

Piezoelectric Fast Steering Mirrors for Optical communication in large satellite constellations

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ABSTRACT

The rapid deployment of Low Earth Orbit (LEO) satellite constellations is transforming the requirements imposed on optical communication terminals. While traditional space missions typically required only a limited number of high-performance Fast Steering Mirrors (FSMs), future optical communication networks will require the production of tens of thousands of reliable and cost-effective units. This evolution introduces new design drivers extending beyond dynamic performances, including manufacturability, reproducibility, interchangeability and overall cost of ownership.

Building upon the heritage of several space-qualified piezoelectric steering mechanisms, CEDRAT TECHNOLOGIES has developed a new generation of FSMs and dedicated electronics specifically addressing New Space constraints. Mechanical architecture, position sensing, electronic control and optical interfaces have been redesigned according to Design-for-Manufacturing principles while preserving the bandwidth and pointing performances required for optical inter-satellite links.

This paper presents the adopted design methodology together with the main technological evolutions implemented on piezoelectric FSM platforms. Qualification results and performance measurements demonstrate that significant reductions in manufacturing complexity and electronic cost can be achieved without compromising the dynamic characteristics required by future optical communication terminals.

Keywords: Fast Steering Mirror, Optical Communications, Optical Inter-Satellite Links, Piezoelectric Actuators, New Space, Design for Manufacturing.

1. INTRODUCTION

Free-space optical communication (FSOC) is becoming one of the enabling technologies for future space communication infrastructures. Optical Inter-Satellite Links (OISL) are progressively replacing conventional radio-frequency links to increase transmission capacity while reducing spectrum congestion and improving communication security. At the same time, optical feeder links between ground stations and geostationary relay satellites are emerging as a complementary solution for high-capacity Low Earth Orbit (LEO) constellations.

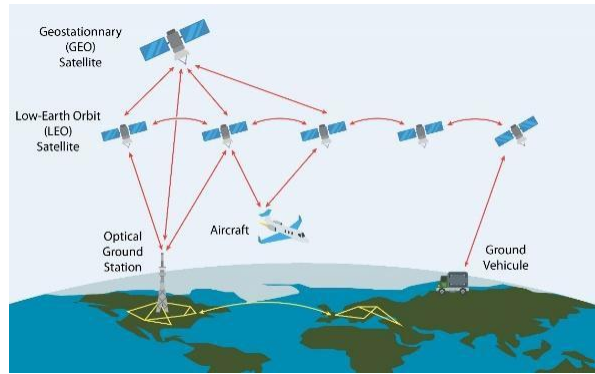


Figure 1. Free Space Optical Communication links.

The deployment of these communication architectures profoundly modifies the industrial context in which optical terminals are developed. Earlier institutional missions generally required only a limited number of optical terminals manufactured individually according to classical space engineering practices. In contrast, commercial constellations may require several optical communication terminals per spacecraft, leading to production volumes of several tens of thousands of Fast Steering Mirrors during the lifetime of a constellation.



Figure 2. Various FSM products from CTEC.

This change in scale creates new challenges. Besides the traditional requirements for pointing accuracy, bandwidth and environmental robustness, future FSMs must also exhibit reduced Size, Weight and Power (SWaP), simplified manufacturing, improved reproducibility and significantly lower recurring costs. Manufacturing repeatability, ease of calibration and electronics standardization have become essential design parameters.

Rather than optimizing only the actuator performance, the complete product architecture must therefore be reconsidered to support industrial production while maintaining the precision required by optical communication systems.

This paper presents the methodology adopted by CEDRAT TECHNOLOGIES to transform its heritage steering mechanisms into industrialized New Space products. The evolution concerns not only the mechanical actuator but also sensing technologies, electronic architecture, optical interfaces and manufacturing processes.

2. HERITAGE TECHNOLOGIES AND DESIGN DRIVERS

CEDRAT TECHNOLOGIES has been developing precision steering mechanisms for space applications for more than two decades. The current family of Fast Steering Mirrors (FSMs) originates from several developments addressing scientific missions, optical communications and precision pointing applications. Although these mechanisms were initially optimized for specific missions, they now constitute a common technological basis for the development of industrialized optical communication terminals.

These developments progressively highlighted that future optical communication constellations would require more than incremental performance improvements. Although bandwidth, pointing accuracy and environmental robustness remain essential, the transition toward high-volume manufacturing introduces additional constraints including assembly time, calibration effort, component standardization and production reproducibility. Consequently, the next generation of FSMs has been designed according to Design-for-Manufacturing principles, aiming at reducing manufacturing complexity without degrading the optical performances inherited from previous developments.

2.1 DTT35XS & PFSM35XS

The first representative of this family is the **DTT35XS** piezoelectric tip-tilt platform, initially derived from the PHARAO (Figure 3) cold atom clock developed for the ACES mission. This PHARAO DTT35XS has also inspired NASA JPL leading to the PAM30, also flying in PSYCHE [6], for Deep Space Optical Communication (DSOC), presently operating an optical link on 2 AU.

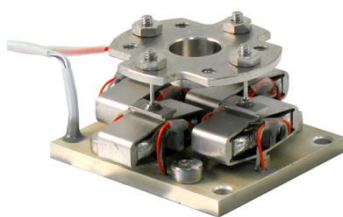


Figure 3. DTT35XS for PHARAO.

The mechanism uses four APA35XS amplified piezoelectric actuators operating in a push-pull configuration to generate angular rotations about two orthogonal axes. The APA35XS actuator produces a $52\mu\text{m}$ stroke when supplied by a voltage varying between -20V and 150V . Its stiffness is $0.5\text{N}/\mu\text{m}$. Each APA35XS is based on a $2\times 5\times 10\text{ mm}^3$ piezo multilayer actuator (MLA) with a $0.25\mu\text{F}$ capacitance. The MLA are equipped with strain gages (SG) acting as sensors for position control. This MLA offers a free stroke of $10\mu\text{m}$ and a blocked force of 360N . The MLA is in a shell ensuring both the MLA prestress and the stroke amplification, by a factor 5. The prestress is required to avoid tensile force in the MLA as the tensile limit is very low, while the compression limit is high. By this technique, the APA® can withstand vibrations and shocks occurring during launching. The metallic shell is designed to ensure the stress generated by prestress, actuations and external forces stays below material stress limits accounting for ECSS space margins. The advantage of the proposed mechanical amplification is high compactness and low power consumption per micron stroke, both meeting SWaP objectives.

To create a tilt motion, opposite APAs operate in push-pull mode. These APAs transmit their linear motion via elastic pivots to the mirror generating the Rx and Ry tilts. As the mechanism is frictionless and operates in deformation, its resolution is limited only by the electronic amplifier noise.

2.2 P-FSM150S

As optical communication terminals evolved toward larger mirrors and wider pointing ranges, the same operating principles were extended to the **P-FSM150S** (Figure 8). This second-generation mechanism incorporates larger APA150S

amplified actuators specially designed for the application needs and provides a total angular stroke of approximately 18 mrad. A large qualification test campaign has been performed on it and results have been presented in [13].

2.3 CCBu20 piezo controllers

The actuator itself represents only one element of the complete pointing subsystem. Dedicated drive electronics are equally essential to achieve the required dynamic performances while ensuring compactness and reliability. The **CCBu20** (Figure 11) controller was therefore developed as a compact dual-channel controller capable of driving various piezoelectric mechanisms operating in push-pull mode (Figure 4), including FSMs and precision positioning stages. Its architecture combines high-voltage amplification, closed-loop control, sensor conditioning and digital communication within a compact package suitable for embedded optical terminals. It is used in embedded and ground electro-optic imaging & laser systems. It is also used as a GSE or Bread Board Model (BBM) and sometimes Engineering Model (EM) for New Space applications.

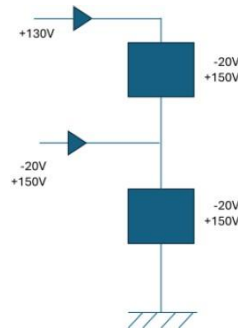


Figure 4. CCBu20 push pull electronic drive.

3. DESIGN EVOLUTION TOWARD INDUSTRIALIZED FAST STEERING MIRRORS

The transition from institutional space programs to commercial optical communication constellations has profoundly modified the design criteria of Fast Steering Mirrors. While previous developments primarily focused on maximizing pointing accuracy and dynamic performances, future optical terminals require a balanced optimization between optical performance, manufacturing complexity, recurring cost and production scalability.

Based on the experience gained through several generations of steering mechanisms, CEDRAT TECHNOLOGIES introduced a series of architectural modifications targeting the entire product life cycle, from manufacturing and calibration to system integration and maintenance. These developments were carried out within the CONECS program and subsequently integrated into the latest FSM product family.

3.1 Sensor architecture simplification

Position feedback represents a critical function for closed-loop operation of piezoelectric FSMs. Previous generations relied on full Wheatstone bridge configurations requiring careful pairing of strain gauges and extensive calibration procedures during assembly.

To simplify manufacturing while preserving measurement accuracy, the sensing architecture was redesigned around a half-bridge configuration. This solution reduces the number of bonded gauges and significantly simplifies electrical wiring without modifying the mechanical structure of the actuator.

The remaining bridge balancing is achieved through precision resistor networks integrated directly onto an internal electronic board. As a consequence, the actuator and the electronics become fully interchangeable, eliminating the need for dedicated actuator/controller pairing during production.

Besides reducing assembly operations, this architecture considerably improves manufacturing reproducibility and facilitates maintenance by allowing independent replacement of actuators or electronic modules.

Experimental production demonstrated a reduction of approximately **50% in strain-gauge integration time**, while maintaining the positioning accuracy required for closed-loop optical tracking.

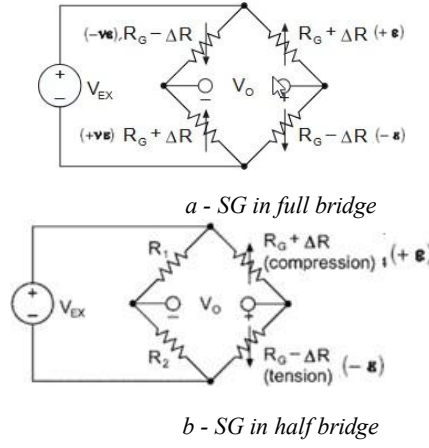


Figure 5. Evolution from the former strain-gauge bridge configuration to the new half-bridge architecture.

3.2 Low-Voltage drive electronics

Piezoelectric steering mirrors have traditionally required driving voltages between 120 and 150 V to exploit the full actuator stroke. Although technically effective, these voltage levels increase electronic complexity through dedicated high-voltage components, insulation requirements and qualification constraints.

A revised actuation strategy was therefore developed to limit the operating voltage below **100 V** while maintaining the angular performances required by optical communication terminals.

This evolution enables the use of a broader range of qualified electronic components while reducing converter complexity, power dissipation and overall controller cost.

The same design philosophy was adopted for the development of the **CCBu20-NS** controller, specifically optimized for Low Earth Orbit applications. The controller retains the modular architecture of the heritage CCBu20 while integrating New Space requirements regarding compactness, power consumption and production repeatability.

3.3 Specific mechanical improvements on DTT35XS-NS

While the standard version of DTT35XS is commercialized for ground optical instrumentation, a new version of the mechanism, named DTT35XS-NS has been developed for New Space markets. It is based on same piezo ceramics, also placed in an APA shell. It also uses 4 APAs to move the platform via pivots. But, as shown in table 1, the DTT35XS-NS offers a 27% larger angular stroke, reaching 6.1 mrad. Note that this value is experimentally achieved with a standard deviation of 2% on a set of few tens of products.



Figure 6. Batch of DTT35XS-NS for FSO constellation.

This larger stroke produces benefits for the customers: It increases its optical angular field of view which makes laser communication stabilization easier. It also permits a decrease in power consumption per millirad by 27%, which is good to reduce electric power demand to the satellite power supply.

This stroke improvement leads, in turn, to a reduction in resonant frequency of approximately 13%. The maximum theoretical bandwidth is reduced but this is not a problem in practice for satellite FSO: The maximum required operational bandwidth in FSO is limited to 500Hz, which can be achieved by the DTT35XS-NS. The last risk is about the resistance to shock and vibration. This has been managed by stress analysis in the design and checked by tests, allowing CTEC to commit to satisfactory values.

Another difference with the DTT35XS-NS is a larger casing increasing weight but offering mechanical interfaces close to the mirror. This makes optical integration easier for the customer. The back side of the DTT contains a compartment for proximity electronics. This manages strain gain sensors offset. Having this offset management on the mechanism rather than in the electronics is also an advantage for the customer. It avoids the pairing with the electronic driver. This interchangeability simplifies the products management in OCTs.

In terms of configurations, DTT35XS offers several options to customize the product according to the need. Upon request CTEC can equip the DTT35XS with a mirror. On Figures 7f and 6, the DTT35XS are equipped with SiO₂ gold-coated mirror. Glued SiO₂ mirrors are presently the cheapest mirror technology.

Figure 7 illustrates the evolution of the different configurations of DTT35XS mechanisms developed by CEDRAT TECHNOLOGIES for large satellites constellations, while Table 1 summarizes the main characteristics.

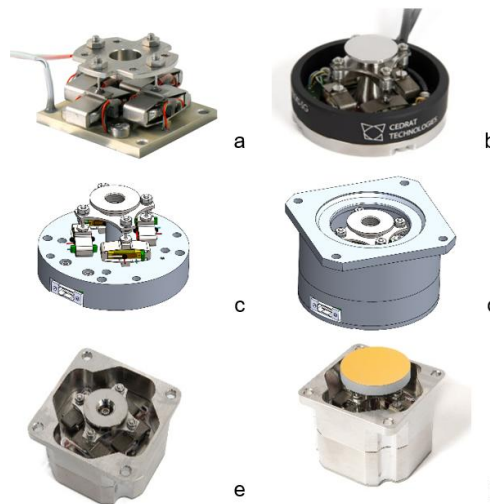


Figure 7. Versions of the DTT35XS from PHARAO (a), COTS lab (b), COTS for FSO (c-e) and P-FSM35XS-NS (f).

Table 1. Performances of DTT35XS and DTT35XS-NS.

		DTT35XS	DTT35XS-NS
Mech. Stroke (open loop)	mrad	4.8	6.1
Mech Stroke (close loop)	mrad	4.5	5.5
Resonance Freq.	Hz	2450	2150
Capacitance per port	μF	0.7	0.7
Height	mm	22	32.45
Section	mm ²	D45	40x40
Mass	gr	65	80
Random Vibration	G rms	-	35
SG Sensor type		full bridge	half bridge

3.4 P-FSM150S mechanical improvements

Since 2023, several end-users have selected this product for various optical communication links from LEO, MEO, ground stations, and provides both feedback and proof-of-concept.

For example, [14] explains that the key applications of a steering mirror in a communications satellite are to correct for the platform jitter, keeping the incoming beam continuously centered on the receiving detector. To simulate this scenario on an optical bench, developed a set-up using silver coated P-FSM150S. The set-up shows a 5-fold improvement in concentration thanks to the P-FSM150S [14] compared to the uncorrected case, where the point track spreads over an angular extent of approximately 3400 μ rad.

The mechanical architecture was redesigned to simplify assembly while preserving stiffness and dynamic performances. Particular attention was devoted to reducing the number of precision-machined components and improving the repeatability of the mechanical interfaces, anticipating future production in larger quantities. From December 2025, the P-FSM150S is proposed in 3 variants as presented in Table 2.



Figure 8. P-FSM150S with SiC mirror.

Table 2. P-FSM150S versions.

Variant	HI-REL	VAC	COTS
Main application	Old space From LEO to Deep Space	New space LEO, MEO & GEO	Lab & New Space Low LEO
Lifetime	10 - 15 years	5 – 7 years	1-3 years
Quality standards & MAIT environ.t	ECSS ISO5-7	ISO9001 ISO 8	ISO9001
Wires Manufacturing	Lead solder	Lead-free solder	Lead-free solder
Parts Manufacturing	Passivation & coating	-	-
Mirror technology	Screw-fixed SiC	Screw-fixed SiC	SiO2 glued on support
Final cleaning	Bake-out	-	-

For New Space applications, the P-FSM150S COTS takes benefit of several changes to reduce its cost. The main rationale is two folds: The required lifetime which is often up to 15 years in orbit for old space, while it is generally less than 5 years for new space. The requested reliability is very high on old space while in new space, the application supports higher risks and a rate of failure in low LEO.

The main difference is the use of a cost-effective Fused silica SiO₂ mirror with 15mm diameter instead of a SiC 17 mm diameter mirror. As the SiO₂ mirror cannot be screwed on the flexible mirror support, the SiO₂ mirror is glued to an aluminum mirror interface offering the same external interface as the SiC mirror (Figure 9).



Figure 9. SiC mirror versus SiO2 mirror on interface.

As consequence, the process leading to the final flatness performance of a SiO2 needs one step more than a SiC mirror. This flatness is characterized by the Reflective WFE (RWE) measured with a Zygo interferometer at the end of different steps (Figure.10 & Table. 3).

The first step, which is gluing at the mirror on the interface, does not induce an RWE degradation (b. vs a.) if done carefully, i.e. by polymerization in oven at low temperature.

The second step which is the screwing of the mirror interface on the flexible support induces a small WFE degradation (c. vs b.).

The third step is achieved when the mechanism is actuated with a maximal Rx angular stroke. This also adds a Delta-RWE.

Compared with SiC RWE [13], the results at this stage on SiO2 are deemed encouraging.

It should be noted that functional performance (strokes, resonance frequency, ...) are the same between all 3 versions of the P-FSM150S.

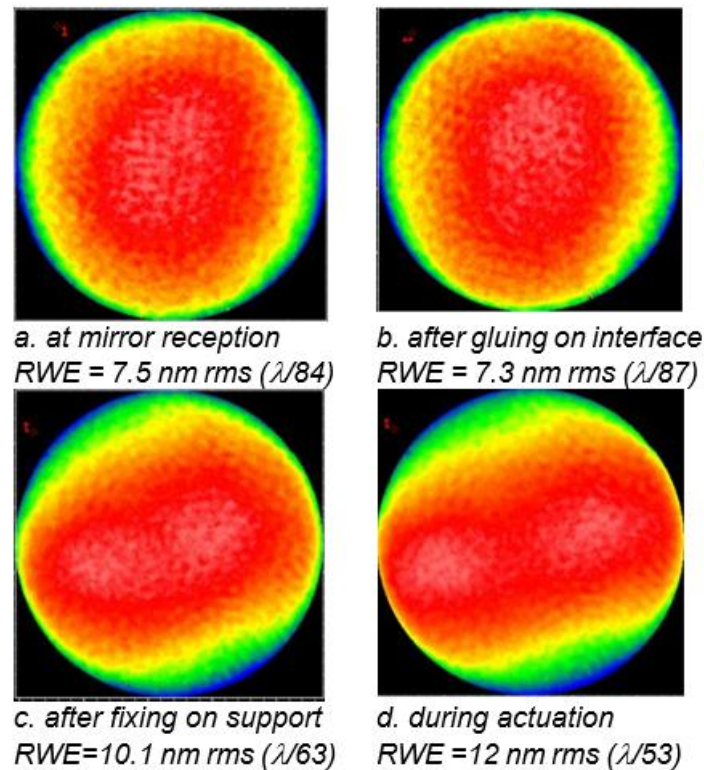


Figure 10. WFE of P-FSM150S SiO2 mirror versus steps.

Table 3. RWE of SiO₂ vs SiC P-FSM150S mirrors.

RWE (nm rms)	P-FSM150S HiRel	P-FSM150S COTS
Mirror type	SiC	SiO ₂
RWE before integ.	14.2	7.5
RWE after integ.	17.5	10.1

3.5 Toward a standardized product family

Beyond the optimization of individual components, the different developments converge toward a common product philosophy based on platform standardization.

The same electronic controller architecture can be associated with several actuator sizes, while common sensing technologies and manufacturing procedures are applied throughout the product family.

Such standardization considerably reduces qualification effort, simplifies logistics and enables progressive industrialization without compromising the flexibility required by the diversity of optical communication missions.

Consequently, the current FSM family should not be regarded as a collection of independent products but rather as a scalable technological platform capable of addressing a broad range of optical communication applications, from compact inter-satellite terminals to high-power optical feeder links.

3.6 CCBu20NS

The CCBu20-NS is a space-grade version of the CCBu20 for New Space. It is also a dual-channel controller. In both CCBu20 and CCBu20-NS, the electronics power amplifiers for piezo are based on discrete components, rather on Operational Amplifiers chips which are not so reliable and have no space equivalence.

In these products, both channels of the piezo drivers can provide the [-20; +150V] range required to supply the piezo actuators in push-pull mode.

Tab.4 compares features of CCBu20 to CCBu20-NS, allowing to see additional features of the NS version to provide a solution for New Space market.



Figure 11. CCBu20-NS and CCBu20

While the CCBu20 makes use of a standard push-pull driving, a new driving strategy invented by CTEC has been implemented in the CCBu20-NS to limit voltages on components below 100V, which is beneficial for electronic price.

The output currents are 35mA rms continuous. Driven with this continuous output current, the DTT35XS and P-FSM35XS can achieve a full stroke open loop bandwidth above 100Hz. The P-FSM150S can reach up to 30Hz.

CCBu20 drivers offer a higher peak current capacity which is limited by heating but can perform typically more than 1s. The CCBu20 can produce a 200mA peak current while the CCUBu20-NS is limited to 150mA because of rad-hard selected transistors (with lower SOA performance). This higher peak current than rms continuous one is useful for dynamic responses to steps or short time order signals, equivalent to 6 times more bandwidth.

Table 4. Comparison between CCBu20 and CCBu20-NS (New Space grade) [12]

	CCBu20	CCBu20-NS	Unit
GENERAL			
Function	All-in-one piezo driver & controller	All-in-one piezo driver & controller	
Number of control channels	2	2	
Integrated sensor conditioning	Strain Gages	Strain Gages	
Digital communication	RS422	RS422 SPI	
PIEZO DRIVER			
Number of channels	2	2	
Delivered voltage range	-20 ... +150	-20 ... +150	V
Max output current	0.200	0.150 Typ. 0.174 @Tmin; 0.134 @Tmax	A
Permanent output current	0.035	0.035	Ams
Small signals bandwidth (-6 dB)	32	11 @-3db	kHz
STRAIN GAGES (SG) CONDITIONER			
Number of channels	2	2	
Reference output voltage	5	2,5	Vdc
Max. reference output current	30	2x15	mA
Typical bridge impedance	350	350	Ohm
Real gain	546,45	1000	V/V
Small signals bandwidth	34 @-3 dB	5.1 @-6dB	kHz
DIGITAL CONTROL			
Control strategy	Tunable PID + Stabilizing filters	Tunable PID + Stabilizing filters	
Stabilising filters	Tunable lowpass & notch	Tunable lowpass & notch	
Sampling rate	20	20	kSps
Digital resolution	16	16	bits
POWER SUPPLY			
Recommended supply voltage	+28	20...30	Vdc
Supply voltage range	+24 ... +28	20...30	Vdc
Supply current	0.2 ... 1	0,2...4	Ams
MISCELLANEOUS			
Mass	0.25	0.715 +/-2%	kg
Dimensions	91 × 80 × 35.5	150 × 100 × 50	mm
Cooling	Natural convection + Heat-sinking surface	Conduction to the base plate	
Operating temperature range	-40 ... +70	-15 ... +60	°C
Storage temperature range	-40 ... +85	-40 ... +85	°C
Warm up time	15	15	min
Protections	OV for HV, Thermal protection,	Driver Thermal protection; OCP,OVP,UVP for primary side; OVP/OCP/ UVP for HV - periodic monitoring by processor @ 1Hz	
Built in test	NA	Initiated Built In Test; Power Up Built In Test; Continuous Built In Test	
Discrete TC	Enable	SHUTDOWN_N: Inhibition CCBU-20-NS	
Discrete TM	Fault	ON-OFF_STATUS: Auxiliary Supply operating and SHUTDOWN-N inactive OPERATING: CCBU-20-NS is operating - Not insulated	
Digital TC/ TM	ORDER #1,2 SENSOR #1,2	ORDER #1,2 SENSOR #1,2; MODE1 OPEN LOOP, MODE2 CLOSED LOOP	
RADIATIONS			
SEL	NA	No latch-up events @LET ≤ 43MeV.cm2/mg	
SEE	NA	No critical effect	
TID	NA	10 to 30 k rad	

MECHANICAL STRESS			
Sine vibration	Industrial level	5g @ 70Hz 2.5g @ 110Hz	
Quasi-static loads	Industrial level	17.7g @ 20Hz	
Random vibration	Industrial level	13.6	gRMS
Shock	Industrial level	50g @ 100Hz 1500g @ 2000Hz	

The bandwidth of CCBu20-NS driver is limited to 5kHz, but this is enough for operation in space where required operation bandwidth is generally 500Hz (for micro vibrations control).

Both CCBs include a strain gauges sensor conditioner for positioning feedback signals.

The close loop positioning control is performed with a 16bits digital controller. The control law is a PID associated with various possible stabilizing filters configurations:

- No filter
- 2nd order lowpass filter
- 2nd order notch filter
- 2×2 nd order notch filters
- 4th order notch filter

In terms of functions, the CCBu20-NS integrates additional functions: SPI communication, Telemetry (TM) and Telecommand data Communication (TC) which are required in space. The CCBu20-NS has been designed to support 5g static load, 13.6g rms random vibration and a 1500g SRC shock.

A last, a key advantage of the CCBu20-NS is its resistance to radiation. This is obtained thanks to selected space-grade components and thicker housing, leading to a larger mass than the CCBu20. A radiation resistance for total ionizing dose (TID) of 10 krad (design dose @ EEE level (die) is obtained with standard mechanical housing. With additional shielding at satellite level by customizing housing, the max TID can reach up to 30 krad.

The CCBu20-NS [4] is available in several versions. The Engineering Model (EM) has the same interfaces and functions as the Flight Models (FM) but instead of the FM space grade components, it is realized with equivalent non-space grade components. The EM allows the user to test its systems at a lower price. Tests can be done on the ground or in In-Orbit-Demo (IOD), provided with a few additional cares. The Flight Models 3 versions (V0, V1, V2) are built with polyimide PCB, Rad-tolerant space grade components and additional shielding, for LEO. Functional and mechanical acceptance tests are performed. The V0 offers a guaranteed lifetime between 1 and 3 years. The V1 offers a guaranteed lifetime up to 5 years. It includes LAT/PAD on components, and MIP & DRB manufacturing reviews as well as data packs.

The V2 is designed to ensure a guaranteed lifetime larger than 5 years. It respects ECSS-Q-ST-70-60C and ECSS-Q-ST-70-61C ESA space norms.

4. QUALIFICATION

Through CONECS project, a first P-FSM Engineering Model (Figure 12) system formed by the P-FSM150S with its SG sensors and the CCBu20-NS controller has been analyzed and tested. The objective of the design was to define the Sensor Gains, the PID and the notches, to get a stable system offering the largest bandwidth and the shortest response time. Both CCBu20 and CCBu20-NS are based on the same control technique (Figure 13), relying on a PID and a double notch.



Figure 12. P-FSM150S connected to the CCBu20-NS

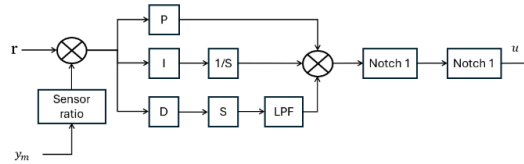


Figure 13. Control scheme of CCBu20s

By analysis of both sub-systems performances, the required Sensor Gain is 7.6 mrad/V, which has been checked adequate by open loop test, supplying an 18 mrad full stroke low frequency sine.

Using the 16bits numerical command of CCBu20-NS, a mechanical stroke of 16 mrad is achieved as with CCBu20, being compliant with product datasheet [11].

Open loop response (Figure 14) shows that both first resonances occur at 720Hz and at 1250 Hz.

So, both controller notches have been exploited to cancel these first resonance frequencies, they are destabilizing the close loop.

Thanks to these settings, the close loop bandwidth is larger than 250Hz (Figure 15).

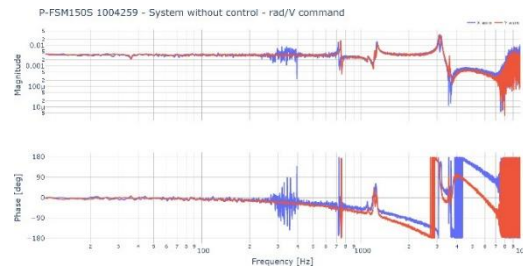


Figure 14. Open Loop Stroke per Volt Bode diagram

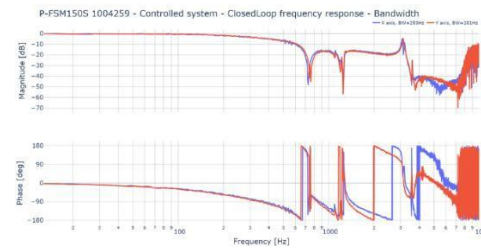


Figure 15. Close Loop Stroke per Volt Bode diagram

Another result of the close loop control is the rapid stabilization of the position when the system is submitted to a step order.

As shown on Figure 16, on a large step of 8 mrad, the rise time (from 10% to 90% stroke) is 1.5ms while the settling time is 4ms. The limiting factor in this case is the available maximum current, which explains the overshoot. On a small step (Figure 17), the rise time is 1.1 ms, being shorter as the current limit does not occur the same way.



Figure 16. P-FSM150S step response in Close Loop



Figure 17. P-FSM150S small step resp. in Close Loop

Some solutions are implemented on the CCBu20-NS controller that might further improve the performance on the step response of the system. One of those solutions is the use of a slew rate limiter on the order of the closed loop (r in Figure 13) so that the order is never faster than the system at current saturation. This method has been tested on CCBu20-NS controller with P-FSM150S, and also on other CTEC mechanisms with great success, such as on a M-FSM45 Magnetic FSM (Figure 18).

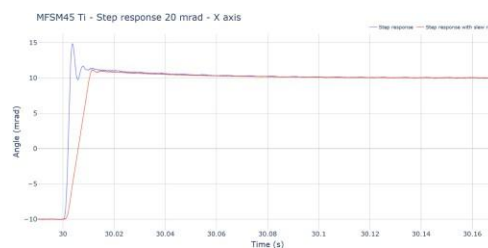


Figure 18. *Effect of the slew rate limiter on the order on the step response of a system*

In the coming weeks, a full qualification test campaign will be performed on both P-FSM150S-NS and DTT35XS-NS systems to demonstrate the capability of those systems to withstand environmental conditions applicable to LEO Satellites constellation.

5. DISCUSSION AND CONCLUSION

The development of future optical communication constellations requires a significant evolution in the way space optical components are designed and manufactured. While traditional space mechanisms have primarily been optimized for maximum performance and mission-specific requirements, the deployment of large-scale optical networks introduces new constraints related to production volume, cost efficiency and manufacturing repeatability.

The developments presented in this paper demonstrate that Fast Steering Mirrors can be redesigned according to a New Space industrial approach while maintaining the dynamic performances required for optical communication terminals. The main objective was not only to improve individual component characteristics, but to develop a coherent product strategy addressing the complete life cycle of the subsystem.

Several key design choices contributed to this evolution:

- simplification of the position sensing architecture through half-bridge strain-gauge implementation, reducing assembly complexity and improving interchangeability;
- optimization of flexural mechanisms to improve manufacturability while preserving stiffness and dynamic behaviour;
- reduction of drive voltage requirements to simplify electronic design and decrease controller cost;
- development of standardized controller architectures compatible with multiple FSM configurations;
- investigation of alternative mirror technologies to reduce recurring costs while maintaining optical performance.

The validation activities confirmed that these modifications preserve the fundamental characteristics required for free-space optical communications, including multi-mrad steering capability, high dynamic response and compatibility with the environmental constraints of space applications.

Beyond the technical performances of individual mechanisms, the main outcome of this development is the transition from mission-specific hardware toward a scalable FSM product family. Such an approach enables the production of larger quantities of optical pointing subsystems while maintaining the reliability and performance levels expected for space missions.

Future optical communication infrastructures will require thousands of optical terminals distributed across large satellite constellations. Meeting this challenge will require not only advanced optical technologies but also industrial manufacturing strategies adapted to the space environment.

The presented developments demonstrate that Fast Steering Mirrors can become enabling components for next-generation optical communication networks by combining space heritage, high pointing performance and New Space industrialization principles.

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