DEVELOPMENT AND PREPARATION FOR INDUSTRIALISATION OF AN AZIMUTH POINTING MECHANISM FOR OPTICAL DATA CROSSLINK TERMINAL

G. Feusier, P.-A. Mäusli and V. Gass

Mecanex SA
Z.I. Nord, CH-1260 Nyon, Switzerland
Telephone: +41 22/361 77 33 / Fax: +41 22/361 67 52
E-mail: gfeusier@mecanex.ch

ABSTRACT

The demand for series production of space electro-mechanical devices is emerging with the development of commercial satellite constellations.
During the present project, processes and design features best suited for series production of space electro-mechanical devices were investigated. An Engineering Model (EM) of a single azimuth axis large range pointing mechanism has been designed, manufactured and tested. This paper summarises some relevant results of this project and presents some new solutions coming from industrial heritage. The cable sheet electrical connection between the fixed and rotating part of the mechanism has been emphasised. The use of a flexible circuit (FLEX Print) was studied and the performed tests are described in the present paper.

1. INTRODUCTION

MECANEX has been working since a long time on space mechanisms and has experience in the production of series of industrial and defence mechanisms. The aim of the present work was to combine these experiences and to investigate industrialisation processes to manufacture large series of space mechanisms. The production of numerous identical items requires changing the classical space manufacturing habits. New manufacturing processes, largely inspired from industrial ones, must be set up. The main concerns of series production are of course to reduce the number of operations and to minimise the rising of assembly errors.

In order to best focus on real cases, a concrete application was studied : the single azimuth axis large range pointing stage of an inter-satellite optical link.
Based on an initial design by MATRA MARCONI SPACE (MMS), the design of the Large Range Azimuth Mechanism (LRAM) was modified by MECANEX, in close discussion with potential customers, in order to reach the following goals, which could firstly seem opposite :

- cost reduction,
- mass reduction,
- compliance with the specifications.

The full optical terminal (Figure 1) consists in the LRAM on which are interfaced a Fine Steering Mechanism (FSM) and an optical bench.

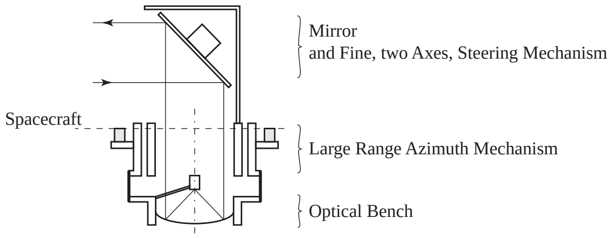

Figure 1. Principle of the complete inter-satellite optical link terminal. The azimuth pointing mechanism has been studied in the framework of this project.

The LRAM is fixed on soft mounts, which interface it to the spacecraft. The rotating part of the LRAM supports the FSM, on which is fixed the mirror. The FSM performs the fine pointing around the elevation and azimuth axis. An optical bench is fixed on the other side of the LRAM, on the non-rotating side.

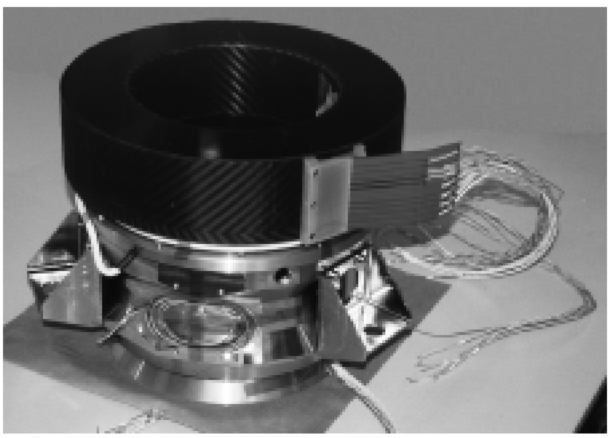

Figure 2. Picture showing the EM of the Azimuth Pointing Mechanism after manufacturing and testing by MECANEX.

Components of the LRAM consist in mechanical parts and electrical parts. The number of parts was reduced as much as possible in order to make their assembly easier (Figure 3) :

- body (rotating part, I/F with FSM),
- housing (fixed part, I/F with S/C and optical bench),
- bearing,
- mechanical end-stops
- thermal screen,
- I/F brackets,
- cable-sheet housing,
- direct drive DC brushless motor,
- optical encoder,
- launch lock (pin puller).

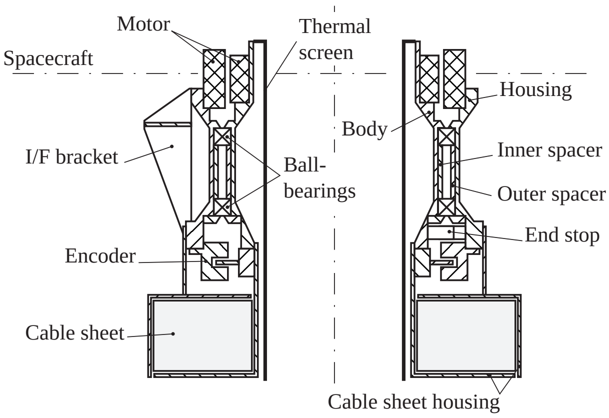

Figure 3. Principle and view of the different components of the Large Range single Azimuth axis hollow shaft pointing Mechanism (LRAM).

An electrical connection between the body and housing is provided by the Cable-Sheet (CS), linking the rotating part to the fixed part of the LRAM.
Some of the main mechanism requirements are summarised in Table 1.

Hollow shaft diameter	167 mm
Angular range	±125°
Maximum angular speed	10°/s
Maximum angular acceleration	$8°/s^2$
Mechanical alignment	< 10 mdeg
Pointing accuracy Positioning mode Tracking mode	 0.015° ±1.4 µrad
Electrical power consumption	5.5 W
Operating temperature	-25°C to +60°C
Operating lifetime	10 years

Table 1. Summary of the pointing mechanism requirements.

2. DESIGN

2.1. Materials

Different material choices have been investigated. The considered materials include metallic and non-metallic ones. The use of materials must be compliant with the specification, but the cost factor is also a main design driver. Thus, expensive materials, like for example beryllium [1], have been rejected.
The choice was then made between several materials :

- aluminium,
- structural steel,
- stainless steel,
- titanium,
- carbon fibre - epoxy composite.

The metallic parts can be manufactured out of bulk material, tubes or cast with final machining of the interfaces. This depends on the size and geometry of the parts, but also on the amount of units. Even if machining out of bulk material is often the only achievable manufacturing solution for very few units, other solutions must be chosen for large series. For example, cast titanium parts could be very cost effective when manufacturing a lot of units.
The main interests in using composite parts, out of the ease of manufacturing large series by the use of moulding, are :

- low density,
- high stiffness (similar to titanium),
- low thermal expansion.

2.2. Structural Parts

The lighter and more cost effective material was used as much as possible. However, for structural reasons as well as thermal expansion coefficients matching, the material choice is sometimes reduced.
The structural parts have been made out of Ni coated 42CD4 steel for the EM. Titanium remains however better adapted in term of mass for the Flight Models (FM).
The cable sheet housing was made of T300 carbon fibres with an Epoxy matrix. This solution was very effective in terms of mass, cost and stiffness. The design of the assembly with the other parts of the LRAM must however be made carefully.
Some non-structural parts (e.g. the thermal screen) were made out of ANTICO 112 aluminium.

2.3. Components

- ***Bearing System***

a) Classical Architecture with Spacers

The classical architecture for a hard preloaded ball-bearing pair, separated from each other, is to include two spacers with an adjusted length difference such that

the preload is defined by the global elasticity of the ball-bearing / spacers / housing / shaft assembly.
The very high stiffness of such a system requires length and spacer parallelism adjustment with sub-µm tolerances. The machining of these elements must be done on special grinding machines where three identical spacers are prepared simultaneously.
Such a procedure is very heavy, costly and long. It is hardly compatible with series production.
The lack of readily available alternative methods for the EM implies that the decision to produce such spacers was decided during this project so that the program was not delayed.
In parallel, a development program was set up to define mounting procedures or modified geometry that overcome the problem.

b) Common Ring Architecture
A proposed solution has been to produce a bearing pair with a common outer ring. The preload is obtained by the adjustment of one of the inner ring length.
This approach prevents from using spacers and is close to the back to back mount, though it is more rigid.
The high radial torque to be supported during the launch phase and the low preload necessary to reduce the axial torque in function led to the necessity of having a distance between the two ball-bearings. The above solution seems thus to be inadequate with this respect.
An increased load on the bearing due to the distance reduction between them increases the Hertz pressure. Ball-bearing with larger balls, more balls (allowed for example by the use of appropriate cages or ball-spacers), and an increased contact angle, would improve the load capacity. A new calculation to evaluate the double bearing approach will be necessary should this solution be retained.
An other solution preserving the distance between the bearings could be to manufacture a bearing pair similar to the former proposition, but with longer outer and inner rings.
This solution would improve the production aspect with respect to the double ball-bearings + spacers proposed for the EM. It cannot however be envisaged without a series production, as tools have to be developed for it.
The proposed solutions with common outer rings respect the matching specification.
The total unit price of the solutions proposed in this paragraph is somewhat similar to the classical one (cf. a)). The advantage resides in the higher stiffness and less severe constraints on housing diameter adjustments.

c) Cemented Architecture
A very attractive assembly proposition was to assemble the ball-bearing pair with structural adhesive. The interests of this approach are :

- No spacer (the only spacer is machined together with the housing for "O"-mount; care must be taken that the faces are parallel).
- No need for clamps and screws.

The mounting procedure needs however :

- A special tool to apply a defined preload during polymerisation.
- To define a structural adhesive, compatible with space applications, that is able to withstand the permanent shear forces applied by the preload, the vibrations and the thermal cycling.

This type of mounting is already used in some aeronautical applications. It needs evidently to be qualified for space. Due to the uncertainties related to the development of this process, the choice to implement a standard technology on the EM has been decided.
However, preliminary tests of such an assembly were performed at MECANEX (cf. § 4.2.d)).

- ***Motor***

With the considered motor sizes, the required high torque / power ratio and due to the need of a low level of cogging torque, the only suitable motor technology is the "permanent magnet synchronous motor" technology (generally called "brushless DC motor").
A trade-off was performed by ETEL between different motor designs :

i) A classical slotted motor design which includes : (1) a stator made with a laminated magnetic stack with slots on which the winding is wounded; (2) a rotor, placed into the stator internal hollow shaft, made with magnetic yoke on which the magnets are fixed.
ii) A so-called "toothless motor design", which does not produce any cogging torque effect.

The design ii) was selected because of the low level of cogging required (< 5 mNm), objective which could not be matched by design i). However, the design i) has the advantage of having a significantly lower mass than design ii).

Total mass	1.7 kg
Motor constant	0.9 $Nm/W^{1/2}$
Number of stator phases	2
Max. cogging torque (peak to peak)	10 mNm
Hysteresis torque	480 mNm

Table 2. Summary of the motor characteristics.

- ***Encoder***

The optical encoder which is used for the EM is an off-the-shelf 21 bits capacity absolute encoder without redundancy. It has an absolute accuracy of ±2.8 mdeg.

The EM encoder was integrated by its manufacturer into the LRAM. However, new technology optical encoders being less sensitive to misalignment and which are now space qualified could be integrated by MECANEX in the LRAM, without a complex procedure needing special equipment.

- ***Cable-Sheet***

The electric link between stator and rotor is realised through continuous metallic connections. Two line configurations have been studied.

a) Cable-Wrap

A flat cable is made of an assembly of single and twisted cables, shielded or not. The main advantage of flat cables is that there is no impedance change of the connected lines. Moreover, the characteristics of this type of cables are well known and it exists space-qualified solutions [2] as well as already flying items.
However, the harness so defined is quite stiff and cannot be bent at low radii. With this technology, the choice of a cable-wrap (spiral harness) is necessary.
The integration of connectors on such harness is a long and costly operation not adapted to this application.
The evaluation of the length of the harness in the EM led to the necessity to mount 1.5 m to cover the full 250° specified. This length is not favourable with respect to vibration, friction torque, line resistance and torque noise.

b) Rolling Sheet

The cable sheet could be a flexible circuit (FLEX Print), much thinner than a flat cable. The FLEX Print can be bent to lower radii and is less heavy. The cable-wrap configuration is not favourable with this type of harness due to the needed length and to the conductor reduced cross-section inherent to the laminated construction.
An interesting harness mounting is the rolling sheet or "gooseneck" configuration (Figure 4).

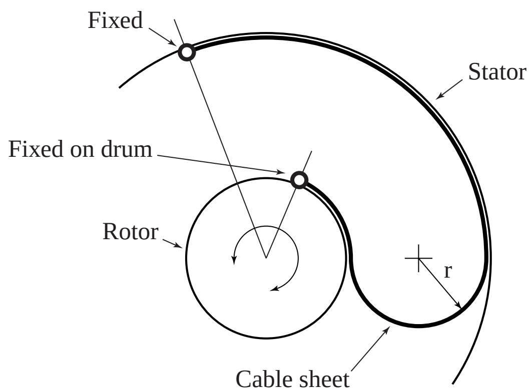

Figure 4. Principle of the cable sheet electrical link

This solution, better adapted to the present situation, can be achieved at much lower costs than the flat cable assembly. The bending radius r of the FLEX Print can be reduced and the torque profile of the rolling sheet configuration does not depend on the angular position, what is also an advantage with respect to the pointing function.
The characteristics of the FLEX Print sample manufactured for testing purpose are showed in Table 3.

Copper thickness	70 µm
FLEX Print length	900.0 mm
FLEX Print width	69.90 mm
Number of tracks	24
Track width	2.2 to 7.0 mm

Table 3. Summary of the KAPTON flexible circuit characteristics.

For the EM, three layers of FLEX Prints were assembled together. The two external layers (FLEX Prints) could also be used as shielding for the intermediate FLEX Print.

3. INDUSTRIALISATION

3.1. Machining and Material Furniture

As already stated in the above chapters, different materials have been considered (structural Ni coated steel, Ti-6Al-4V, aluminium, carbon fibre - epoxy composites). These different potential choices could lead to production technologies different from simple machining, such as casting or forging.
For example, for the "housing" and "body", which shapes show thin walled structures, the most economical production with steel is to machine the pieces from tubes, though much material must be chipped off (for 300 to 400 units, the raw material flow to manage ranges from $20 \cdot 10^3$ to $30 \cdot 10^3$ kg). In the case of titanium, the casting of near-net-shape parts is the most economical production for large series, because it will reduce the wasted material volume.
Near-net-shape casting is also very interesting because it would reduce the number of machining operations.

3.2. Assembly

The achievement of the technical performance must be managed for large production rates (maximum of 5 units per day) within a very limited budget. These elements have been considered as design drivers on the same level as the most sensitive technical requirements.
An assembly procedure was elaborated and the assembly duration calculated. Logistic schemes were defined depending on the series to manufacture.
Numerical models were then developed from the logistic schemes. They permit to calculate the delay due to production flow jam.
The performed study demonstrates that series of at least 300 to 400 mechanisms, at a rate of 3 to 4 mechanisms

per days, could be manufactured at a competitive price. With larger series (more than 400 mechanisms), a refined study should be performed in order to simplify as much as possible the design and the assembly.

4. TESTS

4.1. Functional and Acceptance Tests

The starting torque was measured at different angular position and at different levels of integration. The dynamic torque noise was also measured at these different levels of integration with a specially developed tool.

The design goals were :

- Starting torque : < 0.25 Nm.
- Dynamic torque noise : < 0.02 Nm.

a) Ball-bearings

After ball-bearing integration (w/o motor and cable-sheet), the measured starting torque (0.12 Nm) is low due to the small preload.

The measured torque noise is below the requested value (average value of $7 \cdot 10^{-3}$ Nm with peaks at $16 \cdot 10^{-3}$ Nm).

The requested characteristics have been reached with off-the-shelf industrial ball-bearings. However, for flight models, space qualified lubrication must be achieved.

b) Motor

After motor integration (w/o cable-sheet), the measured starting torque without powering the motor exceed the requested value (0.60 Nm). This high hysteresis torque of the motor could be dramatically reduced by the use of an other steel grade. A starting value below 0.25 Nm should be achievable.

The torque noise remains below the requested value (average value of $12 \cdot 10^{-3}$ Nm). The presence of the motor does not increase the peak values, but it increase slightly the average value. The peak values seem mostly to be due to defects at ball-bearing level : presence of small dust particles, bad distribution of the lubricant.

c) Cable-sheet

After complete integration, no modification of the starting torque could be measured due to the presence of the cable-sheet (average starting torque : 0.60 Nm).

The dynamic behaviour of the LRAM is modified by the presence of the cable-sheet. Some times, the friction torque jumps to a slightly higher or lower level. This could be due to the storage or release of elastic energy in the FLEX Print. More accurate tests shall be performed in a future work. Moreover, the FLEX Print used during the present project does not exactly reflect the specified one due to prototype manufacturing constraints : a small coverlay overlapping (thickness increase) exists in the middle of the flexible circuit. The effect of this overlapping is significant.

4.2. Evaluation of Components and Procedures

a) Cable Sheet Lifetime

A belt of the FLEX Print tape (the two ends are assembled with KAPTON sheets and adhesive) was placed between two concentric cylinders of a test rig. The inner cylinder was rotating. The movement of the FLEX Print belt is then representative of the actual movement that follows a FLEX Print mounted in a rolling sheet (or gooseneck) configuration.

Electrical contact points were created for each individual line at both extremities so that an easy access to line resistance measurement was available.

A visual inspection of the FLEX Print belt as well as track resistance measurements were performed periodically during the test (test conducted at room temperature, under air atmosphere).

Experiments showed that this cable sheet withstood at least 650'000 cycles with the very small bending radius of 17 mm, this after having already seen more than 425'000 cycles with fewer constraints, though of the order of those relevant for the rolling sheet of the LRAM (30 mm).

This preliminary feasibility test was considered to show that the mechanical resistance in fatigue of the FLEX Print could be sufficient for the LRAM application.

Further validations shall be made in temperature, thermal vacuum and life on an LRAM itself in a qualification program.

b) Cable Sheet Thermal Evaluation

The thermal properties of a FLEX Print sample (Table 3) were evaluated. The tests were performed in air and under preliminary vacuum (10^{-1} mbar) for a long FLEX Print segment, with electrical current ranging from 1 A to 20 A.

The temperature of three gages was recorded : one at the middle of the FLEX Print, one at the end and one on the FLEX Print support as a reference.

An empirical model was developed from this experiment which link the temperature increase to the flowing current, the track resistance, the track number and the average track coverage of the FLEX Print.

c) Cable Sheet Cross-Talk Evaluation

The cross-talk attenuation (CTA) was evaluated on a FLEX Print representative of real configuration.

As the FLEX Print is fully contained in a shielded box (cable-sheet housing), the main concern is related to the cross-talk between tracks. For this reason, the two faces of the FLEX Print should be metallic to obtain a better shielding.

The FLEX Print sample was defined so that various track / gap ratios could be measured. The most

favourable size could thus be selected for the final FLEX Prints execution.
First results have shown that the following geometrical parameters can significantly modify the CTA :

- shielding,
- gap between tracks.

When appropriately shielded, the cross-talk values are better than 55 dB at 1 MHz and better than 40 dB at 10 MHz.

d) Ball-bearing Assembly Evaluation
The cementing of the ball-bearings, though already practised in some terrestrial applications, has no known application in space. The process should thus be qualified prior to any application for an LRAM.
The feasibility of the process and the search for adequate techniques (tools, housing and shaft definition, adhesive selection, polymerisation scheme, etc.) were evaluated.

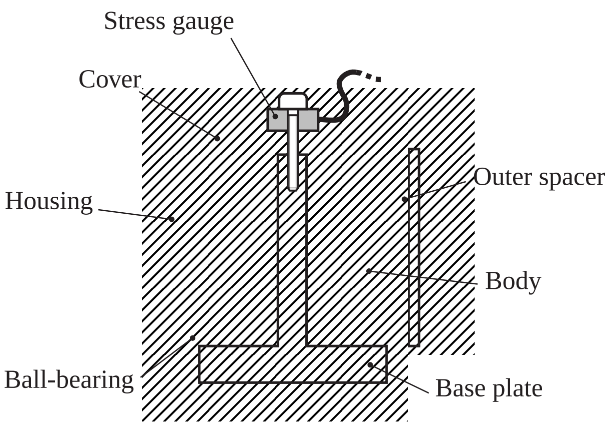

Figure 5. Ball-bearing test assembly.

The preliminary tests were done on an assembly composed of reduced size ball-bearings (Figure 5). The tests showed that the adhesive could creep under permanent shear stress. However, vibration tests and thermal cycling gave very promising results. There was no rupture of the cemented interface.
The adhesive choice and the assembly procedure need to be very carefully defined. Once this performed, and with respect to the manufacturing process, it is then possible to implement an assembly / cementing procedure for the series production that could improve a lot the ease of assembly of an LRAM like mechanism.
Further tests to check the acceptability of the performances have however to be conducted.

5. CONCLUSION

The present work permits to emphasise some critical aspects that could be encountered during the designing and manufacturing of large series of space mechanisms.
This project gives MECANEX the opportunity to gain a lot of knowledge about new technologies or technologies coming from an industrial heritage.
The characteristics of flexible circuit (FLEX Print) technology were investigated and first preliminary models of the FLEX Print behaviour were developed.
New assembly procedures were studied which are very promising, like the cementing of the ball-bearing pair.
Compared to conventional space projects MECANEX is dealing with, the assembly of the LRAM was simplified in a large extend by a convenient design. The assembly time of the LRAM was at least a factor ten less than other similar mechanisms.

ACKNOWLEDGEMENTS

This project was co-funded by ESA/ESTEC under contract number 12781/98/NL/US in the field of the ARTES 4 program. The LRAM was based on an original MATRA MARCONI SPACE design, who participated actively to the discussion during the entire project. The motor was specially developed by ETEL for this project under ESA subcontract. The authors wish also to thank all the suppliers for support and timely delivery.

REFERENCES

[1] P.-A. Mäusli, M.-T. Ivorra, V. Gass and J.-F. Berthoud, *Coarse Pointing Mechanism for Satellite Interlink Experiment*, Proc. 30th Aerospace Mechanisms Symposium, NASA Conference Publication 3328 (1996), pp. 91-102.
[2] F. di Gesu and A. Brunschvig, *Silex Mechanisms: Which Lessons After Qualification?*, Proc. Sixth European Space Mechanisms and Tribology Symposium, ESA SP-374 (1995), pp. 235-243.