The European Robotic Arm: A High-Performance Mechanism Finally on its way to Space

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Abstract

This paper describes the design and qualification of the European Robotic Arm (ERA), which is planned to be launched by the end of 2015. After years of changes, a shift of launcher and new loads, launch preparation is underway.

The European Robotic Arm ERA has been designed and manufactured by Dutch Space and its subcontractors such as Astrium, SABCA and Stork with key roles for the mechanical aspects. The arm was originally designed to be launched by the STS (mounted on a Russian module for the ISS) in 2001. However, due to delays and the STS disaster, a shift was made to the Russian Proton rocket. ERA will be launched on the Multipurpose Laboratory Module (MLM). This module, which is now planned for launch to the ISS in 2015, will carry the ERA. The symmetrical design of the arm with a complete 3 degree-of-freedom wrist and general-purpose end effector on both sides, allows ERA to relocate on the station by grappling a new base point and releasing the old one, and move to different working locations.

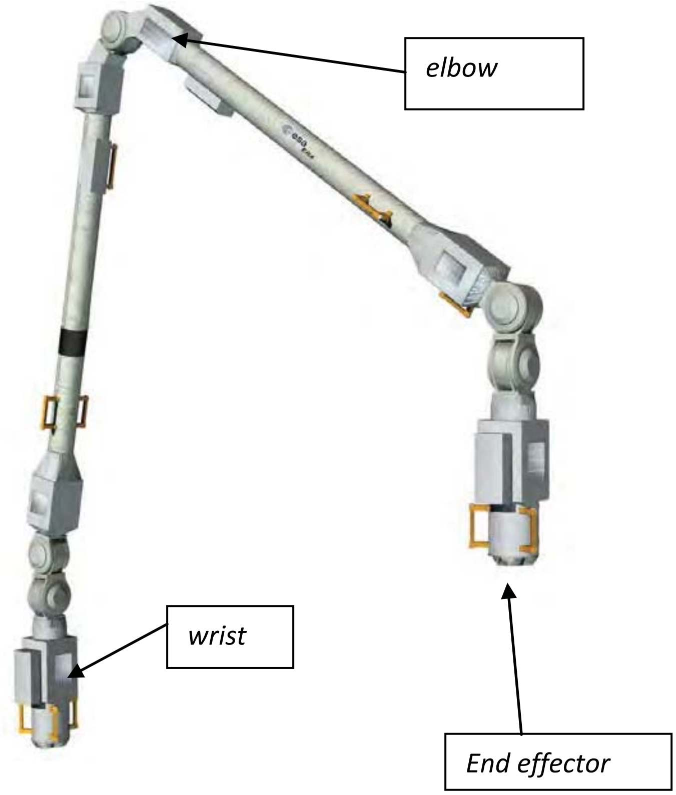

Figure 1. Overall ERA arm architecture

ERA Overall Design Description

The arm consists of 2 limbs which are connected by motorized hinges. The arm has an end effector which has the possibility of grabbing Space Station components for transport or tools for support of EVA activity.

This end effector includes other features such as electrical connections and a mechanical drive that can operate like a wrench tool. The arm is symmetrically designed, meaning that the arm shoulder joints and wrist joints are identical. This allows the arm to “walk” fully autonomously from base point to base point on part of the ISS. This “walking” arm capability allows it to reach remote grapple points.

The arm structural capability enables it to move 8000-kg payloads. The arm is controlled by an integrated computer and has a camera vision system for close proximity operations and can provide camera images of the working area.

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ERA has been designed from the beginning to be serviceable and to allow exchange of big parts via EVA in case of failure or an emergency situation. Such parts are called ERU (EVA Replaceable Units). During the launch of STS 132 in 2010, one ERU was launched and put into in space. It has been stored on the outside of the ISS on the MRM-1. A special launch interface had to be designed to allow launch in orbit. This ERU is still fixed in this launch configuration and is protected with a special bag of MLI. In case of failure or specific maintenance, the arm can be activated by EVA. ERA is also designed to perform servicing tasks originally allocated for EVA.

The main technical characteristics are listed in Table 1.

Table 1. ERA Key Characteristics

Total Length	11.3 m
Range/span	9.2 m
Degrees of Freedom	7
Mass	630 kg
Peak power dissipation	800 W
Stand-by heat dissipation	420 W
Hibernation heater power	250 W
Accuracy open loop	± 40 mm
Accuracy closed loop	± 5 mm
Maximum moveable mass	8000 kg
Maximum payload dimensions	3x3x8.1 m
Maximum speed of movement	0.10 m/s
Braking distance at max joint speed	0.15 m

The ERA consists of the following major subsystems:

1. The **End Effector Subsystem** (EES) consists of two Basic End Effectors (BEE), Base Points (BP) and Grapple Fixtures (GF).
2. 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.
3. The **Manipulator Limb Subsystem** (MLS) consists of two limbs of carbon fiber reinforced plastic material.
4. The **ERA Control Computer** subsystem (ECC or On board Computer, OBC), is the brain of the system that communicates with the Space Station through the external data bus and with each subsystem through the internal data bus.
5. The **Camera and Lighting Unit subsystem** (CLU) consists of 4 units. One on each End Effector and one on each side of the elbow mounted on the two limbs.

Other key elements are related to the manual control of ERA. These are:

6. The **EVA Man-Machine Interface** (EMMI) is a control panel that provides the capability to control ERA during EVA.
7. The **IVA Man-Machine Interface** (IMMI) control panel is a laptop computer for control of ERA from the pressurized modules of the station.

The EVA-MMI is a dedicated console with switches and LED displays, designed to be operated by a crew member in EVA suit and able to be exposed to the space environment for extended periods of time. The IVA-MMI is a software application running on an IBM system which is located inside the pressurized module of the Russian Segment of the ISS. The workstation near the IVA-MMI will be able to display ERA camera views.

ERA Mechanical Subsystems and Mechanisms

The first two above mentioned subsystems represent mechanical subsystems composed of mechanical assemblies. These main subassemblies are:

1. End Effector Subassembly (EES):
    a) Grapple mechanism (GM) – incl. Base point (BP) and Grapple Fixture (GF)
    b) Integrated Service Tool (IST) (incl. receptacle in GF)
    c) Torque Force Sensor (TFS) incl. the Torque Rigidization Mechanism (TRM)
2. Manipulator Joint Subassembly (MJS) consisting of 3 modular hinges of which all are very similar, except the roll. These 3 hinges form together the so called "wrist" joint. See Figure 1 for the overview.
    a) Pitch Joint / Yaw Joint / Roll Joint; located at both ends of the arm (3 D.O.F)
    b) Elbow Joint: The elbow joint uses the same basic hardware as the wrist pitch joints but has only one degree of freedom.

A further major mechanical subsystem is:

3. Launch Fixation Mechanism: Its function is to restrain the ERA during launch. The launch fixation mechanism on the Russian Segment-MLM structure consists of:
    a. Fixation Hooks and support pads, being part of the MLM
    b. Pins and support pads, being part of the ERA structure

These mechanisms will be activated by EVA, when the unfolding of the arm from the launch support starts. The cosmonauts will release the fixation hooks. Furthermore, special mechanical features are included to allow for EVA. These are implemented to enable repair maintenance, exchange, etc. The design and the size of certain mechanism are driven by the accessibility requirements for EVA tooling.

4. EVA-Compatible Mechanisms:
    a. Camera & Lighting Unit (CLU): The connector mate/de-mate mechanism.
    b. EVA Man-Machine Interface (EMMI); only switches.
    c. EVA overrides for GM, IST, TRM and joints.
    d. EVA ERU mate/de-mate mechanisms (Elbow/Wrist, CLU, CLU windows).
    e. EVA placeable handrails.

    N.B. For a., c. and d., special EVA tools are used.

The above four mechanical subsystems and mechanisms are described below:

End Effector Subassembly (EES) Mechanism Design Details

During the operations in orbit, one end effector is connected to a base point in order to provide a sufficiently stiff connection between the Russian Segment of ISS and ERA and to transmit power, data and video signals for the operation of the ERA system. The second end effector then serves as the gripper, able to grapple an object outfitted with a grapple fixture or a basepoint. Furthermore, the second end effector will support ERA by monitoring force/torque values during the insertion/extraction and during the transportation of objects. The second end effector provides mechanical and electrical power to the grappled object and allows for data transfer. In order to provide the above mentioned capabilities, the following functions are assigned to the EES:

- measure torques/forces
- grapple/guide
- power, data and video transfer
- insert the Integrated Servicing Tool (IST) head to provide mechanical power
- provide sufficient stiffness.
- rigidization, if no measurement of torque/force is needed (by design implementation)

The rigidization capability of the torque/force sensor is necessary to provide the required stiffness when the end effector acts as the shoulder and if "hand" stiffness is required during transportation operations.

The End Effector Subsystem (EES) consists of:

1. Structure housing.
2. Actuation and Sensing Unit
    a) Actuator Unit
    b) Torque/Force Sensor (TFS)
    c) TFS Rigidization Mechanism
3. Moving Platform
4. Grapple Mechanisms
5. System Harness Connectors
6. Integrated Servicing Tool (IST)
7. Base points (BP)

The EES is also equipped with specific mechanical elements for EVA manual override.

1. Structure housing The main load-carrying structure of the end effector consists of the lower housing structure and the housing that contains the Electronics Unit. The lower housing structure is built up by the three stiffeners; the cover sheets, which are attached to the stiffeners; interface ring; and the guidance. The Electronics Unit housing provides the interface to the roll joint of the ERA Manipulator Joint System (MJS) and to the Camera and Lighting Unit (CLU). All parts of the housing structures are manufactured from high-strength aluminum alloy, the interfacing ring and the guidance from titanium, the spindles and the hooks from steel.

2. Actuation and Sensing Unit The Actuation and Sensing Unit consists of the Actuator Unit, the Torque Force Sensor, and the TFS Rigidization Mechanism.

a) Actuator Unit: The actuator unit drives with its electromotor and mechanisms the moving platform. The actuator unit consists of an internally redundant brushless-type electromotor, a redundant set of Hall sensors mounted to the motor shaft, a gear train, and three roller screws with nuts that are mounted to the moving platform. The gear/motor assembly rotates the synchronized roller screws. Three roller screw nuts are mounted with a restricted floating capability to a platform, which will move upwards/downwards by the rotating roller screws.

b) *Torque/Force Sensor (TFS):* The TFS is an electro-mechanical unit equipped with strain gauges, which measures torques and forces in 6 degrees of freedom. The analog TFS signals will be acquired and processed by the TFS electronics and will be sent via the Electronic Unit to the ERA OBC. The TFS is temperature compensated and is protected against mechanical overloading by rigid end stops. In case the measured function of the TFS is not needed and an increased stiffness for the TFS is required, the TFS will be blocked by the Torque Force Sensor Rigidization Mechanism.

c) *TFS Rigidization Mechanism*: The TFS rigidization mechanism (TRM) will block the TFS when its function is not needed. It will automatically form a stiff structure when not in operation and a flexible structure to protect the arm from overloading when disengaged. The TRM consists of the following items:

    - one electrically redundant brushless motor, which is the same as being used for the Actuator Unit and the Integrated Servicing Tool; the motor control is included within the Electronics Unit;
    - one worm gear, to provide the required gear ratio (N= 105);
    - three conical shaped blocking elements; each of it consisting of a solid inner cone and a flexible, slotted outer cone;
    - a cam wheel, which is driven via the worm gear by the motor; the cam wheel includes three tracks that transform the rotation of the cam wheel into a translational motion of 3 mm;
    - three rods, which transfer the translational motion of 3 mm from the wheel to the inner cones. The rods are connected to the tracks of the cam wheel via deep groove bearings;

The following procedure will be performed to rigidize the end effector:

- The motor will be switched on and turns the cam wheel by 60^o clockwise; two mechanical end switches will monitor the starting and the end position.
- The inner cones, connected to the rods will move 3 mm within the outer cones. The movement will cause the expansion of flexible outer cones. This expansion will now block the TFS.
- The TRM will stay in the blocked condition due to the non-backdriveability of a worm gear and the shape of the cam wheel tracks.

For the de-rigidization of the TFS, the cam wheel will be rotated in the opposite direction. The inner cones will be pushed actively by the rods, to allow for the contraction of the flexible outer cone, which consequently will de-block the TFS.

3. Moving Platform The moving platform actuates the grapple mechanisms, performs the Integrated Servicing Tool (IST) head insertion, and mates the system harness connectors (for power, video and data lines). The male connectors will be mated to the female parts located at the Base Point/Grapple. Redundant switches (3 off) are monitoring the platform position to provide status information for the EES electronic unit. Three platform positions shall be reported by this device:

- the upper end position, which will be used for a zero setting
- the position at which the BEE is aligned with the BP/GF, i.e. the gap between the BEE and BP/FG is closed
- the position where the grapple latches are completely closed and pre-stressed. At this position the connector mating and IST head insertion is also performed.

In addition to monitoring by the switches, the platform position is at any time provided by the Hall-effect sensor output signals of the actuator unit motor.

4. Grapple Mechanism: Grapple fixtures (GF) will be mounted to all objects that have to be handled by the EES. Each GF includes the female part of the connector, through which the power, signal and video data is routed to the grappled object. In addition, a GF contains the IST head receptacle, by which the torque will be provided for the grappled object (e.g. to screw/unscrew). The Grapple Mechanism of ERA consist of a three hook/lever systems, which are coupled to the moving platform The grapple mechanisms start pulling at the grapple fixture (GF) or base point (BP) until the gap between the GF/BP and the end effector is closed and the grapple mechanisms are rigidized and pre-tensioned. The hooks of the grapple mechanism are constantly pressed outwards by coil springs. When one hook touches an obstacle during grappling of a grapple fixture (GF) or a base point (BP), the hook induces a force of about 30 N due to the spring deformation to the obstacle. The reaction force will be measured by the TFS, transmitted via the EU to the ERA OBC. The EES will then be re-positioned with respect to the grapple fixture/base point to ease the induced loading.

5. System Harness Connectors Three connectors, which are mounted to the moving platform, will transfer power, video and data between the end effector on one side and the grapple fixture or base point on the other side. The connectors are mounted via floating devices to the moving platform, to provide a lateral and angular misalignment compensating capability. Each connector provides the capability to monitor the mated/unmated status.

6. Integrated Servicing Tool (IST) The IST will be used to provide torque for a grappled object (e. g. to screw/unscrew bolts or a stowed radiator stack). The IST is mounted within the lower end effector compartment. The IST consists of an electrically redundant brushless motor, similar to the actuator unit motor, a gear box, and a tool head with a “pop-in” device. The gear box output shaft drives the IST head, which will be inserted into the IST head receptacle, located at the grapple fixture to provide the mechanical power to the screw interface. The IST drive shaft will be inserted into the receptacle at the grapple fixture during the platform downwards movement.

The IST head will start rotating slowly upon system command, until it pops into the IST head receptacle. If the tool insertion has not been successfully performed immediately during the platform downwards movement, the IST receptacle provides a compliance capability. A sensor will detect the proper IST head insertion. A redundant set of Hall sensors will provide the necessary data for the Electronics Unit to control the IST actuation.

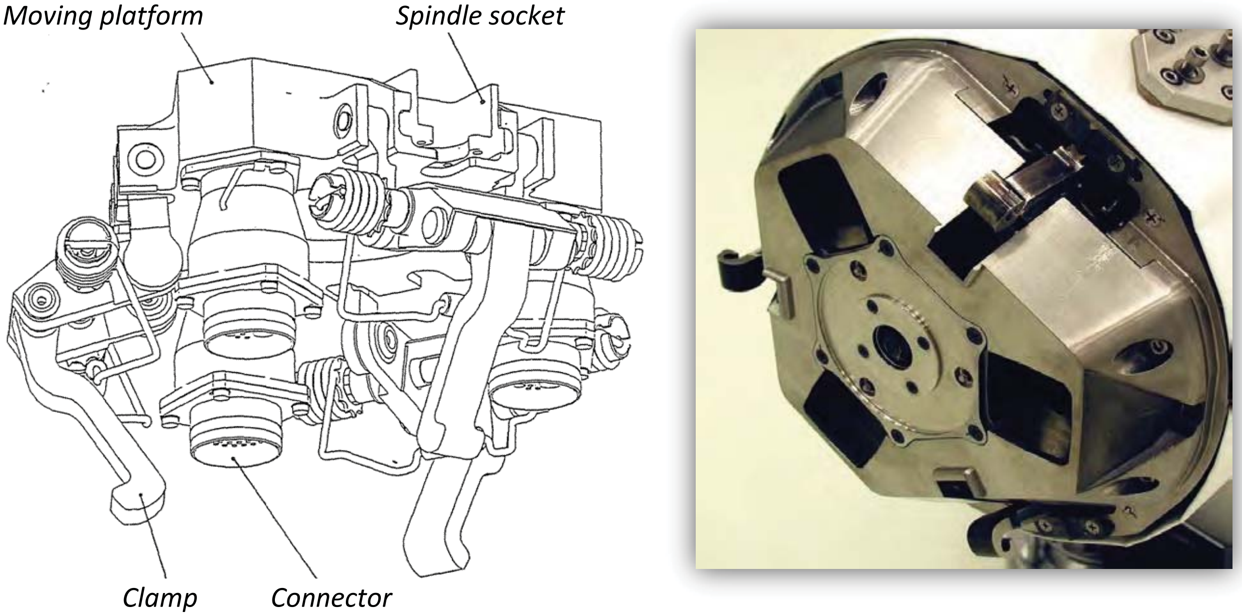

Figure 2. Grapple mechanism with moving table showing the 3 clamps and 3 connectors (retracted)

7. Base Points (BP: The base points are mechanically identical to the grapple fixtures. They do not contain the receptacle for the IST but they provide all system harness connections between ERA and the Russian Segment of ISS. They contain the female parts of the three system harness connectors, through which the power, signal and video data for ERA operation are routed. The base points also provide the mechanical interface between the grapple mechanisms on the end effector side and the Russian Segment of ISS on the other side.

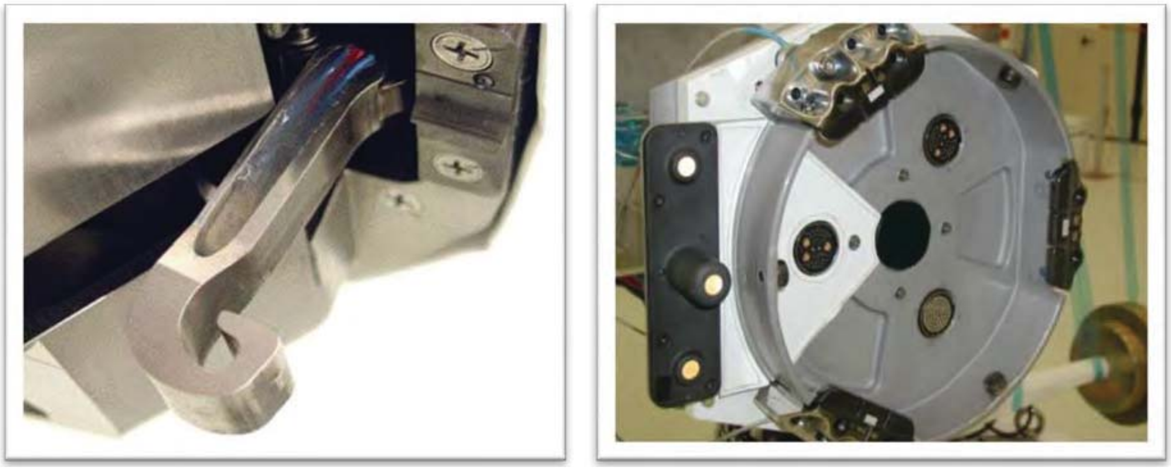

Figure 3. Base point and engagement hook of end effector

Manipulator Joint Subsystem (MJS) Mechanism, Design Details

ERA is approximately 10-m long and has to move large payloads. At the same time, the mass of ERA had to be limited to comply with launch requirements. Its mass is about 620 kg. This makes ERA a much more flexible (elastic) arm than most industrial robots. The first bending mode of the arm is important, as it contains more than 90% of the total inertia. It is the dominant mode to deal with for control. The combination of compactness, limited weight, high stiffness, small backlash, long life time, and thermal vacuum circumstances put high constraints on the development of the joints and the hinge unit.

The wrists and elbow joints are composed of three joints. The pitch and yaw joints are very similar in design. The pitch joint provides a rotation around the Y-axis, the yaw joint around the Z-axis, and the roll X-joint axis. (See Figure 5 below for axis definition).

The wrist contains an electronic box, which drives all the 3 motors independently. Redundancy is included as well in the electronic device via 2 PCBs. Hence, the shoulder joint and the wrist contain a separate electronic box for the drive function, i.e., power and telemetry functions. This is also the case for the elbow. This box is located as a rectangular box in between the limbs and forms part of the structural load path. Hence, the size and the stiffening of the box have been implemented with plates equipped with ribs.

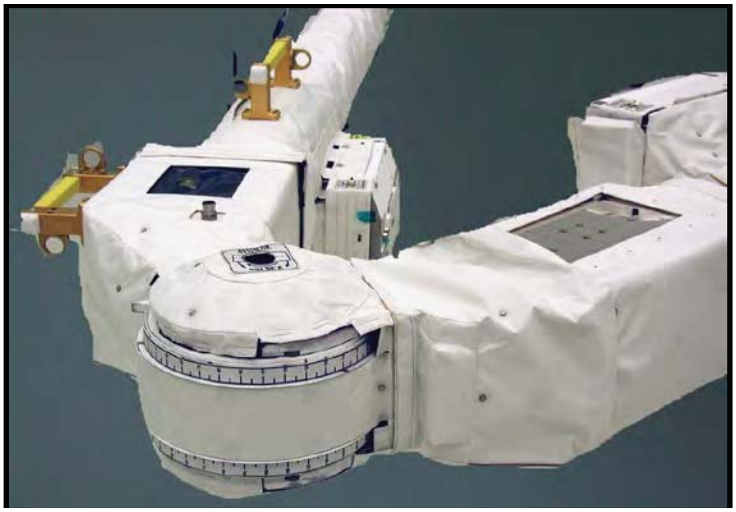

Figure 4. The elbow joint for pitch motion. Showing the EVA hand rails and the 2 CLU's. In the middle of the hinge is the EVA receptacle hole.

Each joint consists of the following mechanical elements:

1. Motor unit: Motor, resolver including the Joint Position Sensor for the feedback of the joint position to joint control electronics and brake.
2. Gearbox assembly: Four-stage planetary gear train for torque capability and speed reduction including the bearings including lubrication / grease (N=450)
3. Motor housing and yoke.

In addition, an EVA access provision is included for manual override. Other non-mechanical elements include:

- Cables and connectors; crossing wires passing the joint for external use and entrance wires being connected to electrical components within the joint
- MLI thermal hardware, heaters
- Cable covers / Connector covers.

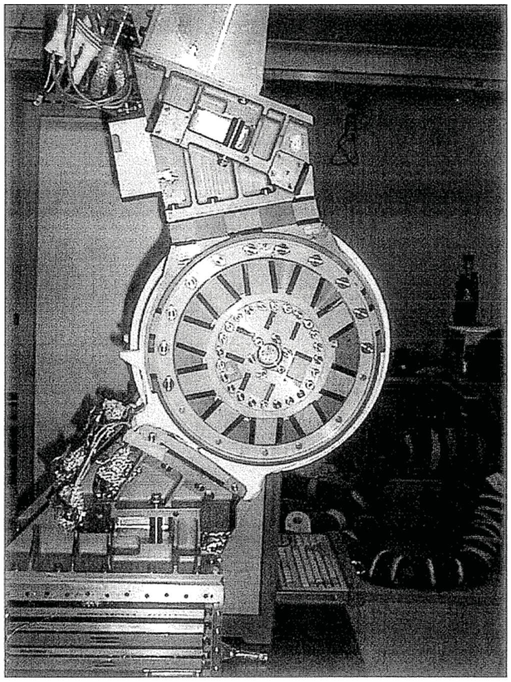

Figure 5. Elbow joint and brackets launch interfaces; pins and hard plates.

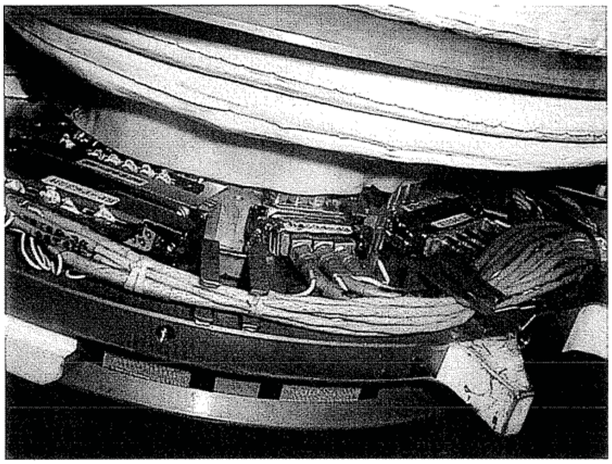

Figure 6. Elbow joint without cables cover: ribbon cables (data & power) separation wall.

Details of the mechanical elements are described below.

1) The motor unit: The motor, resolver and brake are integrated as mechanically self-contained device, which interfaces with the Mechanical Unit of the hinge. This unit consists of the following items:

a) Motor: The motor is based upon a permanent magnet synchronous motor (often called brushless DC motor) and has a two-phase redundant winding. The electronics are adjusted in such a way that the motor provides a ripple-free torque. For this purpose but also for commutation reasons, a resolver is used, providing the instantaneous position information required by the current-torque controller.

b) Resolver: The resolver is built with a primary winding supplied with a high-frequency voltage, inducing a high-frequency signal in each of the two secondary windings. Both of these signals have an amplitude related directly to the rotor position (e.g., varying respectively with the cosine and sine of the angular position). The analysis of these two signals allows detection of the instantaneous rotor position of the electrical motor drive shaft.

c) Joint Position Sensor: The sensor measures the angular rotation of the arm joint at the exit axis and provides the angle position input to the joint control electronics. Each Joint Position Sensor contains a redundant set of read stations, light emitting diodes, digital signal processing circuitry, and cable harness.

d) Brake: A brake is integrated into the joint, providing the braking torque by the contact of two smooth friction surfaces. When the brake coil is not energized, the brakes are engaged, provided by an adequate axial force created by eight dedicated springs (which provide on average a total of approximately 85 N of force). Conversely, the brakes are disengaged by supplying the coil with a constant current, effecting separation of the two braking surfaces by magnetically attracting the moving armature fixed to the axially-translatable brake disc. A microswitch position sensor provides the brake status information (i.e., whether the brake discs are in contact with one another or separated). This information must be very reliable, as the distance of brake disc separation in on the order of 0.25 mm to 0.30 mm.

2) Gear box assembly:

a) Gear train & bearings: A four-stage planetary gearbox has been chosen with a gear ratio of 1: 450. The gear trains are made from SST. Nitrided steel has been used as gear material. The thermal expansion shall be compatible with the gearwheel material, to keep the influence of thermal deformation on the backlash at the lowest achievable level. Radial deflections at the ends should be small, they are critical for the motor assembly and gearbox. For the gear train, radial deflections affect the backlash; for the motor, they affect the torque ripple due to an adverse effect on the motor resolver.

b) Number of planet wheels: A strong preference was maintained in the design to apply three planet wheels per stage. This is due to the fact that a three planet wheel system possesses a self-balancing capacity for the loads within the system. This acts as a load distribution system. If more than 3 planet wheels are applied in one carrier, the equal load distribution over the wheels is not ensured automatically. However, to save space, and to make sure that the stress levels do not exceed the maximum allowable Hertzian stress, it was necessary to apply 6 planet wheels in the last stage. To obtain a good load distribution over all 6 planet wheels, the planet wheels are supported by a floating system.

c) Tandem configuration: Gear stages 1 and 2 share the same ring wheel, as well as stages 3 and 4. Self-adjustment of the stages in one subassembly is improved by this configuration when a torque is applied. In a planetary gear, it is important that the load is distributed equally to the planet wheels to take advantage of the compact arrangement. This can be done by leaving unsupported the sun wheel, the planet wheels carrier assembly, or the ring wheel. The other parts are mutually supported by bearings. In the ERA joint, it was chosen for a floating ring wheel. It can also be considered as a floating planet wheel carrier sun wheel assembly, hence floating with respect to the ring wheel.

d) The floating component has to be kept aligned with respect to the other gear wheels. In large industrial high-performance gearboxes, this is generally accomplished by the width of the gearwheels. In this case however, the wheel widths are too short for self-aligning per stage. Therefore, two stages are mutual connected by using a common ring wheel. The planet carriers with sun wheels are supporting them mutually by bearings. The self-centering effect of each stage provides the alignment of the assembly, which is called a tandem. The self-aligning effect of a tandem is used to make each set of two gear stages self-supporting. These supports are a flexible plate flexure for the planet carrier sun wheel assembly and a tooth coupling for the ring wheel. Between these interface points there is no connection between the housing and gear train. This ensures isolation from deflections of the housing.

e) Bearings: The roll joint is equipped with three main bearings: for the radial and axial support one set of two angular contact bearing is used. The single bearing is a deep groove ball bearing which gives only a radial support. The lubrication is with Bray oil. Belleville springs are implemented in the design in order to preload the bearings (to resist launch vibrations). Load on the bearing due to thermal expansion is reduced and is equally distributed on the bearing, due to the lateral elasticity of the yoke fingers that are adapted to the required minimal stiffness.

f) Flexible elements: The large number of interfacing components inside the joint requires consideration of internal or external disturbances such as :
   - Thermal deformation.
   - Mechanical deformation during launch and during operation.
   - Manufacturing inaccuracies in a statically undetermined support
   - Radial and axial play.

This compensation is realized by the introduction of flexibility to several components. The pitch joint has been equipped with several details by which flexibility is introduced. Because the motor is made of AISI 420 (steel) and the housing material is aluminum, a thermal problem may occur. In order to make it possible that the motor can expand freely, for the coupling between motor and housing the same coupling with square teeth has been used as for the housing and ring wheel connection.

3) Housing and yoke: The yoke structure is replaced by a cylinder rotating around the fixed housing. The hinge construction of the joint consists of two major parts, the housing and the yoke. The housing is the “fixed part”, being the part in which the driving components (gear train and motor) are connected. The yoke is the part that rotates around the housing (the “moving part”). The housing contains the gear train including the EVA-device, the motor, the Joint Position Sensor and cabling. It also supports the main bearings. End stops are incorporated. The housing is designed sufficiently stiff by flanges at the end to reduce radial deflections. Loads shall be transferred with sufficient strength and stiffness of the housing to the main bearings. Care is taken to ensure that loads are equally distributed around the main bearings and excessive loads on the main bearings due to thermal expansion are prevented.

Launch Fixation mechanism

Launch Configuration: The ERA arm is located in the launch position on this MLM module. Interfaces to the end effector are:

- the Base Points, which are fixed to the Russian Segment of ISS
- the Grapple Fixture, which are fixed to objects to be handled by ERA.

Both base points and grapple fixtures are part of the end effector subsystem. During launch, both end effectors are grappled to a special base point, each acting as a load suspension system. During the hibernation phases in orbit, both end effectors are also mated to base points. In this configuration all electrical connectors will be mated to the Space Station.

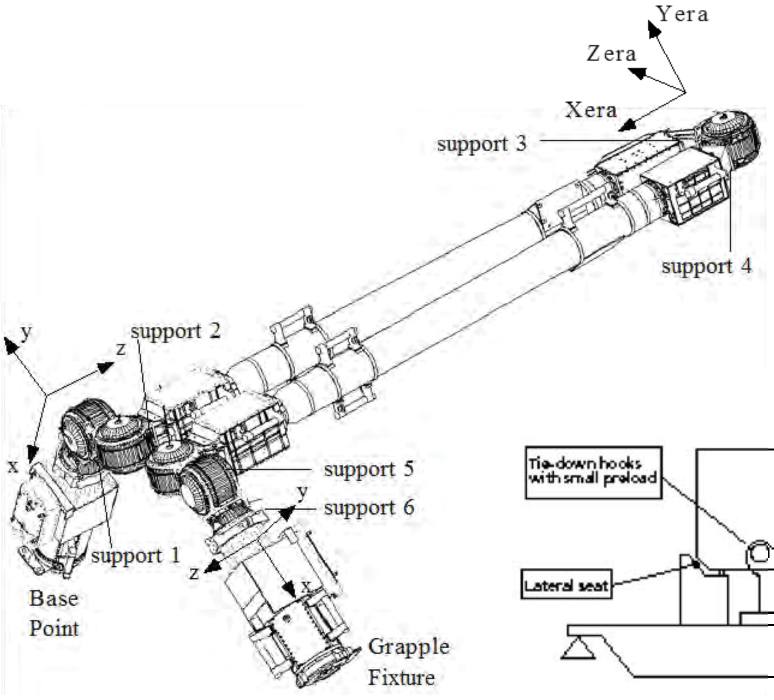

Figure 7 Illustration of ERA in the “Charlie Chaplin” configuration for launch

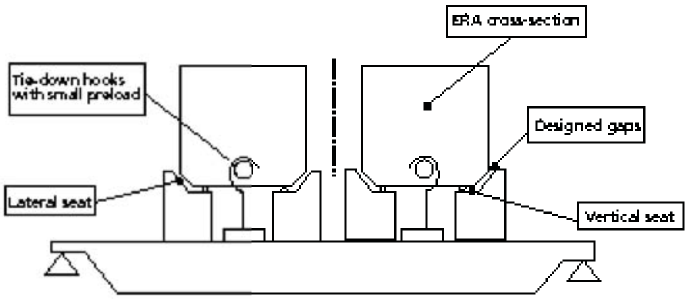

Figure 8. Schematic illustration of a Launch fixation point for the MLM

Launch Fixation Mechanism: During launch, ERA is configured in its so-called "Charlie Chaplin" configuration (see Fig. 7) and is attached to the MLM by means of six launch fixation mechanisms. Basically, each mechanism consists of one or two EVA-driven hooks to tie down and release ERA from the mounting seats. The hooks are adjustable. The engagement pins on ERA are fixed. The mounting seats are made to fit to minimize the backlash. The preload in the hooks is 500 to 1000 N. Gaps between ERA and its support are introduced in order to allow for easy assembly, to cope with thermal expansion, and to ensure proper release. These attachment points are located at the elbow joint (supports 3 and 4), on the wrist electronic boxes (supports 2 and 5), and on the roll joints (supports 1 and 6). At the Launch BP, the End Effectors are supported in all directions.

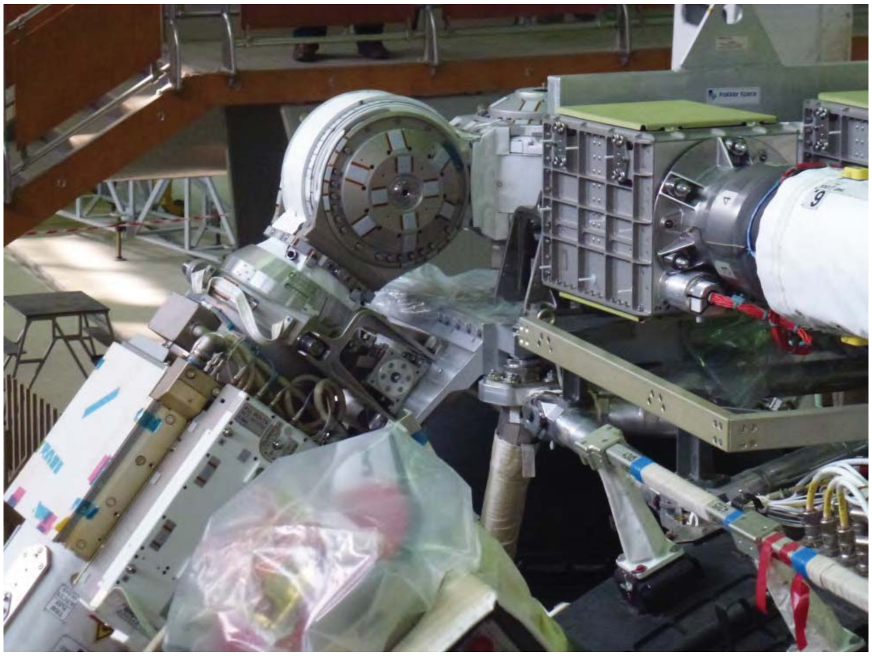

Figure 9. Launch interface points for the MLM

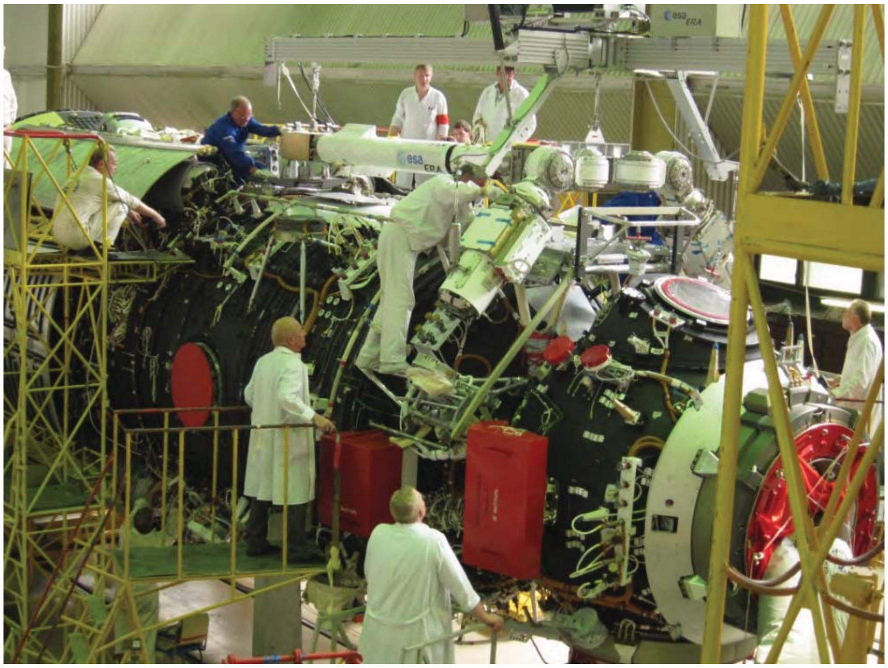

Figure 10. ERA integration fit checks on the MLM

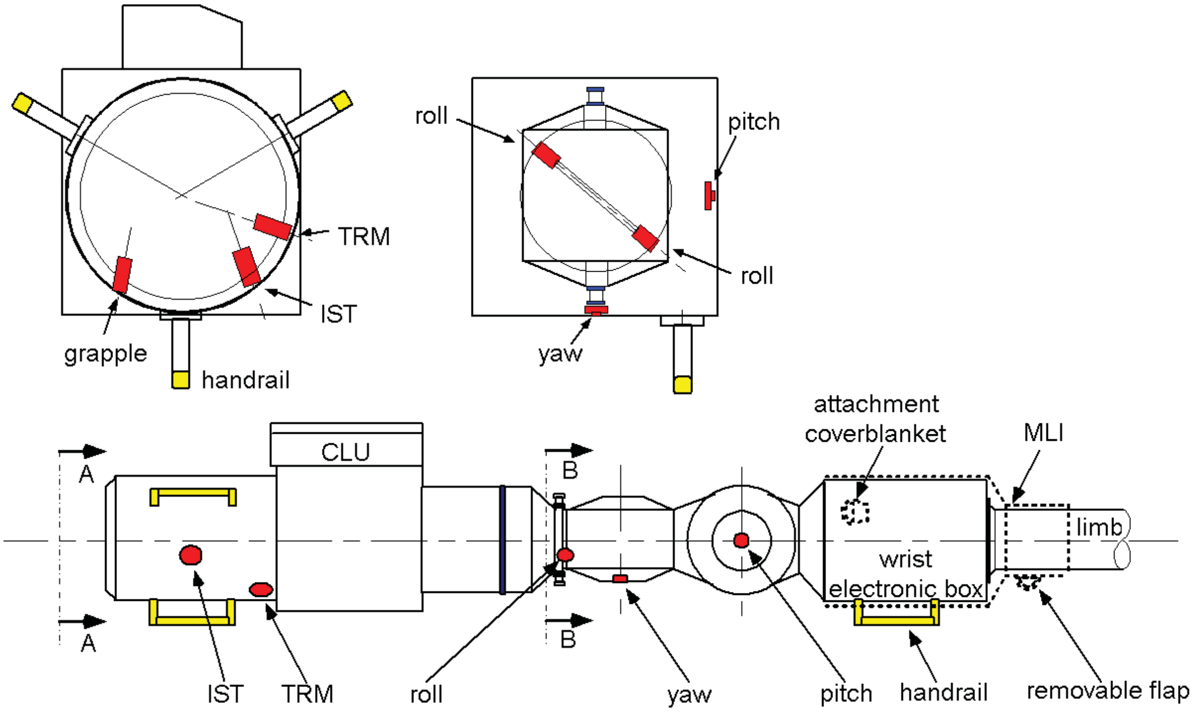

Figure 11. Location of ERA manual overrides

Manual Overrides in the End Effector Subsystem: An EVA manual override is implemented in the EES Actuator Unit, the Integrated Service Tool (IST) and also for the Torque Force Sensor (TRS) Rigidization Mechanism (TRM). The manual overrides for the Actuator Unit and for the TRM will be blocked during launch to secure the rigidization mechanism is in the closed position. Just after launch during installation of ERA in orbit, the launch lock has to be de-blocked. For de-blocking, the override tool has to be inserted into the 7/16-inch hexagonal receptacle of the Actuator Unit and of the TRM manual override interface. By this first insertion, a pin located within the hexagonal receptacle will be pushed backwards into the de-blocked position. The blocking device ensures that the pin will stay within this de-blocked position during all the following in-orbit operations.

The manual override inlets and position indicators are covered by MLI in order to prevent sun trapping and heat leaks. Before actuating the EVA override, the cosmonauts have to fold back the related parts of the MLI, which then will be secured in the back folded position.

Manual Overrides in the Manipulator Joint Subsystem: Each hinge line in the joints contains an override mechanism. The special tooling can be inserted at the locations at the central drive axis. For the pitch and yaw and elbow hinges, the backdriveability is achieved by inserting the pin mechanism in the central hole, directly engaging the electrical motor unit, hence at the input axis. This means that no backdriving of the spur gear is required. For the roll axis, the accessibility of this hinge prevents this approach. A special engage-disengage mechanism ensures that the gear train is by-passed; hence no back driving of this gear train is needed.

As the ERU hinges can also be dismounted from the tube, special bolts are used to allow decoupling. These 6 bolts are accessible via a tool. Handrails are required for momentum equilibrium, when the astronaut is turning these bolts. Again, special tooling is foreseen.

Other EVA interface: Several other interfaces are included to allow opening of MLI blankets, and opening lids of boxes such as the Elbow ERU. Other interfaces which are serviceable are the CLU's. (2 CLUs at the End Effector location as well as the 2 CLUs at the limbs).

Qualification Aspects

Unit Level Qualification Testing: For ERA, a mixture of a normal Qualification Model/Flight Model approach and Proto-flight approach was selected. The Engineering/Qualification models ((EQM) are structurally and thermally representative for the flight standard, but electrically they are built-up from MIL standard B parts. Most of these models do not have complete flight redundancy. Each subsystem has been thoroughly subjected to qualification testing. The testing was first done on subsystem level. Thereafter, the hardware was integrated to form a complete EQM for the system qualification.

System qualification on EQM: 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 were verified at system level on the flight model. The final end-to-end functional and electrical qualification has been done on the flight model, as only this model contains the Hi-rel Electronic, Electro-Mechanical and Electronic parts, and full redundant electrical circuits.

System-level functional performance testing: For performance testing including alignment, only one plane (the pitch plane) can be tested. The qualification of the three-dimensional robotic operations has been achieved via a combination of two-dimensional tests and three-dimensional simulations with the ERA Simulation Facility.

For functional testing on a flat floor, a special test rig had to be developed. There are 2 versions of this ERA test facility. One rig is for the coarse functional testing and end-to-end performance testing such as grappling. This test set up contains a simple derrick with airpad support near the tip of the arm to allow grappling of a test payload (see Figure 8). For performance measurements, the airpad under the tip was replaced by a more dedicated support vehicle. On this support vehicle, a small flat disc is included which acts as a flat floor on top of the moving flat floor (see Figure 8). The moving carriage is controlled by means of lasers at the corner of the test facility. With this test set–up, calibration of the control model is performed. The following tests have been done:

1. Functional testing:
    - Alignment / Stiffness
    - Free motion control test: for large unconstrained moves, at a safe distance. Feedback will be provided by the encoders.
    - Proximity motion control test: for small unconstrained moves, close to the space station. Feedback will be provided by the encoders in combination with the CLU.
    - Compliant motion test: for constrained moves, very close or in contact with the space station. Feedback will be provided by the encoder, but also the torque force sensor (TFS).
2. Thermal vacuum and thermal balance testing
3. Modal Survey testing and thereafter Boosted Modal Survey testing
4. EMC testing

The functional test with the arm was also done at maximum velocity. These tests were performed with and without payload attached in order to investigate the inertia effects in the control motion software and the response in the hardware. Note that for the functional testing, a protocol has been issued to test the extremities. These tests are executed with and without payload attached to the EES:

- Normal approach mode / fast mode, precision insertion mode
- Contingency mode with EVA
- Safe mode dynamic stopping distance in emergency mode.

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 maximum tip velocity of 10 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.

Figure 8. Moving flat floor disc on large flat floor surface (double decoupled)

Boosted Modal Survey: The aim of the boosted modal survey test was the qualification of the interfaces between ERA and the launcher in terms of proto-flight limit loads. Modes measured during the low-level modal survey test were selected in order to achieve qualification loads at the interfaces by exciting these modes on a high excitation level. Not all predicted qualification levels could be reached since the behavior of the test structure was extremely non-linear. The source of the non-linearity was investigated by additional test runs. The non-linearity was caused by interface conditions, which depend on the loads applied on the ERA. Moreover, the dynamics of ERA were characterized by hammering noises at high excitation levels. The elbow interfaces could be completely qualified during the Boosted Modal Survey testing. Qualification was not feasible for some components of the other interfaces especially for the axial components. Additional static strength tests were performed to complete the qualification. From the boosted modal survey test it could be deduced that the modal parameters like the mode shapes and Eigen frequencies found in the modal survey test do not apply for ERA under high overall launch loads. Thus, they are not directly applicable for the validation of the finite element model. However, qualification was feasible for the lateral components. Qualification for the axial components was expected to be difficult to achieve and turned out to not be feasible. In order to qualify these components, a separate static test was required and performed.

Finite Element Analysis: Control performances such as tracking and positioning must rely on good modeling of the arm dynamics. This part is mainly determined by the flexibility in the limbs and the controlled joint behavior. Extensive finite elements analysis with the NASTRAN tool forms the basis for providing model data for the limbs in a multi-body dynamics model within ERA Simulation Facility. For final validation of the modeled flexible behavior of the arm, the real arm will be kicked during test and the position is measured. During this test the joints are not active, and the brakes will be on. The controlled behavior of the joints is mainly driven by the properties of the gearbox. The final achieved backlash including any hysteresis effects was less than 1 mrad.

Flight Acceptance testing: Each subsystem has been thoroughly subjected to flight acceptance testing. The testing was first done on subsystem level. Thereafter, similar functional testing has been executed as done for the EQM.

EVA check by cosmonaut: On the ERA EQM, an astronaut "walk-around" was performed as part of the ERA Critical Design Review. This was the first time that cosmonauts saw the full-sized ERA arm (previously only the MMIs had been seen by cosmonauts). 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.

Lessons Learned

The Boosted Modal Survey testing can be a good alternative, but keep in mind:

- Non-linear behavior in launch configuration; Hammering (deflections are larger than gaps). Slip and stick motion (frequency change, damping). The qualification may only be partly possible, still requiring static strength testing necessary for other interface points.
- Assessment on non-linearity and damping to find the correct excitation levels / internal loads
- Care should be taken to prevent any over testing.

Conclusions

The ERA arm has been subjected to a rigorous test program on the subsystems and for the EQM. The mechanisms have been designed for EVA and specific tests have been executed to demonstrate this aspect. The flight model has undergone functional testing and integration testing with the MLM. Spare ERA parts have already been launched upfront to the ISS in 2010. The flight model is now ready for final integration on the MLM and launch in 2015.

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