ERA EQM AND FM TEST RESULTS

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

- Development programme on the EQM almost finalised
- EQM Thermal Balance qualification completed
- FM Boosted Modal Survey test completed
- FM EMC test in progress

This paper will present the latest status and focus on the results of these tests and the test facilities and test configurations used.

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 the middle of 2001 for a launch in the autumn of 2003.
ERA is designed to assist with and whenever possible to substitute for Extra Vehicular Activities (EVA) which require very hazardous and difficult operations for Cosmonauts. ERA operations will first begin with the assembly of the Russian segment and then afterwards continue with the routine tasks such as inspection, maintenance, payload handling, etc.

The on-board ERA system (Figure 1) consists of an arm, an EVA Man Machine interface, an IVA Man Machine Interface, Base Points and Grapple Fixtures.

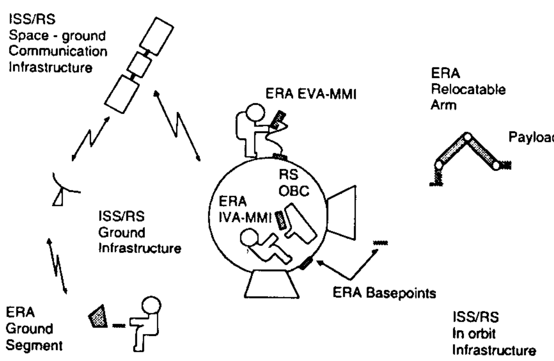

Figure 1: The ERA system

The ERA arm is anthropomorphic (see Figure 2). It is made of one elbow with an identical limb, wrist and end-effector on each side. One end-effector is attached on the space station to a dedicated base point. At this base point, connections enable data and video signal exchange with the space station as well as the supply of electrical power. With its free end-effector, ERA can grapple and move payloads or EVA support platforms. With its Integrated Service Tool, ERA can also provide torque to payloads, for instance for the deployment of the solar arrays. Power can be provided to the payload through the arm. Cameras each with its illumination unit placed on the Limbs and on the wrist are used to guide the arm during its automatic motion, and to provide general overview pictures of the work-site to Cosmonauts inside the Station.

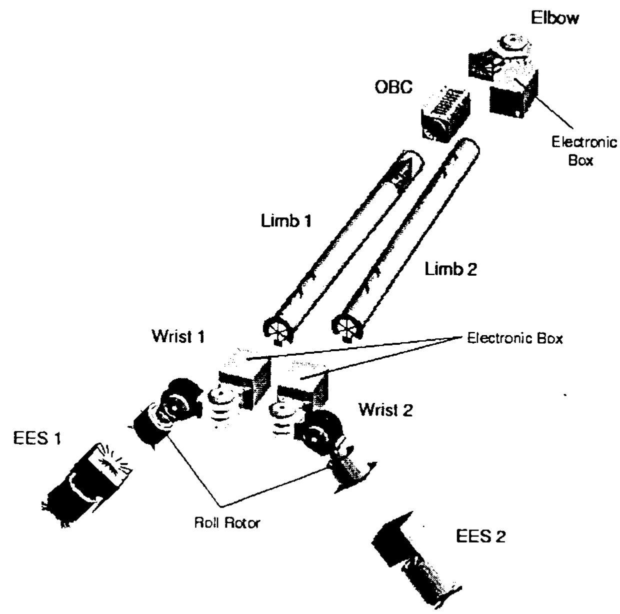

Figure 2: Exploded view of ERA in the launch configuration (By courtesy of DLR)

ERA can relocate itself from base point to base point, extending considerably its effective working volume. To enable this relocation, as indicated above, ERA has been made symmetrical with respect to the Elbow. The free end-effector grapples a new base point, and the other end-effector un-grapples from the old base point. The camera placed on the end-effector of ERA will enable automatic grappling of a base point or of a payload.
In addition to its mechanical dexterity, ERA has its on-board computer which makes it autonomous and independent from space station computing resources. Mission plans will be prepared on-ground and then transferred to the ERA computer. For safety reasons, the execution of a mission will be monitored by the Cosmonauts in Intra Vehicle Activity (IVA) or Extra Vehicle Activity (EVA) who's role will be to confirm each step of the mission utilising man-machine interface devices with the possibility to interrupt the mission if an unsafe situation should occur (autonomous control). The man machine interface will also be used for unplanned missions where the Cosmonauts will directly control ERA by selection of commands from switches, menus and if needed general-purpose mission plan sequences (manual control).
ERA is divided in a number of subsystems:

1. **The Manipulator Joint Subsystem (MJS)** consists of two wrists and one elbow. Each wrist is made of 3 joints (roll, yaw and pitch) and one electronic box for their

control. The elbow is made of one joint (pitch) also with its own electronic control box.

2. **The End-Effector Subsystem (EES)** consists of two Basic End-Effectors (BEE), Base points (BP) and Grapple Fixtures (GF). Each BEE is equipped with:
   - a grapple mechanism and a torque force sensor to grapple a base point or a payload.
   - an integrated service tool to provide torque to payloads
   - electronic units for the control of the different Basic End-Effector functions
3. **The Manipulator Limb Subsystem (MLS)** consists of two Limbs of carbon fibre reinforced plastic material.
4. **The ERA Control Computer subsystem (ECC)**, is the brain of the system which communicates with the space station through the external databus and with each S/S through the internal databus.
5. **The Camera and Lighting Unit subsystem (CLU)** consists of 4 units. One on each Basic End-Effector and one on each side of the elbow. The Basic End-Effector cameras are used for video and proximity control during grappling and un-grappling operations whereas the elbow cameras are only used for video. All cameras are equipped with lighting units. Targets are mounted on payloads and ISS mounting structures.
6. **The EVA Man-Machine Interface (EMMI)** is a control panel which provides the possibility to control ERA from EVA.
7. **The IVA Man-Machine Interface (IMMI)** control panel is a lap-top computer for control of ERA from the pressurised modules of the station.

Parameters	*Values*
Total length	11.3 m
Range / span	9.2 m
Degrees of freedom	7
ERA mass	630 kg
Peak power dissipation	800W
Standby heat dissipation	420W
Hibernation heater power consumption	250W Maximum
Accuracy	
- open loop	+/- 40 mm
- closed loop	+/- 5 mm
Maximum moveable mass	8000 kg
Maximum payload dimensions	3x3x8.1 m
Maximum speed of movement	0.2 m/s
Braking distance	0.15 m

Table 1: ERA Key Figures

2. Model Philosophy

For ERA a mixture of a normal Qualification Model/Flight Model approach and Protoflight 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.

3. System level test approach

The verification approach of ERA explained in chapter 2 and the characteristics of the EQM and FM leads to a system level test programme where the various tests are divided among the EQM and FM. Table 2 gives an overview for this division for the major test blocks and their validity (development, qualification or acceptance).

Test	EQM	FM
Communication test	Development	Qualification
Single joint moves on the Electrical test bench	Development	Qualification
Alignment test	Qualification	Acceptance
Stiffness test	Qualification	Acceptance
Free motion control tests	Development	Qualification
Stopping distance test	Development	Qualification
Electrical test	Development	Qualification
Reliability, Availability, Maintainability and Safety (RAMS) /Exception Handling	Development and partly qualification	Qualification for the remaining part
Compliant Motion Control tests	Development	Qualification
Proximity Motion Control tests	Development	Qualification
Worst case load	Qualification	
Data Communication Simulator test	Development (Qualification still TBD)	-
Operations	Development	Qualification
Astronaut Walk Around	Development	Qualification
Thermal Balance	Qualification	-
Boosted Modal Survey	-	Protoflight Acceptance
Electro Magnetic Compatibility (EMC)	-	Qualification

Table 2: Overview of tests performed on EQM or FM for the major tests blocks

4. Test Facilities

This section gives an overview of the test facilities and test set-ups used during the ERA system level test program and their main characteristics.

1. ERA Test Facility (ETF).
2. Large Space Simulator (LSS).
3. Boosted Modal Survey test facility (BMS)
4. EMC test facility

4.1 ERA Test Facility

The ETF is used during the functional/performance tests on ERA and is situated at the technical building of Fokker Space in Leiden, the Netherlands. The ETF consists of the items as described in the following sections (section 4.1.1 up to 4.1.6).

4.1.1 Flat floor description

The flat floor is an area of 18 x 14 m^2 in the technical building at Fokker Space in Leiden. The flatness of the floor in combination with the active support vehicle (SV) will limit the occurrence of vertical forces on the ERA allowing near zero gravity condition for tests in the pitch plane of ERA. The following requirements were applicable for the Flat Floor, the measured result is given in brackets:

1. The height variation smaller then 10-mm (measured +4.5 & -1.5mm).
2. The inclination flatness smaller then 1 mm per 0.5 m (at 32 points the floor was out of specification).
3. The inclination variation smaller then 1.5 mm per mm (at 330 point out of specification).

The results showed that the flat floor was out of specification, but it was concluded that the requirements were set too stringent. In order to check the flat floor in a more realistic way, a test was performed in combination with the active SV (see 4.1.4.2) in order to measure the static and dynamic disturbance loads on ERA. The result of this test showed that the disturbance loads on the ERA elbow were within specifications (see section 4.1.7).

4.1.2 Derrick and mast

On each side of the flat floor a derrick is installed for the suspension of ERA, one for the EQM and one for the FM. A Base point adapter supports ERA at the shoulder. The BEE is grappled to a base point, 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 and the SV supporting the hand is schematically shown in Figure 3. A guidance block and boom are mounted in a way that the movement of the arm (elbow) is followed with minimum disturbance forces in the arm.

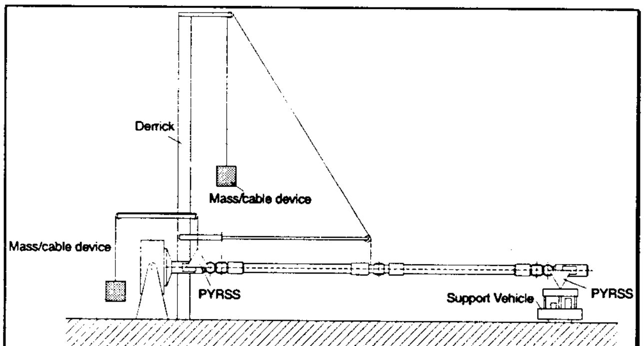

Figure 3: ERA suspension during integration in ETF

4.1.3 PYRSS

At the shoulder ERA is suspended in the so-called PYRSS (Pitch Yaw Roll Support System). At the hand a support vehicle (passive or active) supports ERA with a PYRSS which is mounted on the spherical bearing of the SV. The frame of PYRSS, which provides these suspensions, will make sure that no disturbance forces will be introduced in the wrist. The PYRSS at the hand also unloads the Torque Force Sensor in the Basic End Effector. This makes it possible to perform grapple tests, without the introduction of a disturbance torque's/forces which are applied by the weight of the grappling mechanism of the BEE.

4.1.4 Support vehicles

To support ERA EQM and FM on the flat floor, two support vehicles were developed. A passive support, which is used for development tests, and an active support vehicle, which is used for qualification tests.

The passive support vehicle has no active control. ERA will 'drag' this support vehicle. This support vehicle moves on air pads and therefore almost without friction. A spherical air bearing supports ERA.

The active support vehicle itself is moving over the flat floor with three drive/steering wheels and an air pad. A spherical air bearing supports ERA. This spherical bearing is moving with minimum friction over a so-called mini flat floor (a glass plate) by means of an air bearing. The glass plate is kept horizontal by means of 6 sensors, which get a horizontal reference from the lasers inside two lighthouses mounted at two corner points of the flat floor . Potentiometers mounted on a positioning arm register and adjust the position of the support vehicle for the movement of the arm.

4.1.5 ETF safety system

The ETF safety system assures that no dangerous situations can occur during functional/performance tests of ERA on the flat floor. This means that ERA is protected against moving out of the flat floor area or collides with other obstacles. This is done by creating a light curtain which will cut the power to ERA when interrupted.

4.1.6 Measurement equipment

For the Control test it is required to measure the actual position of 5 testpoints on ERA during the operation with an accuracy of better than $\pm$ 1 mm. This measurements will be performed by a laser tracking system in combination with 5 transponders installed on ERA.

During Grapple tests the torque's and forces exerted by ERA on the GF of the Payload will be measured by loadcells installed between GF and Payload. The accuracy of this measurements shall be better than 5N and 2 Nm.

4.1.7 Conclusion

The maximum allowed disturbances on the ERA without a payload introduced by the ETF system was specified to be not higher then 35 Nm, measured at both the shoulder and elbow joints. The measured value was well below this 35 Nm.

4.2 Large Space Simulator

The Large Space Simulator at ESTEC consists of a large chamber of 15 metres high with a diameter of 10 metres. Attached to the main chamber is, a horizontal cylinder holding a 6-metre mirror and a lamp-house to create the artificial sunlight.
The ERA-EQM has been tested under extreme thermal conditions (vacuum, -80°C, solar simulation) in the LSS. In

this test facility, ERA was supported by a dedicated structure, the Thermal Adapter (TAD).

4.2.1 Thermal Adapter

Main requirements for the Thermal Adapter (TAD) were:

- to support ERA in hibernation configuration fully exposed to the solar beam
- not to introduce exceptional forces in the joints
- to be grappled by ERA using one base point and one grapple fixture
- not to be exposed to the solar beam
- provide adiabatic interfaces between ERA and its fixations and through all the harnesses
- not to disturb the radiative environment of ERA

The Thermal Adapter consisted of two major parts:

1. The first part was the bottom frame which was the interface with the LSS motion system and which supported the suspension frame and the Base Point and Grapple Fixture Interface beam.
2. The second part was the frame in which ERA was suspended.

During the final integration of ERA in the LSS, the bottom frame was provided with scaffolding parts, allowing access to the test item during installation. These were removed prior to the test and the remaining frame parts were covered with MLI and black painted aluminium plates to ensure a homogeneous and well known temperature.
The suspension frame was placed on two spherical bearings and was fixed with six stainless steel cables to the bottom frame. Six sets of spring suspensions were used for the cables to compensate for the loss of tension due to the thermal contraction of the aluminium poles of the frame during cold phases.

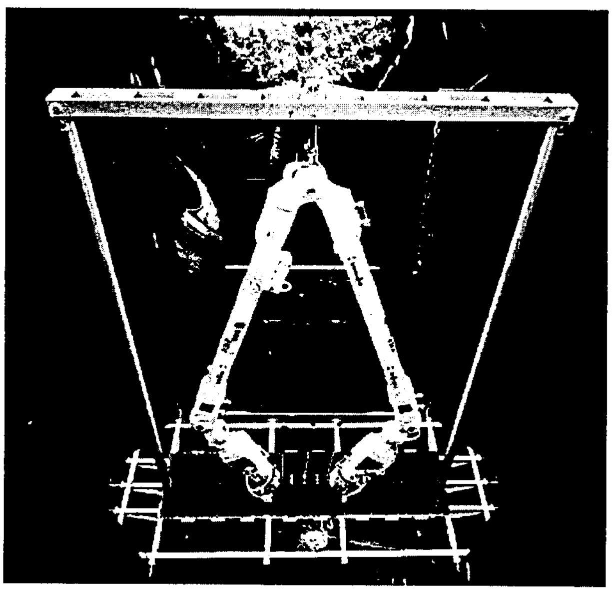

Figure 4: ERA in the ESTEC Large Space Simulator

4.2.2 Test set-up

ERA was placed centrally in the Large Space Simulator facility such that one set of radiators of the arm was oriented towards the Solar Simulator and the other set of radiators towards the shroud, see figure 4. The test item was equipped with ~370 thermocouples to monitor the internal and external temperatures.

4.3 Boosted Modal Survey test facility

During the test, ERA was configured in the so-called Charlie Chaplin launch configuration and was mounted on a vibration adapter via the Launcher Interface Rig (LIR), see figure 5. The LIR fixes ERA during its launch to the Russian Science & Power Platform (SPP). The LIR consists of four pallets with hooks. These hooks are motor controlled so that ERA can be released from the SPP after launch.

4.3.1 Test set-up

The vibration adapter is designed in such a way that there is no influence of its stiffness and mass on ERA's dynamic behaviour. The vibration adapter is mounted on interface plates, which are mounted in the Large European Acoustic Facility (LEAF) at ESTEC. The LEAF is used for this purpose because of its foundation, which is de-coupled from the rest of the buildings. The acoustic testing capabilities of the LEAF are not used for ERA testing. Exciters are used to introduce sufficient excitation to reach the required launch loads mainly on the external interfaces at different locations on ERA. A number of rigid points have been identified on the ERA-outer surface, which are suitable for introduction of the dynamic load. In order to apply the exciter loads in the ERA-structure, a number of load introduction brackets have been manufactured which fits to the hard points. These brackets are connected to the exciters using push-pull rods. The dynamic behaviour of the test set-up is monitored by means of accelerometers and straingauges. A total of 175 accelerometers are mounted on ERA, the Launch Interface Rig and the Vibration Adapter. 12 Straingauges, to monitor the stress levels, are mounted at the hooks of the Launch Interface Rig.

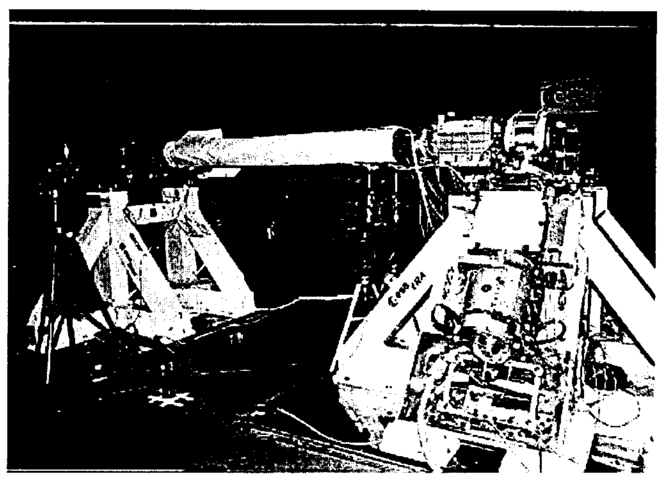

Figure 5: BMS test set-up

4.4 EMC test chamber

All EMC performance tests on ERA FM are carried out at the ESTEC EMC test facility. The size of the chamber is 6m x 7m x 5m.

4.4.1 ERA EMC Ground Support Equipment (GSE)

The ERA EMC GSE consists out of three EMC-trolleys: one elbow-EMC-trolley and two wrist-EMC-trolleys (see figure 6). ERA is to be subjected to an EMC test-program at the ESA ESTEC facility. The interface between ERA and the test facility will be the EMC-trolleys. The EMC-trolleys will also be used for the simulated 0-g reconfiguration of ERA from the transport mode to the hibernation mode and the transport of ERA to the EMC test chamber at ESTEC. The EMC test at ESTEC will be executed while ERA is in a hibernation pose.

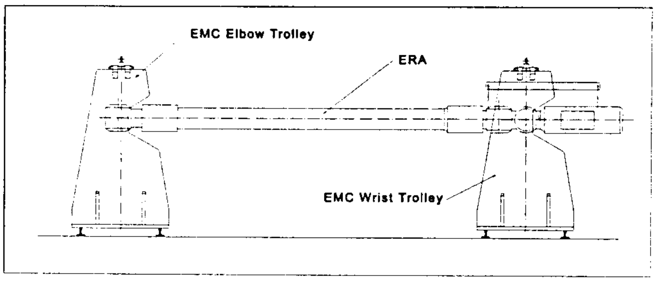

Figure 6: Schematic test set-up for the EMC test

The EMC trolley's are mainly made from wood and have been build on a wooden base plate, to ensure that EM radiation can penetrate freely without any reflection from metal objects..

4.4.2 Test set-up

The way ERA will be positioned (stretched, folded, hibernation) during the tests may influence the EMC radiated test results. For conducted EMC tests, the actual configuration has no influence on the measurements. During Radiated Susceptibility tests, ERA will be illuminated from the front and side. See figure 7.

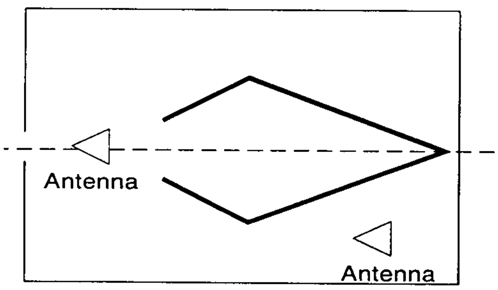

Figure 7: EMC test set-up.

5. EQM and FM Test Descriptions and Results

5.1 Electrical bench communication tests

The objectives of the tests on the electrical test bench were to verify the communication between the ECC and a) the ERA S/S's via the Internal MIL STD 1553 bus and b) the Russian Segment (RS) of the ISS via the External MIL STD 1553 bus. For these tests the Central Post Computer of the RS (CPC) was simulated in the Electrical Ground Support Equipment (EGSE). Considering the amount of NCR's and SPR's raised, this test proved to be most valuable. The majority of the problems identified could be classified as: detailed timing discrepancies between ECC and Subsystems (S/S), incorrect order of messages and messages with incorrect (number of) parameters.

5.2 Single joint moves on the electrical test bench

The operation of ERA integrated in ETF is limited to the pitch joints and the hand roll joint. The operation of remaining joints has been verified on the electrical test bench. The following objectives of the test bench test have been met: during single joint movements the communication between ECC and each of the joints is correct, the control of the joint is stable and the joint moves in the correct direction.

5.3 Alignment

After the integration in the ETF an alignment measurement has been performed. For the alignment measurements position references (needlepoint's) have been installed at the Basepoint I/F , at the Grapple Fixture I/F and on each of the three pitch joints. Orientation references (mirror cubes) have also been installed on the Basepoint mounting plate interface ring and on the three pitch joints.

Two types of alignment measurements have been performed:
a) three dimensional co-ordinate measurements to determine in an orthogonal axis system the x, y and z co-ordinates of the position references
b) angle measurements of the mirrors to determine the orientation (horizontal and vertical angles) of the mirror cubes on the three pitch joints and on the Basepoint Adaptor.
The measurements, performed with two theodolites, were based on trigonometry and established the three-dimensional co-ordinates of the object points. Figure 8 shows the test set-up and the used ERA co-ordinate frame.

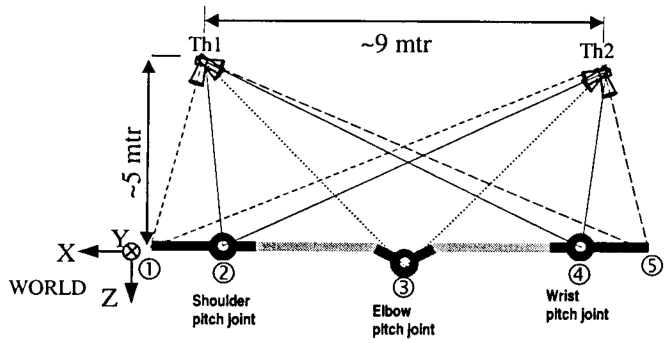

Figure 8: Alignment test set-up.

The alignment measurements have been performed for both the EQM and FM. In this paper only the FM system level test result will be discussed. The misalignment measured at S/S level inside the MJS S/S have already been compensated by offsets in the MJS SW. Table 3 gives an overview of the pass/fail criteria and the measurement results.
The readings of joint position sensors in the Yaw joints are nominally zero which means that these joints do not cause a tilt out-of-plane. The vertical tilt angles of the BP & GF I/F, measured with a theodolite, as well as the height differences as measured (not shown here) indicate that ERA has more or less a slightly bent shape. Prior to the alignment measurements, ERA was balanced on its supports in the ETF as accurate as feasible, but this out-of-plane bending is most likely due to small remaining unbalanced forces.

Pass/Fail Criteria from the ERA Alignment Test Requirements document	Measurement result:
The measured location of the tip shall not differ more than:	
+/- 33 mm in X-direction	- 0.4 ±1 mm
+/- 13 mm in Z-direction	5 ±1 mm
with respect to the theoretical position of the tip.	
The measured rotation of the tip shall not differ more than:	
+/- 12 mrad around the Y-axis	0.3 ± 0.2 mrad
with respect to the theoretical rotation of the tip.	

Table 3: FM alignment test results

5.4 Stiffness

Figure 9 shows the test set-up for the ERA Stiffness measurements.

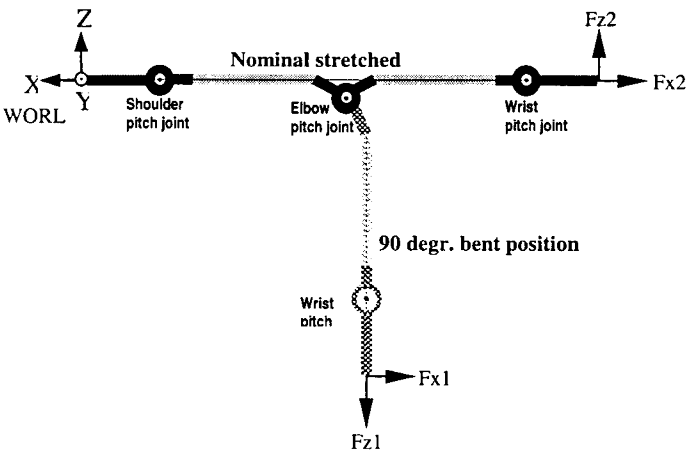

Figure 9: Stiffness test set-up

For the qualification on the EQM the stiffness has been measured for two configurations: the nominal stretched configuration (Fz2) and a bent configuration with Elbow joint bent over 90° (Fz1 and Fx1). Table 4 shows that for these configurations the measured stiffness is significantly higher than the required stiffness.

Test case	Lateral tip stiffness [N/mm]	
	Required	Measured
Fz2	0.375	0.515
Fz1		3.62
Fx1		1.10

Table 4: EQM Stiffness test results

Verification of the stiffness requirement will be done on the basis of analysis, since ERA's stiffness is at a minimum in an out-of-pitch-plane configuration which can not be tested. For the FM acceptance test only the stiffness in the nominal stretched configuration has been measured showing that the deformation of the FM arm is within 10 % of the values from the EQM.

5.5 Worst case load test

The worst case load test will verify that ERA can handle the worst case communication load, which is two MMIs on the external bus and one on the internal bus, operating simultaneously. This test is still in progress.

5.6 Electrical test

The objectives of the Electrical tests are to verify the system electrical design. The following tests are foreseen: power supply voltage variation, power consumption in standby mode, voltage drop, voltage dip test, thermal control power Check-out, hibernation thermal monitoring, payload power and video signal level. Part of the tests has already been performed and no major non-compliance's have been identified.

5.7 Astronaut Walk Around

The ERA EQM astronaut walk-around was performed as part of the ERA Critical Design Review (CDR). This was the first time that astronauts had seen the full sized ERA arm (previously only the MMI's had been seen by astronauts). Two ESA astronauts, a NASA safety representative, the ESA ERA responsible for operations and for PA/safety, and the FS ERA responsible for Operations, Safety, PA and HF conducted an inspection of the EQM ERA. (except the EMMI and the EVA tools, which was not yet available). The ERA arm was set in a typical operational pose. In particular the EVA overrides for all ERA mechanisms, the labels/marking and the EVA handrails and tether eyes, were presented (MLI was fitted at representative places). No major problems were identified (many of the comments had already been incorporated into the FM ERA). The walk-around will be repeated for FM.

5.8 Control tests

A considerable number of control system tests have been specified to analyse the dynamic behaviour and verify motion control performances. ERA motion control consists of three types of control: Free Motion Control, Proximity Control and Compliant Motion Control. Tests are performed commanding the ERA Actions which use these different types of control and can be described in a typical way such ERA Actions are performed.

Free Motion Control enables Free Moves along a planned path in Cartesian Space (straight lines). Setpoints are generated by the ECC and send to the joint controllers. Single Joint Moves are also controlled by Free Motion Control. When ERA is at about 1.5 m distance from its destination its camera is switched on and focused onto target dots which are on the payload or space station. Pose measurements from this camera are used by *Proximity Motion Control* to compensate for misalignments in the arm and space station. An Acquire Target is performed to align the arm at a fixed distance. This is followed by an Approach towards the Grapple Fixture correcting the path with help of camera information. Just in front of the Grapple Fixture the arm is stopped, the camera is switched off, and the Torque-Force Sensor (TFS) near the ERA tip is switched on. The TFS information is used by *Compliant Motion Control* to yield in the correct direction during the move inwards the Grapple Fixture while making contact. After such Insert the Grapple command is given and grapple hooks in the EE will pull the arm onto fixation surfaces at the Grapple Interface. During a Grapple, Compliant Motion Control is again active, compensating torque-force build-up by yielding. When ERA is handling a payload similar steps are followed performing a Payload Latching rather than a Grapple.

During the different Actions such as the Free Move, Acquire target, Approach (Retract), Insert (Extract) and Grapple (Ungrapple) or Payload Latching (de-Latching), control performances are measured and used for verification. Dedicated test-moves are added to verify specific ERA system requirements, among others the maximum and minimum speed required (3 mm/sec and 0.2 m/sec.). A Payload Test Module (PTM) of 435 Kg, on air-patches, is used for grappling a payload, move it and latch it. During large moves (Free Moves) the deviation from the desired path may not be more than 80 mm. This includes mechanical and thermal misalignments of the arm. The requirement for the position accuracy thereafter without the camera is 40 mm, while accurate placement with a camera shall be 5mm. Torque's and Forces must be kept below 25 Nm and 40 N. Performance data are obtained from ERA sensors such as the Joint Position Sensors and of course from external measurement equipment (see section 4.1.6).

Figure 10 shows the Square Move path, part of the Free Motion Control tests. Figure 11 shows a zoom of the tip position with respect to the reference, from above. Figure 12 shows the tracking performance of the ERA tip as a function of time. Both are without the bending of the limbs as the tip position is based on kinematics calculation using joint angles. The maximum tracking error is 20 mm; the maximum deviation from the planned path is 15 mm. Tests will be repeated using an external laser tracking system for absolute position measurement of the tip.
Grapple tests have just started. Tests are similar to successful tests already conducted on an ERA Development Model (of 8 m) in 1996 with a prototype of the ERA Grapple Mechanism.

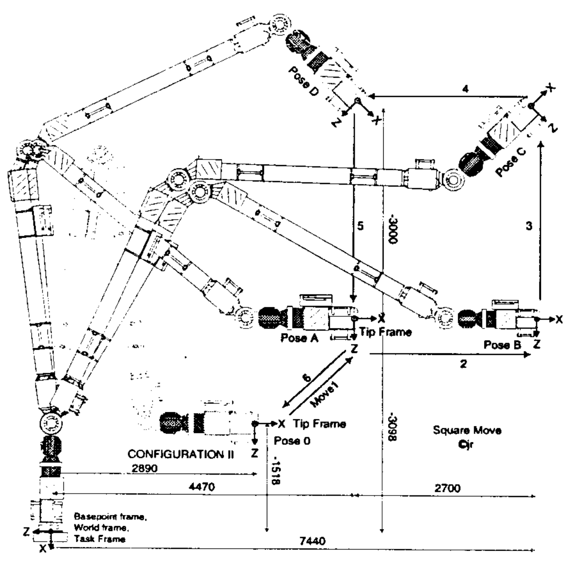

Figure 10 Square Move, a Free Move test

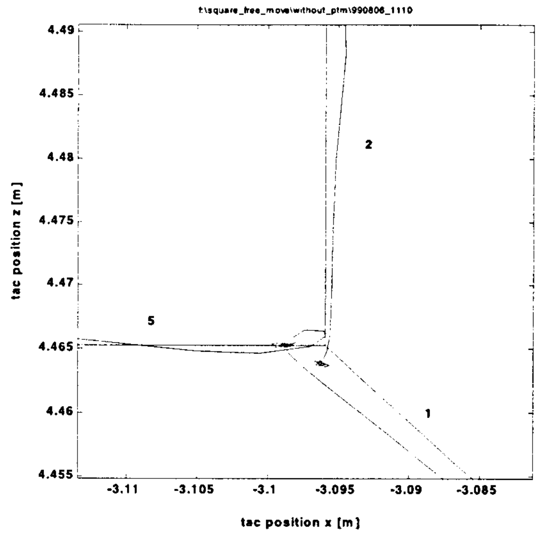

Figure 11 Calculated path of the Square Move

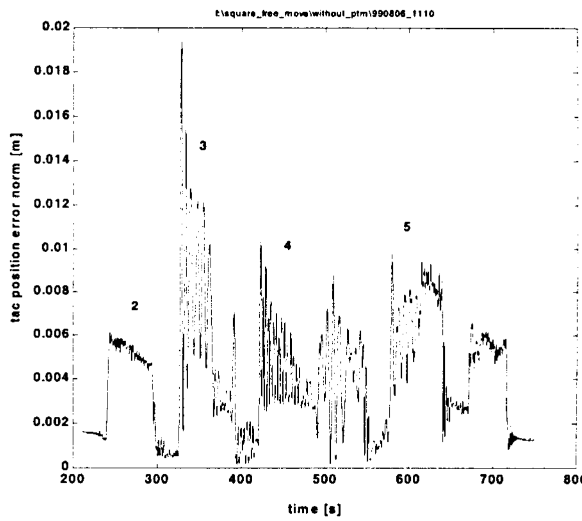

Figure 12 Calculated tracking error of the Square Move

For Proximity Control the ECC Application Software (ASW) requires three target dots in the CLU proximity data. As it can be expected that apart from the target data also reflections will be part of the field of view of the CLU data, the ASW contains checks to filter unwanted reflections. These checks must be detailed enough to filter out unwanted clusters, but also must be flexible enough to accept the true clusters over the whole operational range (0.4 m to 2.0 m from the CLU) and the angle range of the CLU proximity operations. Figure 13 shows an example of a CLU image of an ERA GF , with on the left side the output of the CLU analogue video monitor and the right side the corresponding Charge Coupled Device (CCD) data received by the ECC. Apart from the target dots (the three bright spots on the left) the figure also shows reflections in tens of clusters. Although the target dots are clearly visible the ECC ASW rejects the data of the target as being a non-valid target, because the maximum number of clusters has been exceeded (10). This test resulted in two major modifications: a) reflections on the GF shall be removed to reduce the number of invalid spots b) an ASW modification using a CLU windowing principle to reduce the effective field of view of the CLU to the actual location of the target.

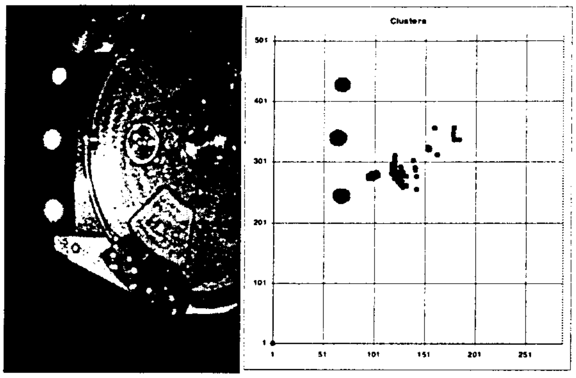

Figure 13: CLU video image of ERA GF and equivalent CLU CCD data

5.9 Stopping distance test

The objective of the stopping distance test is to demonstrate that the maximum stopping distance for any part of ERA is maximum 15 cm at a tip velocity of 20 cm/s. Due to (temporary) limitations imposed by the test facility the test could only be performed at a maximum tip speed of 8 cm/s. The test has been performed with and without a Payload grappled to the arm. The measured stopping distances were in the range 4-7.5 cm. The test will be repeated at maximum velocity.

5.10 Data Communication Simulator (DCS) test

ERA and the MMI's communicate with the ISS via the Central Post Computer (CPC) using Mil bus 14. The hardware for the CPC is supplied by Astrium, while the ASW has been written by RSC/E. The DCS consists of the CPC Qualification Model (QM), the CPC laptop and the ASW. The objective of the DCS test was to verify the correct implementation of the interface requirements as they were agreed and written down in the External Interface Control Document (ICD). Three tests were planned: 1) a preliminary test to verify connections/disconnection's of ECC and MMI's 2) Communication of MMI's with the DCS (switching off/on, changing redundancies, loading of data sets) 3) Communication of the MMIs with the ERA via the CPC.

The main conclusion of the test was that the basic communication between ERA and the CPC was correct; on a more detailed level a number of requirements need to be corrected/detailed to resolve non-conformance's on e.g. timing between stacked commands, dumping of MMI data sets, incorrect modes in MMIs.

5.11 RAMS/Exception Handling

The objectives of the RAMS and Exception Handling tests are to verify all safety-critical functions by end-to-end system level testing. For each possible failure condition the following steps will be checked: Has the relevant check triggered? Has a saving action being initiated? Has the failure been correctly been reported to the operator (on the MMI). The detection means are distributed over the central checks in the ECC and the local checks in the S/S's. Exception Handling focuses on the checks active in the ECC, while RAMS concentrates on the S/S level check. The non-nominal condition which leads to a triggering of the check is for most of the tests created by increasing or decreasing the trigger limits either prior to the start of the test or during the test.

The main conclusion from the tests so far is that due to the amount of safety related software the tests are very time-consuming, but have not shown major deficiencies.

5.12 Operations

The main goal of the Operations test is to show that the cosmonauts will be capable of conducting the missions with ERA for which it was designed. A representative Operational Reference mission (ORM) will be used which contains all procedures where real hardware interaction needs to be considered under its worst case operational circumstances. The test is planned for next year.

5.13 (Boosted) Modal Survey test

At the time this paper was written the Modal Survey (MS) and BMS test are in progress. The objective of these tests is to verify the strength requirements for ERA under launch loads. The tests are specially focused on the launcher interface at the wrist and elbow electronics boxes and at the wrist internal interface between pitch joint and electronics box.

5.14 Thermal balance test

For further details on the ERA thermal balance test, please refer to reference 1.

5.15 EMC test

At the time this paper was written the EMC test is in preparation.

In the EMC test facility, ERA is not able to move and the full range of flight situations and operations cannot be realised. Although full representative with flight operations cannot be achieved during EMC testing, emissions and susceptibility tests can be performed in such a way, that sufficiently accurate 'flight representative' results are obtained. Measurement of emissions will be carried out for operating modes with expected maximum emissions (i.e. motor commanding, max. data transfer). As actual joint movement is not possible in the EMC test facility, for emission measurements this will be simulated by building up torque in the motors without movement of the actual joint: the so-called "run-in-brakes" test.

6. References:

[1] THERMAL BALANCE TESTING OF THE EUROPEAN ROBOTIC ARM by Jan Doornink, John Kanis and Eduard van den Heuvel, Fokker Space B.V. Leiden, The Netherlands, Giovanni Colangelo ESA/ESTEC Noordwijk, The Netherlands.
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How to build a Space Robot; ERA Lessons Learned

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Abstract

The **European Robotic Arm** [ERA] is being built for use on the Russian Segment of the International Space Station. The project is commissioned by ESA as part of their manned-space program, with Fokker Space as Prime Contractor, and 23 companies from 7 European countries participating in the development of the arm. The ERA is scheduled to be launched as part of the SPP by Space Shuttle to the ISS, and is planned to operate on the ISS for ten years. Testing of the Flight Model is currently underway. This paper focuses on some of the lessons learned from this project.

1. Introduction to ERA

The ERA system (Figure 1) consists of an arm, an EVA Man Machine interface , an IVA Man Machine Interface, a Refresher Trainer [RTR] and a Mission Preparation and Training Equipment [MPTE]

The ERA arm is a 11 meter, 6 Degree-of-freedom arm , whose most striking feature is the ability to cover large distances on the ISS by "hopping" from one basepoint (which supplies the power and communication interface) to another. For an overview of the operational aspects of the arm, see [SO].

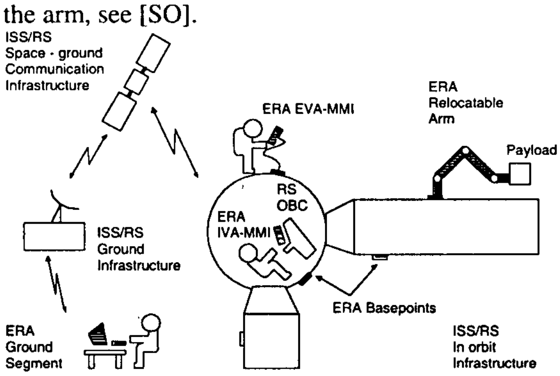

Fig 1: The ERA system

The arm itself contains a multitude of processors. The ERA Control Computer (ECC) is the central nexus for communication with the sub-systems on the arm on one side, and communication with the MMIs (through the Russian Segment Central Post Computer) on the other side. It consists of a main ERC32 processor and three smaller communication and housekeeping processors. The Manipulator Joint Systems (MJS), End Effectors (EE) and Camera and Lighting Units (CLU) each contain two or more processors of their own.

2.Lessons Learned

The ERA program successfully passed the Critical Design Review in the fall of 1999. Although the ERA still has to undergo Final Acceptance, we can already look back and compile lessons learned from the development of this , both technically and organizationally, complex system. With a project which has taken so long to complete, there are almost no areas which do not have elements which (in retrospect) should have been done differently. From early on n the project, we have recorded these lessons before they were forgotten once the arm was delivered. Some of these have already been discussed previously, most notably the dramatic change of the ECC processor from a Thor to an ERC32 (see [PB]).
In this paper we will focus on two aspects, Firmware design and the Man Machine interfaces.

3. There is no such thing as simple Software

The ERA contains close to ten different software systems, developed by as many companies all over Europe. ERA is even dependent on a critical interface with, and functionality contained within, the Russian Segment, the development of which ERA has had little control. Many of the subsystems were initially thought to contain very simple Firmware (or in some cases early on none at all!). Note that the term "Firmware" is used to signify non-maintainable SW. ESA initially required all SW in ERA to be maintainable in flight, not only to allow upgrading, but only to take into account that the performance of the arm in space conditions could not be fully verified on ground, and thus could require modification. This requirement was waived for SW components which were regarded to contain simple functionality, the parameters of which could be modified through the 1553 interface.
The problem with this SW/FW split in practice is threefold: First of all, almost all the FW items became more complex as the sub-system design evolved. Figure 2 shows the average increase in the memory estimate of the FW elements in ERA, starting from system PDR (i.e. when the design was already well underway). The 10% increase over 3½ years does not seems much, but this includes FW items of which the design was straight-forward from the start (e.g. 1553 interface boards). For a

comparison, the trend of the most fluctuating sub-system is shown. The current size is almost 2½ of that initially estimated.

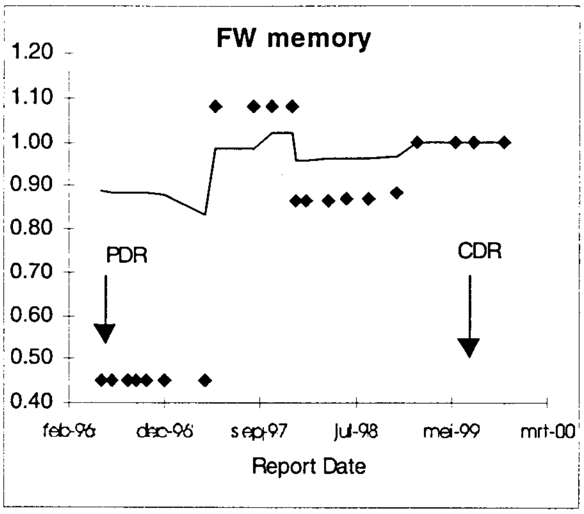

Figure 2: Estimated FW memory, scaled to the final figure. Line: average estimate, diamonds: worst-case sub-system

Secondly, once a decision is made to declare a component FW, it is very difficult to change the design into a maintainable SW system later on. Nevertheless, this was partially done for one sub-system, with significant consequences on both the ECC design and operations. ERA now contains FW with up to 3500 lines of code (based on 10 bytes = LOC), see Figure 3. In some cases, the FW is neither small nor simple with state machines which are more intricate than the ECC.

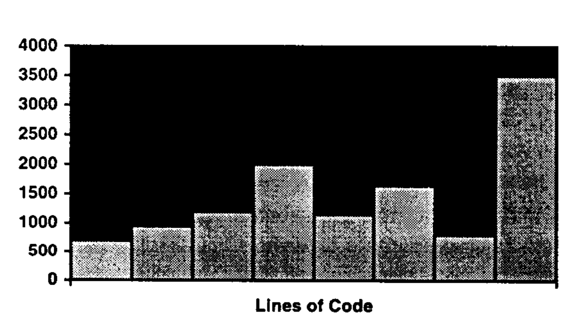

Figure 3.Current estimated Lines of code for FW items

Finally, declaring a component FW contains a dangerous trap. The argument "the code is simple, therefore it requires less rigorous testing and documentation, and therefore less shadow engineering" is both easy to believe (especially when the FW is embedded within a complex HW system which requires much attention) and fallacious. Because the FW is non-maintainable, it requires extra attention, verification and documentation. In ERA (also for maintainable SW) it was frequently not clear just how much and what level of coverage was required for adequate verification. In addition, the development of the systems were constantly out of phase. The management and interface control of these different baselines, the associated shadow engineering efforts, and the problems in achieving workable intermediate integrated systems for EQM testing proved to be quite a challenge. Especially, it was extremely difficult to verify at an early stage that the functional interface between the ECC and the sub-system SW corresponded in detail to the system level concepts. No amount of detail in ICDs can guarantee in advance that two systems are developed such that they can function together to their full extent. Even when the Flight Units were fully developed, detailed tests at system level uncovered features in the S/S FW which clashed with the ECC SW design, and thus required modification of the latter. With so many sub-systems connected, there is always the danger that a correction necessary to achieve correct functioning of one interface results in a problem in another interface.

The lesson to be learned is that even the smallest SW component deserves full attention from the higher-tier contractors. Given the understandable limitation that one person cannot shadow-engineer all aspects of a sub-system, a full time shadow-engineer should be appointed who has the difficult task of monitoring all SW development, making sure that the lower-tier FW developers understand the context of their component with in the system, and making sure that a consistent functional interface is established which allows the entire system not only to function, but also to be operable.

4. The Human Element

The human element, the ERA operator, added an extra complexity. Several reviews by the astronaut community of the Man Machine Interfaces resulted in significant changes. It has to be realized that the ERA design preceded the ISS-level standardization efforts. With almost no precedents (the SSRMS being sufficient different in design not to allow reuse of concepts developed there), Fokker and their MMI subcontractors basically had to invent most MMI related aspects themselves. A good example of this is the design of the EVA Man-Machine Interface (EMMI). As ERA is part of the Russian Segment, the early design of the EMMI was based on discussions with Russian experts. The resulting concept (Figure 4) allowed little monitoring and intervention capabilities during ERA automatic operations, and a number of isolated manual operations. The resulting layout contains a large number of switches with a single function, small display capabilities, and a large Execute handle to confirm automatic commands.

When the decision was made that astronauts from all ISS user nations should be able to operate all robots on and in the station, in as much as possible standard way, as well as more detailed Human Factors Analyses (which resulted in the rejection of the Execute handle because of the excessive strain on the operator), significant changes had to be made. Both the number and complexity of the operations which should be possible with the ERA without ground-planned automatic sequences increases, and the required monitoring capabilities had to be extended. This all had to be achieved within the physical limitations of the existing EMMI box. The result is shown in Figure 5. The number of displays has not increased significantly, but the information which can be displayed has been increased dramatically by allowing the operator to select several display modes. Note that there are still Russian experts which prefer the original layout!

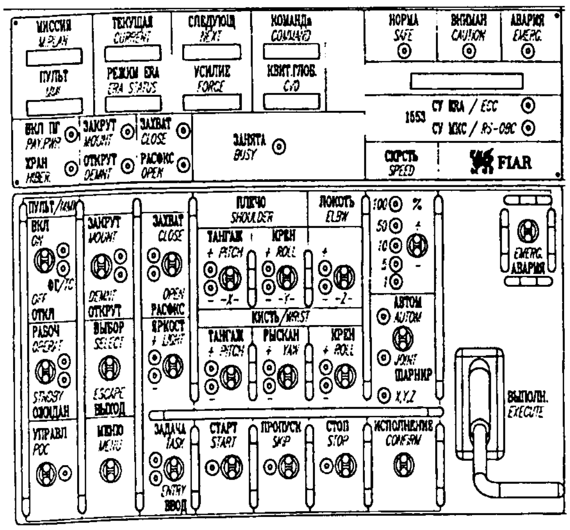

Figure 4: The original EMMI Layout

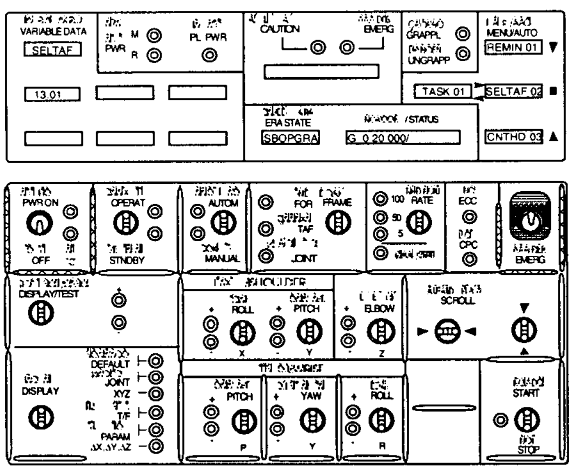

Figure 5: The final EMMI Layout

The MMI layout is now considered frozen unless there is full consensus in the astronaut community that a certain aspect is unacceptable, and even then modifications will only be made if they are feasible (i.e. by modifying SW only). Efforts are underway for several years now to write ISS-level MMI display standards, but they mainly focus on IVA MMIs, are slow in reaching consensus, and all already designed MMIs are excluded from the standard. ERA would have benefited greatly from an already existing mature standard on space-robot MMIs, but understandably these did not exist yet. Hopefully, future MMI designers can profit from the guide-lines originating from the intense scrutiny of the ERA MMIs by the astronaut community.

5. Conclusions

In a long and complex projects like ERA mistakes are made. To avoid similar mistakes in future, it is important to already realize and document lessons learned during the development, not only afterwards. Two important lessons learned in ERA:

Even the smallest and simplest SW component requires full attention, to avoid it becoming large and complex.

In Man Machine Interface design, expect radical changes when the users start using the MMI. Strive for good MMI design guidelines.

References:

[PB]: Beerthuizen, P: “ERA- The Processor Challenge”, DASIA 1999

[SO]: Schoonejans and Oort, “ERA the Flexible Robot”, ISAIRAS 99