panel Deployment Hinges.
An image of the SMA based pin puller is reported in figure 7.

Piezoelectric motors

Piezoelectric motors are using friction to drive their rotor and have become a standard for refocussing in single reflex camera. Their use is space equipment's can be of high interest due to their fully non-magnetic feature, their fine resolution and their resistive high torque at rest. For those reasons, they have been used in the following projects :

- Instrumentation (ROSETTA [3], SWARM),
- Free-floating object handling (LISA-PF [4]).

Their qualification is so far approached on a case-by-case basis, since they rely on requested minimum friction, which is not addressed in the relevant existing space standards especially with respect to life time reliability. The implementation of redundancy has been identified as a challenge as well as the verification by test that particulate contamination resulting from this tribological interface will not jeopardize functioning of the device itself or of the surrounding instruments.

New technologies for next generation of actuators

Performances specified for space actuators are constantly becoming more and more challenging in terms of precision, accuracy and stability on one side but also reduced mass and envelop on the other. In this view, a continuous effort shall be put into optimization of currently used technologies as well as exploring new possibilities within smart materials family. ESA has been fostering R&D activities on this new solutions for several years now, and despite not always successful and conclusive results, there is a great and increasing interest about them, especially for specific applications where traditional technologies may not be successful. Here below a quick overview of the current progress of some smart materials in terms of suitability for space usage.

Magneto(electro)-strictive materials

Existing theoretical and experimental data on magnetostrictive and electrostrictive materials are quite scarce for the purpose of space applications, although these materials are well suitable for cryogenic environment, and exhibit almost no hysteresis. Operational and non-operational temperature ranges of application may still represent a problem for most missions.

Magneto-rheological fluids

Magneto(electro)-rheological fluids [8] have found very little applicability in European space systems, so far. However, some R&D activities have been started to evaluate major performances and weak points of this technology, mainly for semi-active dampers applications. In this context, their characteristic low dependency on temperature changes might be considered advantageous compared to traditional viscous dampers, and in light of their small power consumption.

Self-Healing structures

Composite structures with embedded self-healing properties are attractive for space applications in view of possibly extending the life expectance and durability of future space explorers and manned habitats (Moon, Mars, and beyond…).
Some explorative interest has been dedicated by ESA to self-healing technologies [9], in order to better assess its capability to repair the high speed impact damage resulting from collisions with micrometeoroids and orbital debris as well as the internal matrix microcracking damages arising from the usual repeated environmental thermo-mechanical cycling.
Currently, these technologies are still at an embryonic stage (TRL 1-2), and only the successful scientific observation of the basic phenomena and their compatibility with the general space environment has been proven: for example, evidence has been shown that strength of hollow composite fibres could be recovered, in principle, up to 87% when outgassing is properly managed.

Electroactive Polymers

Until now, no space application of these technologies has been successfully brought to a TRL level higher than a preliminary feasibility investigation (TRL 2-3), due to insufficient maturity of this technology and the scarce compatibility with space environment. Some interesting developments were supported in 2006 by ESA [10,11,12], in the frame of the possibility to employ these technologies in large aperture reconfigurable antennas and solar sails. An example of this research is reported in figure 8.
The outcome, although promising in principle, presented an unfeasible development cost and risk prospective, which holds still valid today. Mainly, the limits are identified in the following characteristics: outgassing, contamination and radiation compatibility, extremely high voltage units and harness, with complex power electronics and expensive controller strategies, low reliability and process repeatability, and occasional unpredicted behavior, fast degradation and high dispersion of functional performance in vacuum.

Fig. 8: *Demonstrator of a reconfigurable antenna, courtesy of Keyser Italia (I)*

Conclusions

Today, more conventional and mature technologies are still widely preferred for mission critical subsystems, namely electric motors in combination with gearboxes. Smart materials have been considered enabling technologies for specific purposes, frequently related to an extremely challenging scientific objective. At the same time, other flight applications may have also suffered from the additional effort required to consider them within the appropriate Quality Space Standards.
Currently, piezoelectric actuators are undoubtedly the most commercially successful smart materials. Their applications cover a wide range of technological and industrial areas, as well as some precision space instruments: mainly in optical instruments, laser beam pointing and control as well as active microvibration isolation and damping of sensitive scientific payloads.
Among other smart materials, SMA is the second most mature smart technology for space applications. Several on-orbit experiments and actual missions have been successfully flown, and new European components exist for release and deployment mechanisms, with increased non operational temperature range.
The remaining more exotic smart materials have only been studied at a level of feasibility, although encouraging results have been obtained in the fields of adaptive optics, reconfigurable antennae, distributed sensing, cryogenic devices.
In conclusion, while substantial technological improvement is felt necessary before becoming

widely attractive for the space business, the European Space Agency is interested in monitoring the progress accomplished in smart structures and mechanisms, as they may soon become the enabling technology of future long duration space missions.

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Actuators for Space Applications
State of the Art and New Technologies

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    b. space missions portfolio

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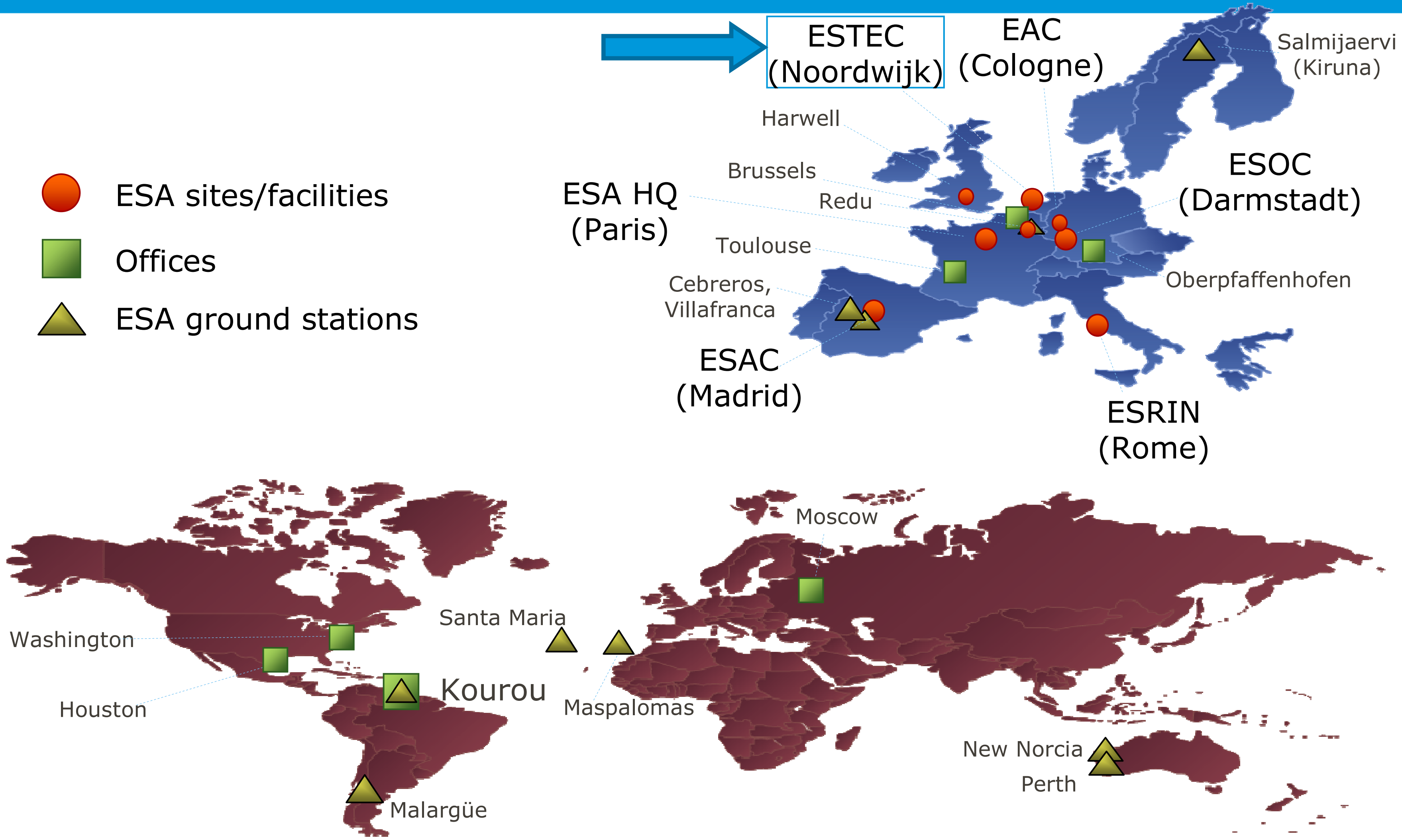
Purpose of ESA

"To provide and promote, for exclusively peaceful purposes, cooperation among European states in **space research** and **technology** and their **space applications.**"

Article 2 of ESA Convention

ESA's locations

- ESA sites/facilities
- Offices
- ESA ground stations



ESA facts and figures

ESA has 20 Member States:
18 states of the EU (AT, BE, CZ, DE, DK, ES, FI, FR, IT, GR, IE, LU, NL, PT, PL, RO, SE, UK) plus Norway and Switzerland.

Eight other EU states have Cooperation Agreements with ESA: Estonia, Slovenia, Hungary, Cyprus, Latvia, Lithuania, Malta and the Slovak Republic. Bulgaria is negotiating a Cooperation Agreement.

Canada takes part in some programmes under a Cooperation Agreement.

Activities

ESA is one of the few space agencies in the world to combine responsibility in nearly all areas of space activity.

- **Space science**
- **Human spaceflight**
- **Exploration**
- **Earth observation**
- **Launchers**
- **Navigation**
- **Telecommunications**
- **Technology**
- **Operations**

* Space science is a **Mandatory programme**, all Member States contribute to it according to GNP. All other programmes are **Optional,** funded 'a la carte' by Participating States.

ESA / ESTEC
Structures and Mechanisms Division

ESA / ESTEC **TEC-MS** Terms of Reference:

➔ **Provide** functional **support** to feasibility and definition studies as well as approved spacecraft- and launcher projects in the:

- preparation of **specifications**;
- analysis of industrial **proposals**;
- monitoring of **procurement** and **development** contracts;
- **evaluating** design and test results;
- supporting analysis tasks;
- supporting spacecraft **test** programs;

➔ **Definition and Execution of R&D** studies for related technologies:

- **coordination and harmonisation** of activities with specific roadmaps
- **subsystems/element** developments;
- development of **tools** and **methodologies**;

Focal point within the Agency for all Structures & Mechanisms aspects

Mechanisms, Tribology and Pyrotechnics

✓ **Requirements** specifications, **design**, analysis, manufacturing and **testing** of:

- **Space mechanisms** and **space mechanical systems**, including actuators, motors, deployment systems for solar arrays, masts, antennae; pointing and scanning mechanisms; hold-down, release and separation systems; reaction and momentum wheels; gradiometers and mechanical devices operating at cryogenic and hot temperatures;
- **Mechanical elements** for launcher, re-entry and landing systems (load attenuation devices, valves, seals, turbopump bearings, parachute systems, landing gears, etc.), as well as mechanical elements for robotics and planetary exploration tools;
- Miniaturised mechanical devices and mechanical **micro-nano technologies**;
- Electrical motor **command and control loops** for actuators;

✓ **Tribology** for space mechanisms;

✓ **Pyrotechnics**;

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ESA missions (partial)

ESA missions: highlights

- **Rosetta** (2004– ?) the first long-term mission to study and land on the 67P/Churyumov-Gerasimenko comet
- **BepiColombo** (2016) a satellite duo exploring Mercury (with JAXA)
- **Solar Orbiter** (2017) studying the Sun from close range
- **JUICE** (2022) studying the ocean-bearing moons around Jupiter
- **EXOMARS** (2016 and 2018) orbiter and landing vehicle to Mars (with Roscosmos)
- **MTG and METOP** (2016 -?) Earth observation for climate and weather forecasting
- **Copernicus Constellation:** Earth global monitoring for environment and security (with European Commission)
- **European Data Relay System** (2015) for reducing delays in data transmission
- **NEOSAT** new geostationary satellites for telecommunication
- **GALILEO** constellation of 30 satellite for navigation (with European Union)

Space environment

Different phases of S/C and payload life:

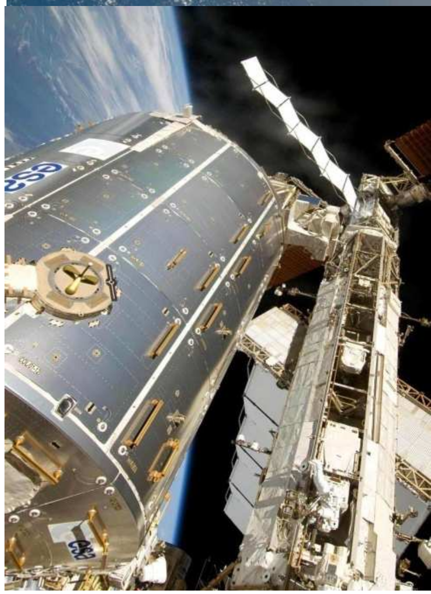
- On – ground MAIT
- Launch
- Commissioning
- Operation

Major constraints in space:

- High vibration levels during launch
- No gravity
- Vacuum
- Temperature range
- No maintenance

Challenge:

- Improving performances
- Reliability against longer life application
- Reducing costs/miniaturisation



ECSS standards

esa

Design and qualification of structures and mechanisms for Space applications are deemed to **satisfy** the European Cooperation for Space Standardization (**ECSS**) standards, handbooks and technical memoranda.

- Structures: *ECSS-E-ST-32-01*
- Mechanisms: *ECSS-E-ST-33-01*

Typical qualification test sequence:

- Functional and performance tests
- Vibration campaign
- Thermal vacuum
- Life test
- Functional and performance tests

ECSS

ECSS-E-ST-10-03C
1 June 2012

Table 5-2: Space segment equipment - Qualification test levels and duration

No	Test	Levels	Duration	Number of applications	NOTES
1	Life	Expected environment and maximum operational load	For duration and cycles: For mechanisms, apply ECSS-E-ST-33-01 Table 4-3 For batteries, apply ECSS-E-ST-20	1 test	
2	Static load	KQ x Limit Load The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	As needed to record data (10 seconds minimum)	Worst combined load cases	Worst combined load cases are determined by analysis
3	Spin	$\sqrt{KQ}$ x spin rate The qualification factor KQ is given in ECSS-E-ST-32-10	As specified by the project	1 test	
4	Transient	KQ x Limit Load The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	As needed to record data	As specified	
5	Random vibration	Maximum expected spectrum +3 dB on PSD values If margins higher than 3 dB are specified by the Launcher Authority, they apply.	2 minutes	On each of 3 orthogonal axes	
6	Acoustic	Maximum expected acoustic spectrum +3 dB If margins higher than 3 dB are specified by the Launcher Authority, they apply	2 minutes	1 test	
7	Sinusoidal vibration	KQ x Limit Load Spectrum The qualification factor KQ is given in ECSS-E-ST-32-10 clause 4.3.1	sweep at 2 Oct/min, 5 Hz - 140 Hz	On each of 3 orthogonal axes	

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http://www.ecss.nl/

Actuators for space: state of the art

- **ELECTRIC MOTORS: consolidated technology** with vast heritage for most of needed applications
- **PIEZOELECTIC ACTUATORS:** well **established solution** with long heritage
- **SHAPE MEMORY ALLOYS: broadly used** for release systems, certainly growing technology
- **Other technologies**

Electric motors (1/2)

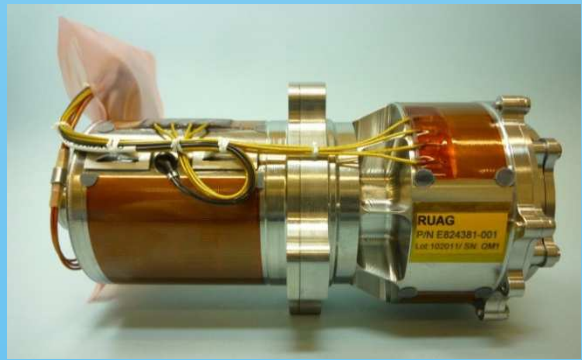
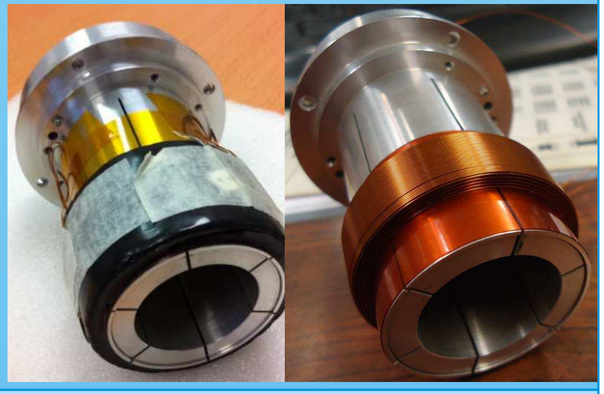
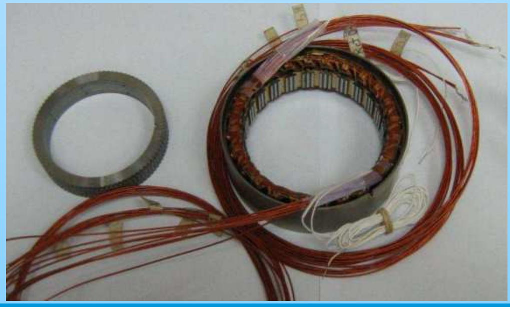
- Most of spacecraft appendages (Solar Arrays, Antenna Reflectors, Radiators, Instruments, Doors, Sensors, Booms, …etc) are held stowed during launch and **must be deployed** in orbit to their operating position.

- Once the final position is reached, the appendage is either latched at a defined position or the deployment mechanism is used as a **re-pointing** or trimming device in order to achieve specific mission related functions.

Most of these applications are covered with electric motors and actuators:

- **Stepper motors**
- **Brushless motors**
- **Brushed motors**
- **Electromagnetic actuators**

Electric Motors: (2/2)
Examples of Space applications

Stepper motors	Brushed and brushless motors	Electro mechanical devices
Harmonic Drive Rotary Actuator flight model Courtesy of Sener (E) 	View of the Sealed Brushed Gear Motor Qualification Model Courtesy of RUAG (CH)  	Development of an engineering model of Voice Coil Motor Courtesy of Cedrat Technologies (FR) 
View of 4phases stepper motor qualification model Courtesy of Soterem (FR) 	View of brushless motor qualification model for attitude control Courtesy of Soterem (FR) 	Reaction Sphere for attitude control Courtesy of CSEM (CH) 

Smart materials advantages and difficulties at System level

- ✓ Applications of **smart materials technology to aerospace** and other systems are **expanding rapidly**, and this field has evolved from a bench-top curiosity to system level demonstrations for application to high precision spacecraft, formation flying and large precision space-based systems.
- ✓ The overall spacecraft mass and volume is driven by launchers capacity and cost, therefore obtaining a very **compact** satellite **package** in stowed configuration is a **very attractive** opportunity.
- ✓ On the other hand, the effort to improve subsystems miniaturization conflicts with the evidence that **space environment** is quite **challenging for** the actuation of **mechanisms** and satellite **structures**.
- ✓ **Mechanisms** are single point failures, major contributor to global **risk** of **premature degradation** or loss of the mission: European standards (**ECSS**) **privilege** appropriate mechanical design **margins**, avoidance of unintended activation, internal redundancy **over** the equipment **mass** and volume (and **cost**).

Specific advantages and constraints

Advantages:

- exceptionally **high precision** pointing enabling capability
- miniaturised actuators solutions
- **ease** mechanisms **tribological aspects**

Acknowledged constraints for Space:

- compatibility with current platforms **power and signal** interfaces
- compatibility to **vacuum, radiation and contamination** requirements;
- applicable **failure tolerance criteria** and risk mitigation actions
- on-ground integration, **qualification and testing policies**, set to preserve adequate mechanical margins shall not be underestimated
- **product assurance**, processes and quality controllability and reliability, functional and processes reproducibility and repeatability

Piezoelectrics: (1/3) established technology

- In most cases, multi-layer configurations are preferred, in order to achieve higher strokes or exerted forces; amplification of displacement is often realized via mechanical means.

- Most of the applications are covered with piezo actuators. Less cases of piezo motors usage.

- Major **advantages** of piezo actuators are their magnetic cleanliness, high operating frequency, easiness of control, high accuracy and repeatability.

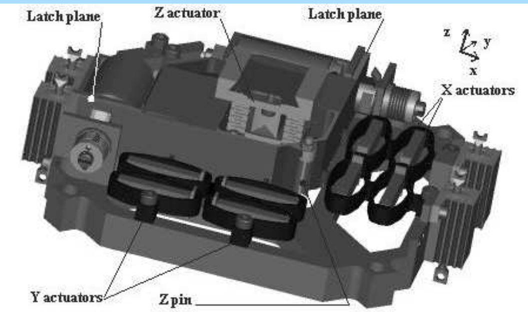
- Their major **drawback** consists of the sensitivity to humidity which is exhibited by some MLA. Issue namely for on ground testing. Furthermore, current absence of applicable standards for space oriented Product Assurance is also of concern, but is being covered at the moment..

Piezoelectrics: (2/3)
Examples of Space applications

The Scanning Mechanism for Rosetta/MIDAS

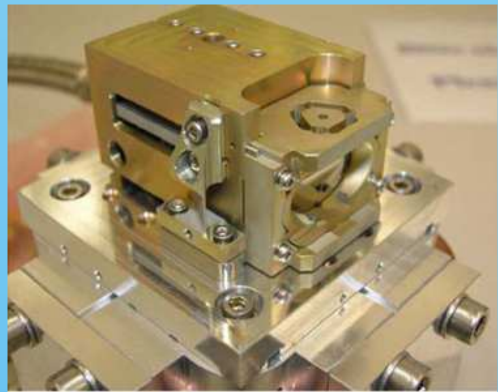
View of Flight Model
Courtesy of Cedrat Technologies (FR)

Basic design of the XY stage
Courtesy of Cedrat Technologies (FR)

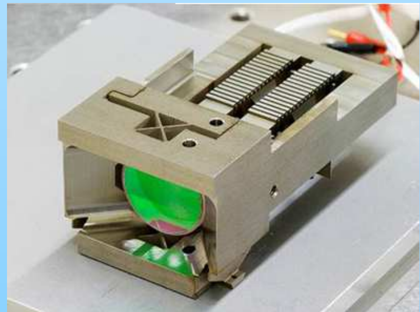


Point Ahead Angle Mechanisms for LISA

Breadboard model
Courtesy of RUAG (CH) and CSEM (CH)



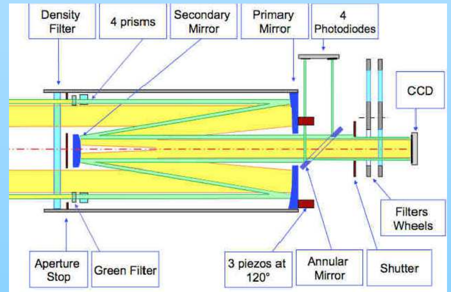
Breadboard model
Courtesy of TNO (NL)



The EChO Cryogenic Fine Steering Tip Tilt Mechanism

CFSM Engineering model
Courtesy of Cedrat Technologies (FR)

SODISM optical system
Courtesy of CNRS (FR)



Piezoelectrics: (3/3) applications

Pointing applications

- ARTEMIS/SILEX/PAM (ASTRIUM Porsmouth, 1999) Point Ahead Mechanism for laser communication
- ISS / PHARAO / MEF (CEDRAT Tech. to be launched in 2015) : Pointing mechanism for laser insertion

Optical fiber

- EARTHCARE/ATLID (CEDRAT Tech, to be launched in 2016) : Laser Beam steering of the lidar
- SOHO/LASCO (Kayser Threde, 1995) : Coronograph pointing

Laser control

- AEOLUS/ALADIN (CEDRAT Tech. to be launched in 2015) : Extended cavity control
- ISS / PHARAO / LCE (CEDRAT Tech. to be launched in 2015) : Extended cavity control
- EARTHCARE/ATLID (CEDRAT Tech. to be launched in 2016) : Extended cavity control
- SWARM/ASM ((CEDRAT Tech. to be launched in 2013) : Laser Fiber Extension control

Optical delay line

-LISA-PF/LMU/OPDA (CEDRAT Tech. to be launched in 2015) : Optical delay line

Micro vibration cancellation

- PICARD/Sodism/SMP (CEDRAT Tech. 2010) M1 pointing

Instrumentation

- ROSETTA/MIDAS (CEDRAT Tech. 2003) : scanner of the Atomic Force Microscope
- ISS/MISSE7 (CEDRAT Tech. 2009) : reciprocating tribometer flown on the ISS
- CURIOSITY/SAM/ (CEDRAT Tech. 2012) : Piezoelectric sieving

Free-floating object handling

- LISA-PF/ISS/GPRM (RUAG Z, to be launched in 2015) : repositioning of the free floating mass
- FOTON M3/DIMAC (CEDRAT Tech. 2007) repositioning of the free floating mass

Propulsion

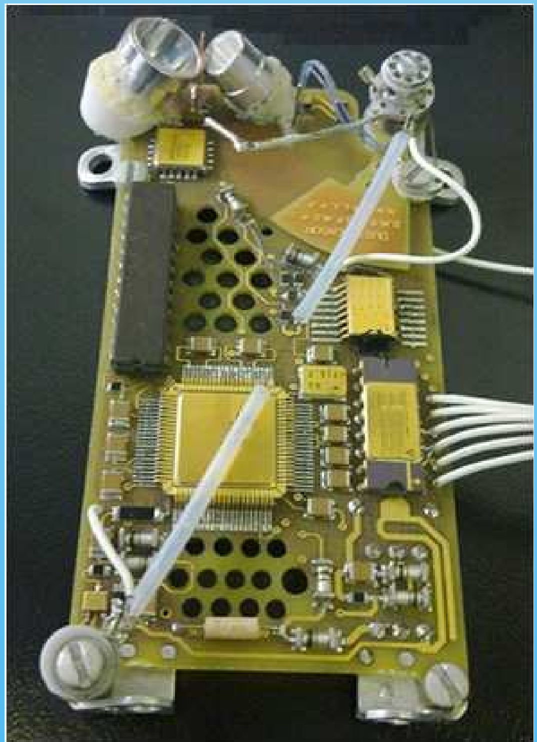
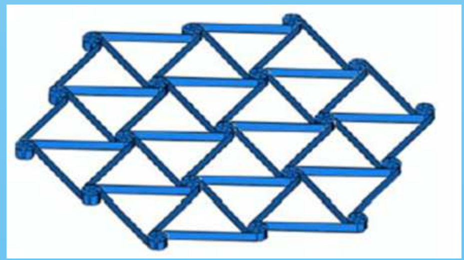
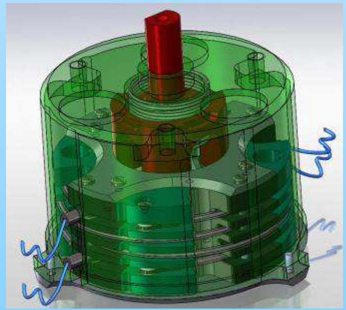
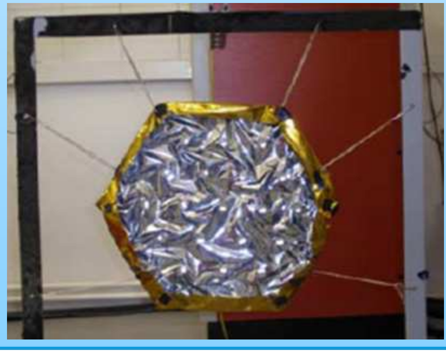
- Cold Gas Proportional Thruster (Selex galileo) to be flown on GAIA(2014), LISA-PF (2015), (possibly EUCLID in 2020)

Shape Memory Alloys: (1/2) successful breakthrough

- SMA **pin pullers** are baseline for several deployment systems and the achieved flight heritage on these components is wide. One of the limits of this technology has been the number of actuations capability and the **typical thermal transition temperature** (commonly about 70degC), which may not be fully compliant with launch and post launch environments.

- Currently, **a new class of alloys** have been studied and characterized **with European contribution**, which allow for successfully increasing the operating temperature range of a European SMA based actuators above **120degC.** This **novel, fully European, SMA technology** has already been tested in space environment and demonstrator models for several space applications based on SMARQ have been successfully probed

Shape Memory Alloys: (2/2) examples of Space applications

Dust Sensor instrument of the MEIGA-MetNet Mission	Pin puller mechanisms based on a novel shape memory alloy (SMA)	Deployable SMA demonstrator based on an auxetic chiral structure
Qualification model Courtesy of Arquimea (ES) 	Pin Puller Demonstration Models Courtesy of Arquimea (ES) 	Dynamic deployment simulation of the concept design Courtesy of Univ. Bristol (UK) 
	Transparency of Pin Puller Courtesy of Arquimea (ES) 	Deployment test with zero-g compensation device Courtesy of Univ. Bristol (UK) 

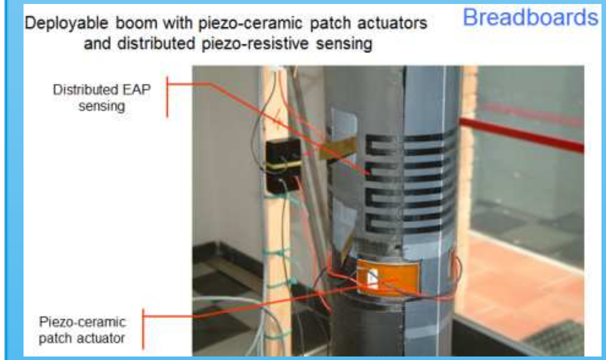
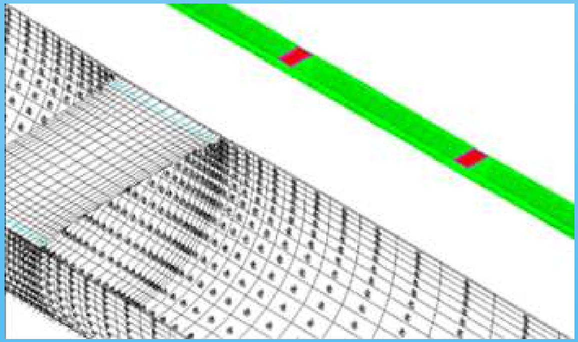
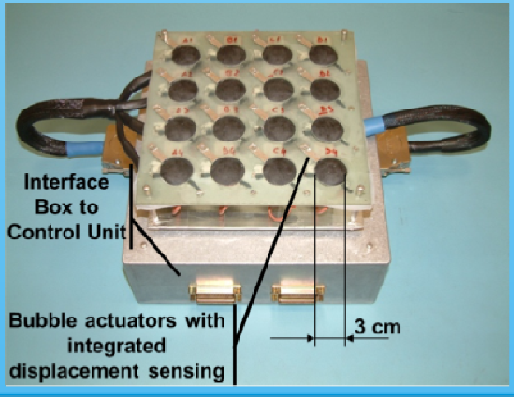
Electro-Active Polymers: (1/2) areas of improvement

- No space application of these technologies has been successfully brought to a TRL level higher than a preliminary feasibility investigation (TRL 2-3), due to insufficient maturity of this technology and the **scarce compatibility with space environment today**.

- Some interesting developments were supported in the frame of **large aperture reconfigurable** antennas and **solar sails** technologies. The outcome, although promising in principle, presented an unfeasible development cost and risk prospective, which holds still valid today.

- Identified areas of improvement: problematic **outgassing**, **contamination** and **radiation** compatibility, extremely **high voltage** units and harness, with **complex** power **electronics** and expensive controller strategies, low reliability and **process** repeatability, occasional unpredicted behavior, **fast degradation** and high dispersion of functional performance **in vacuum**.

Electro-Active Polymers: (2/2) examples of technology demonstrators

<table>
<tr><th>Health monitoring and active vibration control concept for lightweight deployable booms</th><th>Integrated active vibration control and sensors concept for inflatable booms</th><th>Distributed actuators concept for reconfigurable antennas</th></tr>
<tr><td>Technology demonstrator during validation tests
Courtesy of Risoe (DK)

</td><td>FEM model design concept
Courtesy of HPS (DE)
</td><td>Demonstrator ready for functional testing in vacuum chamber
Courtesy of Keyser Italia (IT)

</td></tr>
</table>

Other smart technologies: (1/3) self-healing structures

- Composite structures with embedded **self-healing** properties are **attractive for space applications** in view of possibly **extending** the **life expectance and durability** of future space explorers and manned habitats (Moon, Mars, and beyond…).
- Some explorative interest has been dedicated by ESA to self-healing technologies, in order to better assess its capability to repair the **high speed impact damage** resulting from collisions with micrometeoroids and orbital debris as well as the **internal matrix microcracking damages** arising from the usual repeated environmental thermo-mechanical cycling.
- **Currently**, these technologies are still at an **early stage** (TRL 1-2), and only the **successful scientific observation of the basic phenomena** and their compatibility with the general space environment has been proven: for example, evidence has been shown that strength of hollow composite fibres could be recovered, in principle, up to 87% when outgassing is properly managed.

Other smart technologies: (2/3) (electro)magneto-rheological fluids

- Magneto(electro)-rheological fluids have found very little applicability in European space systems, so far. Some R&D activities have been started to evaluate major performances and weak points of this technology, mainly for semi-**active dampers applications**.

- In this context, their characteristic **low dependency on temperature changes** and potential "controllability" might be considered advantageous compared to traditional viscous dampers, and in light of their **small power consumption**.

Other smart technologies: (3/3) magneto(electro)-strictive materials

- Existing theoretical and experimental **data** on magnetostrictive and electrostrictive materials **related to space** applications **are scarce**, although these materials may well be suitable for cryogenic environment, and exhibit almost no hysteresis.

- Evaluation of the material characteristic is under definition as preliminary feasibility screening.

- it is worth remembering that magneto-strictive devices are already used for **on-ground space equipment**, e.g. for contactless position sensors.

Conclusion (1/2)

1. **Electric Motors and Actuators** (typically based on Steeper and Brushless motors) are certainly covering most of the application needs for space and they are typically preferred due to their wide heritage and high reliability

2. **Piezoelectrics** are undoubtedly the **most successful smart actuators for space**. Their applications cover a wide range of technological and industrial areas, as well as some precision space instruments: mainly in optical instruments, laser beam pointing and control as well as active micro-vibration isolation and damping of sensitive scientific payloads.

3. **Shape Memory Alloys** is the **second most mature** smart technology **for space** applications. Several on-orbit experiments and actual missions have been **successfully flown**, and new European components exist for release and deployment mechanisms.

Conclusion (2/2)

4. The **remaining** more **exotic smart materials** have only been studied at a **level of feasibility**, although encouraging results have been obtained in the fields of semi-active damping, adaptive optics, reconfigurable antennae, distributed sensing, cryogenic devices.

5. Even when not all these technologies are yet suitable for flying in space, they might be often of key importance in the space sector during the extremely demanding process of manufacturing, ground testing and verification of most spacecraft structures and mechanisms.

6. While **substantial technological improvement** is felt necessary before becoming widely attractive for the space business, the progress in **smart structures and mechanisms** is regularly monitored by the European Space Agency, because they **may soon become the enabling technology of future** long duration **space missions**.

Acknowledgements

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