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Some mechanical design aspects of the European Robotic Arm

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Abstract

The European Robotic Arm (ERA) is a contribution to the Russian Segment of the International Space Station Alpha. It will start operating on the Russian Segment during the assembly phase. ERA is designed and produced by a large industrial consortium spread over Europe with Fokker Space & Systems as prime contractor.

In this paper, we will describe some of the overall design aspects and focus on the development of several mechanisms within ERA. The operation of ERA during the approach of its end effector towards the grapple interface and the grapple operation is discussed, with a focus on mechanisms. This includes the geometry of the end effector leading edge, which is carefully designed to provide the correct and complete tactile information to a torque-force sensor (TFS). The data from this TFS are used to steer the arm such that forces and moments are kept below 20 N and 20 N•m respectively during the grappling operation. Two hardware models of the end effector are built. The problems encountered are described as well as their solutions.

The joints in the wrists and the elbow initially used a harmonic drive lubricated by MoS_2. During development testing, this combination showed an insufficient lifetime in air to survive the acceptance test program. The switch-over to a system comprising planetary gearboxes with grease lubrication is described. From these development efforts, conclusions are drawn and recommendations are given for the design of complex space mechanisms.

Introduction

On the International Space Station Alpha, the assembly of the Russian elements will be supported by a robotic arm, the European Robotic Arm, as a result of the joint ESA-Russia cooperation. After completion of its assembly tasks, the arm will be used for inspection, External Vehicle Activity (EVA) support, and exchange of Orbit Replaceable Units (service units and experiment units). By having two end effectors, the arm can "walk" over the Russian Segment of the Space Station. Its many tasks, its long life in orbit, and its mobility over the Space Station impose severe environmental conditions on the ERA.

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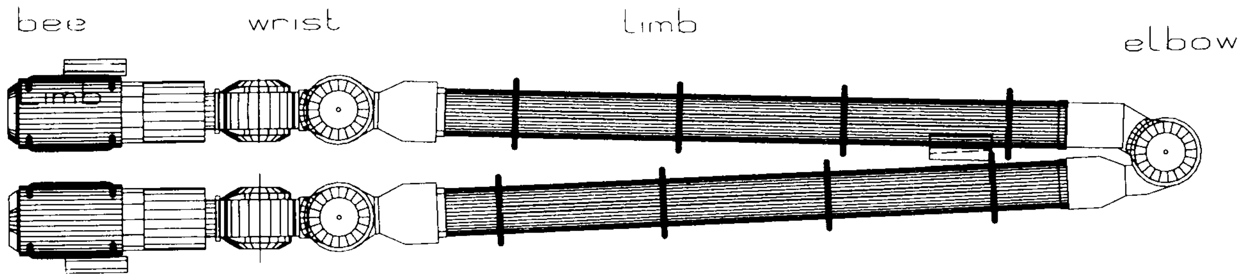

Figure 1. ERA arm configuration

ERA tasks and operations

<u>Tasks</u>
ERA will be used as the robotic arm on the Russian Segment. The tasks that it will perform can be divided into four main categories:

- moving payloads
- mechanical and electrical servicing of payloads
- inspection with video cameras
- support to extra vehicular activities

The category "moving payloads" firstly requires ERA to grapple a payload. To this purpose, a grapple fixture (GF) will be attached to every payload that will be moved by ERA. The GF is a standard interface bracket, containing the interfaces necessary to transfer data, video signals and electrical power to the payload. Also built-in is the capability to transfer mechanical power to the payload. This mechanical power will be delivered by a servicing tool, an "electrical screwdriver," integrated in the end effector. Not all payloads will use all servicing capabilities. However, the possibilities are provided in the standard interface to allow more flexibility to the payload designer.

Inspection of the station or a payload will be performed by video cameras mounted on ERA. To assure that video images can be supplied in all light conditions, each camera is equipped with its own lighting unit. The camera near the elbow can be used for an overview of the working site, whereas the camera in the end effector delivers a close-up view for detailed inspection. The video images can be inspected on monitors inside the Space Station, but it is also possible to perform an off-line inspection after telemetry to a ground station.

Support to EVA can be performed in two ways. The ERA can hold and manipulate a payload to enable the cosmonaut to perform the necessary tasks. Alternatively, the cosmonaut uses ERA as a support platform. ERA will grapple the EVA support tool on which the cosmonaut can stand and moves the cosmonaut to the location where he has to work. An EVA man-machine interface, operated by a second cosmonaut, controls the ERA during the process.

To be able to perform these tasks, ERA must be able to reach all potential work sites. There are two ways for ERA to move on the Russian Segment. The first is to move along the main truss structure of the Russian Segment, mounted on a trolley. The trolley is a Russian development. It runs on two rails over the truss structure. The four basepoints (BP) on this trolley enable it to form a moveable working site for ERA operations. To reach other parts of the RS that cannot be reached from one of the BPs on the trolley, ERA needs to relocate itself. The symmetrical design with two identical end effectors enables ERA to step over from one BP to another. These BPs are located on all parts of the Russian Segment where ERA has to perform tasks.

Example of operation

An example of a typical ERA task is the installation of the solar arrays of the Russian Segment. This task consists of the following sequence. At first, ERA moves to the docking port where a transport vehicle is located. Then the GF of the solar array module is grappled by ERA. The structural interface between the solar array and the transport vehicle is decoupled by EVA. After decoupling, ERA moves the solar array to the trolley and fixes it temporarily onto the trolley, relocating itself back onto the trolley. When the trolley moves from the docking port to the end of the truss structure, ERA is in stand-by mode. Then ERA moves the solar array from the trolley to its installation site where the solar array is connected to its interface by EVA. For the deployment of the solar array, the mechanical servicing capability of ERA may be used, the servicing tool driving the deployment mechanism of the solar array. After full deployment and latch-up, ERA ungrapples (disconnects) and moves with the trolley to its home-position on the truss structure.

Design and characteristics of ERA

The design of ERA is driven largely by the requirement to be self-relocating and the necessity to have autonomous computing capabilities. Among the features resulting from this are:

- (almost) symmetrical layout
- 7 joints (only 6 degrees of freedom needed for operations)
- control computer built in, part of load bearing structure
- stiffness and torque requirements for the hand and wrist side are equivalent (=stringent) to those for the shoulder side

Configuration

Because the layout of ERA is symmetric, the two end effectors are identical, as well as the two wrists. Each wrist has three degrees of freedom. Together with the elbow joint (1 degree of freedom), ERA has 7 rotating joints. ERA will be operated as an anthropomorphic arm with only six degrees of freedom. Thus, only six joints will be used simultaneously while one joint, the yaw joint at the shoulder side, will be fixed in neutral position during operations.

The total length of ERA is 10.4 m. The total mass is about 400 kg. The speed at the end effector level can be controlled within a range of 0.001 $^{m}/_{s}$ to 0.2 $^{m}/_{s}$. At a low speed or at standstill, ERA can exert external forces up to 30 N and moments up to 100 N•m.

Electrical

The on-board computer gives ERA a high level of autonomy. All kinematic translations and all subsystem control functions are performed by the control computer. Its RISC processor, the THOR, also performs the image processing to locate the visual target on the GF, this closed-loop position control allowing an accurate positioning of the end effector. Communication between the control computer and the Russian Segment is performed by a Manchester databus, the 1553 protocol.

The design of ERA includes many sensors to monitor internal parameters. Some of these sensors are used for control purposes. Examples of these are the sensors to measure the motor speed in the joints and the encoder to measure the angular position of the output shaft. Other sensors are primarily used for safety functions, like the electrical current monitors, mechanical microswitches, and thermal sensors. A very sophisticated sensor is the Torque-Force Sensor in the end effector. It includes 32 strain gauges to measure the torques and forces transferred through it during grappling operations.

EVA compatibility

The tasks to be performed require ERA to be compatible with manned operations. This imposes not only stringent requirements on safety, but also on the strength and the overall stiffness. The latter is necessary when the EVA uses ERA as a working platform. A firm support is required in this case. Regarding the safety, the requirements for ERA are to be single failure operational and double failure safe. These requirements have largely driven the electrical and software design of ERA.

All mechanisms within ERA have the capability to be manually driven by EVA. For this purpose, a $^{9}/_{16}$" hexagonal input shaft is included at the motor axis of the joints and at an intermediate stage in the gear train of the end effector.

Mechanical

The mechanical configuration can be characterized by the fact that almost all subsystems are part of the primary load path. Even the box for the control computer is integrated in the limbs of the arm. Only the cameras are attached to the outside of the arm. The limbs themselves are carbon-fiber reinforced plastic tubes, with the cable harness and thermal hardware attached to the outside. The joints are driven by a brushless motor, electrically redundant. A disc brake is connected directly to the motor output axis. The brake is automatically engaged when the electrical power is switched off. A four stage planetary gearbox performs the reduction between the motor and the output axis of the joint. The total reduction ratio is 1:450. The design of the end effector will be described later in more detail.

Approach and grapple strategy

Approach in four phases

The approach of the end effector to an object to be grappled is performed in four phases:

A - open loop positioning
B - positioning with optical proximity target
C - contact phase with tactile feedback
D - rigidization with three grapple hooks

The final accuracy that will be reached in each of these phases is:

A - 40 mm, 1°
B - 5 mm, 1°
C - <1 mm, <1°
D - 0.1 mm, 0.1°

Open loop positioning (phase A)

The open loop positioning is performed without any optical or tactile feedback. The overall positioning accuracy in this phase depends entirely on the accuracy of the systems within ERA. Sources of errors are production tolerances, resolution and accuracy of angular position sensors and thermal distortion of all structural parts of ERA. The achievable accuracy in this phase is 40 mm linear and with an angular error of less then 1°. Since this mode does not need feedback from external references (e.g. targets), the accuracies are relative to the ERA BP.

Positioning with optical proximity target (phase B)

Each grapple fixture and each basepoint includes an optical target. This target is brought into field of view of the camera of the end effector with open loop positioning. The location of the end effector relative to this target is determined by the control computer. The optical pattern of the target is recognized and analyzed. The positioning accuracy achieved in this phase is 5 mm linear and 1° angular. When the end effector is within the acceptance cone of the grapple mechanism, ERA switches over to the contact phase.

Contact phase with tactile feedback (phase C)

The TFS in the end effector consists of two parts, one connected to the arm side of the end effector and one connected to the hand side. The two parts are connected to each other by flexible elements. The deformations of these elements are measured by strain gauges. This provides the information about the torques around three axes and the forces in three directions transferred through the TFS.

During operations where it is not necessary to measure the torques and forces and where the additional flexibility of the TFS is a disadvantage, the TFS will be rigidized. When the end effector acts at the shoulder side, the TFS will always be rigidized.

During the contact phase, the torques and forces measured by the TFS are used by the control algorithms of ERA to keep the contact forces below 20 N and moments below 20 Nm. The grappling mechanism can grapple and rigidize with these disturbing forces.

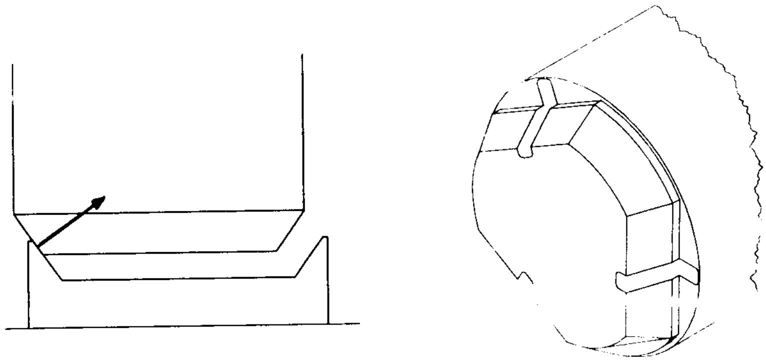

Figure 2. Geometry of the end effector leading edge

The geometry of the end effector front end and of the part to be grappled are carefully designed to provide correct and complete information. The information provided can be used to identify the correct movements of the end effector to arrive at the correct final position.

Geometry of contact areas

The following example illustrates the necessity of designing the contact geometry in order to get a correct tactile feedback. The end effector shown on the left in Figure 3 has a box-shaped front, which is to be inserted in a complementary box-shaped hole in the surface. A linear +Y misalignment results in a force +X and a moment -Z. However, a rotational misalignment +Z results in the same force +X and moment -Z. Thus the signals from the TFS do not lead to unique and correct information about the corrections needed to achieve a proper alignment. The end effector shown on the right side in Figure 3 is designed to provide unambiguous tactile feedback to the TFS. The correct information about the axial rotational position requires a triangular or rectangular baseform. The signals from the TFS can successfully be used to make the correct alignment corrections. The achievement of a correct final position during the contact phase is essential for a good start of the next phase, the rigidization.

Rigidization phase with three grapple hooks (phase D)

The rigidization of the connection between the end effector and its counterpart is performed by the grapple mechanism in the end effector. This grapple mechanism consists of three grapple hooks that capture three corresponding contact plates.

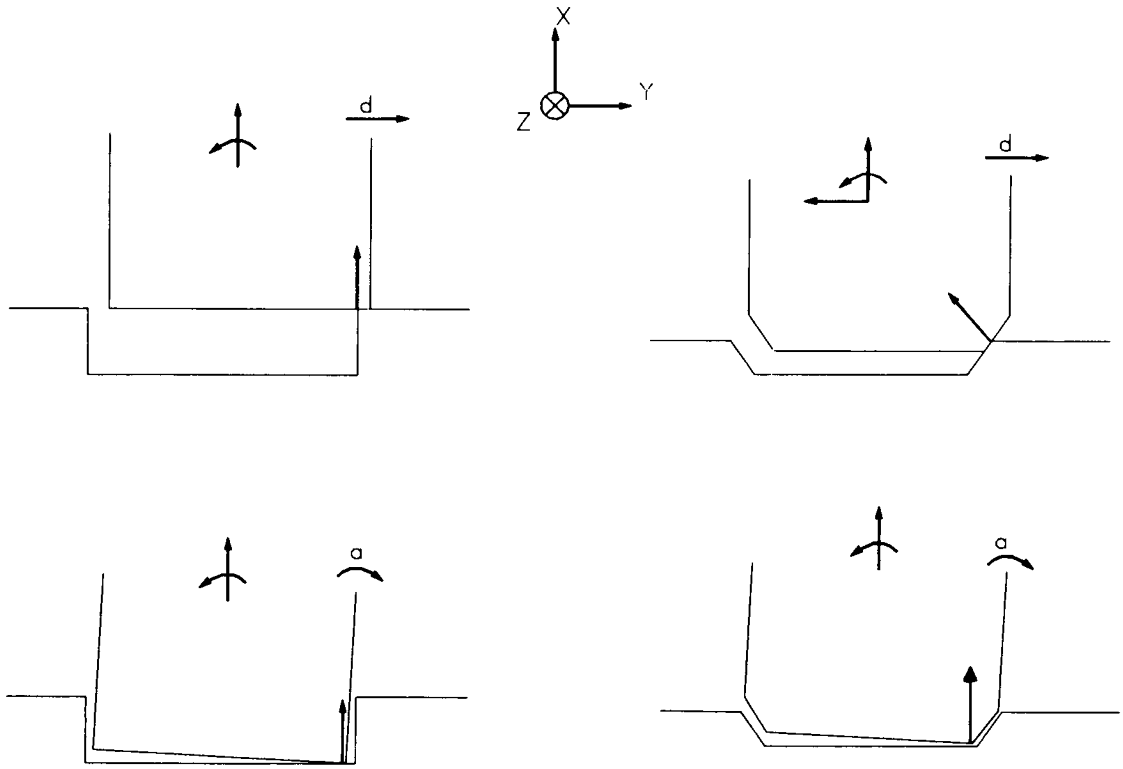

Figure 3. Tactical feedback from contact point

The movement of the hooks is indicated in Figure 4. In the final phase, the hooks are preloaded by over-centering the driving shaft. These provide a rigid connection between the end effector and the GF or BP. Especially for the end effector acting as the shoulder this rigid interface is extremely important.

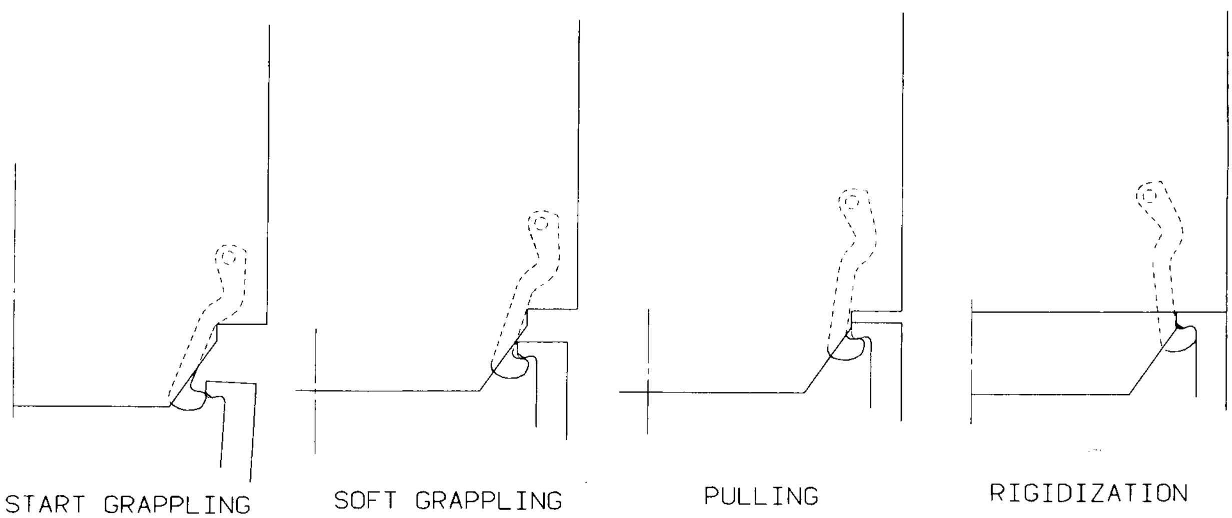

Figure 4. Rigidization of the grapple mechanism

Requirements for the end effector

The strategy for approach, grappling and rigidization as described above requires that the end effector is designed to be compatible with this approach. The main requirements that guarantee this compatibility are described below, focusing on the requirements associated with the grappling mechanism.

- The end effector must be able to perform the grappling operation for starting misalignments of up to 25 mm in any direction, including the axial direction and a rotational error of up to 3° around any axis.

- During the grappling operation, the grappling mechanism must also be able to cope with external disturbance forces of up to 20 N in any direction and moments of up to 20 N•m around any axis.

- Each of the grapple hooks must be rigidized with a preload of 7000 N. This high preload is necessary to provide the high stiffness and high strength required to function as a shoulder.

- The TFS in the end effector must have the ability to measure torques up to 100 N•m and forces up to 100 N in any direction. The accuracy of these measurements must be better then 2 N•m and 2 N. The TFS must be able to transfer loads above the measuring range without damage, up to 500 N and 500 N•m. To achieve this, the flexible element is protected by mechanical end stops. When the end effector acts as a shoulder, the TFS must be rigidized. In this rigidized configuration, measuring capability is not required.

- The cable harness is routed via the end effector. During grappling, the end effector must mate three large connectors to connect the total system harness, consisting of 42 pairs or triplets of cables.

- The mechanical servicing tool must be integrated in the end effector. The pop-in device for insertion of the tool head into the payload is located at the center of the end effector.

End effector design

Overall layout

In Figure 5, the overall layout of the end effector is given. The motor is a brushless DC motor. It drives a reducing gear train including a worm gear to prevent the mechanism from being backdriven. The worm gear actuates a large central spur gear, which rotates the three spindles. The bearings at the top of the spindles, which are mainly axially loaded, need a hard preload to avoid axial play. The three roller screws on the spindles are mounted with a limited floating capability onto the central platform. The central platform is moved upwards and downwards by the rotating roller screws.

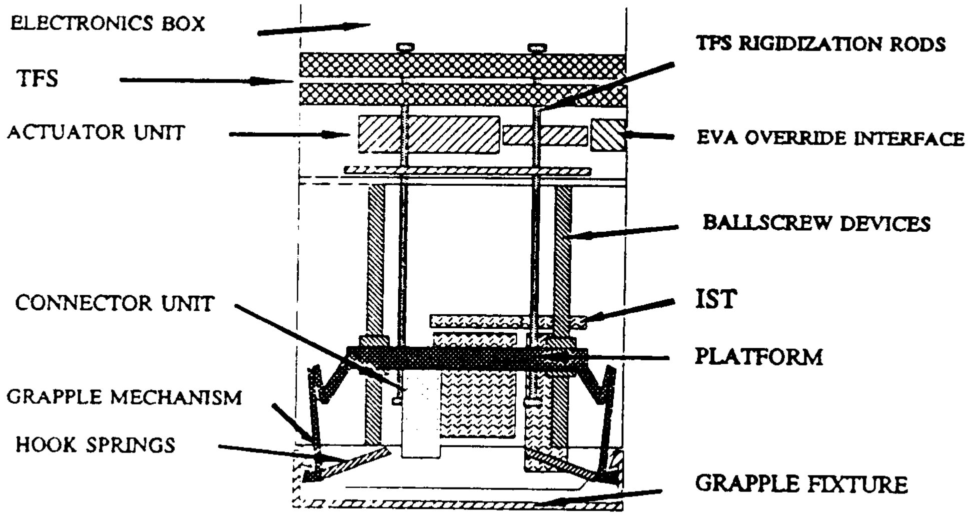

Figure 5. Layout of the end effector

The moving platform performs four functions. In order of actuation, these are driving the grappling mechanism, inserting the three connectors, inserting the mechanical tool head, and rigidizing the TFS. The torque-force sensor itself is mounted between the mechanisms described above and the electronics unit.

Grapple mechanism

The grapple mechanism comprises three hook / lever systems, which are coupled to the moving platform. The set of two levers and one hook is needed to perform the complicated movement of catching, soft grappling and rigidizing. The relative motion of the levers and hook is illustrated in Figure 6. The hook is constantly pressed outwards by coil springs. When the hook touches an obstacle during grappling, the coil spring exerts a force of about 30 N to the obstacle. During the soft grappling phase, the three grapple mechanisms start pulling at the grapple fixture until the gap between the grapple fixture and the end effector is closed and the grapple mechanisms are rigidized. In the final rigidized phase, the mechanism is slightly over-centered. No electrical power is needed to maintain this rigidized state.

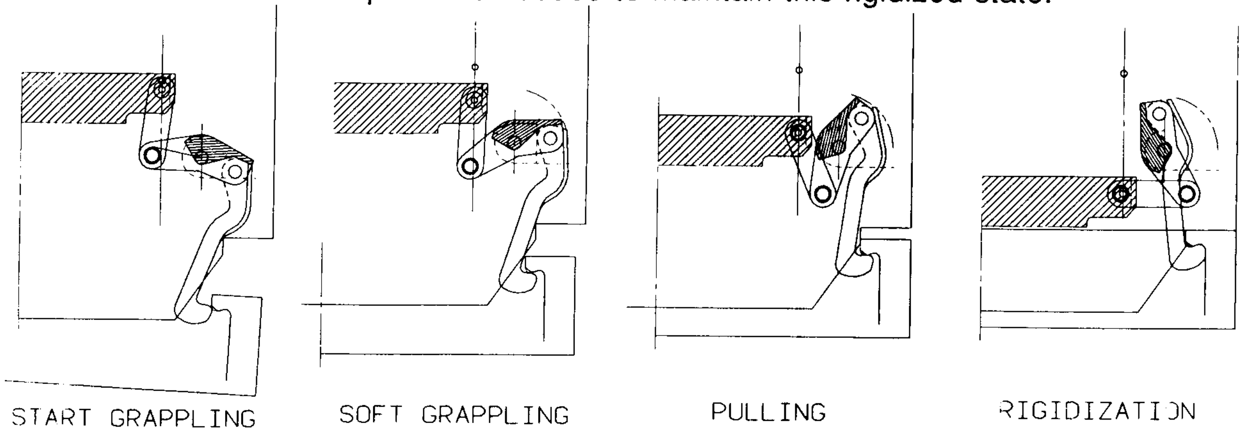

Figure 6. Motion of the grapple mechanism

Development model

A breadboard model of the end effector was built of hard polystyrene foam to assess the action of the mechanical parts. The movement of the platform was hand-driven and care was needed to avoid applying too much force after reaching the end position. Still, this breadboard model fully satisfied its objectives in that the concept of the lever system driven by a central platform was proven and the self-alignment capability of the mechanism was demonstrated. The model also enabled refinement of the geometry of the grapple hooks.

The current model is a full-scale model, constructed of flight-representative materials. During integration and the subsequent testing, several problems were encountered. They are summarized below as "lessons learned."

The grapple mechanism comprises complicated three dimensional movements (see Figure 7). During integration, several small interferences were found between the levers and the hooks of the grapple mechanism and the moving platform. These interferences had not been detected on the two dimensional design drawings. They could have been prevented by early application of 3-D CAD, which enables checking the position of the mechanism in every intermediate position. On the other hand, a 3-D CAD system is not a substitute for hardware and having an early hardware model gave valuable experience with the design.

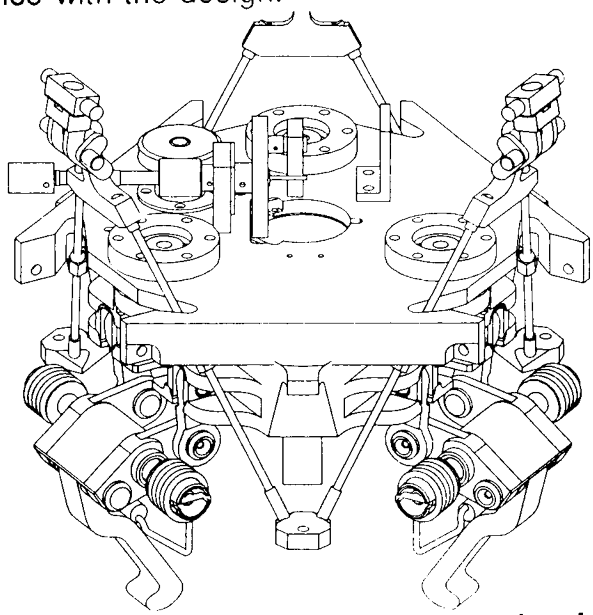

Figure 7. Complicated 3-D mechanism

It has been difficult to achieve a constant preload in the grapple hooks. This preload proved to be sensitive to small variations in dimensions and adjustments. The solution was found in maintaining tight tolerances and introducing shims in a few locations. A better solution would be to incorporate flexible elements. Small, well-designed flexibilities in the system will provide more predictable and more stable behavior.

Wear areas were found on the front face of the end effector after several tests (see Figure 8). These were caused by scuffling by the relatively sharp edges on the contact plates of the grapple fixture. The problem was solved by introducing a radius of 2 mm on the edges and the corners. A consequence of this was that the surface hardening of these contact areas was lost, at least on this development model.

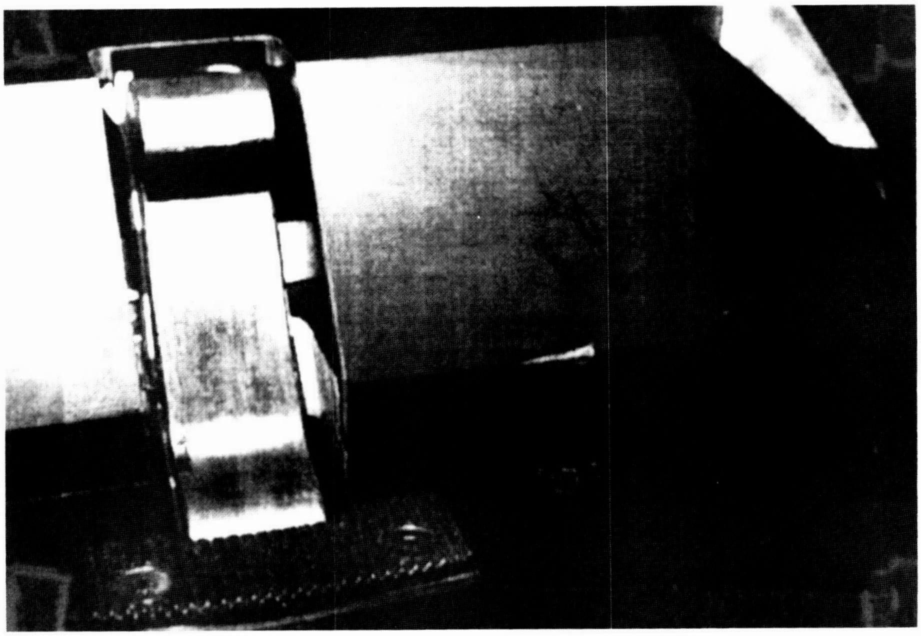

Figure 8. Scratches on the grapple fixture

Tribology

Duty cycle and lifetime

The lifetime of ERA on the Russian segment of the ISSA will be 10 years. In addition, a lifetime of 5 years for ground testing and storage is required. The duty cycle for ERA is heavy. It can be characterized by the following key parameters:

joints:
- 1000 hours running time
- 450 N•m maximum motor driving torque
- 750 N•m maximum braking torque
- 300 brake operations with maximum inertia

end effector:
- 2000 grappling operations
- 7000 N preload on each grapple hook

In addition, an extensive acceptance test program on subsystem as well as system level is foreseen. The design of the elements of ERA must take this test program into account. It is impossible to perform the complete test program in vacuum and almost impossible to provide flushing with dry nitrogen for all mechanisms. Therefore, the lubricants must be compatible with use in air as well as in vacuum. For the mechanisms within the joints and the end effector, the operational temperatures will span from -50°C to +80°C.

Gear tribology

The gearbox of the joint is heavily loaded and a long lifetime is required. Because of the precision required for the robotic functions of ERA, the gearbox is required to deliver a high stiffness and a very low backlash.

In the drive mode, i.e. the motor drives the movement of the joints, the torque losses in the gearbox must be minimized. The brake is connected directly to the motor, i.e. to the input axis of the reduction gearbox. In the braking mode, the variations in the backdrive behavior of the gearbox must be minimized to provide a predictable braking behavior. In practice, this means that the backdrive efficiency of the gearbox should be high.

The initial design consisted of a harmonic drive gearbox lubricated with sputtered MoS_2. The advantages of this design were the compactness, the virtual absence of backlash and the low weight. The forward drive efficiency was acceptable, but backward drive efficiency was marginal. The advantages of sputtered MoS_2 are the low friction in vacuum and the friction being almost independent of the temperature. Disadvantages include restrictions on in-air use and the release of wear particles inside the gears.

Two test models were produced. Both models were subjected to tests. This test program consisted of a duty cycle comparable to the acceptance test program. The tests were performed in air, because this is the most critical environment for MoS_2.

After the tests, the harmonic drives were disassembled and inspected. Scratches were found on the flexspline and on the outer gear surfaces. The MoS_2 had been removed locally (Figure 9). Although the gearboxes performed well until the end of the test program, the damage was considered unacceptable, and a change in lubricant considered necessary.

One option was to lubricate the harmonic drive with a grease. However, the efficiency of this combination will be lower; especially the backdrive efficiency at low temperature would be unacceptably low. Therefore, the design of the joints had to be changed more drastically. The new design of the joint includes a four-stage planetary gearbox. Braycote 601 is chosen as the lubricant. The advantages of the new design are the good forward and backdrive efficiency, the long lifetime, the reliability and the improved air-run capabilities. The disadvantages are the higher mass and the increased backlash.

To decrease the backlash of the planetary gearbox to the low level required for a robotic application, it was necessary to use extremely small clearances on the last stage. This makes the gearbox more sensitive to external moments and thermal loads. To overcome this problem, the last stage is supported with a radial flexible suspension. This reduces mechanical loads on the gearbox itself and prevents high thermal gradients within the gearbox. The design is currently in development stage.

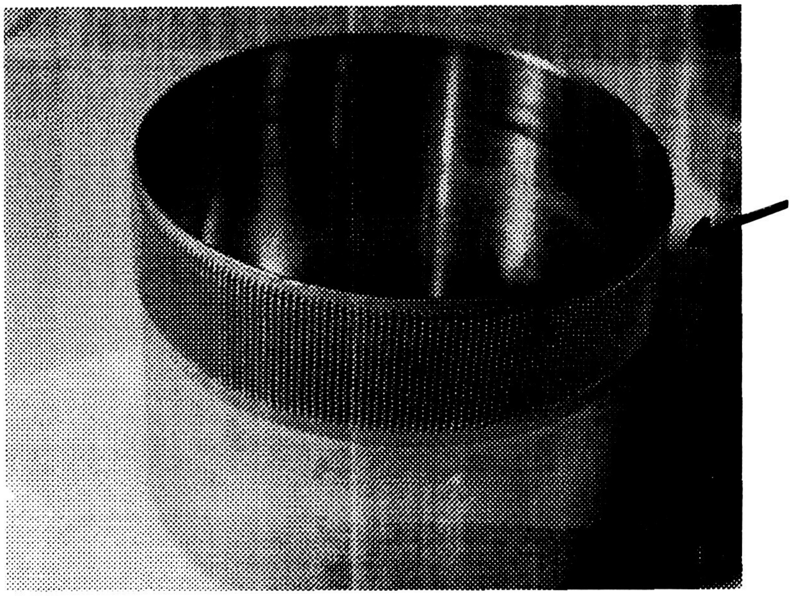

Figure 9. MoS_2 is locally removed from flexspline (scratch on right side)

Conclusions and recommendations

From the development efforts described in this paper, conclusions can be drawn that are applicable to the design of many space mechanisms.

- Start with a simple hardware model of the mechanism as soon as possible.
- If the mechanism includes complex movements, a 3-D CAD system can be useful to check the geometry in all positions.
- For high preloads, try to use flexible elements. This decreases the dependency upon tight tolerances, i.e. it improves repeatability of the preloads and reduces thermal sensitivity.
- When designing mechanisms, consider from the start:
  - The complete operating and survival environments. Ground testing or launch may very well drive the design.
  - Materials and lubrication must be selected as a combination. These two can not be chosen independently. A non-optimal combination may affect the performance of the mechanism more than expected.