ERA PERFORMANCE MEASUREMENTS TEST RESULTS

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Abstract

The system level test campaign of the **European Robot Arm** [ERA] is currently at the final phase. At the moment of the symposium the following status is obtained:

- Development test programme on the EQM completely finalised
- Qualification test programme on the EQM completed
- FM Qualification test programme almost finalised, not yet performed are the compliant motion test and the Operational Reference mission.

This paper will present the latest status and focus on the results of these tests, provides an overview of the measured versus the specified performance parameters and describes the difficulties encountered to test an eleven meter long robot arm under zero-g conditions.

1. Introduction

ERA is an ESA project intended for use on the Russian segment of the International Space Station (ISS) project. Currently the Flight Model is planned to be delivered by 2003 for a launch in the 2005.

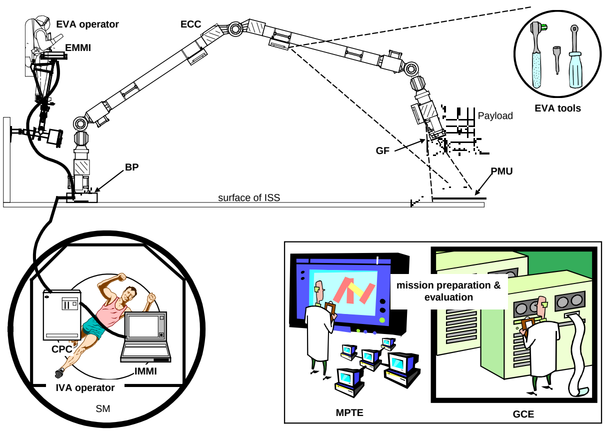

Fig.1: The ERA system

ERA is a symmetric seven-joint anthropomorphic relocatable arm to be used for external assembly and servicing activities of the Russian Segment (RS) of the International Space Station, and for Extra Vehicular Activity (EVA) support tasks.

One can distinguish the Flight segment and the Ground segment. ERA Flight Segment consists of:

- the relocatable manipulator arm,
- software for commanding ERA from inside the station, the so-called IVA Man-Machine-Interface, or IMMI. This software runs on one of the laptops at the RS Central Post,
- software and control panels for control during EVA, so called EVA Man-Machine-Interface, or EMMI; one of them is the nominal point of control, the other one is redundant in stand-by. The EMMI can be operated on an arm-chair of the Portable Working Platform (PWP),
- The Central Post Computer (CPC) is required to handle power on/off commands from ERA, including the Emergency stop. The CPC is also intermediate in the communication between ERA and Ground,
- supporting infrastructure on the station which consists of basepoints (BP) mounted on the external surface of RS, grapple fixtures (GF) mounted on payloads to be handled by ERA, and electrical cabling to the various BP. There are currently 4 base points planned on SPP: Two at the centre of the truss, one near the top of the pressurised part and one near its bottom ,
- A set of EVA tools is available for contingency situations, if ERA cannot be operated anymore from one of the MMI. Some of these tools are also required for the initial installation of ERA on SPP.

ERA missions are prepared on ground. The Ground Segment consists of the ERA-specific Mission Preparation and Training Equipment (MPTE), with which missions are designed, trained, on-line supported and evaluated, and the generic Ground Control Equipment (GCE) that uplinks all ERA ground commands and software updates, and that also handles, processes and distributes all telemetry data. GCE and on-line MPTE are installed at MCC and at RSC/Energia. Off-line MPTE is installed at GCTC and at ESTEC.

ERA has two limb segments, at both sides of the elbow joint; the limbs connect the wrists with the elbow. The two wrists each contain three joints with mutually perpendicular rotation axes, denominated (from the inside to the outside) pitch, which axis is parallel to the elbow pitch axis, yaw, and roll. In normal use, the shoulder yaw joint is locked, leaving 6 Degrees of Freedom (DOF's) for control. Each joint is equipped with a mechanical brake.

ERA has two Basic End Effectors , each can serve as fixation for the shoulder. These BEE's are designed to perform the following main functions:

- grappling and ungrappling a (standard) grapple fixture
- transfer of mechanical power to an external device/load
- transfer of electrical power to an external device/load
- exchange of information with an external device/load
- transfer of video signals from/to an external device/load
- measure forces and torque's with a Torque Force Sensor (TFS)
- data processing for sensors and actuators

With the Integrated Service Tool (IST), a kind of built-in motorised "screwdriver" in each BEE, ERA can provide mechanical torque actuation services.

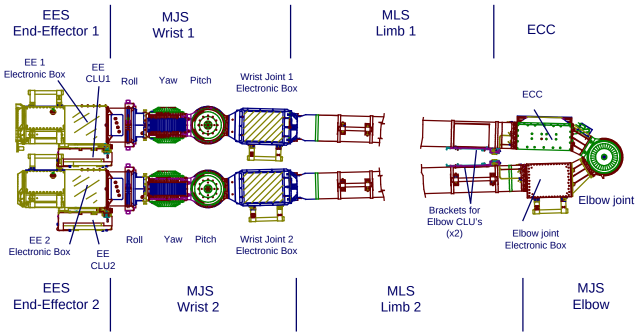

Fig.2: The Manipulator arm

ERA is equipped with Camera and Lighting Units (CLU's), which are mounted at both sides of the elbow joint, and on both EE's. The CLU's on the EE's support automatic proximity tasks of the ERA Control Computer by pre-processing of video images. The proximity function enables ERA to approach grapple fixtures automatically and smoothly.

All mechanical functions of the arm have a mechanical override, which is accessible for a crew member in EVA in case of failure.

2. Model Philosophy

For ERA a mixture of a normal Qualification Model/Flight Model approach and Proto-flight approach was chosen. Based on the PDR status, Engineering Qualification Models (EQM) are built. These models are structurally and thermally representative for the flight standard, but electrically they are built-up from MIL standard B parts. Most of the models do not have complete flight redundancy.

Structural and thermal qualification has been done on the EQM. The structural qualification of some external interfaces, which were not possible to test on subsystem level will be verified at system level on the FM. The final end-to-end functional and electrical qualification will be done on the FM, as only this model contains the hirel Electronic, Electro-Mechanical and Electronic (EEE) parts and full redundant electrical circuits.

An overview of the ERA Performance test program can be found in Table 1. Apart from the Alignment, Stiffness and Thermal Balance test all these test were performed on the FM. The test results of the ERA Qualification Programme have been reported in other papers, their references are shown in the second column.

Test	Where reported
Alignment test	[2]
Stiffness test	[2]
Free motion control tests	this paper, section 3.1.2
Stopping distance test	this paper, section 3.2
Compliant Motion Control tests	no results available
Proximity Motion Control tests	this paper, section 0
Operations	this paper, section 3.3
Thermal Balance	[1]
Boosted Modal Survey	[3]
Electro Magnetic Compatibility (EMC)	this paper, section 3.4

Table 1: Overview of Performance Test Programme

3. Qualification Test Descriptions and Results

3.1 Control test

3.1.1 Overview

ERA motion control consists of 3 parts

1. Free motion control: for large, unconstrained moves, at a safe distance of the space station. ERA can follow feed-forward trajectories relative to its

BP in either joint space or Cartesian space. The ERA control computer computes purely feed-forward position setpoints for the joint controllers. Control is done locally in the joints only, with feedback only from the joint position and motor velocity sensors. The joint controllers run at 300 Hz.

2. Proximity motion control: for small, unconstrained moves, close to the space station. When ERA gets within approximately 1 m from the space station the Wrist CLU is switched on. This camera focuses on special "targets" that are put on the space station. All BP's and GF's are equipped with a target. With proximity motion control ERA can position itself relative to a target. In this way ERA can compensate for possible misalignments in itself or the space station. The proximity controller is an outer loop around the inner joint controller loops, that computes delta's to the feed-forward position setpoints. The proximity motion controller runs at 20 Hz.
3. Compliant motion control: for constrained moves, very close or in contact with the space station. When ERA gets within approximately 5 cm of the space station the TFS is switched on. The TFS can measure the contact forces and torque's between ERA and the space station. If a large, unwanted force is measured in a certain direction, the compliant motion controller complies into that direction. This is necessary for example for grappling a BP, or for mounting a payload. The compliant motion controller is an outer loop around the inner joint controller loops, that computes delta's to the feed-forward position setpoints. The compliant motion controller runs at 20 Hz.

ERA motion control is verified both in simulations on the ERA Simulation Facility (ESF) and in tests on the ERA Test Facility (ETF). ESF is validated against ETF. Because of gravity, on ETF ERA can only be tested in 2D on a flat floor. On ESF ERA is simulated in 3D.

The below sections contain the FM ETF test results from the free motion control and proximity motion control tests. The compliant motion control tests are still ongoing.

3.1.2 Free motion control tests

Fig.3 shows the trajectory of the square move test. The square move consists of several free moves in which ERA has to go to certain positions and orientations.

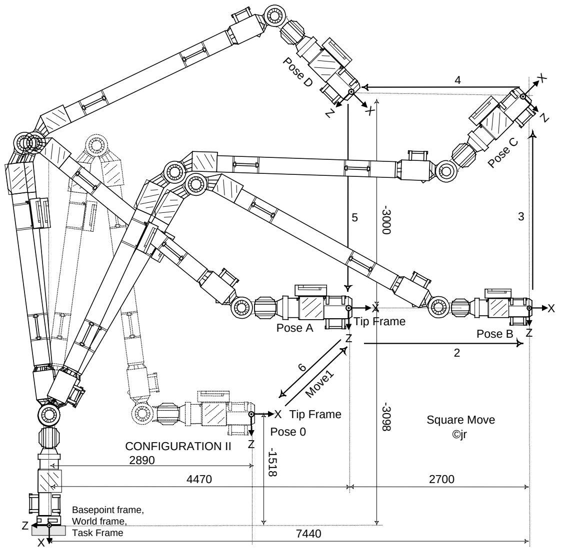

Fig.3 Square Move, a Free Move test

The square move test is performed with an empty arm and with a payload of 435 kg. The position and orientation of ERA is computed with the forward kinematics as a function of the measured joint positions. The resulting translational control tracking errors are shown in Fig.4 for the case without payload, and in Fig.5 for the case with payload. The numbers correspond to those in Fig.3 For the reported tests the maximum control error is 15 mm without payload and 22 mm with payload.

These FM results are very similar to those from the EQM reported two years ago in [2]. Note that these are only control errors. The total error also includes mechanical and thermal contributions.

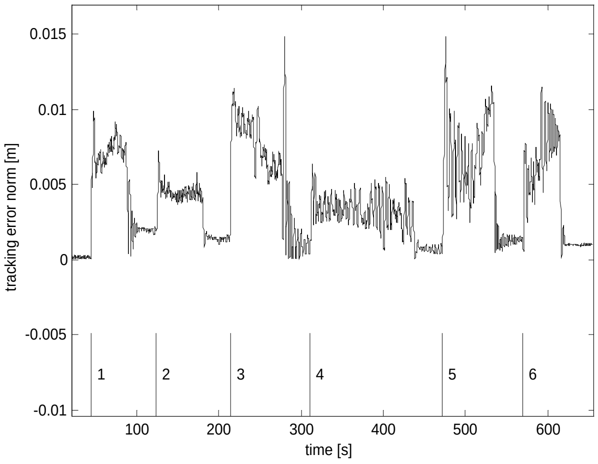

Fig.4 Free motion without payload

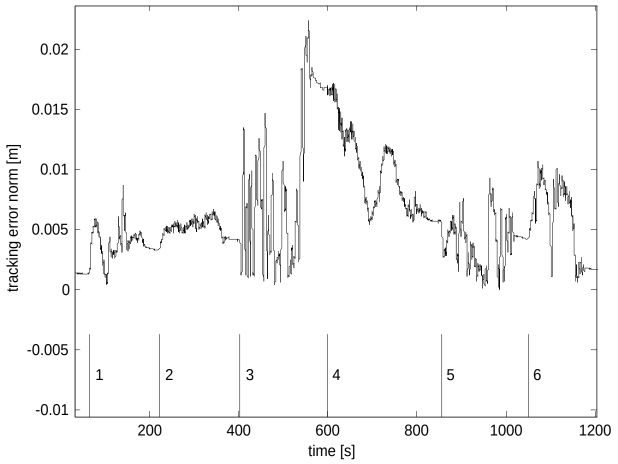

Fig.5 Free motion with payload

3.1.3 Proximity motion control tests

The proximity motion tests starts in the safe approach frame at 1 m distance with an acquire target during which the CLU looks for the target, and removes any possible misalignment with it. For the reported tests, in the safe approach frame an intentional misalignment of 150 mm and 35 mrad is applied. Second, it approaches towards the insert start frame at distance of 5 cm during which the feed-forward trajectory is continually refined as the CLU measurements grow more accurate. Now it can grapple a BP or latch a PL. Afterwards it retracts back to the safe approach frame.

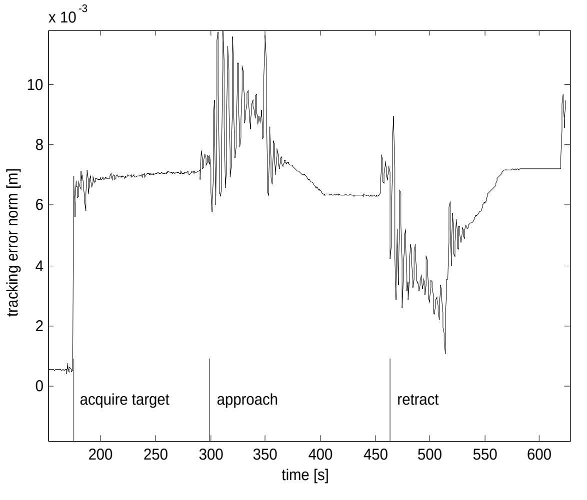

Fig.6 Proximity motion without payload

The proximity motion tests are performed with the empty arm and with a payload of 435 kg. Note that for the tests with payload the CLU is further away from the target (and hence less accurate) as the payload is in between them. The position and orientation of ERA is measured using Krypton measurement system which has an accuracy better than 1 mm and 1 mrad. The resulting total tracking translational tracking errors are shown in Fig.6 for the case without payload and in Fig.7 for the case with payload. Note how the tracking error decreases during the approach as the CLU gets nearer to the target. For the reported tests the total translational positioning errors in the insert start frame are 6 mm without payload and 5 mm with payload.

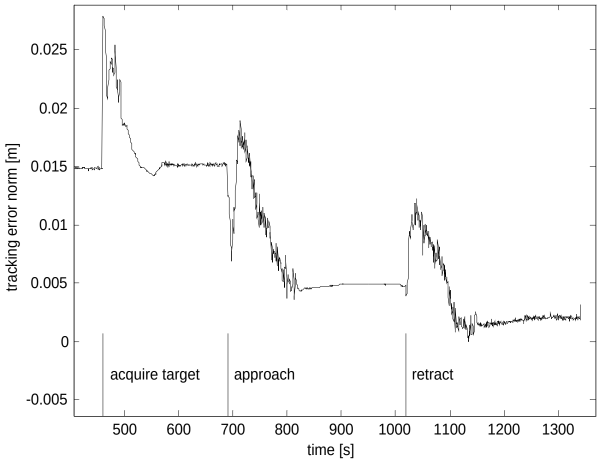

Fig.7 Proximity motion with payload

3.1.4 Performance

The worst-case control performances as measured on the flight model on ETF are shown in Table 2, together with the applicable requirements. All inaccuracies are total inaccuracies (including control, mechanical and thermal contributions).

It can be seen that the free motion tracking and positioning inaccuracies are within their requirements. The measured proximity motion positioning inaccuracy is somewhat larger than required: approximately half of it can be explained by the inaccuracy of the CLU and the other half is from the controller. However it is still amply sufficient to allow safe grappling or latching.

parameter	required	worst case measured on the flight model on ETF
free motion tracking inaccuracy	< 80 mm / 17 mrad	38 mm / 6 mrad
free motion positioning inaccuracy	< 40 mm / 17 mrad	23 mm / 4 mrad
proximity motion inaccuracy	< 5 mm / 17 mrad	8 mm / 6 mrad
joint positioning inaccuracy	< 0.5 mrad	1.3 mrad without and 2.4 mrad with payload

Table 2 Control performance parameters

On subsystem level the measured joint positioning inaccuracy is also larger than required. The 1.3 mrad can be explained by the play in the gearboxes. The 2.4 mrad is probably due to friction between the payload test module and the flat floor, which is not realistic for flight. Note that on system level the positioning errors are well within their requirements.

3.2 Stopping distance test

The verification of the true stopping distance of ERA can only be verified by simulation in ESF, because the operation of ERA in ETF is limited to 2-D. The objective of the stopping distance test was therefore to generate inputs for the validation of ESF. For this purpose three different tests have been performed with the FM:

- a shoulder single joint move without payload
- an elbow single joint move without payload
- horizontal free move without payload

The velocity of the tip of ERA during these three tests was 10 cm/s. The travel of the tip of ERA, after the brakes had been applied, was measured with the Krypton system. The results of the single joint moves shows a maximum travel (including the overshoot due to the flexibility of the arm) of 19 cm, while the free move test gave a maximum travel of 11 cm. Although the requirement is 15 cm, there is confidence that the stopping distance requirement will be met in flight after space-conditioning of the brakes and by means of some operational precautions.

3.3 Operations

3.3.1 Overview

The high-level purpose of Operations verification is to show that with ERA the cosmonauts will be capable of conducting the missions for which ERA has been designed.

Missions with ERA are preferably pre-planned on Ground but can also be unplanned. A pre-planned mission design consists of an autosequence of commands (AS) and corresponding written procedures for the crew. Both have to be verified. To this end a complete set of generic task descriptions (the building blocks of each AS) and generic procedures have been derived and are part of the MPTE library.

Verification of unplanned ERA missions encompass both simple manual motion commands like Jog, and complex semi-automatic so-called Mini Auto Sequences (MAS). Also these are described in generic tasks and procedures.

To handle contingency situations, procedures for diagnosis and recovery have been developed. The verification of these procedures require dedicated "contingency missions" and repair rehearsals.

3.3.2 Verification Approach

ERA operations planning and verification in the flight situation using the MPTE is done in several stages as indicated in Fig. 8.

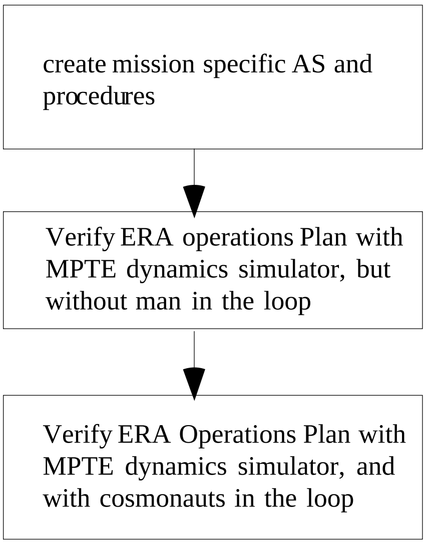

Fig. 8 Stages in ERA operations planning using MPTE

Before a full scale verification of the ERA operation is conducted, first the correctness of the generated AS and some dynamic performance parameters have to be verified. This is done using the MPTE dynamics simulator with the actual ERA Control Computer (ECC) in the loop, but without a man in the loop. Necessary operator commands are generated from a pre-planned file. The purpose is to

- verify that all commands in the AS are given in the right context (no triggering of semantic command checks)
- verify that the ERA performance is within nominal bounds (no dynamic motion checks will trigger)
- verify that the path is collision free as determined by the Collision Avoidance function in the ECC

The next stage is the verification of the ERA Operations Plan with the MPTE dynamics simulator and a man in the loop. The purpose is to

- verify (mission specific) operational procedures
- verify operator visibility issues
- verify operator commandability issues
- verify the time needed

For Operations the following tests have been developed:

1. ORM-MPTE (see section 3.3.3)
2. ORM-ETF (see section 3.3.4)
3. Ground-Space integrated mission test (section 3.3.5)
4. MPTE and ETF Contingency tests (section 3.3.6)

3.3.3 ORM-MPTE

The ORM (Operational Reference Mission)-MPTE is a complex mission of several AS's, encompassing the entire nominal scope of ERA capabilities. It simulates the installation of a solar array on the Russian SPP module on ISS and specifies – on purpose – a part of the command sequences as manually executed actions, such as to imitate an unplanned mission. Fig. 9 gives an overview of the locations and orientations of the BP's and PMU's used in the ORM-MPTE. The ORM-MPTE will be executed on the MPTE under worst-case operational conditions as may be applicable (e.g. during night, or with the largest possible payload, or with the least user-friendly MMI etc.).

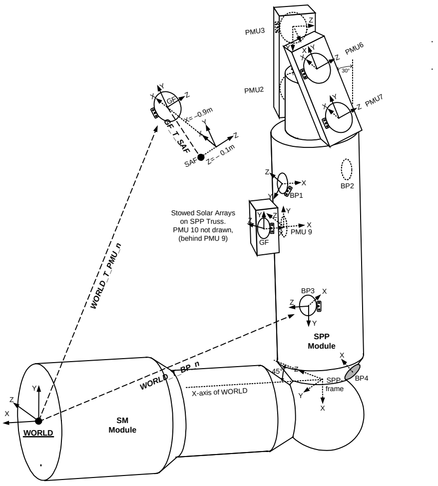

Fig. 9: 3-D view of locations and orientations of Basepoints and PMU's.

3.3.4 ORM-ETF

For all operations which require the real hardware, another test sequence has been designed for execution with the ERA Flight Model on the Flat Floor test facility (ETF). Also here worst-case operational conditions are selected. The ORM-ETF is a reduced set of operations in the 2-D world of the test floor, consisting of a payload pick-and-place operation, a payload inspection, a shoulder relocation and a yield test. A graphical illustration of the ORM-ETF, carried out with the ERA Flight Model on the flat test floor, is shown in Fig. 10.

The final verification sessions are conducted by cosmonauts or astronauts, or their training instructors. This way feed-back from the user community is obtained. Each major session has a duration of 1 - 2 weeks.

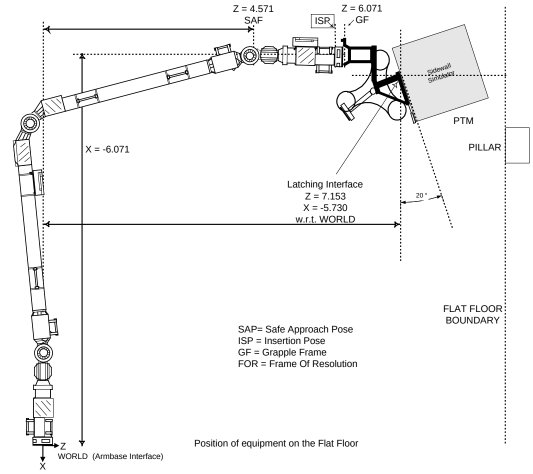

Fig. 10: Typical operation during the ORM-ETF

3.3.5 Ground-Space integrated mission test

In addition to this, one so-called Ground-Space integrated mission test is foreseen, where:

- a mission is planned using the MPTE
- the AS is loaded into the ERA ECC on ETF
- the mission is executed on ETF
- the ERA telemetry, that has been recorded during the ETF test, is loaded into the MPTE for mission evaluation

3.3.6 Contingency tests

Also the contingency procedures are verified in a number of tests on MPTE and ETF. Because real failures must not be introduced in the ERA hardware, anomaly procedures are tested by failure injection in the communication flow. Also the process of software maintenance in flight has been tested. Hardware repair procedures, of course, are all verified on the real hardware, though their final verification will take place in the Neutral Buoyancy facility at GCTC.

3.4 EMC test

The objective of the EMC test was to verify that ERA is electro-magnetically compatible with itself and with its space station environment. The pose of ERA in the test chamber is not relevant for the conducted measurements, but may influence the test results for the radiated tests. Based on EMC analysis and constraints from the EMC test chamber, its was decided to configure ERA in the hibernation mode in the chamber and to illuminate ERA during the susceptibility test from the front and side. **Fig.11** shows the pose of ERA in the EMC chamber. ERA was supported by three wooden EMC trolleys. Actual joint movement was not possible inside the EMC test. Representative emission measurements were achieved by switching ERA in the so-called “run-in brakes mode". In this mode the joints are building up a torque, which will always stay below the minimum brake torque.

The following tests were performed:

- Conducted emission: 120 V power lines, common mode, video lines
- Conducted susceptibility: 120 V power lines, common mode, video lines
- Radiated emission: E-field, H-field
- Radiated emission: E-field, H-field, Lightning

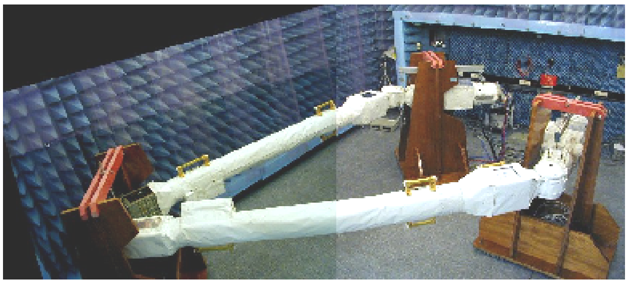

Fig.11 EMC Test configuration

All the test results were within the pass/fail criteria, with one exception, during the radiated emission E-field test the emission level was slightly exceeded in the range of 2-10 MHz.

4. Overview of ERA required performance versus measured performance

This section gives an overview of the measured performance of the key ERA parameters.

At the current stage of testing and test evaluation, not all performance data have been evaluated. Note that measurement data may originate from tests on the hardware or from simulations on the validated software models.

Parameters	*As measured*	*As specified*
Total length	11.17 m	11.3 m
Range / span	9.2 m	9.2 m
Degrees of freedom	7	7
ERA mass (relocatable arm)	619 kg	630 kg
Peak power consumption	637 W	800 W
Standby power consumption	302 W	420 W
Hibernation heater power consumption (max.)	232 W	250 W
Maximum moveable mass	8000 kg	8000 kg
Maximum payload dimensions	3x3x8.1 m	3x3x8.1 m
End position accuracy after free move: (thermal/mechanical misalignments, JPS error, control error)	23 mm, 4 mrad	40 mm, 17 mrad
Trajectory deviation during free move	38 mm, 6 mrad	80 mm, 17 mrad
External position measurement resolution (closed loop), using proximity loop with respect to a nearby target	8 mm, 6 mrad	5 mm, 17 mrad
Allowable deviation of insert position for compliant motion	n.y.a.	25 mm, 17 mrad
Torques and forces		
- before (un)grapple and yield	n.y.a.	40 Nm, 50 N
- afterwards	n.y.a.	6 Nm, 6 N
Maximum deliverable force at tip of EE (stretched arm)	35 N	30 N
Tip velocity: (depending on payload / velocity setpoints)	3 to 100 mm/s	3 to 100 mm/s
Stopping distance		
- in Proximity safety zone	0.215 m	< 0.15 m
- in free space	0.375 m	< 0.40 m
Arm flexibility shoulder to tip (stretched arm)		
- for lateral force	0.4 N/mm	>0.375 N/mm
- for bending moment	646 Nm/deg	>100 Nm/deg
<u>IST ("screw driver") performance:</u>		
continuous torque	50 Nm	50 Nm
peak torque (stall mode)	100 Nm	100 Nm
max. velocity	10 rpm	10 rpm
<u>Joint performance</u>		
Joint velocity range:	0.2 to 50 mrad/s	0.2 to 50 mrad/s
Joint torque range at min. speed	495 - 540 Nm	350 - 750 Nm
Joint torque at max. speed	> 110 Nm	170 - 235 Nm
Joint angular control accuracy	1.3 - 2.4 mrad depends on payload size	0.5 mrad
Joint Brake torque	480 Nm	350 - 750 Nm

Table 3: ERA Performance parameters: measured versus specified (n.y.a. = not yet available)

5. Challenge of testing an eleven meter robot arm under zero-g conditions.

For ERA a dedicated test facility was built to allow 2-D operation of ERA (Fig. 12).

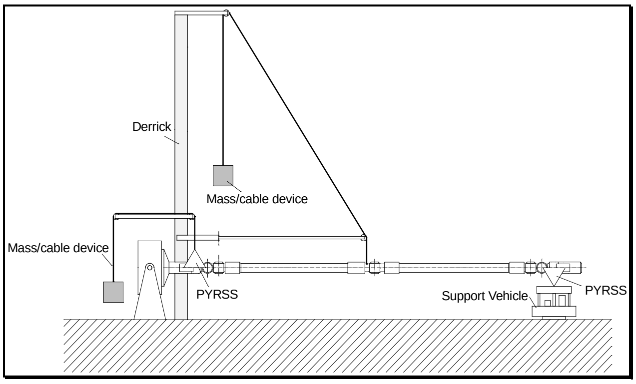

Fig. 12 The ERA Test facility

The BEE is grappled to a BP, which is mounted to the base point adapter. The base point adapter allows the arm to rotate around the adapter axis in vertical direction. The derrick suspends ERA in the shoulder and the elbow and the SV supports the wrist via PYRSS (Pitch Yaw Roll Support System). The frame of PYRSS will make sure that no disturbance forces will be introduced in the wrist and moreover also unloads the TFS in the BEE. For a more detailed description of ETF see [2].

During the development and qualification test programme we have experienced a number of limitations of both the ETF as well as the design of ERA. These limitations will be summarised in this section.

1. During the transition from standby to controlled the joint first releases the brakes and then applies one cycle later a torque to the motor. During this transition the gravity of the earth causes a peak acceleration of the yaw joint, which is detected by the two safety checks inside the joint controller. These checks are coded in the firmware and can not be updated. The only solution during ground testing is to disable these checks.
2. The small movement in the yaw joints during the transition to controlled hold, also cause a change in the orientation of the wrist joint. If the transition standby-controlled hold is performed several time (e.g. during an operational reference mission) the orientation changes such that the path deviation check will trigger.
3. ERA is suspended and supported in the centre of the arm. The mass distribution is not balanced around this centre line, because the elbow CLU's are mounted on the same side of ERA. These elbow CLU's introduce a torsion torque in the arm, depending on the pose of ERA, resulting in a rotation around the roll axis. This leads to a misalignment between PYRSS and SV, which could only be prevented by changing the balancing for various poses of ERA.
4. For Payload tests a Payload Test Module (PTM) was provided by RSC/E. This PTM was equipped with air-pads. EQM Free Motion tests showed that the friction of the PTM was that high that performance measurements were not feasible. The solution could be support the PTM actively or mass compensate the PTM, but this has the disadvantage that the operational range of payload is very limited and i.e. a representative operational reference mission with a payload is not feasible.
5. When the scene as seen by the CLU becomes too dark, the "average pixel signal " Built in Test (BIT) will trigger with a caution event, which will also trigger the BIT check in the ASW. This situation happens when the CLU is looking in deep space. However in the Dutch Space clean room with the TL light switched on the "average pixel signal " BIT also triggered because the spectrum of the TL light in the clean room do not contain sufficient IR. The solution of this problem was disable this check when the CLU laser is not switched on.

6. Conclusions

The paper has described the current status of the ERA Qualification test programme. The remaining activities are the execution of the compliant motion tests, the completion of the operations verification and the completion and acceptance of the MPTE. The challenging test programme performed so far has demonstrated that ERA is capable of performing the currently foreseen operations.

7. References:

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