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# The ERA System: Control Architecture and Performances Results

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## Abstract

The **European Robotic Arm** [ERA], is one of the contributions of ESA to the International Space Station (ISS). ERA, built under the system responsibilities of Fokker Space (the Netherlands), will be installed on the Science Power Platform, one of the modules of the ISS Russian Segment. ERA will be used for the Russian segment assembly and its in-orbit inspection and maintenance, for exchange Orbital Replaceable Unit (ORU) and it will provide support to EVA cosmonaut sorties. This set constitutes the ERA reference missions, for which essential activities were defined and arranged in a hierarchical structured way of tasks and actions, with a corresponding set of required control capabilities. As a result, library of actions and tasks has been defined for ERA.

Three essential controlled motion mode are distinguished for ERA:

- **Free motion: Single joint, pitch motion or Cartesian motion**. In this motion mode, the internal ERA joint position sensors (JPS) are used to position the ERA in either in joint space or in Cartesian space.
- **Proximity motion**: In proximity motion, the ERA camera and lighting unit on ERA end-effector is used to correct the ERA approach/ retract path. The CLU processes at 10Hz the proximity target pose, and the proximity motion controller corrects possible offsets.
- **Compliant motion**: In compliant motion, the ERA Torque and Force unit in ERA end-effector is used to correct the ERA insert/extract path. The TFS information is used to correct for eventual offsets and obtain the programmed arm behaviour along certain direction: e.g. pushing force or a yielding behavior in certain direction or around certain axis

For each of this controlled motion, Fokker Space has defined control test specifications and qualified the associated test environment for the control performance verification. This paper will:

- Present the control architecture and required performances for the ERA system, for its various controlled motion.
- Give an overview of the test infrastructure environment that is used at Fokker Space to verify under emulated zero g condition the ERA control performances.
- Present the different test cases and the associated test results obtained for ERA in the various controlled motion modes

*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]

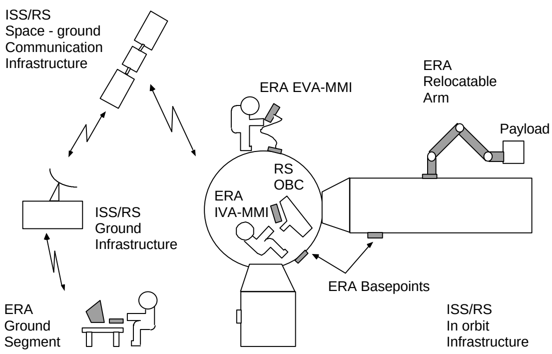


**Figure 1: ERA overview**

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. Figure 2 shows the ERA FM during the Thermal Balance Test.

**Figure 2: The ERA FM**

The ERA operations are composed of a set of tasks containing one or more or actions, which together form an “Auto Sequence”. The Auto Sequence is stored in the ERA Control Computer [ECC}, and is launched by the ERA operator. The auto sequence is executed autonomously under the operator supervision, and may switch between different controlled motion modes during its execution. Manual, Single-degree-of-freedom or single-joint commanding is possible as well.
For a more detailed overview of the operational aspects of the arm, see [SO].

# 2. Control Requirements and architecture

The control design is implemented for three types of motion:

· ***Free Space Motion Contro*l**, providing feed forward controlled maneuvers. Time scheduled poses in Cartesian space are translated by inverse kinematics into angular position setpoints for each joint. Single joint moves and co-ordinated joint (pitch plane) maneuvers are also possible;

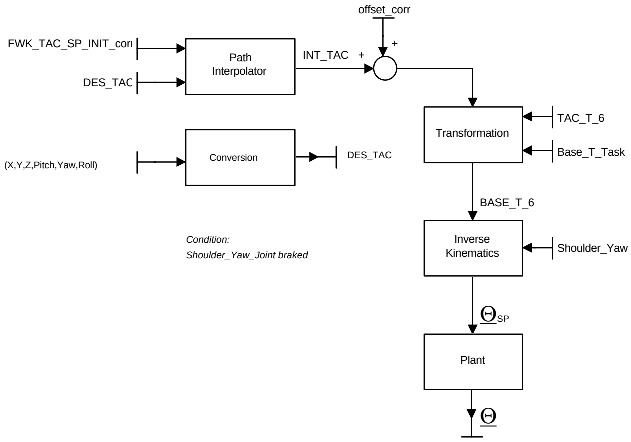


**Figure 3: Free Motion Control scheme**

***Proximity Motion Contro*l**, with visual target feedback from a Camera and Lighting Unit (CLU), where ERA approaches a target; the objective is to eliminate the effects of misalignments while executing an approach path towards the grapple fixture (grappling with an empty arm) or latching interface (connecting a payload to the space station);

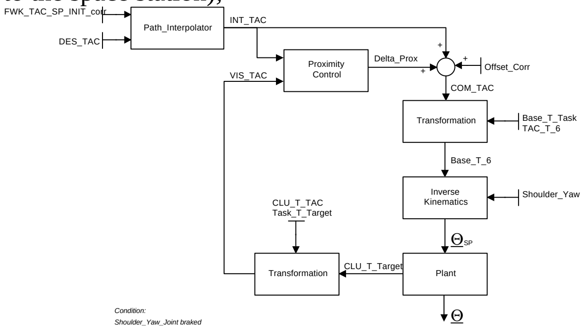


**Figure 4: Proximity Motion Control scheme**

***Compliant Motion Contro*l**, with feedback from the Torque and Force Sensor, with or without carrying a payload; it is required to guide the Basic End Effector (BEE) or a grappled payload to its eventual fixation position, after mechanical contact.
During large 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. Considering the fact that the arm is about 10 m long and payloads can be up to 8000 Kg, high demands are imposed on the ERA control system.

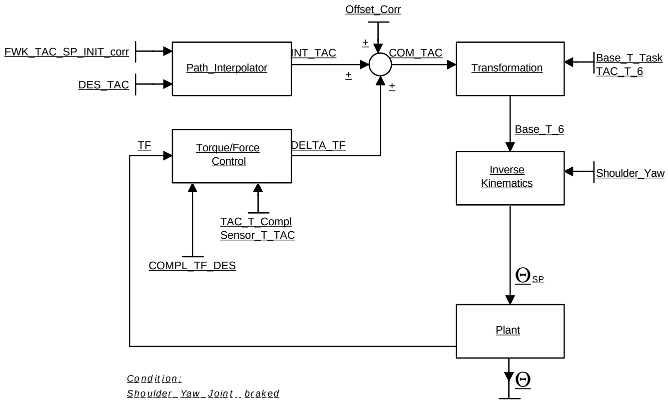


**Figure 5: Compliant Motion Control scheme**

# 3. ERA Test Environment

*3.1 ETF*

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 following main items

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 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.

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 are schematically shown in Figure 6. 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.

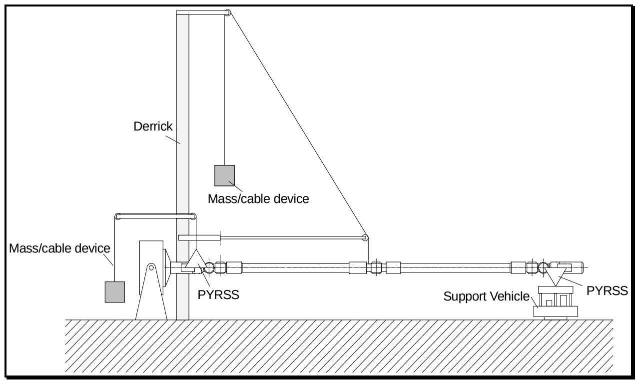


**Figure 6: ERA suspension during integration in ETF**

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.

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.

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.

Measurement equipment

For the Control test it is required to measure the actual position of 5 test points on ERA during the operation with an accuracy of better than $\pm$ 1 mm. These measurements will be performed by a laser tracking system in combination with 5 transponders installed on ERA. In addition, an independent position system is used for local, high accuracy measurements.

During Grapple tests the torques and forces exerted by ERA on the GF of the Payload will be measured by load-cells installed between GF and Payload. The accuracy of this measurement shall be better than 5N and 2 Nm.

### *3.2 Hardware In The Loop Test [HILT] Facility*

The Hardware In the Loop Test (HILT) facility is used for testing the ERA on-board software running on the ERA Control Computer (ECC). To be more precise, the hardware tested is a breadboard version of the ECC (CBB) and the software testing activities also involve integration of the on-board software on the hardware as well as integration of layers of that software. The HILT facility is build around a dedicated version of the ERA Simulation Facility (ESF). ESF models in real-time the ERA Subsystems, the dynamic arm behavior (including flexibility modes), the Russian Central Post Computer (CPC) and Man Machine Interface (MMI). The HILT facility provides the capabilities for the preparation of test scripts that can be used by ESF, retrieve necessary onboard software from CVS, compile/link the sources, execute a test or series of tests and evaluate the result in an automated batch session. There are also secondary tools developed, for example to convert an ACCESS database dump into an Ada database specification.

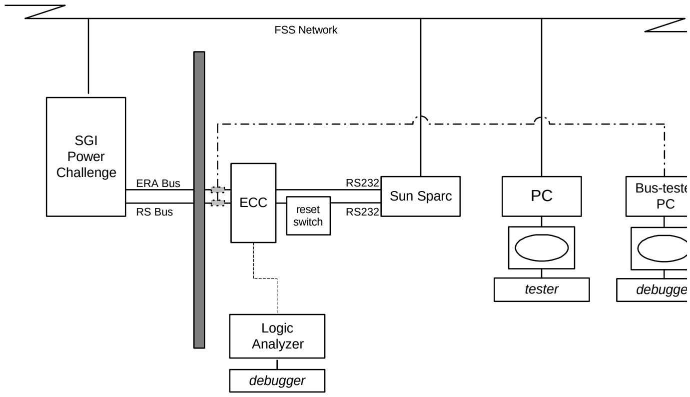


**Figure 7 System overview of the HILT facility**

The above figure shows the hardware systems used in the HILT facility.

For debugging purposes a MIL1553 bus tester is used to check bus communication. Moreover, the need for a logic analyzer to monitor the CPU down to an execution cycle has been allowed for. Although no commercial product is available to directly perform this debugging on the ERC32 processor, efforts are being taken to create such a debugging environment.

The preparation phase includes a tool to retrieve memory address information (needed within test scripts for some tests). The ECC image is built using the AdaWorld compiler and downloaded to ECC with a dedicated tool using an optimized MIL1553 protocol. ESF generates the CPC/MMI commands and provides the correct S/S data for the OBS software running on the ECC. The results (ESF hex dump file and event log file) are post-processed to generate a test result file. For debugging purposes a MIL1553 bus tester is used.

The Software In the Loop Test (SILT) facility is used for testing the ERA on-board software (specifically the AL/SL software layers) together with the ERA Simulation Facility (ESF). But in contrast to the Hardware In the Loop Test (HILT) it does not use the flight OS or ERA Control Computer (ECC) hardware, instead it uses an OS emulation to run the software on a SGI (R10000 processor). It also uses a different Ada compiler Verdix instead of AdaWorld. The main purpose of SILT was to allow testing to be carried out prior to the availability of the OS software layer and ECC hardware.

The SILT facility is build around the same version of the ERA Simulation Facility (ESF) as for the HILT. It will only differ if the MIL1553 shared memory simulation is used; in which case a different library must be used. The SILT facility provides the same basic capabilities as the HILT facility: preparing test scripts that can be used by

ESF, retrieve necessary onboard software (ported version) from CVS, compile/link the sources, execute a test or series of tests and evaluate the result in an automated batch session.

# 4. Present ERA Test Results

The verification approach of ERA and the characteristics of the EQM and FM leads to a system level test program where the various tests are divided among the EQM and FM. Table 1 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 1: Overview of tests performed on EQM or FM for the major tests blocks**

A considerable number of control system tests have been specified to analyze the dynamic behavior 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.

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. Torques 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 from external measurement equipment

<u>Square Move</u>
Figure 8 shows the Square Move path, part of the Free Motion Control tests. Figure 9 shows a zoom of the tip position with respect to the reference, from above. Figure 10 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

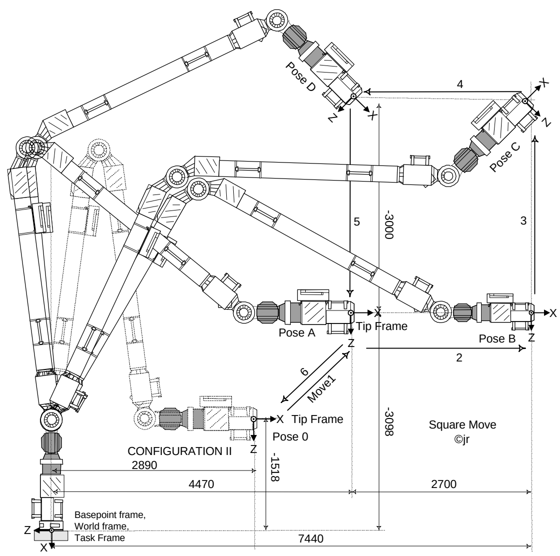


**Figure 8 Square Move, a Free Move test**

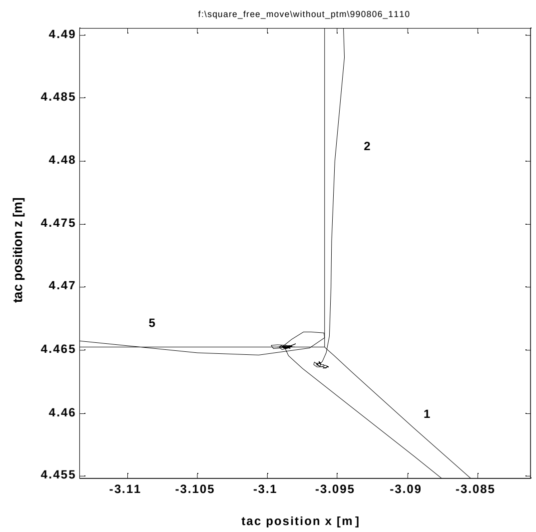


**Figure 9 Calculated path of the Square Move**

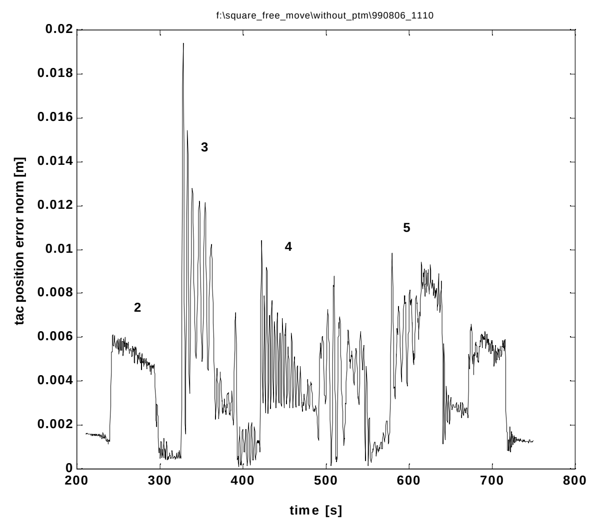


**Figure 10 Calculated tracking error of the Square Move**

Small Square Move

These tests have been repeated using an external laser tracking system for absolute position measurement of the tip. The results of this Small Square Move can be found below. During this test, ERA while commanded in free motion control mode is required to automatically follow a Cartesian trajectory consisting of four corner points located at P1[-4600,-5700], P2 [-4600,-7170], P3[-6100,-7170], P4[-6100,-5700], visited at a speed of 5cm/s and an acceleration/ deceleration time of 5 seconds. In addition, while moving from P2->P3 and P3->P4 the hand pitch orientation is changed by 25degrees then –25degree. This test data serves both for arm control performance evaluation as well as to compare the simulation prediction with actual test data.

The performances (see Figure 11) show a static accuracy better than 10mm and a maximum path deviation smaller than 17mm, well within the ERA performances requirements.

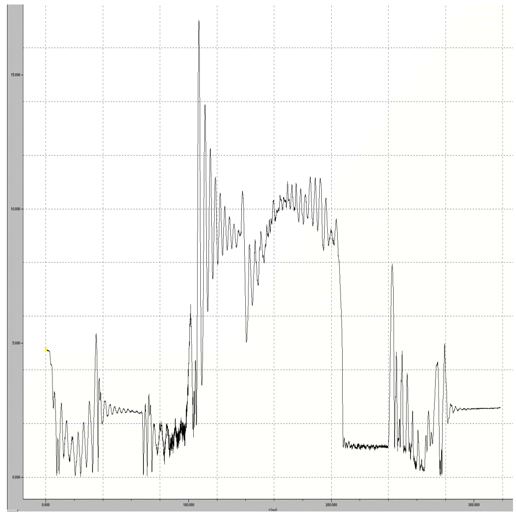

**Figure 11 Measured tracking error of the Small Square Move**

Stopping Distance

Several tests were performed to assess the maximum stopping distance of ERA, i.e. is the maximum distance ERA covers after a soft emergency stop command has been submitted to the ECC. Among others, while ERA was fully stretched, its shoulder pitch was moved to its maximum speed, resulting in a tip speed of 18cm/s. A brake command was sent to ERA and its tip position was measured. The ERA tip came to rest within 12.5cm, which include command latency, small brake slippage and dynamic effects such as gearbox flexibility's. This is within the required 15cm maximum stopping distance. The test was repeated and has shown to give similar results from one run to another.

Grapple Test

Nominal grappling tests have been performed showing that control is smooth and torques and forces stay within required limits. Tests are continued with medium and large misalignments. Figure 12 shows the path inwards the grapple fixture during the Insert. This is followed by a movement enforced by the grapple fixture during Grappling. Figure 13 shows that the force build-up in the pull direction of the grapple fixture is being compensated by the torque-force feedback controller.

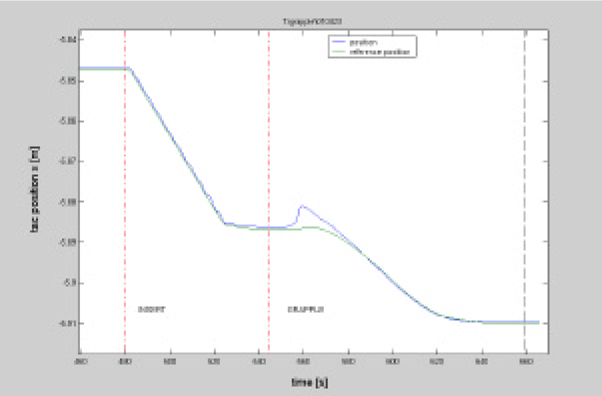


**Figure 12 Calculated path during Insert and Grapple inwards the grapple fixture**

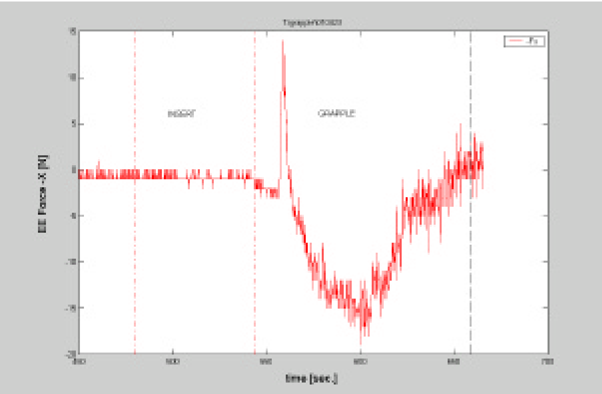


**Figure 13 Force in forward direction during Insert and Grapple.**

# 5. Conclusions

An overview of the complex test and verification environment has been presented. The performed tests for Free Motion Control and Compliant Motion Control show smooth, stable control complying with requirements. Tests for Compliant Motion Control will be continued to test the performance and robustness for more stringent circumstances. Also, latching with a 435 Kg payload test module will be performed. Simulations with HILT showed that latching of different payloads with active Compliant Motion Control is feasible with torque-force levels within specification. Control tests with the camera are planned on short term with the improved image processing. Sensitivity simulations with different payloads showed that tuning of the arm pose with the camera in all 6 Degree of Freedom directions is working smoothly. The accuracy is determined by the accuracy of the camera, which is a function of the distance which is 5 mm close by (0.5 m) and several centimeters at 2 m.

# References

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