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DESIGN OF A COMPACT TOOL EXCHANGE DEVICE FOR SPACE ROBOTICS APPLICATIONS

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INTRODUCTION

Robotic capabilities planned for planetary exploration or for ISS extravehicular operations generally require to use various kind of tools, ranging from socket driver and wrench tools, to parallel jaw gripper and dextrous robot hands, each designed to be used for a specific task. To allow a single robotic arm to mount/dismount each of them during an operational campaign, a properly designed device shall be used at the tool interface of the arm.

The development of the Compact Tool Exchange Device (CTED) is one of the several R&D activities that will prepare the technology for EUROBOT [1], a multi-arm robot complementary in capability to an EVA crewmember to be used for ISS extravehicular operations or for planetary explorations. CTED enables the exchange of End Effector / Tool while allowing signals and electrical power to pass from the arm to the Tool.

The CTED consists of two parts, one active part (CTED-R) fixed to the robot and several passive parts (CTED-T), each fixed to corresponding End Effector / Tool. The idea is that, once properly positioned by the arm, CTED should be able to perform, in an automatic way, the grappling and releasing of the passive side with the End Effector / Tool and the mating/de-mating of the electrical connection from the robot to the Tool.

Given the envisaged scenario, the most important aspects of CTED development are:

- minimisation of on-board resource usage, requiring a compact and lightweight tool exchange device;
- safety of tool exchange operation, with respect to inadvertent release of objects;
- high structural strength, to allow a stable and safe grip of the tool during operations;
- wide capture range, to allow the robot arm (in compliance mode) to compensate the initial misalignment before final locking.

SYSTEM REQUIREMENTS

The main requirements that have most importantly driven the design of CTED are summarized here below:

- Functional requirements:
  - ✔ The CTED shall provide interfaces to properly attach various gripper tools, among which a dexterous hand, a socket-driver tool, a wrench tool, and some EUROBOT tools;

- The CTED shall route from the arm to the End Effector / Tool one 28Vdc power line, one 28Vdc heater line, two CAN bus and six service lines.

- Performance requirements:
  - The CTED-R shall be able to capture CTED-T when the relative positional misalignment between CTED-R and CTED-T is less than 2mm in distance and 2.0deg in angle;
  - The CTED shall be capable to transmit a load of 300N and 30Nm;
  - If the robotic arm is used during Tool Exchange operations, the CTED shall not rely on more than 100N and 10Nm as actuation force / torque from the arm.
- Physical characteristics:
  - mass less than 0.8kg;
  - height less than 60mm height;
  - diameter around 100mm;
  - power consumption less than 20W during operations and 5W in hibernation state.
- Safety requirements:
  - space station safety requirements are applicable, particularly concerning robotic related hazards like inadvertent release of the End Effector / Tool and possibility of collision with other space station elements.

CANDIDATE CONCEPTS

An extensive conceptual design activity has been performed where four different CTED concepts have been analysed and a trade-off has been conducted. The four concepts are briefly described here below.

Concept 1

The locking effect of this concept is based on a ball cam migrated from industrial technology to space. The alignment is based on a tripod that aligns the two parts during their approach. When an axial motion is applied, the compliance in rotation and radial directions produces the cammed surfaces to align the two parts leaving only the axial degree of freedom. Once the two parts are aligned, the device is actuated by the axial motion of an inner cam that pushes the latch balls outwards until the locking is achieved.

The inner cam pushing out the balls has a final cylindrical contact surface, which produces irreversibility and isolates the actuation system from external loads. To reach the final position an enforced displacement is needed. The outer ring of the tool part is pulled by the balls storing the actuation as a preload in the leaf springs. Thus the tool exchange is not affected by thermal loads or small misalignments. Once the device is unpowered a preload remains, and the external forces cannot backdrive the actuation system.

The preload between the tool side and the robot side creates compression contact forces in the alignment features. The alignment features become the main load path from the device tool and robot interfaces independent from of the actuation system, with high stiffness and no gapping under axial, radial, bending and torsion loads.

The axial actuation is obtained by a ball screw and a stepper motor well thermally coupled to the structure. The axial movement produces also the mating of the connectors, which do not mate until the system is locked, through not fully preloaded.

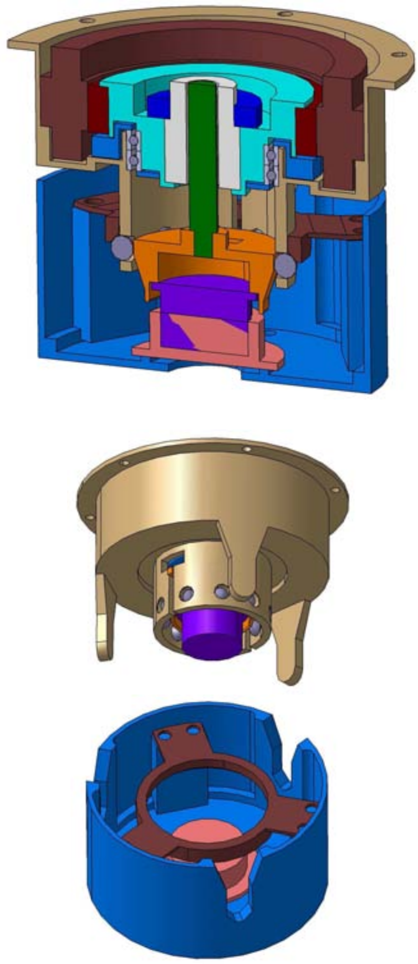

Fig. 1. Concept 1

Concept 2

Concept 2 mechanism consists of a linkage where three rollers spaced at 120° expand/contract inside the CTED-T interface, respectively grappling/releasing the CTED-T. Approach of CTED-R to CTED-T is carried out by the robotic arm until capture range is reached. During this phase active compliance of the arm and guiding elements such as the conical casing of CTED-R and the alignment cones shown in Fig. 2, are used to correct misalignments. Once in the capture range final locking is performed by the CTED mechanism.

The heart of the mechanism is the central sleeve connected to the rollers through a set of levers. Sleeve's upward/downward linear motion forces the rollers to grapple/release the CTED-T. The mechanism is designed to be in a near-singular configuration of the leverage to obtain the maximum effect of the high stiffness spring force to expand the rollers inside the CTED-T. This ensures the preload between the CTED-T and the CTED-R, necessary to avoid gapping during operations.

A low stiffness spring present in the configuration serves to maintain a soft lock during mating/demating of electrical connectors attached to the sleeve.

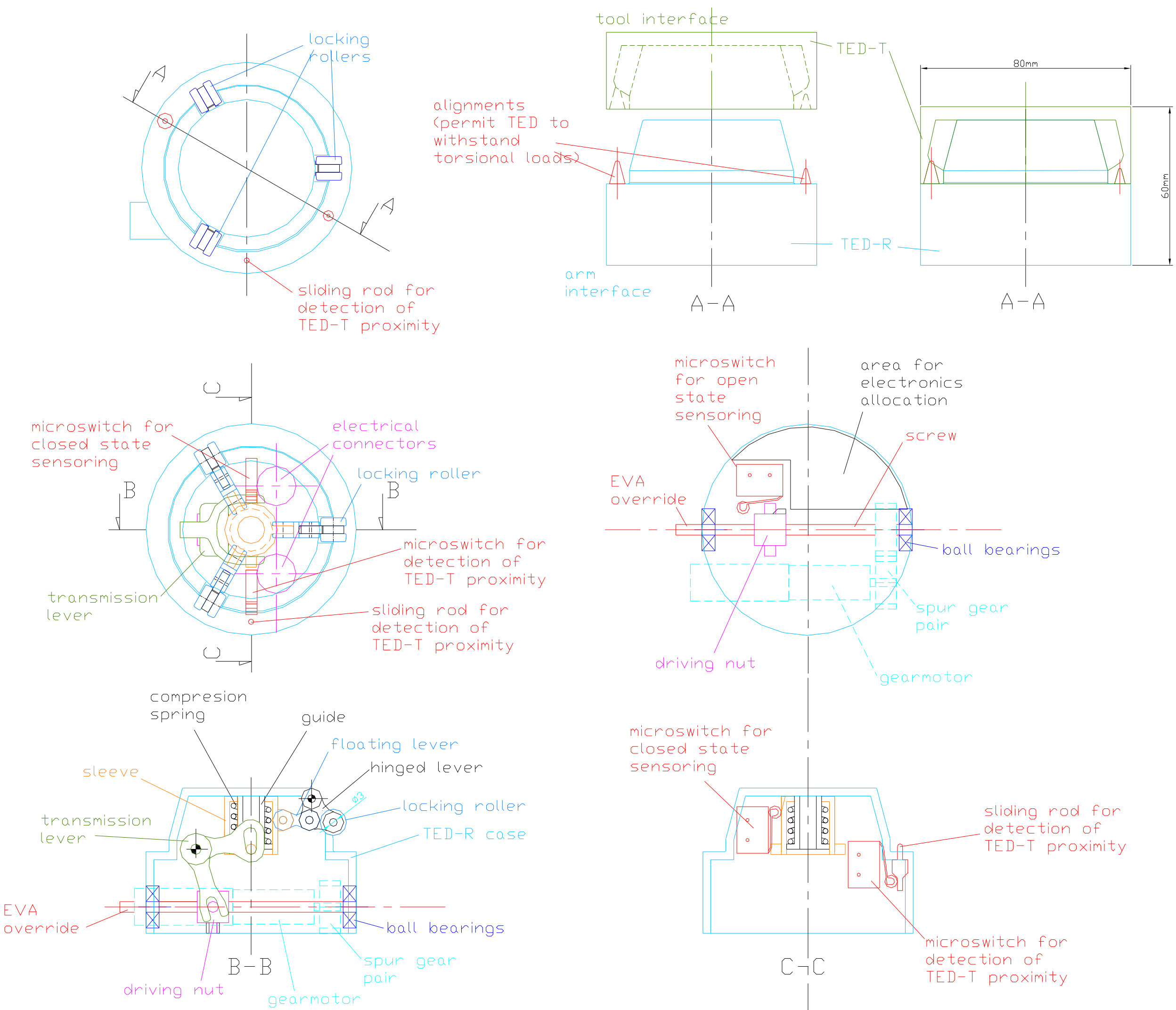

Fig. 2. Concept 2 general configuration and main components

Concept 3

Concept 3 is based on the use of a “tripod like approach” for capturing and alignment and a combined system of lead screw plus preloading spring for locking and connector matching. CTED-R is equipped with three engagement paths of male type to engage with female ones mounted on CTED-T.

Approach of CTED-R to CTED-T is carried out by the robotic arm, and leads to contact between these two parts. Once in contact, the alignment features guide CTED-R by inhibiting the two horizontal displacements and the rotation around vertical axis. The compliance for those DOF provided by the robot arm control strategy allows CTED-R to slide along the vertical axis. This action continues until CTED-R reaches its final position. Then the CTED-R DC brushless motor makes the protrusions mounted on the CTED-R central wheel to engage with a corresponding bar on CTED-T; such bar is mounted on the CTED-T screw-nut assembly, and its rotation allows to reach the preload required.

Two couples male-female 15 pin connectors are foreseen, which would be connected during the straight approach of CTED-R to CTED-T. Proximity and contact sensors are used to monitor the operation and for safety reasons.

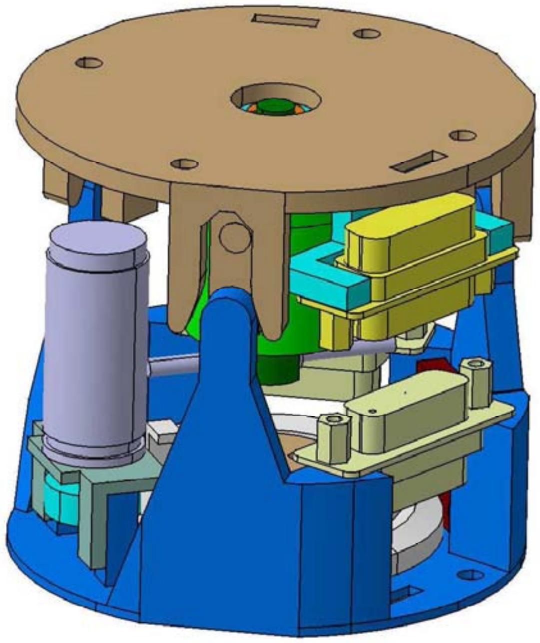

Fig. 3. Concept 3 overall view

Concept 4

The concept shown in Fig. 4 constitutes a completely mechanical actuated version of the concept 2 presented here above. The basic principle used for mating/demating CTED-T with CTED-R is an actuation system based on a cammed cylinder inside CTED-T, cam-followers and actuation rod inside CTED-R.

The actuation is provided by the rotation of the arm wrist. This provides a relative displacement between the cam and the cam followers to drive the actuation rod. The displacement of the actuation rod induces the expansion/retraction of the locking rollers of the CTED-R inside the CTED-T, thus providing the mating/demating between these two parts. Additional mechanical locking devices are foreseen on CTED-T to ensure locking between CTED-T and tool tray (the ball lock device), and CTED-R and CTED-T (locking mechanism for preloading).

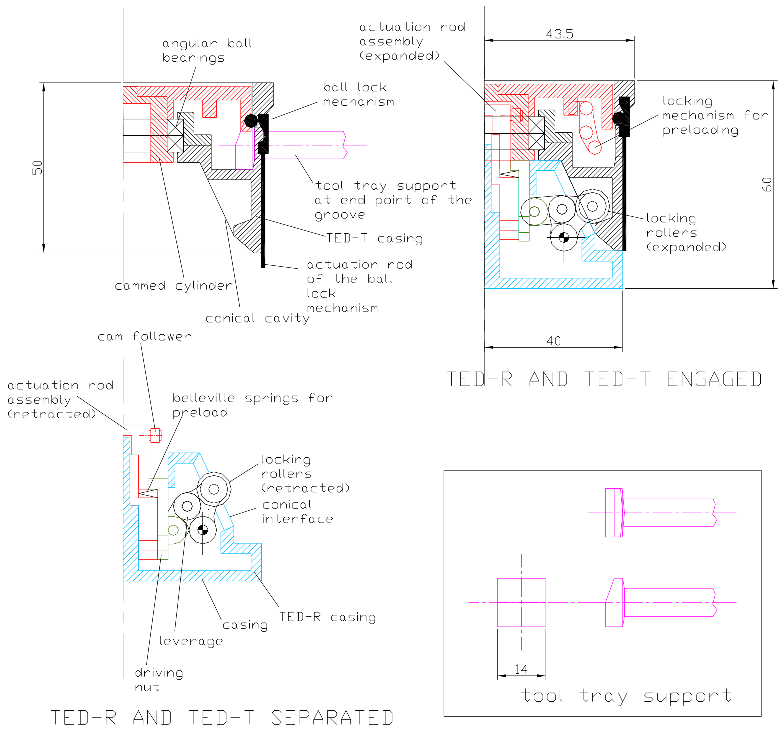

Fig. 4. Concept 4 general configuration and main components

TRADE-OFF AND FINAL SOLUTION

All the four concepts presented above are valid concepts for the CTED. Each concept is a design compromise trying to match the given requirements and particularly size, capability to withstand and transmit loads, mass, safety of operations, capture range and mechanism simplicity.
To select the most promising concept, a trade-off has been conducted in accordance with the following criteria:

- Capture range;
- Loads;
- Release-grapple cycle time
- Mass;
- Power;
- Volume;
- Dependability;
- Safety;
- Manual release mechanism;
- Actuation mechanism;
- Space environment compatibility;
- Technical risk / cost.

The trade-off results are presented here below.

In Concept 2 the presence of leverages increases mass and adds complexity to the mechanism. Leverages could help during the capture and alignment phase, to properly adjust the action from large capture movements to fine locking action. Since the first part of the capture and alignment action is performed with the aid of the robotic arm, the introduction of leverages seem excessive and other solutions seem to lead to more efficient and compact mechanisms.

Concept 4 is an interesting concept, because it does not need a motor and the electronics is simpler. However the mechanism itself is more complex and the associated risk is higher. Particular care should be taken to make the design robust with respect to thermal deformation, effects of friction/wear and to tribological aspects in general. More system level testing would be required to prove the concept.

Concepts 1 and 3 are both robust concepts based on well-known coupling principles. Concept 3 gets the best score on capture range and space environment compatibility. This is mainly due to the fact that it is more tolerant with respect to misalignments and thermal deformations, allowing some displacement between the bar and the protrusions in which the bar is engaged. Concept 1 gets the best score on loads and mass. It is the only one that allows separation between the external loads and the actuator loads. Once the spheres are engaged, no axial loads (on motor/screw) are present.

The final design solution has been obtained as a merge of Concepts #1 and #3, using a “tripod like mechanism” for capturing and alignment, and a combined system of linear motion that pushes outwards a set of balls for actuation and locking. An external view is shown in Fig. 5, while Fig. 6 shows the section view.

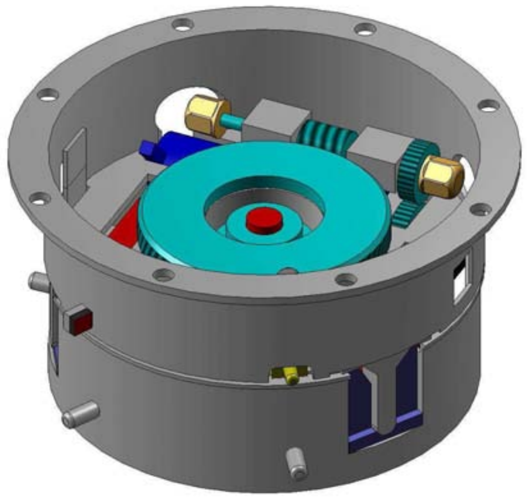

Fig. 5. Final Design overview

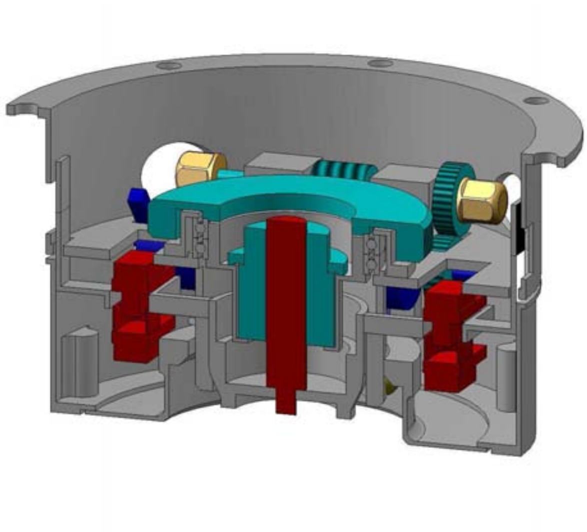

Fig. 6. Final Design section view

Capture and Alignment System

Approach of CTED-R to CTED-T is carried out by the robotic arm. Once CTED-R is at about 25mm from CTED-T, the robotic arm is switched into compliant mode for all axes except the axial directions of CTED. Approach continues to reach contact between CTED-R and CTED-T.
Once the parts are in contact, CTED-R tripod alignment features enter in the CTED-T caves that act as a straight slider. Thanks to the compliance provided by the robotic arm control strategy, alignment features' simultaneous action allows to align CTED-R w.r.t CTED-T while leaving the vertical displacement as the only possible movement. Then the robotic arm continues to push TED-R toward TED-T until each alignment feature has reached its final position at the end of the corresponding grove.

The locking principle is based on a tapered piston and locking balls mounted on a cylinder in the centre of CTED-R. Referring to Fig. 6, when the piston moves downward, it pushes outward the locking balls. During the last part of its movement, the piston has a cylindrical contact surface with the balls. This forces a preloaded hyperstatic configuration, and once latched the actuation system is isolated from the external forces; backdriving is precluded and the axial loads are transmitted directly from the CTED-T central cylinder to the CTED-R housing.
The actuation system responsible for engagement and latching also links the two red connectors, which occurs during the last part of the piston movement.

Actuation

Load requirements require CTED-R to retain CTED-T with a given preload force. Such preload is achieved by a DC Brushless motor plus gearhead. Such assembly moves a worm gear reduction, sustained by a preloaded bearing pair, which directly actuate the worm screw to move the central piston. Preliminary evaluations, made according to ECSS procedures, lead to select a motor having 3mNm as reference value for continuous operations.

Sensors

Some sensors are required to monitor CTED status during operations. The following ones have been selected:

- a proximity sensor used to measure the distance between CTED-R and CTED-T during the Capture & Alignment phase with a detection range that fully covers the entire 25mm movement;
- a spring sensor to monitor the CTED-T spring movement towards CTED-R allowing to detect the achievement of the given preload;
- a piston sensor to sense the axial movement of CTED-R piston for its entire stroke;
- a Tool Tray sensor to detect whether the CTED-T has been properly latched within its Tool Tray.

Electronics

The CTED is equipped with its local electronics that is implemented as a node on the system bus, receiving power and exchanging data. The electronics is in charge of performing the following functions:

- auxiliary power generation from 28 V power bus;
- data bus interface (CAN bus) for telecommands and telemetry;
- CTED actuator control;
- CTED sensors monitoring;
- housekeeping data acquisition;
- health function checks.

The electronics is implemented with one or two small circular boards connected by a flat cable and embedded in the CTED housing.

Manual Release Mechanism

In case a failure in the CTED motor would inhibit automatic operations, it shall be possible for an astronaut in EVA to manually operate the CTED mechanism. Such goal is achieved by two EVA interfaces available on two opposite sides of the CTED. Each interface, shown in Fig. 7, is made by an ISS standard interface bolt so that no dedicated tool is required beyond the ISS standard ones. A visual indicator of the internal status of the piston is also present near each bolt.

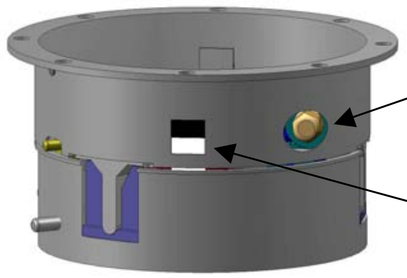

Fig. 7. Manual release mechanism

Safety Aspects

CTED's being a candidate for the use on the ISS implies severe safety requirements. They can be summarized into two main hazards:

- *Sharp Edges, Corners, Protrusions, Pitch Points*: since the CTED-R gets separated from the CTED-T during the operations, it is important to design the CTED such as to avoid sharp edges, corners, pinch points, etc. Proper design and proper selection of materials has been done to satisfy such requirements (e.g. smoothing of all potentially dangerous edges and corners).

- *Inadvertent Release of Tool*: this hazard is an important design driver because the inadvertent release of the tool is classified as a catastrophic scenario for the ISS. Risk mitigation is implemented by three conditions:
  - ✔ CTED-T can be removed from the Tool Tray only when it is safely grappled by CTED-R;
  - ✔ CTED-R can maintain a safe grappling of CTED-T when operating;
  - ✔ CTED-T can be released by CTED-R only when it is safely installed in the Tool Tray.

  The first two conditions are achieved by combination of mechanical design and proper monitoring of sensor status before execution of each task. The last condition is instead achieve by purely mechanical design by using a safety release spring which inhibits the release of CTED-T by CTED-R and is opened by the Tool Tray.

CONCLUSIONS

The design of CTED, described in this paper, has been derived considering different candidate solutions, gathering potentially different ideas and expertise on different fields, from precision mechanisms, compact electronics, robotics systems and space station safety. The main characteristics of the proposed solution are a tripod like centering path, for capture and alignment, a tapered piston, a compression spring and compression spheres for locking. Such solution is very compact and lightweight, at the same time complying with the functional, performance and environmental requirements posed by the application.

The CTED study has just completed the architectural design phase and the detailed design is going on. Final objective is the development of a prototype whose features and performances will be verified during a test campaign. The ability of the CTED system to perform in an environment similar to the worst conditions in-orbit will also be verified by replicating some tests in thermal vacuum chamber.

Another R&D activity on the way to EUROBOT is the development of DEXARM [2], a dextrous robot arm similar in size to a human arm. In perspective, CTED and DEXARM will be integrated together in the ESTEC laboratory, to demonstrate dextrous robotic operations with tool exchange capabilities.

REFERENCES

[1] P.H.M. Schoonejans, "*EUROBOT System Requirements Document*", ESA Doc. n. MSME-RQ-EB-0001-ESA, Issue 1 Revision 1, 6 April 2004.

[2] A. Rusconi, PG. Magnani, T. Grasso, G. Rossi, J.F. Gonzalez Lodoso, G. Magnani, "DEXARM - a Dextrous Robot Arm for Space Applications", *Proceedings of the 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation - ASTRA 2004*, ESTEC, Noordwijk, The Netherlands, 2-4 November 2004