BEAM STEERING MIRRORS:
FROM SPACE APPLICATIONS TO OPTRONIC APPLICATIONS

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KEY WORDS: Beam steering mirror ; Fast Steering Mirror ; Optical pointing ; Point Ahead Mechanism ; Optic communication ; Laser ; Image stabilisation ; Microscanning ; Piezoelectric ; Actuator ; Tip-tilt ;

ABSTRACT:

Fast growing Laser and new optic applications drive more and more needs for beam steering mirrors (BSM) and Fast Steering Mirror (FSM). For space optic instruments, CEDRAT TECHNOLOGIES has developed for 20 years several piezoelectric tip-tilt mechanisms. Presented recent examples include the ATLID BSA small tit tilt for quasi static nano pointing and MEFISTO, a large tit tilt for fast micro positioning. These space mechanisms perform high precision functions while being compact, lightweight and resistant to external vibrations and shocks. As shown in the paper, these advantages allow these technologies addressing several needs for other optronic applications than space, such as active stabilisation, micro scanning, disturbance compensation in IR imagers or telescopes.

1. INTRODUCTION

Fast growing Laser and new optic applications drive more and more needs for beam steering mirrors (BSM) and Fast Steering Mirror (FSM). Those applications can be found for example in:
- optics: interferometer, Lidar, laser guide star
- telecom: optical free space communication link
- defence: laser designator, Laser Weapon System
- optronics: image stabilization, micro scanning
- medicine: ophtalmological laser
- industry: 3-D printer, rapid prototyping, material processing machine, laser engraving …

For space optic instruments, with the support of CNES, DGA, ESA, BPIF and with own funding, CEDRAT TECHNOLOGIES (CTEC) has developed for more than 20 years several piezoelectric actuators [1], XY stages [2,3] and mirror tip-tilt mechanisms [4,5] offering high precision and high bandwidth for BSM and optic systems. Because of space launching requirements, these mechanisms should not only perform high precision functions but should also be extremely reliable while being compact, lightweight and resistant to external vibrations and shocks. Two recent examples are presented: The BSA is a small tit tilt for quasi static pointing correction in ATLID Lidar; MEFISTO is a large tit tilt for motion compensation for space telescopes of CNES future observation satellites

The paper shows also that these advantages allow CTEC piezo technologies to address several BSM & FSM needs for other embedded applications than space (among those mentioned above), where severe environment and high reliability are demanded. Given examples are combined active stabilisation and micro scanning in IR imagers, and disturbance compensation in ground telescopes.

2. SPACE STEERING MIRRORS MECHANISMS

2.1. ATLID Space BSM

Thanks to its space heritage from PHARAO [4], CTEC has developed the ATLID BSA [6] (Fig. 1 & 2) required by AIRBUS SODERN. ATLID is an Atmosphere Lidar instrument for EarthCARE space mission. This Beam Steering Mechanism, named BSA (Beam Steering Assembly), included in the emission path, aims at deviating a pulsed high energy UV laser beam to compensate the pointing misalignment between the emission and reception paths of ATLID. The requirements were particularly severe regarding the long term stability and the cleanliness.

The developed BSA is a Tip-Tilt mechanism based on 4 Amplified Piezoelectric Actuators APA60SM including Strain Gauges (SG).

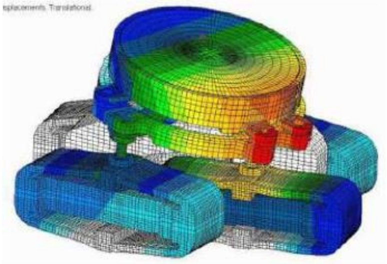

Figure 1. ATLID BSA : tilt motion FEM

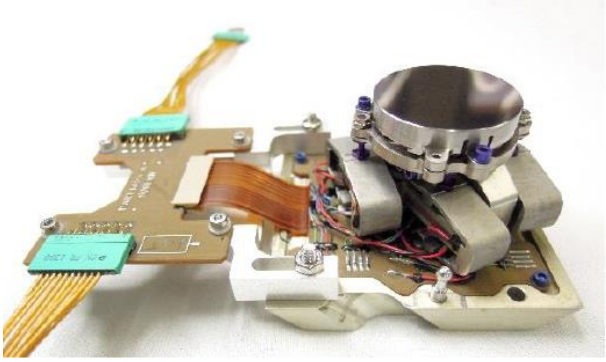

Figure 2. ATLID BSA Flight Model

The APA® are patented compact actuators from CTEC [7] based on a low voltage multilayer piezo ceramics (MLA) and a shell ensuing both MLA pre-stressed and amplification of the MLA displacement. The APA60SM offers a stroke proportional to the voltage. When voltage varies from -20 V to +150 V, the stroke is about 80µm. It is based on a 5×5×20 mm3 MLA.

The required Rx and Ry strokes being different, a non-symmetric mechanism configuration of the 4 APAs is chosen, which optimize the mechanism size. The 4 actuators move a 3-point isostatic support for the mirror to avoid stress in the mirror. Fig. 1 shows the tilt motion computed by FEM, accounting for push pull drive of opposite APAs.

Achieved experimental performances according to CTEC and AIRBUS tests [8] are given in Tab. 1.

Table 1. ATLID BSA Performances

Total tilt stroke Rx	4.3mrad
Total tilt stroke Ry	3.0 mrad
Resolution	< 0.4 µrad
Repeatability	< 70 µrad
Long term stability	< 200 µrad
Resonance frequency	> 2 kHz
Shock level	100 g
Random Vibration level	15.5 g rms
Quasi Static acceleration	26 g
Particular Cleanliness	< 50 ppm
Molecular Cleanliness	< 5.10 10^{-8} g/cm²
Mirror diameter	27mm

High stiffness of APA60SM (1.3 N/µm) and additional guiding have led to the high resonance frequency of the mechanism, which is one key to pass vibration qualification tests. This high resonance frequency would offer a wide range of operational frequencies but in this fine positioning application, operational range is 0 to 10 Hz, and actuators are used in quasi static modes (no inertial effect).

To obtain the desired stability and accuracy in closed loop, this mechanism is controlled by strain gauges (SG) position sensors deposited on the MLA piezo ceramics of the APA60SM (Fig. 3). A particular development effort has been undertaken to get adequate SG within the application: The SG should not unreliabilize the MLA piezo ceramic, noting its coating is fragile and any defect in coating would induce an electrical breakdown; The SG gluing should be compliant with very low out-gassing budget; The SG performance should exhibit high stability, meaning no drift, even with aging and temperature. Therefore a careful deposition process has been defined and qualified. A full bridge configuration was also selected to optimize the sensitivity while limiting the thermal impact and non-linearity errors on its performance.

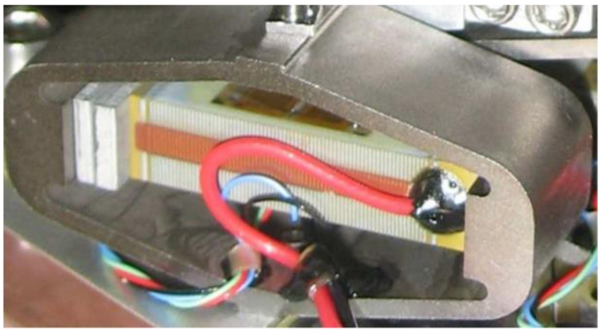

Figure 3. ATLID APA60SM-SG

High Cleanliness for the whole mechanism was required to avoid laser-induced contamination (LIC) of ATLID instrument optics. It was achieved by careful cleaning, selection of low-outgassing materials and assembly in ISO5 assembly room.

A long qualification campaign was performed including shocks tests, vibrations tests, EMC and thermal cycle tests to establish the compliance with requirements.

CTEC has successfully delivered the BSA Flight Models to SODERN for ATLID in 2015. Launching is planned in 2019. These FM will increase CEDRAT TECHNOLOGIES existing flight heritage started with ROSETTA in 2004 [9].

2.2. MEFISTO space mechanism

In the framework of the MEFISTO R&D Rapid project, funded by DGA and in collaboration with SODERN, CTEC have developed a new space mechanism which is at the opposite of ATLID BSA in term of size and objectives. Its application is the satellite motion compensation for space telescopes of CNES future observation satellites. The objective of the mechanism is to move a large mirror of 730 gr with a fast saw tooth motion.

A typical targeted stroke is given on Fig. 4. A back and forth stroke of typically 50 to 70 µm has to be done in less and 10 ms. Additionally this motion should include a constant speed time called the integration time of the telescope, as shown in Fig. 5. This is the most important performance for application: This time allows a stable telescope image acquisition in spite of the satellite motion.

In addition the signal is pre-shaped to minimize the generation of high frequency harmonics.

At last, the mechanism should also limit the generation of vibrations in the satellite structure. Therefore the shape of the stroke as Figure 4 is already optimised to reduce the excitation of vibration mode of the structure.

To achieve this specification, an unusually-large tip-tilt mechanism (Fig. 6) has been designed and tested. It moves payload formed by a mirror and an isostatic mirror holder, which total mass is about 2 kg.

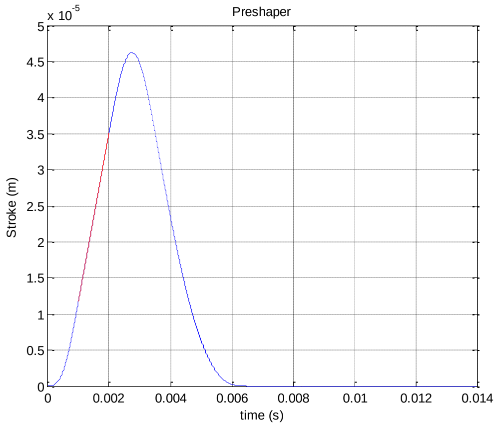

Figure 4. Pre-shaped stroke of a piezo foot (Red part is integration time)

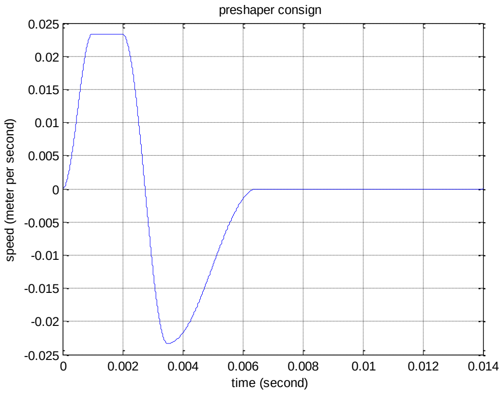

Figure 5. Speed deriving from Fig. 4 (Constant speed is for integration time)

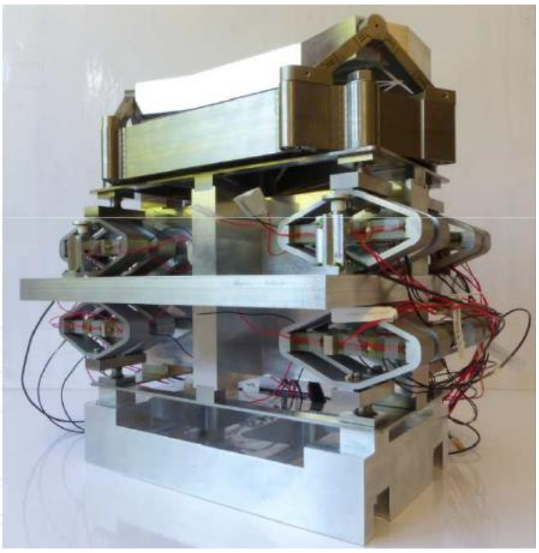

Figure 6. MEFISTO mechanism with its mirror

The mechanism is based on 2 sets of 4 piezo feet separated by a base plate in the plane of quasi-symmetry. Such a quasi-symmetric configuration is obtained with a counter-mass having same mass as the payload. The base plate is used for fixing the mechanism to the satellite structure. Both sets of actuators are excited with the same voltages. The vibration forces due to the payload motion are compensated by moving the counter mass in the opposite direction of the payload. This aims at reducing the transmission of vibrations to the satellite structure [11].

Each piezo foot is made of 2 APA120ML actuators to get a redundancy, for reducing failure impacts. An APA120ML offers a 130µm free stroke and 1400N blocked force.

For their individual motion control, each APA120ML actuation foot is equipped with CTEC new Eddy Current Sensors ECS75. This sensor offers compactness, high resolution (10 nm), good linearity (0.1 % on 100 µm) and large bandwidth (20 kHz). Each Eddy Current Probe is placed in front of a metallic target fixed on the side of the moving head of the actuation foot (Fig. 7).

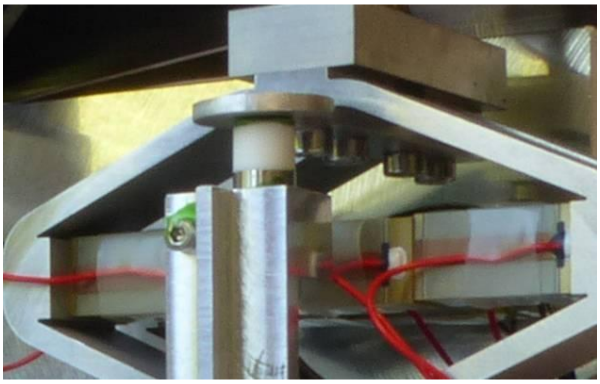

Figure 7. APA120ML foot with ECS75 sensors

Because of the actuator high stiffness the mechanism resonance frequencies are in the 500-900Hz range (Fig. 8). This offers a bandwidth high enough for a 100Hz saw tooth motion.

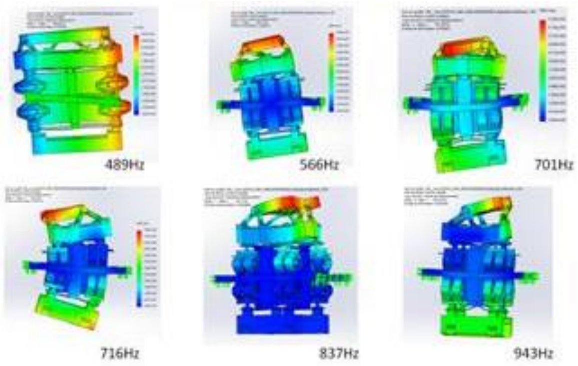

Figure 8. Vibration modes of the mechanism

The capacitance of the APA120ML is 20 µF meaning 40 µF per foot. With a 170 V voltage variation in 1ms (worst case considered), the required current per foot is 6.8 A, which is a large current involving a reactive power of 1 kVA. To address this requirement, Switching Amplifiers SA75B have been selected. These new switching amplifiers designed by CTEC [12] are able to provide up to 10 A with 170 V per channel. They offers energy recovery feature, meaning their power consumption is only 50 W to generate 1 kVA reactive power. Therefore this technology is appropriate for embedded applications.
Close loops controls are realised to achieve the desired motion. CTEC UC65 DSP-based controllers deal with the order signal and the measured actuator displacements to command the amplifiers. Fig. 9 shows the test set up including from left to right, the controllers, the mechanism, and the amplifiers.

Fig. 10 gives a typical results of the close loop. The motion of a foot presents a delay inducing a tracking error up to 20µm but this error is nearly constant in the integration time. So the speed error is less than 1 %. A trigger could be added to overpass this issue to give the top to the image acquisition processing.

Performances are in Tab. 2.

Figure 9. MEFISTO test set-up

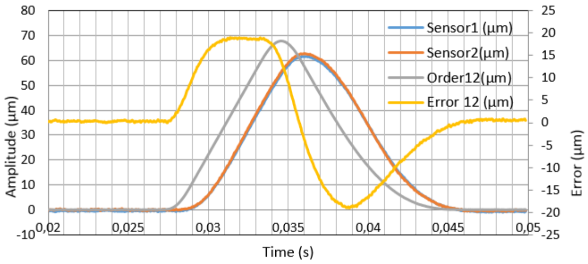

Figure 10. Order, stroke & error of a foot versus time

Table 2. MEFISTO Performances

Tilt stroke	0.7 mrad
Tip stroke	80µm
Resonance frequencies	700-800 Hz
Speed	0.5 mrad in 2 ms
Sine Vibration level	20 g rms @ 100Hz
Random Vibration level	15 g rms
Dimensions	279×250×293 mm
Mirror mass	730 gr
Mirror size	220×96×23 mm
Total mass	12.7 kg

3. OPTRONIC FSM

For some years, CTEC has applied its actuation technologies developed for space mechanisms to non-space needs, in particular Fine Steering Mirrors (FSM) for optronic applications [13] especially Infrared (IR) imagers. Two different examples are given hereafter.

3.1. Stabilisation & microscan tip-tilt

Fig. 11 unveils a batch of small FSMs ensuring both image stabilisation and micro scanning for optronic cameras. Micro scanning is an oversampling technique increasing the image resolution by 4 which is also performed in THALES IR cameras by XY25XS stages microscanner from CTEC [14].
Because of 2 functions, the required strokes are separated in two bandwidths. In 0-100 Hz, the desired stroke is 700 µrad, while in the 100-480 Hz the stroke is 200 µrad. This impact both the mechanical and electronic design.
The solution developed by CTEC inherits from its works in PHARAO and ATLID. The FSM is built on a DTT15XS tip tilt mechanism driving a 10gr mirror. The DTT15XS is based on 4 APA15XS micro actuators. These actuators are customised extra small (XS) amplified piezo actuators, deriving from

the APA35XS. The open loop response of a Rx tilt given in Fig.13 shows hysteresis inherent to piezo effect.

The motion control is performed by high stability SG sensors on APA MLA. The actuators are controlled in push-pull mode to control Rx and Ry tilts.

Each mechanism embeds an electronic board performing the SG conditioning and including an EEPROM memory, a temperature monitoring and a thermal compensation.

With each FSM, CTEC delivers a custom embedded electronic and controller board called CCBU20-PROX (Fig.12) for driving and controlling the FSM.

Figure 11. Batch of DTT15XS-SG

Figure 12. CCBu20 and DTT15XS-SG

Two controllers have been studied. The first controller optimises the response on the 100Hz bandwidth, and thus microscanning functionality and stabilisation higher than 100Hz are reduced. The second controller optimises the response on the 480Hz bandwidth and micro scanning, and thus the functionality in the 100Hz bandwidth is lower. At low frequency their performance is similar.

The linearity of closed loops has been verified against an autocollimator. As it can be seen in Fig.14 the stroke-to-voltage response is linearized. Fig. 15 gives the closed-loop gains versus frequency for both controllers.

Fig.16 and Fig.17 show the mechanism time response on a fast trapezoidal order with 1ms rise time, comparing both controllers. Overshoots are present with controller 1 (Fig. 16) while they reduced with controller 2 (Fig. 17) as expected because the controller 2 is optimised for microscan.

Final performances are given in Tab.3.

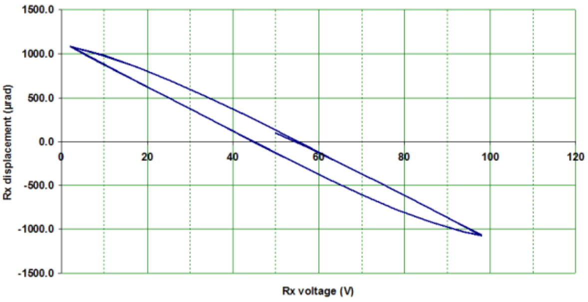

Figure 13. Open loop Rx tilt stroke vs voltage

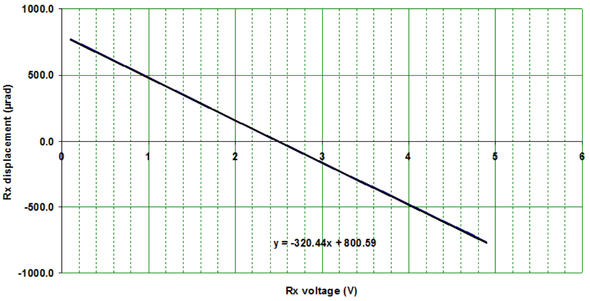

Figure 14. Close loop Rx tilt stroke vs voltage

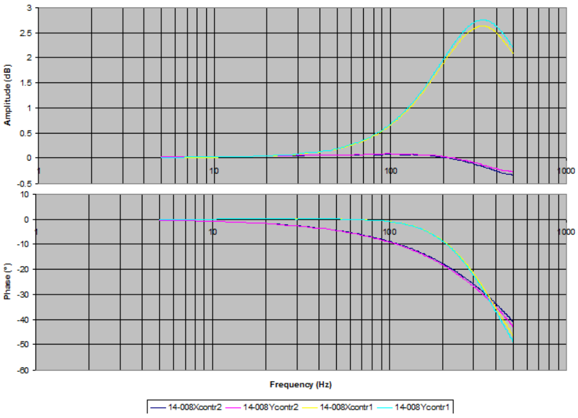

Figure 15. Close loops tilt vs freq. (2 controllers)

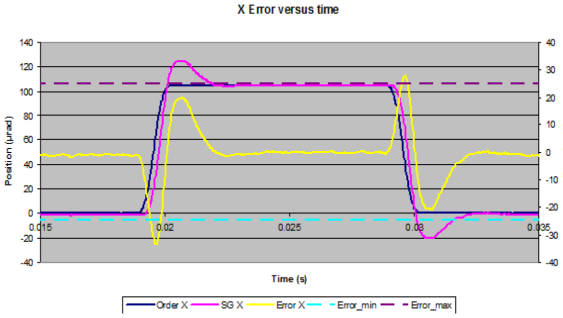

Figure 16. Microscan response with controller 1

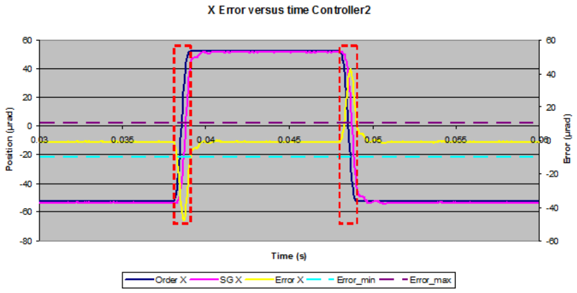

Figure 17. Microscan response with controller 2

Table 3. DTT15XS-SG Performances

Total stroke	2.1 mrad
Settling time	1 ms @ 5 %
Resolution	0.05 % FS
Stability	<25 µrad
Resonance frequency	2600 Hz
Total mass	136 g
Mirror	30×30×4.85 mm
Dimensions	40×40×28 mm
Power @ 50 Hz +/- 700 µrad	9 W with CCBU20
Power @ 480 Hz +/- 200 µrad	13.5 W with CCBU20

3.2. Disturbance compensation tip-tilt

A large FSM for atmospheric disturbance compensation in the laser guide star (LGS) of a ground telescope is shown in Fig. 18. The mirror is elliptical. The mirror substrate is made from SiC material.

This mechanism is based on 4 APA300MML piezo actuators, the stroke of which is 370µm. It offers 5.4mrad tilt motion on two directions on a 0-100Hz bandwidth.

This motion is controlled via Strain Gage on the APA ceramics. The Strain Gauges conditioning is performed by an embedded electronics board located below the mechanism.

The device performances are given in Tab.4.

Figure 18. Large FSM based on APA300MML

Table 4. APA300MML-based FSM Performances

Total stroke	5.4 mrad
Resolution	+/- 0.2 µrad
Accuracy in quasi static	+/-3 µrad,
Accuracy in FS dynamic	+/- 2 %
Total mass	1.8 kg
Mirror mass	900 gr
Resonance frequency	320 Hz
Control bandwidth	>100 Hz
Temperature range	-20°C to +55°C
Mirror size	200×140×36 mm3
Dimensions	145×145×100 mm3

4. CONCLUSION

For 20 years the need for Space tip-tilt mechanisms has led the development of precision mechatronics technologies at CEDRAT TECHNOLOGIES: piezo actuator components, mechanisms structures, strain gages and eddy current sensors, powerful electronic amplifiers, numerical controllers and close loop laws for fine motion control.

Because space mechanisms require very high performance and reliability, these developments have provided strong qualification and flying heritages in Fast Steering Mirrors and Beam Steering Mirrors.

This heritage in FSM and BSM is being industrially exploited by CEDRAT TECHNOLOGIES for filling various innovative fine pointing functions as active stabilisation and micro scanning in IR imagers and disturbance compensation in ground telescopes.

5. ACKNOWLEDGEMENT

The authors would like to thank BPI France, CNES, DGA and ESA for their long term support.

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