EUROPEAN ROBOTIC ARM (ERA) MANIPULATOR JOINT SYSTEM MOTOR UNIT AND TRIBOLOGICAL BRAKE

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ABSTRACT

Europe's interest in in-orbit operations has extended over many years and, as part of the European contribution to the Russian segment of the International Space Station 'Alpha' (ISSA), expanded to include the European Robotic Arm (ERA). Included within the ERA system are the various subsystems and units, within which the Manipulator Joint System (MJS) Motor Unit (MoU) is integrated. The complete ERA includes seven MoUs. Designed, integrated and tested by ETEL SA, the MoU incorporates : a medium speed, permanent magnet synchronous motor (often called a 'brushless DC' motor); a friction brake; a speed-one resolver; and a 'State-of-the-Art' control/drive electronics.

This paper will present the details inherent in the design of each of the Motor Units' electromechanical elements, in particular the tribological brake; the results obtained from both the development and qualification testing campaign at unit level; particular lessons learned and the conclusions drawn. In parallel, the electronic circuit protection philosophy and the overall mass and power budgets will be presented.

1 INTRODUCTION

The ERA MJS MoU's purposes within the anticipated greater-than 10 year operational scenarii are the following : precise velocity control ; stable, limited, 'clean', selectively controlled output torque and backdriveability ; position holding ; accurate and reliable position feedback ; and emergency braking for each of the seven integrated joints of the self-relocatable ERA. Slated for launch in the year 2000, its functions include cargo removal, scientific and power platform assembly, ISSA maintenance, freight handling, displacement and fastening of solar arrays.

The above-mentioned system requirements have been incorporated into the design of the MoU and are guaranteed by the extensive development and qualification testing performed in-house as well as at higher-level contractors' or external facilities. At the present time, the Qualification Model MJS MoUs are nearing the conclusion of their qualification campaign, the Flight Model MJS MoUs have all been delivered, the Flight Spare MJS MoUs are in production and testing and all of the applicable models demonstrate full specification requirements compliancy.

The data provided herewithin have not previously been published and address a potentially large domain of end-users within the automation, robotics and mechanisms fields.

2 DESIGN DETAILS

The ERA is composed of three joints at each extremity, considered as Wrists 1 and 2 (each including one pitch ; one yaw ; and one roll) and a single joint (one pitch) centrally located at what is commonly identified as the Elbow, for a total of seven joints, within which are located the MoU's. Controlling each of the seven MoUs are sophisticated, 'State-of-the-Art', dedicated, failure-tolerant drive electronics.

For maintainability and commonality reasons, the ERA MJS MoUs are identical with respect to form, fit and function and differ only in the specific and unique motor electronic control parameters used for each of the separate single degree-of-freedom joints.

Among ERA's attractions are that it will help minimise joint output torque disturbances and vibrations during routine tasks as replacing instrumentation, ISSA inspection, maintenance and freight handling.

The joints are essentially composed of a motor coupled to an epicyclic low-speed gear stage. As high precision trajectory control is required, a ripple-free low noise torque control is necessary to avoid critical speed stability ranges and potentially destructive shocks within the MoU-coupled gear stages.

Noise and vibrations created by usual drive assemblies are often harmful and classical torque ripple values of 15% of mean torque are typically attained. The ERA program's challenging low ripple requirements allowed ETEL to develop a special electronics capable – via Look-Up-Tables - of introducing sophisticated currents into the motor phases.

The result demonstrates that this can suppress any type of mechanical, manufacturing and magnetic defaults. By using an adequate test bench associated to an iterative compensation process, this 'State of the Art' controller can easily deal with common motor imperfections and achieves ripple torque levels lower than 0.3% peak-to-peak across the overall torque range.

2.1 General

Each Motor Unit is composed of a biphased, permanent magnet synchronous motor; a speed-one resolver; a tribological, low-wear friction brake used for safety purposes and its associated high performance drive/control electronics.

For each of the ERA MJS MoU complementary elements mentioned above, rigorous and challenging requirements were imposed to ETEL which were either met or exceeded. The minimisation of the classical mass/volume/power trio, applicable for virtually each and every space program, was exploited to nearly its fully optimized potential with exceptionally good results: the overall mass came in at more than 15% under specification; the volume was easily accommodated; and the overall power allocated for the complete operational states across the program's worst-case thermal conditions was met at as low as 75% of the requirement!

Details of each of the Motor Unit's complementary elements follow.

2.2 Motor

The biphased, redundantly-wound, permanent magnet synchronous motor integrated in the MoU is coupled to an epicyclic low-speed gearbox (provided by Stork Product Engineering) within the MJS, providing a reduction ratio of 454:1. The motor is driven by its dedicated electronics (described below) shared in two identical parts in order to drive both the main and redundant windings.

Due to the high performance phase compensation techniques employed to drive the motor, one can accurately state that the motor's electronic assembly exhibits a virtually ripple-free behavior. Low power consumption and mass, low detent torque, linear magnetic behavior, small diameter, long life and high reliability are some of the important design optimisations attained.

Some of the motor’s characteristics are the following:

- Design voltage: 30V±10%
- Torque at stall: >1.45Nm
- No-load speed: 345rpm@30V
- Torque at V_{max} (25rad/s): 0.60Nm
- Detent torque: <40mNm
- Power at stall (100^{o}C): 28W
- Torque constant: 0.83Nm/A
- Motor constant: 0.316Nm/√W
- Back emf constant: 0.83V/rad-sec^{-1}
- Ext. Diameter: 120.0mm
- Length: 29.0mm
- Mass: 0.750kg

2.3 Resolver

To accurately acquire the motor's position, a speed-one resolver (a type of position encoder) is integrated. The stator is redundantly-wound, with the primary winding supplied by a high-frequency voltage, in turn inducing a high-frequency signal in each of the secondary windings. Each of the secondary winding signals have an amplitude directly related to the motor rotor's position (varying, respectively, with the sine and cosine of the angular position).

Its innovative design incorporates absolutely no rotor windings. Rather, a patented rotor lamination stack design and assembly technique, permitting a precise waveform periodic feedback signal, discretely associates a ‘zero-position’ reference point. The further analysis of these two signals enables the instantaneous acquisition and control of the motor rotor position.

Low mass, high resolution (14-bit), small external diameter, long life and high reliability are some of this resolver’s attractions. The position accuracy is not a strong design driver and, therefore, the limited resolver accuracy does not present any functional drawbacks.

Several of the resolver’s characteristics are:

- Type: 6040 Rotasyn / speed 1 / transmitter
- Accuracy: <32arcmin
- Resolution: 14-bit
- Mass: 0.420kg
- Rotor inertia: 0.96^{E-03}kgm^2
- Diameter: 65.0mm (ext.)
30.0mm (int.)
- Length: 20.0mm

2.4 Brake

A tribological brake, electromagnetically-attracted and based on passive spring elements, is integrated into each of the seven MoUs' housing. The brakes are composed of an electromagnetically-attracted moving armature, two friction brake disks, a flexible membrane and corrosion-resistant high performance springs. Only the brake’s electrical components (brake coil and driving electronics) are redundant.

The MoU’s brake provides the specified in-vacuo braking torque necessary for the ERA within the very tight torque bandwidth requirement, providing a maximum brake torque variation, irrespective of the braking condition, of less than ±22% of the average brake torque across the complete brake torque range specified. Its tribological characteristics provide excellent resistance to sliding wear and abrasion while maintaining a stable and continuous friction coefficient across the lifetime of the ERA.

The brakes' main functions are to ensure both astronaut and payload safety, particularly under power loss or joint runaway conditions. They are functionally identical. Under nominal ERA operations, the brake disks are separated by a distance of 0.2mm by the attractive force of the brake coil.

Once a safety-critical condition is detected and either the command to cut power is effected or an actual power drop is physically present, the brake elements are forced into contact (via the spring elements and the release of the brake winding current) and the ERA’s respective moment of inertia is brought to a complete stop within less than 3.5 seconds. This remains the case across the full operational thermal (-55^{o}C≤T_{op}≤+85^{o}C) and vacuum (Low Earth Orbit) regimes.

Figure 1 shows one of the eleven flight model ERA MJS Motor Units with its integrated brake subassembly (including membrane, brake discs and position pins), while Figure 2 illustrates the same model from the gearbox interface to the ERA Mechanical Unit.

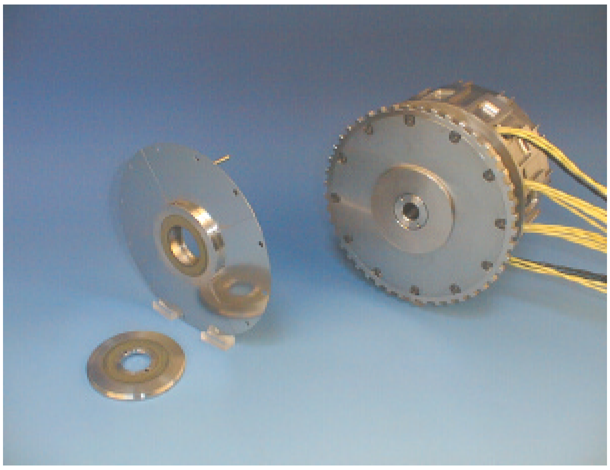

Figure 1
Flight Model ERA MJS Motor Unit & Brake Subassembly

Low power consumption and mass, superb brake hold and release characteristics, reliable and low-wear friction coefficient material, long lifetime and high reliability are inherent to the brake's design across its duty cycle of 4,380 hours and more than 10,700 various brake operations.

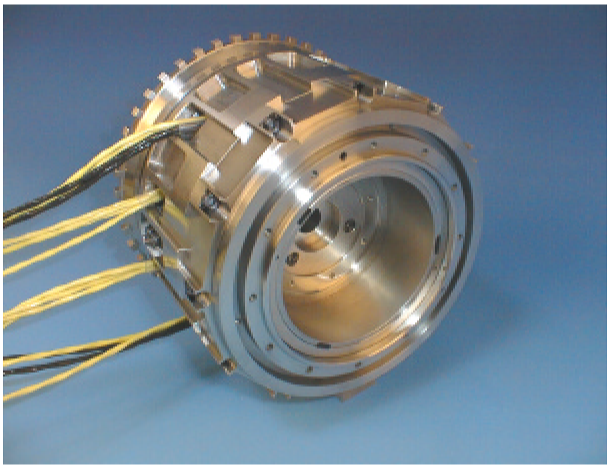

Figure 2
Flight Model ERA MJS Motor Unit
(Gearbox Interface With Motor Rotor)

2.4.1 Friction Coating & Development Process

Literature surveys (1, 2, 3) and expert advice from the INSA, Laboratoire de Mécanique des Contacts in Villeurbanne (Lyon-France) enabled us to narrow the search for a suitable contact friction material for the intended in-vacuo conditions for the ERA.

This search was focused primarily on several aspects: stable friction coefficient under continuous vacuum conditions (for both performance and safety); low wear rate (for its extensive duty cycle); and thermal stability (for its overall reliability).

The ceramic material selected for the brake is a plasma spray-deposited chromium oxide (Cr_2O_3) coating upon a metal substrate. The deposition process was handled by the Union Carbide company, Praxair, while the metal substrate in the ERA MJS MoU design is an X46Cr13, AISI 420-type stainless steel.

Essentially, for the friction coating to effectively execute its 'mission', several characteristics must be present:

1. a proper and controlled in-vacuo 'running-in' process must be realized on the planar, parallel, mirror-polished contact surfaces, rendering them matte overall and microscopically rough;

2. sufficient quantities of 'third-body' particles of the chromium oxide coating must have been generated; and

3. the operating conditions for which it has been designed, namely in-vacuo, must be respected.

The breadboard development campaign was focused on a lower-force, large median diameter contact surface brake, enabling us to validate the concept. The breadboard brake disc median diameter was approximately 85mm. The results of this campaign were promising, yet a redesign effort was subsequently undertaken to conform to updated specifications for the ERA (lower mass, reduced geometry, lower power).

The subsequent redesign campaign effectively highlighted several different potential contact friction geometries which were then thoroughly tested. The internal geometry of the brake subassembly drove us to reduce the mean diameter of the brake contact friction surface to between a maximum of 46.5mm to a minimum of 33.4mm, with corresponding contact surface areas of between 2444mm^2 and 300mm^2.

With such large variable geometries and with the tight torque and power specifications, extensive efforts were undertaken over an 18-month period to effectively determine the design best suited for the Engineering Qualification Model, and subsequent Flight Model, development.

2.4.1.1 EQM/FM Development & Test Campaign

Once the correct geometry was found, a variety of iterative steps were undertaken to generate a repetitive and reliable manner of ensuring that the Motor Unit brake would perform as expected, given the power, operational scenarii and physical constraints imposed by the ERA design (limited output angular displacement capacity).

This stage of the development campaign was quite a challenge and a number of 'bugs' required ironing out in the shortest possible time and with limited resources.

The most trying challenges were the following:

1) Establishing an effective running-in procedure under vacuum for the Cr_2O_3 coating, necessary for creating the correct interface morphology in order to ensure stable, high friction torques over extended periods[3];

2) Once exposed to the ambient conditions of relatively high humidity, providing an accurate order of magnitude of the time between the running-in procedure under vacuum and the ambient exposure necessary to recover the stable friction characteristics attained after step 1, above;

3) Eliminating an effective brake torque peak characteristic during an operational condition wherein a joint's moment of inertia rapidly increases and must be arrested; and

4) Guaranteeing the performance of the overall ERA MJS MoU brake subassembly in all conceivable operational scenarii.

Addressing these four points one at a time, we were able to discern and establish the following:

Point 1:
The in-vacuo running-in of the Cr_2O_3 coating is an event which requires close supervision and meticulous observation. The various steps employed throughout the EQM and FM hardware acceptance events included:

a) performing at least 12,000 revolutions (in multiple steps of 500, 250 and 60 revolutions) of the contact surfaces against one another, guranteeing the desired surface morphology;

b) during the complete running-in of the brake discs, performing several de-integration events, thereby verifying the desired surface morphology (essentially ensuring that the complete contact surface was being correctly 'run-in', exhibiting a matte debris texture) and generation of 'third-body' particles;

c) arresting the running-in at a point where the brake torque exhibited the desired, stable friction characteristics and preparing the brake subassembly for further integration and calibration in either an EQM or FM;

d) once integrated within either an EQM or FM, a further controlled in-vacuo running-in event is necessary to recover the stable friction torque characteristics and subsequentlycalibrating the contact force for the particular model under test.

Point 2:
This determination was arrived at after multiple experiments of repetitive tests with various different running-in events and durations exposed to ambient conditions. Today, a guideline has been established and, if adhered to, will ensure the recovery of the in-vacuo friction characteristics as previously established.

Point 3:
As explained[2], the third-body functions as: 1) a load transmitter; 2) accomodating a speed differential; and 3) separating the "1st bodies".

The "1st bodies" are considered as the baseline, morphological structure which has been plasma spray-deposited and is adherent to the metal substrate. Both 3rd and 1st bodies are of identical chemical composition. Figure 3 illustrates this structural interface.

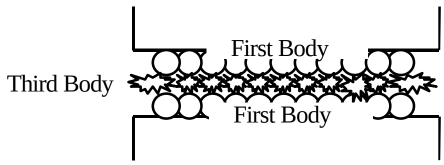

Figure 3
1st/3rd Body Structure

The event of torque peaks in the system presented arise from an inherent lack of sufficient 3rd body particles to adequately distribute the force from a rapidly spinning contact surface.

This lack of 3rd body particles generates a condition similar to 'stick/slip' which, when present in a rotating contact surface, provides the condition of generating a friction torque peak which is maintained and eventually resettles to an acceptable level. In the unit under discussion, excluding subsystem-level 'damping', this torque peak exceeded the mechanical support levels of the ERA (the peaks attained 1.78Nm, where a maximum of 1.1Nm was specified).

This phenomenon has since been resolved and is solely due to the lack of 3rd body particles within the contact region.

Point 4:
The challenges to be overcome concerned the following:

a) thermal effects of the MoU / brake subassembly;

b) brake testing at the next-higher subsystem level under both in- and ex-vacuo conditions, while attempting to correlate the test results under these two different conditions; and

c) component-level reliability across all test conditions.

The thermal effects were tested early on in the EQM development campaign to validate the reliable performance of the chromium oxide coating. This was demonstrated successfully.

Much later in the program, the last two challenges surfaced unexpectedly during the subsystem tests of the ERA joints.

The next-higher level test campaigns do not always allow for testing in-vacuo and, therefore, the contractor was limited to ex-vacuo testing. Unfortunately, the ceramic oxide coating is susceptible to non-linear and 'dysfunctional' effects when subjected to testing in standard thermal and pressure environments, i.e., during ex-vacuo test events.

The main challenge for the subsystem contractor in this off-nominal configuration is to correlate the previously stable and continuous in-vacuo brake torque with the highly variable effects encountered ex-vacuo. The two, unfortunately, cannot be correlated one-to-one.

The main reason for this is that the morphological structure of the 1st and 3rd bodies are different under these two dissimilar environments: under ambient conditions, the 1st body morphology resembles more a 'pasty' film, with relatively large agglomerations of 3rd body particles whereas, under vacuum, the 1st body acquires a hard, non-'pasty' morphology with smaller and drier agglomerations of 3rd body particles. The subsequent results of similar test conditions under these two quite dissimilar environmental conditions will, therefore, be different.

Figure 4 represents nominal, in-vacuo brake torque values across a full test sequence (representing 1/10th the lifecycle of the ERA brake), while Figure 5 represents typical brake torque variations under ex-vacuo conditions of a form, fit and functionally representative model of a similar brake subassembly.

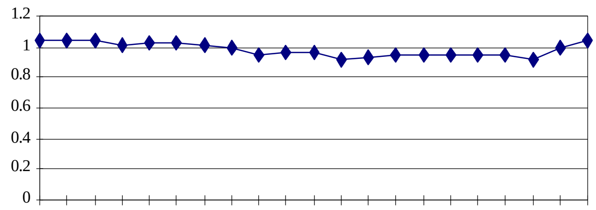

Figure 4
ERA MJS MoU FM-03 In-Vacuo Acceptance Test Results

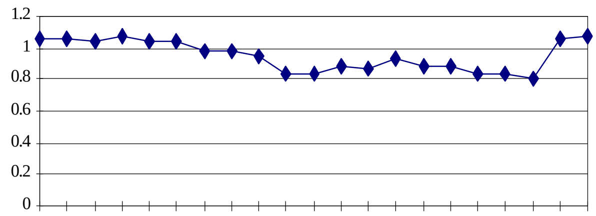

Figure 5
ERA MJS MoU EQM-05 Ex-Vacuo Test Results

The last point, component-level reliability across all test conditions, was the latest challenge with respect to the ERA program which we had to address. The difficulty, essentially, was in developing an adequate integration procedure for implementing redundant microswitches in a configuration for which they nominally should not be used.

The problem is the following: the brake subassembly translation is only 0.2mm, while the hysteresis values for the space-qualified microswitches are on the order of between 0.05mm and 0.35mm. In the worst case, the hysteresis is nearly twice the overall brake subassembly travel! This conceivably cannot work. We, therefore, had to work around this challenge and have now arrived at solving the problem while respecting the operating requirements across all environmental conditions.

Various design characteristics of the ERA MoU brake are:

- ➢ Brake torque range: $0.70Nm<T_{brake}<1.10Nm$ ($T_{brakeavg} = 0.90Nm$)
- ➢ Power consumption: <3.0W/continuous hold <10W/20ms lifting
- ➢ Mass: 1.55kg (shaft / brake coils)
- ➢ Diameter: 52.4 mm (ext.) 18.0 mm (int.)
- ➢ Contact surface area: $663.5mm^2$
- ➢ Contact force: ~100N

Contact pressure: $0.151N/mm^2$

2.5 Drive / Control Electronics

The main functions of the drive/control electronics of the ERA MoUs are to: correctly energise the brushless DC motor (providing a ripple-free average torque) while minimising the power consumed; activate/deactivate the tribological brake; process the resolver's signal to precisely acquire the motor position and speed information and provide an electrical interface in line with the external environment.

To achieve these required functions, the motor torque controller is physically split into two electronic boards, each with their dedicated functions:

1. the Resolver Control board (comprised of the position demodulation electronics and the torque ripple compensation algorithm coupled to different Programmable Read Only Memories, or PROMs, for the Look-Up-Table storage registers); and

2. the Power Control board (comprised of the Pulse Width Modulated, or PWM, control electronics, driving both the motor and brake units).

Special circuitry within the Power Control electronics attends to both the safety and monitoring functions, while an in-rush current limitation circuit is coupled to the input over-power detection circuit.

Since high precision trajectory control is required, a ripple-free low-noise torque control is considered in order to avoid critical speed stability ranges and potentially destructive shocks within the gearbox coupled to the MoU. Mechanical hardware imperfections, specific design choices and various inherent motor characteristics (current, back emf, detent torque) must all be compensated in the process of obtaining an optimized solution. The desired operating solution results from the optimized coupling of these two, power and control, electronics.

The challenging low ripple requirements drove us to develop a special electronics, via the previously stated Look-Up-Tables, capable of introducing the stored, sophisticated currents into the motor phases.

The result demonstrates that this suppresses all types of mechanical, manufacturing and magnetic defaults. By using a test bench coupled to an iterative compensation process, this 'State-Of-The-Art' controller can easily deal with common motor imperfections and achieve levels inferior to 0.3% peak-to-peak torque ripple across the overall torque range[1].

The MoU-level acceptance tests have attained completion and, effectively, point out the excellent motor characteristics and torque ripple performance achieved following the complete torque ripple calibration process[1].

High accuracy and resolution, low power consumption, small dimensions (partially attributable to the use of Surface Mount Device, or SMD, components), long life and high reliability are some of the main design elements inherent to the ERA MoU drive/control electronics package.

The qualification and acceptance test results of the ERA MJS Motor Unit drive/control electronics present the culminating success of a meticulous and objectively-oriented development and integration philosophy within ETEL which is being extended beyond the ERA program.

Based upon the perceived necessity and design philosophy of ETEL for the ERA program, we successfully managed the rigorous and stringent requirements of a qualified SMD Process Identification Document, or PID, component integration certification by the ESA. This process certification was based on and qualified for a wide spectrum of frequently-used components, beyond those solely used for the ERA program. Naturally, all subsequent electronic designs and related component mounting activities will be based upon this experience and will optimally adopt the inherent design principles and lessons learned for the ERA.

The following figure presents a fully mounted Flight Model ERA MJS Motor Unit Power Control Board, ready for further integration in the MJS electronic box.

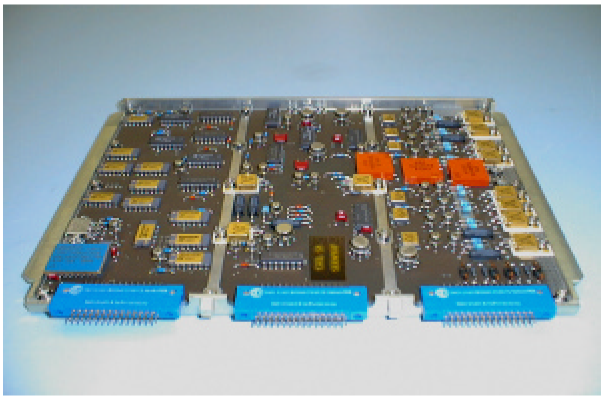

Figure 6
FM ERA MJS Motor Unit Power Control Board (shown with stiffening/integration frame)

3 QUALIFICATION TEST RESULTS

3.1 Mechanical

With respect to the qualifcation test results, performed both at ETEL and by the next-higher level contractor, SABCA, several highlights must be presented:

1. The sinusoidal vibration levels, for both the mechanical and the electronic hardware, as shown below did not present any difficulties;

Frequency (Hz)	**Level**
5 – 18	± 11mm
18 – 60	± 15 g
60 – 100	from ± 15 g to ± 6 g

Table 1
ERA MJS Motor Unit Sinusoidal Vibration Loads

2. When assessed, the random qualification loads imposed to the MoU hardware appear quite elevated;

3. The random qualification loads specified were greater than those to which the MoU and its associated drive/control electronics were physically subjected to under test when mounted within the complete MJS;

4. This is the most complicated system developed by ETEL to have been subjected to such elevated loads.

The specified qualification random vibration input loads (across the defined interface), to which the ERA MJS Motor Unit was subjected, were the following:

	PSD (g^2/Hz) Subsystem Input	
Frequency (Hz)	**Specified**	**Qualified**
20 – 100	+ 3dB/octave	+ 3dB/octave
100 – 400	1.12 g^2/Hz	0.09 g^2/Hz
400 – 2000	- 3dB/octave	- 3dB/octave

Table 2
ERA MJS MoU Mechanical Random Qualification Loads

The effective G_{rms} value for the specified excitation level corresponds to 33.3 G_{rms}. For a complex mechanical system incorporating a motor, brake and resolver, such a level imparts massive acceleration loads to the overall unit, when considering the potential amplification factors, including its complementary internal hardware elements.

During the tests performed by ETEL, with a single MoU mounted and loaded as specified, the levels seen by the MoU far exceeded its design capacity. As a result, the preloaded thin-walled bearing pair was inexorably damaged and required replacement.

The replacement of this ballbearing pair was essential, particularly, due to the non-linear behavior of the motor torque when driven by the 'State-of-the-Art' drive/control electronics. This non-linearity emanated as a result of the brinelling of the ballbearings and race damage, imparting faulty and uncompensated torque acquisition data.

The other effect due to the high acceleration loads to the MoU consisted of one of the microswitch levers being 'snapped' from its laser-soldered membrane base due to the high frequency vibrations transmitted from the microswitch position pin contact. At lower loads this position pin would not have remained in contact long enough to cause any damage. These discoveries have been successfully resolved.

3.2 Electrical

The qualification test random vibration loads, for which ETEL's design was developed, were the following:

Frequency (Hz)	PSD (g^2/Hz)
20 – 100	+ 3dB / octave
100 – 400	0.81 g^2/Hz
400 – 2000	- 3dB / octave

Table 3
ERA MJS MoU Electronic Random Qualification Loads

The effective G_{rms} in this case is equivalent to 27.8 G_{rms}. The ERA MJS MoU drive/control electronics, of which the Power Control Board is shown in Figure 6, successfully withstood this level.

4 CIRCUIT PROTECTION PHILOSOPHY

With respect to the safing and protection philosophy defined for the ERA, several functions have been implemented to suppress or minimize the chance of a Single Point Failure. The complete list of internal protections resulting exceptions - i.e., switch OFF of motor and brake - is listed in Table 4.

Protection Identification	*Intervention level*
Over temperature motor	> 110 °C
Over current motor	I > 1.7 Imax
Over current power bus	> 4 Amps
Over current brake	> 1 Amps
Built In Test rvdt	Loss of speed / position tracking
RDC latchup	Project SEL level
Motor failure status, window between commanded and measured current	$\lvert I_{mesA}-I_{refA}\rvert < \alpha$ (i.e. 10 %) $\lvert I_{mesB}-I_{refB}\rvert < \alpha$ (i.e. 10 %)
Over temperature PCB	85°
Over voltage bus	> 35 V

Table 4
ERA MJS MoUt Electronic Circuit Protection Philosophy

5 MASS BUDGETS

The overall ERA MJS MoU and drive/control electronics mass envelope is allocated according to Figure 5. The drive/control electronics mass is 1676g (15% below specification), with the MoU mass being 5075g (10% below specification).

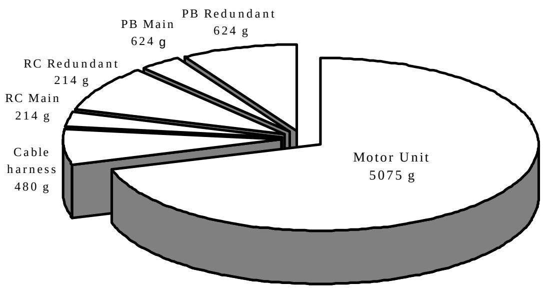

Figure 3
ERA MJS Motor Unit Mass Budget Allocation

6 LESSONS LEARNED

The various lessons learned throughout the conception, development, Assembly/Integration/Test (AIT) and qualification testing phases are different for each of the ERA Motor Unit complementary elements.

6.1 Mechanical

1. The development and qualification campaigns of the tribological friction brake require an extremely targeted and concentrated effort. This effort must be based upon academic research, coupled with subsequent intensive development resources, culminating in multi-year test campaigns which address, inexhaustively, the following issues: friction coating application process; ageing; wear rate; differences between in-vacuo and ex-vacuo test conditions; and factors influencing the friction brake which are external to the brake itself.

2. The electromagnetic analyses of the friction brake demonstrated dramatic magnetic property variations between the different conditions of the stainless steel used for the MoU housing.

3. The specified environmental requirements at the Motor Unit interface far exceeded the actual subsystem input due to damping and other factors. The initial failure of the preloaded, thin-walled bearing pair could have been avoided through closer cooperation and an improved understanding of the complex ERA subsystem.

4. Working with the limited volume and a component (microswtich) hysteresis unmatched to the brake subassembly translation distance should have ellicited a less-conventional approach: a 'Force Sensing Resistor' is an ideal contact proximity detector for such an application.

5. The mass optimisation study demonstrated sufficient margins and provides confidence for future programs.

6.2 Electronic

1. The in-house thermal, vibration and Electro-Magnetic Compatibility (EMC) analyses performed for the electronic hardware demonstrated compliance with the specification and has proven reliable subsequent to the successful qualification test campaign performed on the ERA MJS electronic box. These approaches are currently being applied to further programs with complete confidence.

2. The ESA-certified SMD component use and mounting philosophy has demonstrated ease of use, repeatability, reliability, volume and mass optimisation, small series production capacity and superior production quality, envisioned and being currently employed for a number of ETEL's future space programs.

3. The use of introducing stored, sophisticated current profiles within the drive and control electronics for the

efficient, reliable and high performance operation of a space-qualified electromechanical drive has demonstrated its superior characteristics compared to classical motor control methods and is currently available for dedicated low-torque ripple applications.

7 CONCLUSIONS

The above hardware described is approaching the conclusion of its rigorous qualification and acceptance testing campaigns and further requests have already been tendered for use within similar space applications requiring automated, robotic precision grappling and manipulation events.

Further mass and electronic optimisations are being entertained while maintaining the overall design relatively unchanged. Novel , innovative design concepts and applications can also be discussed.

ETEL has effectively succeeded in qualifying multiple elements for space applications subsequent to the combined targeted efforts of:

1. Performing and concluding the rigorous development test campaign of the brake;

2. Executing a detailed design and analyses of the motor;

3. Performing thorough analyses and tests of the resolver; and

4. Acquiring and applying the comprehensive knowledge gained by developing the ‘State-Of-The-Art’ drive/control electronics, including its detailed noise and perturbation analysis for the ERA.

These elements, taken together to represent the European Robotic Arm Manipulator Joint System Motor Unit, have demonstrated compliancy with the very challenging requirements set forth by the ERA program and can now be applied, together or separately, to numerous other space automation, robotics and mechanism applications.

8 REFERENCES

1. Hawthorne, H.M. and J. Kavanaugh, *The Tribology Of Space Mechanism Friction Brake Materials*, Canadian Aeronautics and Space Journal, Vol. 36, No. 2, p. 57-61, June 1990.
2. Berthier, Yves, *Maurice Godet's Third Body*, The Third Body Concept: Interpretation Of Tribological Phenomena, D. Dowson et.al., eds., Proceedings Of The 22nd Leeds-Lyon Symposium On Tribology, p. 21-30, 5-8 September 1995.
3. Hawthorne, H.M., *On The Role Of Interfacial Debris Morphology In A Conforming Contact Tribosystem*, Wear, Vol. 149, No. 1-2, p. 169-185, 1991.
4. Preston, Shirin and H. Hawthorne, *In Vacuo Testing Of Friction Brake Materials*, SPAR Journal Of Engineering And Technology, Vol. 1, No. 1, p. 22-28, May 1992.
5. Hawthorne, H.M. and S. Preston, *In Vacuo Slip Testing Of Materials For SSRMS Friction Brakes*, 5th International Symposium On Materials In A Space Environment, p. 197-208, June 1993.
6. Mozzon, J.-M. et al 1998, Torque Control Of The European Robotic Arm (ERA), ESA SP-416, 1, 335-342

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