DEVELOPMENT, QUALIFICATION AND MANUFACTURING OF ANTENNA POINTING MECHANISM ROTARY ACTUATORS

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ABSTRACT

In the past 8 years, MDA has developed and qualified eight (8) different Rotary Actuators (RA) for antenna pointing and deployment mechanisms.

This paper presents the design, qualification and manufacturing approaches used to deal with high-volume production. Evaluating RA performances while ensuring high reliability of the end product is a critical challenge when cost effectiveness is mandatory to business success.

Furthermore, the paper describes the high-volume approach using collaborative robots to increase product reliability by minimizing operator tasks while performing quality control and performance evaluations.

Major challenges discussed and related areas of development include:

- Design approach for high volume production using collaborative robots.
- Life testing representativity based on the following aspects:
    - The number of cycles relative to the numbers of travelled output degrees determination.
    - Impact on life and performance due to the acceleration/deceleration and speed.
    - Thermal profile during mechanical cycling.
- Qualification life test health monitoring and remote testing is reviewed based on test experiences.

Finally, many lessons learned have been assimilated throughout the multiple qualifications performed, which enable MDA's mechanism team to perform representative qualification programs including long life testing and performance evaluations.

1. INTRODUCTION

Since 2009, MDA has been heavily involved in developing gimbaled antennas. Most of these are tracking antennas, which all have relatively long mechanical operating life requirements.

Each antenna being different, they all require different Rotary Actuator (RA) designs. MDA had to customize (from a number of basic items) and qualify each new RA.

While most programs are using fewer than a dozen RA assemblies, optimizing manufacturing processes is not necessarily critical. In the past few years, new customers with constellation programs have been important for MDA in terms of manufacturing volume and cost performance targets. With 200 to more than 3,500 RA assemblies needed, MDA was faced with planning challenges for both building and acceptance testing of all these RAs without compromising the end product quality.

Multi-disciplinary teams combining antenna design, structural, thermal, manufacturing and mechanisms engineers are needed to make an RA design work technically at a competitive price that also works operationally.

Continuous technological improvement is necessary to reach higher productivity while maintaining our product quality. Spirit of innovation is required to meet market demands. Automation has allowed MDA to offer competitive RA assemblies to its constellation program customers.

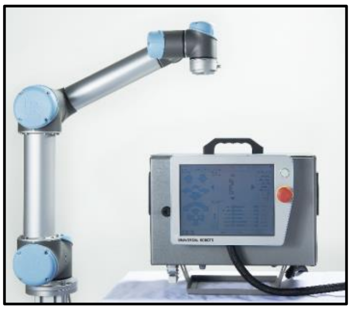

Figure 1. Collaborative Universal robot

During RA qualification, thermal environment is an important aspect. To be representative of program situations, variable temperature ranges, travel ranges and variable speeds are to be taken into account and understood. Severe thermal conditions can cause internal damage and premature failures.

Another important design aspect is related to the electronics behind the application as it will impact life and performance of the RA. At Spacecraft (S/C) level, the main objective is always to save on power and maximize the life of the mechanism. For Ground Support

Equipment (GSE), the goal is to be as much as possible representative of the flight hardware while maintaining the flexibility and cost effectiveness.

During life test, periodic health checks are performed. This paper presents MDA's philosophy regarding remote location testing which was achieved using the internet and compatible Electrical Ground Support Equipment (EGSE). Advantages of flexible EGSE and remote testing are presented in this paper.

Finally, some lessons learned during qualification testing of RA's are presented.

2. RA RELATED DESIGN APPROACH

2.1 Design

In the design phase, attention to detail is required to ensure proper component sizing relative to loads, thermal environment and operating life.

Optimization of load capabilities, output running torque, output accuracy and heat dissipation are aspects of the design that must be reviewed before releasing an RA design.

MDA has developed and qualified eight RA assemblies since 2009. The following tables and figures present a brief description of the RA capabilities and qualification levels.

Constellation RAs

The constellation RA design was developed with the intention of reducing cost, ease manufacturing and downsize to fit within small tracking antennas. The 1st MDA RA design is currently flying since 2013 in Medium Earth Orbit (MEO). A total of 288 RA assemblies have been built, tested and delivered to the customer.

Figure 2. Constellation RA, MEO, 1st RA design

At the time of the 1st RA design, the qualification philosophy had to be developed from A to Z going through all details ensuring the RA would meet the requirements. The EGSE and Mechanical Ground Support Equipment (MGSE) had to be developed from scratch. They are still being used today.

The original design has recently been upgraded with an additional version, where the RA design had to support higher bending loads and survive a more stringent life test duration.

Figure 3. Constellation RA, MEO, High load capability

The life demonstrated capability for these RAs in orbit is continuous tracking for typically 10 to 15 years.

Table 1. Constellation, RA parameters

Motor type	2 phase discrete permanent magnet stepper, no redundancy
Gear train Stage 1	10:1 planetary
Gear train Stage 2	100:1 Harmonic Drive
Step size	0.03 deg. step size
Running torque	19 Nm, Full step, 100% duty cycle, 32PPS at 26 Volts
Qualification levels	22,9M* Output degrees 440k* Mechanical cycles -30°C to 105°C, Operational

***** *Tested up to RA failure.*

Light Weight Constellation RAs

The light weight RA design has recently been launched into space (January 2017). Out of the 648 RA assemblies built and tested, 80 are currently operating in-orbit.

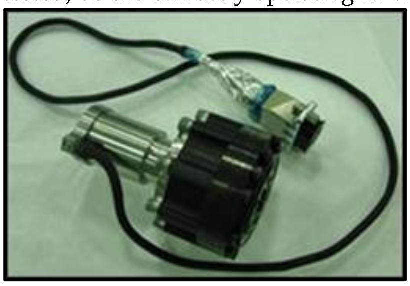

Figure 4. Light Weight Constellation, RA assembly

With a qualified 70M output degrees, this is the RA design that achieved the highest angular travel of the family. This RA was designed for continuous tracking over 15 years.

An additional version of this RA exists where the stepper motor has redundant motor windings. This RA is used on antenna fine pointing mechanisms. The RA integration on the antenna is optimized for Geostationary Earth Orbit (GEO) operation.

Table 2. Light Weight Constellation, RA parameters

Motor type	3 phase discrete permanent magnet stepper, with or without motor windings redundancy
Gear train Stage 1	10:1 planetary
Gear train Stage 2	100:1 Harmonic Drive
Step size	0.03 deg. step size
Running torque	15 Nm, Full step, 100% duty cycle, 50PPS at 28 Volts
Qualification levels	70M Output degrees 300k Mechanical cycles -25°C to 87°C, Operational

Radarsat Constellation (RCM)

The rotary actuator assembly of the deployment sub system (DSS) for the RCM program is used to deploy the SAR Antenna Panel Assembly. This high torque RA is designed for a single use operation in-orbit.

Table 3. RCM DSS, RA parameters

Motor type	2 phase discrete permanent magnet stepper, with redundant motor windings
Gear train Stage 1 and 2	24:1 planetary gear stages
Gear train Stage 3	160:1 Harmonic Drive
Step size	0.011 deg. step size
Running torque	156 Nm, Full step, 100% duty cycle, 20PPS at 24 Volts
Qualification levels	19,700 Output degrees 100 Mechanical cycles -5°C to 106°C, Operational

A total of eight (8X) gimbal RAs have been manufactured. Six (6X) are scheduled for launch in 2018.

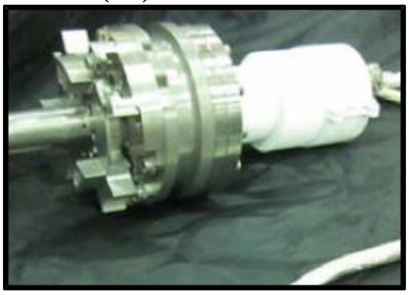

Figure 5. RCM DSS RA

Exomars TGO [1]

The European Space Agency ExoMars 2016 mission required a gimbaled High Gain Antenna (HGA) for orbiter-to-earth communications. MDA has worked for the ExoMars Program to develop and qualify the RA design for the pointing mechanism of the antenna.

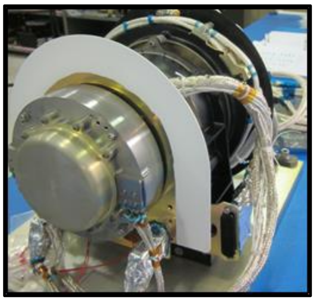

Figure 6. Exomars TGO High Gain Antenna RA

The RA design was challenging since large moments are induced on the APM due to aerobraking forces when entering the Mars atmosphere to slowdown the orbiter. The various phases of the mission and the large travel range of the RA also made the thermal control complicated.

Table 4. Exomars TGO, RA parameters

Motor type	2 phase hybrid stepper, with redundant motor windings
Gear train Stage 1	160:1 Harmonic Drive
Step size	0.011 deg. step size
Running torque	30 Nm, 17.8PPS, 0.23A Current controlled with 32 microsteps/step
Qualification levels	5.9M Output degrees 33,700 Mechanical cycles -23°C to 83°C, Operational
Position sensor	16 bit optical encoder from Codechamps

There are two of this RA design currently orbiting the red planet tasked with ensuring reliable communications with Earth through 2022.

Colka

A Thru Hole Rotary Actuator has been qualified for the Colka program which is foreseen to be used on the International Space Station.

Table 5. Colka, RA parameters

Motor type	3 phase discrete permanent magnet stepper, with redundant motor windings
Gear train Stage 1 and 2	120:1 planetary gear stages
Gear train Stage 3	4.66:1 Preloaded bull gear (anti-backlash)
Step size	0.027 deg. step size
Running torque	20 Nm, Full step, 100% duty cycle, 80PPS, 26 to 27.4 Volts
Qualification levels	16.8M Output degrees 131k Mechanical cycles -35°C to 96°C, Operational

A total of three (3X) RAs have been manufactured and delivered to the customer.

Figure 7. Colka, thru hole RA

High Volume RA Assembly

With more than 3,500 units to be built, MDA needed an RA design optimized for high volume manufacturing. The RA design must support high loads, shocks and survive a requirement of 240,000 cycles.

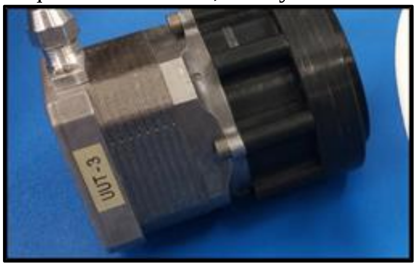

Figure 8. High Volume, RA assembly

The antenna design will be flown in Low Earth Orbit (LEO) with continuous tracking over 5 years duration. The RA components are Commercial Off-The-Shelf (COTS) in order to lower cost. This low cost RA has been qualified to the life listed in Table 6, under continuous thermal cycling.

Table 6. High Volume, RA parameters

Motor type	2 phase hybrid stepper, no redundancy
Gear train Stage 1	100:1 Strain wave drive (Custom Off The Shelf)
Step size	0.018 deg. step size
Running torque	10 Nm, Full step, 100% duty cycle, 139PPS, 19 to 21 Volts
Qualification levels	46,1M Output degrees 415.8k Mechanical cycles -25°C to 105°C, Operational

The design of this RA motivated MDA to seek for new materials with the ability to survive space environment while offering cost effectiveness without compromising the product quality and reliability. Well known space components have been studied, tested and flown multiple times. MDA had to think outside the box and explore new suppliers of the commercial market. Multiple tests have been conducted at various component levels to determine the motor dynamic behaviour and the gear train capabilities and survivability.

2.2 Collaborative Robots

MDA's vision of automation is the use of small collaborative robots. These robots interactively help the employees to perform, with high precision, assembly operations such as positioning, bonding and screw fastening. Inspection steps can be performed while the robot is performing its assembly operation. Tasks such as fastener torqueing, taking pictures, capturing timestamps and production order approval can be done automatically by the robot in line with other manufacturing steps.

When using collaborative robots, each manufacturing operation must be divided into task by task instructions. This process can look painful but is a very good opportunity to review each operations and come to an optimized solution. Issues such as accessibility, in-process inspections and non-value added operations must be considered in the design phase.

The robot also acts as a metronome, setting the manufacturing pace of the work cell. It becomes easier to plan and estimate the task time of each work area.

MDA's automation team has collaborated with the manufacturing engineers, the designers and the mechanism technical experts to develop its RA assembly process for the High Volume constellation programs. Dextrous operations such as wave generator assembly have been made possible. Tools such as screw dispensers, automated torqueing tools and instrumented torque-force wrists allow the robot to work efficiently with full control over the process and interaction forces.

Figure 9. Wave generator assembly insertion in flex cup

A collaborative robot has been used recently by MDA for the antenna final geometric inspection. A photogrammetry scanner is placed at the end of the robotic arm and scans the surfaces to detect the photogrammetry targets.

The photogrammetry inspection cycle lasts approximately 15 minutes and produces a detailed compliance report as compared to the few hours required for an operator including manual data processing.

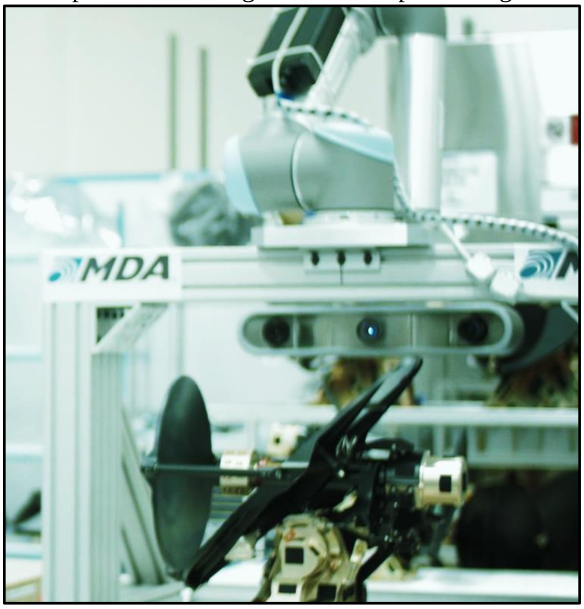

Figure 10. Photogrammetry robot

2.3 Reliability vs High Volume Production

High volume manufacturing is fairly new to our industry. Innovative manufacturing solutions and testing approaches have to be adopted in order to be competitive. The use of collaborative robots can help improve the end product quality with uniformity. The intent here is not to assemble RA's at a very high speed, but to have better contamination control, simplified assembly setups and include instant control steps in the assembly process.

To ensure product quality and reliability for a high volume production, MDA's testing philosophy is to start testing with a higher sampling rate during the initial program phase and, then, have a reduced frequency with random checks throughout the entire manufacturing phase. A Lot Acceptance Test (LAT) approach is being used.

Some test activities are also performed for each unit. At RA level for example, the use of COTS components incorporate a higher risk factor. Test activities such as the initial run-in is very important as this test validates the product assembly conformity and ensures that basic RA performance requirements are met.

This novel acceptance testing approach was used by MDA to meet the program throughput requirements. Multiple RAs can now be acceptance tested in TVAC or thermal in parallel.

Figure 11. Large quantity TVAC testing (24X)

Furthermore, with the use of the automated photogrammetry, MDA saved many hours in data treatment (see Figure 10). The advantages for the program were high as the robot camera angles were taken in various positions always following the same sequence providing reliable measurements with high accuracy.

Other programs are also planning on using a semi-automated inspection work station for RA axis definition. In this case, there will be no robot involved in the operation. The work station is however controlled via a unique EGSE which also controls the antenna movements.

The automated inspection processes are used in order to ensure high quality products. Testing approaches are planned and designed so the level of confidence is of 100%.

3. LIFE TEST REPRESENTATIVITY AND TEST SETUP

During life test planning, fine details such as speed, acceleration/deceleration profiles, gravity vector, MGSE resistive torque, inertial loads and stepper motor pulse profile can affect the RA performance. All these tests parameters must be taken into consideration when preparing the test procedure and test equipment.

3.1 Accelerated Life Test Parameters

The number of cycles is a critical point to determine the validity of a life test as the number of reversal will significantly impact the UUT performances over time. Various parameters such as the numbers of output travelled degrees, accelerations and speed profile are also important.

For our high load constellation RA application, it was required to increase the load capacity of the RA output bearing. The RA mechanical cycling qualification targets were of 438k cycles with 24M travel degrees. At first, it was thought that travel degrees was the differentiator, but the number of cycles ended up to be the limiting factor in the qualification. The RA has been mechanically cycled up to failure. At its end of life, the RA had performed 140k cycles more than our light weight RA design. It had however travelled 22.9M output degrees as opposed to 70M for the light weight RA design. Knowing that both RAs are using identical wear chain, MDA did not expect the failure to come before the end of the life test. The source of the failure was located at the 1st stage planetary gear train where the sun gear, the weakest component in the gear train, did not survive the multiple reversal cycles. The presence of wear debris generated by the multiple reversals was detrimental to the gear train.

Another supporting test observation showing that the numerous reversal cycles can be problematic for RA accuracy occurred on Colka. During the RA qualification, the reversals were abrupt and without pause, especially during the small cycles to mimic the on-orbit dithering behaviour of a closed loop tracking antenna. The objective is always to save time during a life test. The periodic measurements showed continuous degradation of the RA accuracy. The life test speed profile was therefore modified, which completely stopped the gear train wear trend.

Figure 12. Colka RA accuracy trend during life test

3.2 Thermal Cycling Profile

In addition to the numbers of cycles performed during the high load constellation RA qualification, the cold environment testing was also identified to be a major contributor to the RA failure. The life test was performed over a single thermal cycle where the plan was to test 1/3 of the cycles at hot, 1/3 at ambient and finally complete the test at cold. At the time of the failure, excursions at the hot thermal plateau showed that it was possible to re-gain a portion of the RA running torque when returning at cold.

In this particular case, the thermal environment had been detrimental to the RA life expectancy. Based on other RA qualification life tests performed under continuous thermal cycling, results have shown that mechanical cycling, even performed during thermal transitions, was beneficial to the RA life. This variable thermal environment is more representative of the in-orbit life of the RA.

In life testing, a good thermal design is mandatory. The main concern that always comes back every time a qualification program is planned is how to get rid of excessive heat generated by the continuously running motor. Two approaches have been used by MDA to qualify the various RAs.

- **Radiators**
  The use of radiators requires a good thermal model and very good thermal conductivity with the Unit Under Test (UUT). It is very important not to clamp radially on the motor housing and avoid adding too much weight.
- **Thermal strap**
  Thermal straps are good alternative to radiators but they are typically, less thermally effective as they need flexibility. Flexibility is achieved by having thin thermally conductive elements and multiple interfaces which adds resistivity to the design.

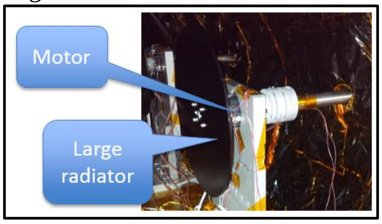

Figure 13. Radiator design

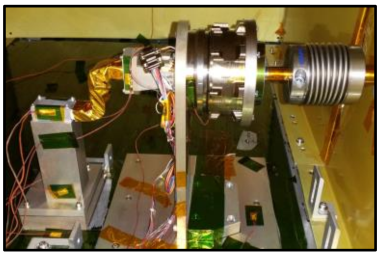

Figure 14. Flexible thermal strap

3.3 Mechanical Test Setups

Mechanical tests setups are designed to ensure proper representativity of the RA loads in the environments. The qualification MGSE used during functional and performance measurements testing is presented in Figure 15. It is composed of a ferrofluidic seal to transition from inside the vacuum chamber to the outside ambient condition. Angular position is monitored by an optical encoder and torque data is recorded by an adjacent sensor. The MGSE motor and slip clutch provide torque loads when required for delivering a continuous resistive spring force.

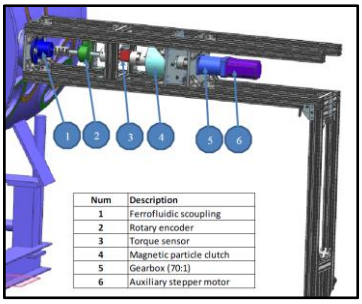

Figure 15. Performance qualification MGSE

To further reduce risk during long duration life testing, simultaneous RA qualification has been performed. In order to validate various aspects of the design, different vehicles have been used. The test setup shown in Figure 16 is using two test vehicles. The first vehicle is designed to measure the RA performances and therefore the UUT is connected outside the TVAC chamber to the qualification MGSE. The second test vehicle is equipped with an inertia wheel representative of the antenna and is connected to the cycling EGSE. The resistive torque (from electrical harness and blankets) is caused by a counter-weight placed on the wheel. The running torque is validated with the use of offset masses (see Figure 18).

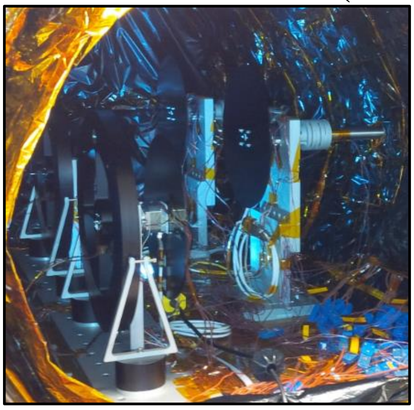

Figure 16. Both life test vehicles in TVAC

4. LIFE TEST HEALTH MONITORING

Designing EGSE and MGSE is an important aspect for the success of the qualification program. The control electronics must, as much as possible, reproduce the flight hardware driving characteristics.

Figure 17. Qualification and cycling EGSEs

The qualification EGSE is composed of various instruments that are used to measure the RA threshold voltage (low voltage driver), low level output accuracy, running torque in full step and half step modes with variable duty cycles, power holding torque and power consumption.

COTS components procured for the high volume projects had not been previously characterized under harsh space environments. The health monitoring equipment needed to be reliable with high resolution measurement capabilities for proper performance validation.

During qualification of our high volume RA design, an unexpected change in the UUT has been observed soon after the life test had started. The change was not related to the RA degradation, but the run-in of the RA wear chain. The consequences of having an MGSE (see Figure 15) with high resistive torque caused the RA measured performances to be out of success criteria.

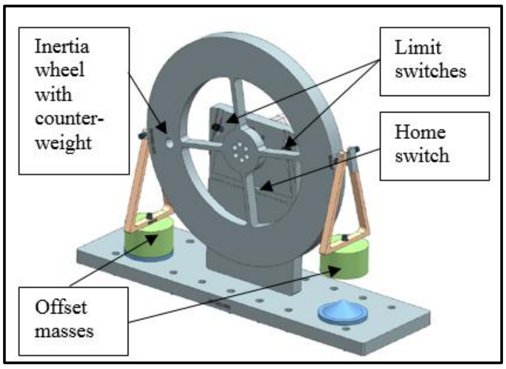

Figure 18. Inertia wheel test vehicle

The inertia wheel test vehicles revealed themselves to be very useful as the home switches could efficiently be used to ensure the UUT comes back to its initial test position, ensuring no commanded steps are missed. Proper torque force margin could therefore be demonstrated due to the presence of a counter-weight on the inertia wheel.

The MGSE design had been well thought out which allowed to continue testing, using alternate test methods without impacting the life test mechanical cycling schedule.

4.1 Remote Testing

In order to maintain program schedules in accordance with test facilities usage and availability, MDA has developed a remote control system that allows multiple RAs to be qualified at the same time in different locations. Such system allows to remotely monitor the performance of the UUTs and control their life testing parameters. Surprisingly simple, remote testing only requires an internet access at the test location. The use of a webcam is also very useful as the test operator is located at his desk in his office in Montreal.

Some delays can be observed as the chamber can only be operated from onsite support, but is greatly compensated by the fact that remote desktop applications allow the possibility to remotely control the UUT via a mobile phone or tablet from any locations with internet access.

The EGSE software interface allows the operator to take full control of the test activities with constant access to thermal parameters of the UUTs, mechanical cycling status and all that with visual feedback.

Figure 19. Qualification EGSE interface

Troubleshooting can also be accomplished at distance. As the EGSE design was made to test one single RA at a time, testing performance of two RAs required multiple electrical interconnections.

At one point during a life test, encoder reading problems started. The results obtained were leading to UUT issues. Investigating remotely and using the home switches for position feedback, it was demonstrated that the RAs were behaving nominally. The problem was caused by a bad electrical connection between the EGSE and the encoder's cable.

To solve the issue, since the MGSE was using a differential incremental encoder, additional signal lines were available for quadrature decoding. Being electrically connected to the EGSE, all four encoder signals could be configured independently via the software.

In the end, a combination of a well thought EGSE design and understanding of the test results can lead to efficient troubleshooting. With remote access and configurable control software, many alternatives can be tested and validated without the need for onsite troubleshooting.

5. LESSONS LEARNED

Throughout the development and qualification phases of multiple RAs, MDA has learned many lessons.

Although the focus of a program is generally on the flight equipment, the MGSE/EGSE should never be underestimated. Flexibility during investigations and troubleshooting is difficult to plan, but a well-designed test equipment, with some redundancy and alternative methods of measurement can avoid the need to stop the on-going qualification.

Some best practices should be kept in mind when planning an RA qualification plan:

- Continuous thermal cycling, with short duration should be considered. The idea is to benefits from re-lubrication of the gear train components while cycling at hot, which is representative of the in-orbit conditions.
- The RA steady state temperature should be in line with mission requirement and the thermal design should be adjusted accordingly.
- Take time to determine proper acceleration rate and speed profile during life test.
- Always use an alternative cycle counter such as a home switch inside the chamber and an encoder outside to monitor drifting of RA or in case of a failure of one of the position sensor.

6. CONCLUSION

Based on MDA's extensive heritage with antenna pointing mechanisms, a wide-range of cost-effective Rotary Actuators have been developed. Being involved in many projects including Rotary Actuators, MDA has developed an expertise in extended life applications such as continuous tracking antennas for satellite constellation programs.

MDA's Rotary Actuator family has the ability to cover a wide range of applications which have survived stringent qualification testing. Not only have these actuators been tested to meet the customer requirements, they were also tested to their design limit ensuring they can be used for various applications with extended life duration. For MDA, the use of automation is an engagement for manufacturing quality products while maintaining cost effectiveness in both high and low-volume programs. The process development along with the lessons learned are key for future programs to benefit from collaborative robots.

Constellation programs with very large quantities are very exciting opportunities for improvement and the horizon is promising. MDA is committed in supporting the demand by providing state-of-the-art steerable antennas equipped with its proven Rotary Actuators.

7. REFERENCES

1) Development and Qualification of an Antenna Pointing Mechanism for the Exomars High-Gain Antenna, ESMATS, Bilbao, 2015