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DESIGN AND DEVELOPMENT OF AN INTEGRATED JOINT FOR THE DEXTROUS ROBOT ARM

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INTRODUCTION

The development of a highly integrated and optimised joint is the first objective to be reached, in order to accomplish the demanding requirements of the Dextrous Robot Arm (DEXARM), a lightweight robot arm designed for space applications.

In phase 2 of the DEXARM project, an integrated robotic joint has been developed and tested. The key aspects of the joint design and the test results are presented in this paper.

DEXARM OVERVIEW

The DEXARM [1] project is focused on the design and development of a robot arm comparable in size, force and dexterity to a human arm. The objective is to prepare the technology for future missions and applications, like external or internal servicing of orbiting platforms or robotics for planetary exploration. The first user programme currently envisaged for DEXARM is EUROBOT [2], a three-arm robot complementary in capability to an EVA crewmember, to be used for ISS extravehicular operations, like crawling along the space station structure utilising standard EVA interfaces, execution or support to routine EVA tasks, removal and replacement of ORUs, assistance in contingency operations that require EVA.

Beyond the design constraints posed by the tough space environment, the main challenges of this development lay in the minimisation of resources (mass, volume and power) that the applications require. To achieve this goal, ESA has encouraged the exploitation of innovative approaches and technologies to drastically minimise mass, volume and power consumption while providing adequate performance (output torque capability and positioning accuracy/repeatability).

The DEXARM project has been divided in three phases. The first two phases have been focused on system requirements, arm architecture, design and development of a joint prototype. The third phase, currently in progress, is the development of an engineering model of DEXARM (Fig. 1 shows the preliminary configuration, which is currently being finalised).

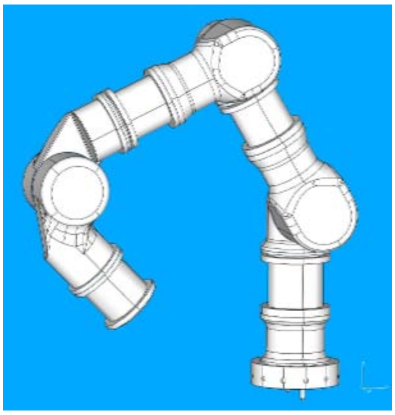

Fig. 1 DEXARM preliminary configuration

JOINT CONFIGURATION

In a robot arm with a size comparable to the human arm, a large portion of the mass is allocated to the robot joints. From this consideration, it is clear that that in order to accomplish the demanding resource requirements, the development of DEXARM was first focused on the development of an optimised joint.

In phase 2 of DEXARM project, a prototype of an intermediate class joint (elbow type) has been developed and tested. The components selection and arrangement have been studied throughout the activities in order to optimise joint simplicity and performance. The result is a highly integrated mechatronic joint, with a minimum number of structural parts, where all the components are tightly integrated together to minimise mass and volume requirements.

The complete joint integrates together the mechanics and the electronics as shown in Fig. 2.

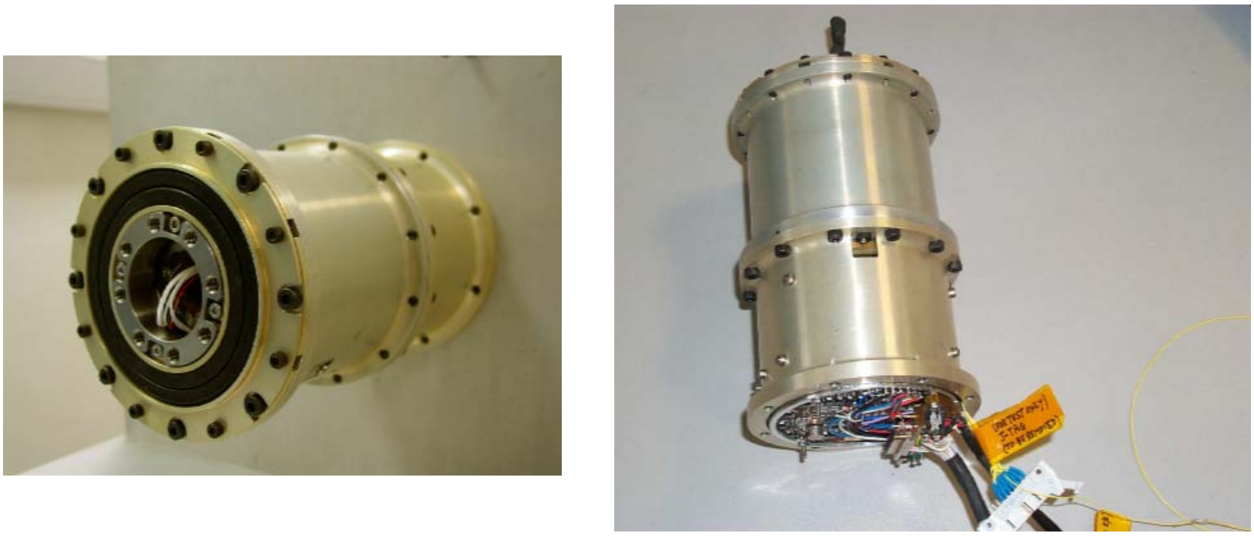

Fig. 2 Joint prototype overview

The integrated joint key performance characteristics are summarised in Table 1.

Table 1 Integrated joint (mechanics + electronics) characteristics

Parameter	Value	Notes
Mass	2.9 kg	
Size (overall encumbrance)	D = 112 mm, L=175.2 mm	
Central hole for cable passing	D=16.5 mm	
Maximum output torque	100 Nm	
Worst case power consumption	20 W	at 100 Nm stall condition
Nominal power consumption	7.7 W	0g at 0.1 rad/s
Minimum output shaft speed	6.3e-6 rad/s	
Maximum output shaft speed (at no load)	0.5 rad/s	
Positioning accuracy	0.01 deg (1.74e-4 rad)	
Positioning repeatability	0.00016 deg (2.8 e-6 rad)	
Operative temperature	from –30 °C to +70 °C	
Non-operative temperature	from –55 °C to +125 °C	

A description of the main design aspects and joint components is given here below.

Electro-mechanical components

Motor

DC brushless motors are the candidates for the application of the DEXARM joint (robotic application: closed loop control), because they offer many advantages with respect to other solutions like brushed motors and stepper motors. A customised version of a rare earth permanent magnet motor has been developed, in co-operation with the manufacturer. This motor can achieve a high torque density by means of an innovative stratified winding system (ideally suited to the realisation of very short torque or pancake motors) and non laminated soft magnetic materials.

Brake

The classical approach of electromagnetic fail-safe brake has been taken. The chosen solution allows the tuning of the braking torque capability (and therefore of power need).

Gear

The gear is one of the core components of the joint, since it drives the torque capability, accuracy, size and life of the joint. The selection of the gear type to be used in a robotic joint is based on the torque capability at output shaft, geometrical envelope and compactness, lifetime and duty cycle in space, reduction ratio and thermal performance. Due to the stringent torque needs of DEXARM, a high reduction ratio is mandatory. The Harmonic Drive™ technology is capable to achieve the highest reduction ratio in one single stage, as well as the highest torque/mass and stiffness/mass ratios and the lowest backlash. For this application, one of the most recent versions of Harmonic Drive gears has been employed, allowing for very limited thickness, to help reducing axial encumbrance of the joint.

Bearing system

Bearings for the joint must be carefully selected since they are critical components in the interface between the rotary and the stationary part of the joint, and can drive the maximum loads to be supported by the joint. In addition, these elements are needed to ensure the required stiffness and strength during both launch and in-orbit environments along with the needed lifetime. Bearings at the output shaft must ensure a high stiffness, since they are in direct contact with the load, as well as being able to support combined radial and axial forces and bending moments. A preloaded pair of ball bearings has been employed for the output shaft, assembled on a structural case common also for the reducer circular spline fixation and motor stator fixation. This allows:

- high accuracy in performance since assembly misalignments are minimised;
- high stiffness since structural paths provide less discontinuities;
- reduction of bolted joints.

With respect to the input shaft, bearings must support reverse thrust loads to ensure good performance of the Harmonic Drive, the level of radial loads and bending moments not being significant. Super-duplex ball bearings have been employed for the high-speed part of the joint.

Sensors

For robotic applications where a control loop concept is used to control the robot output at every condition of movement, a position sensor must be joined to the motor, to provide motor commutation and to actively control motor velocity (to damp high frequency oscillations). Additionally, another position sensor is needed to control the joint output position. A driving requirement for the selection of the position sensor is the angular accuracy. Moreover, the lifetime and the environmental conditions are important requirements to be considered, along with the need for minimum mass and volume. Several encoder technologies have been considered (optical, magnetic, electrical), together with other options such as resolvers, potentiometers or inductosyns.

As a motor position sensor, a low weight and low inertia electric encoder has been employed, capable of providing accurate shaft position information so to implement a very good sinusoidal commutation and velocity control. The utilization of Hall linear sensors would also allow for motor shaft position information to support both commutation and speed control and a saving in joint length likely achieved; however, motor performance in commutated mode, would degrade with respect to a true shaft position sensor.

As output position sensor, a resolver has been employed, with a large central hole allowing a very high output shaft stiffness (transversal and axial) and not requiring excessive mounting accuracy in the relative position of its rotoric part with respect its statoric part (therefore being not too sensible to the output shaft deformations under high load conditions). The utilisation of the electric encoder as output shaft sensor, instead of the resolver, was considered but then not pursued mainly due to a sensibly lower internal diameter which may affect the output shaft stiffness and due to some more constraints in the sensor rotor mounting.

Torque acquisition is also required in DEXARM joints in order to determine the actual torque being delivered by the joint. Torque sensors are used in combination with a torque control loop so that non-linearities (cogging, backlash, friction) derived from mechanical components and other elements can be compensated. The torque sensing has been implemented by means of four strain gauges organised in full bridge, applied to the ribs of a duly machined output flange. The optimum design of the output flange with torque sensor is a trade-off between the sensing accuracy and the stiffness of the joint and load capability, since these two requirements are directly in opposition. The choice was to design a robust output flange, with a stiffness at least five times higher than the Harmonic Drive stiffness, and to obtain the required sensor accuracy through the use of a high performance instrumentation amplifier in the acquisition electronics.

Thermal design

The thermal design of the joint has been driven by the following guidelines:

- the important power dissipative item (motor stator) in the electromechanical part of the joint is directly connected to the outer case to reduce the thermal path resistance to the outer environment;
- the important power dissipative items (power MOSFET) in the electronics part of the joint are tightly connected to the outer case to reduce the thermal path resistance to the outer environment;
- the remaining parts (both electromechanical and electronics) are thermally verified based on the specific interface approach utilized.

Electronics

The joint electronics is integrated in the joint itself, by means of three circular boards, interconnected with flex cables, and is schematically shown in Fig. 3.

Each joint electronics is a node on the DEXARM power (28 V) and data bus (CAN bus). This distributed architecture, with the electronics incorporated into the joints, eliminates the need for multi-wire cable harnesses, thereby saving system mass and increasing system reliability, improves robustness with respect to EMC, having joint electronics located close to the sensors and the actuators, and still provides the needed data exchange frequency, satisfying control system bandwidth requirements. The three boards are respectively in charge of the following main functions:

- generation of auxiliary voltages from 28 V power bus;
- motor and brake driver, motor and brake current acquisition;
- position and torque sensor acquisition, CAN bus interface and DSP based joint control.

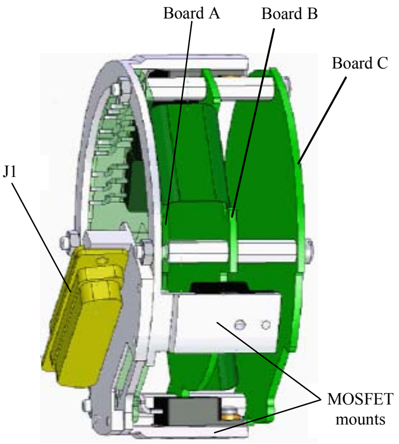

Fig. 3 Overview of joint electronics

The electronics design is complete also in terms of additional features that will be needed at arm level, as:

- a safety chain, to immediately stop the arm whenever a fault condition is detected;
- a dedicated brake release line, which allows to release the brakes by means of a redundant circuit, to be used to manually backdrive the arm when a failure on the control system prevents nominal joint motion.

The pictures of the three electronic boards, laid on a plain and folded, are shown in Fig. 4.

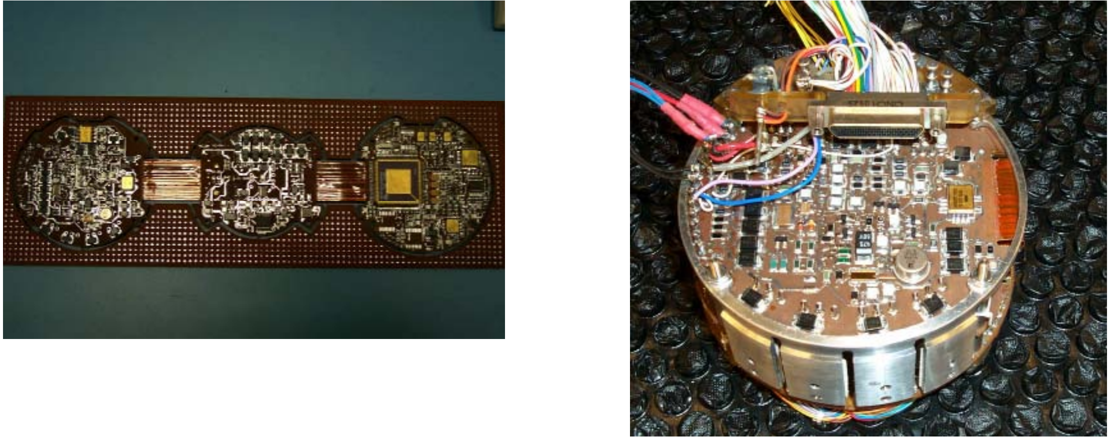

Fig. 4 Joint electronics boards, laid on a plain and folded during integration

The design of the electronics has been very challenging and several design iterations were needed to reach the required dimensions and to optimise power consumption. The components mounted on the prototype are as a minimum of industrial type, with existing flight equivalent in the same package. This means that the board layout, apart from minor modifications, is already suitable for mounting flight components.

Cabling

The joint is designed with a hollow shaft to allow central cable passing. The cable recovery is implemented inside the joint hole by means of longitudinal cable enrichment and clamping system.
The joint prototype has been developed taking into account the full bundle of cables that will be needed at arm level, including power and data bus, service cables, safety chains and brake release for manual backdrive. All these electrical interfaces have been implemented and are operational.

Joint servo control

The joint control software, installed in the electronics, implements the following functions:

- receive and execute commands through the CAN Bus;
- transmit status and housekeeping data through the CAN Bus;
- acquire sensors;
- perform motor commutation and motor current control at 20 kHz (50 µs);
- perform position, velocity and torque control at 2.5 kHz (400 µs);
- drive and control the brake;
- implement safety checks (speed and torque).

In the joint control software, the following control modes are available:

- Position control with inner velocity loop, described in Fig. 5;
- Position control with inner torque loop, described in Fig. 6 (impedance control is a special case of this mode);
- Torque control, described in Fig. 7.

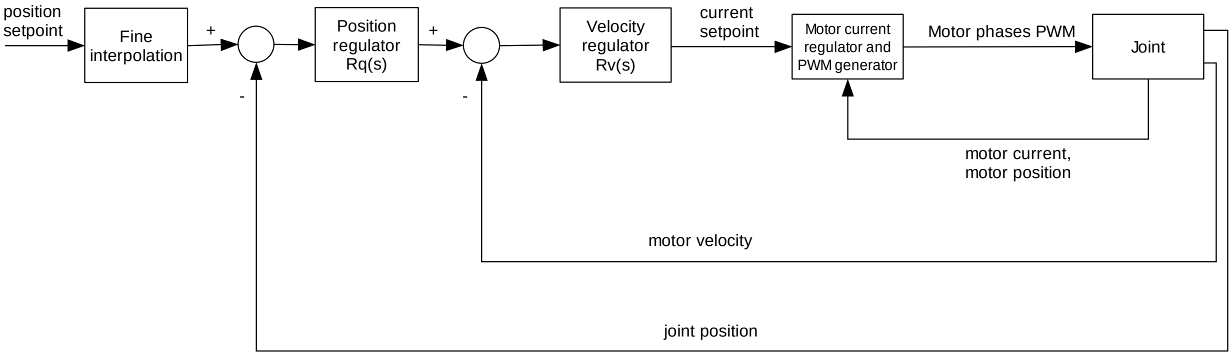

Fig. 5 Position control with inner velocity loop

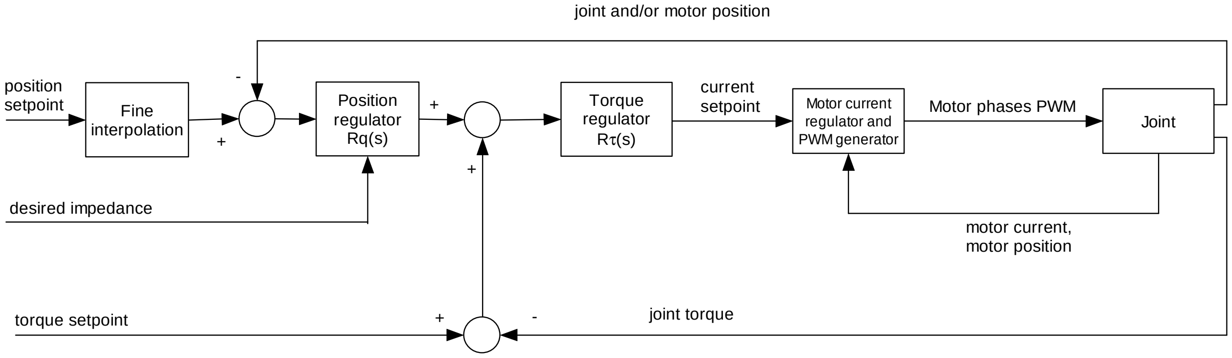

Fig. 6 Position control with inner torque loop

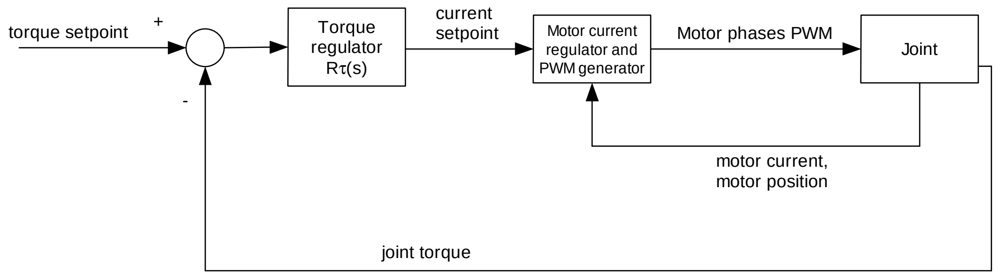

Fig. 7 Torque control

The theoretical and simulation work performed ([3], [4]) has indicated two strategies for non-contact motion:

- position control with inner motor velocity loop;
- position control with inner torque loop.

Position control with inner motor velocity loop provides a very smooth motor velocity, good for microgravity environment (minimum microgravity disturbance). Joint position control performance decreases for high inertia.

Position control with inner torque loop gives higher oscillations on motor velocity, but provides a joint position control performance which does not depend on load inertia. This can be beneficial when DEXARM is required to carry large payloads (100-500 kg) where large variation of inertia can be expected during robot motion.

In fact, if an inner torque loop is cascaded to the outer joint position loop, the control performance is little dependent on load inertia, provided that the position controller is retuned for each specific load. On the contrary, if an inner motor velocity loop is used, the performance can decrease for higher loads even if the position controller is properly retuned.

For contact motion, the following strategies are available:

- joint position loop, to support implicit impedance control at Cartesian level and mixed schemes controlling joint impedance (by simply setting the position loop parameters in accordance with the desired impedance);
- output torque loop, to support explicit impedance and hybrid control at Cartesian level.

JOINT TEST SET-UP

The actual performance of the joint has been measured by means of the test equipment (MGSE/EGSE) shown in Fig. 8.

The joint is mounted on a support structure (MGSE), while the output shaft is connected with an external high precision encoder by means of a very stiff shaft. This shaft can be connected to an external load.

Five configurations are available:

- Unloaded, free motion configuration;
- Asymmetrical bar for external load applications;
- Symmetrical inertia bar;
- Hard stop configuration (allowing free motion until a hard stop is encountered);
- Locking flange for fully locked joint configuration.

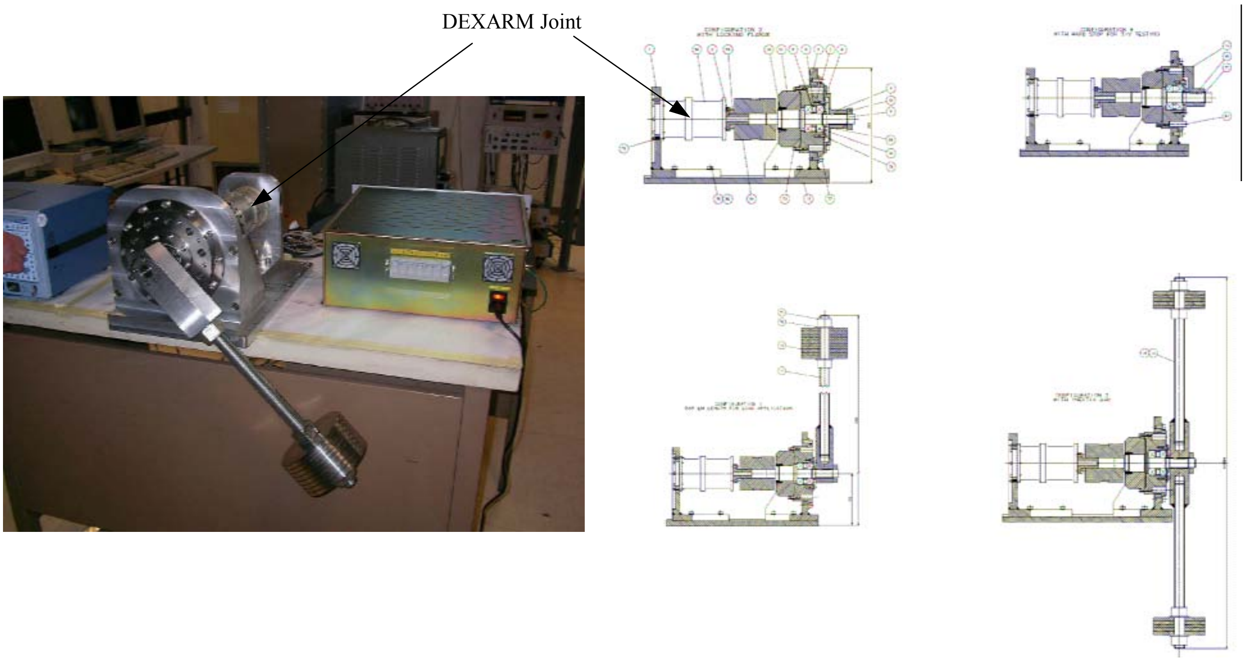

Fig. 8 Joint test set-up

JOINT TEST RESULTS

The joint prototype has been subject to an extensive test campaign. The following set of tests have been performed:

- Mass and dimension properties;
- Power consumption;
- Electrical tests;
- Functional and performance tests: communication protocol (TC/TM over CAN bus), current loop, velocity loop, position loop, trajectory execution, accuracy, repeatability, stopping distance and stabilisation time, angular range, torque loop, manual backdrive, stall torque, stiffness, capability to hold position against external load.

The tests conducted have shown a very good behaviour. The functional performance has been verified in laboratory environment and under the specified operative thermal conditions, i.e. between –30°C and +70°C.

The figures below report some brief examples of the test results.

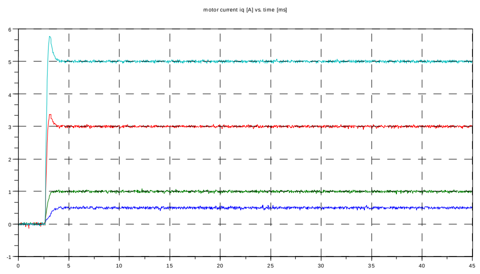

Fig. 9 Motor current step response

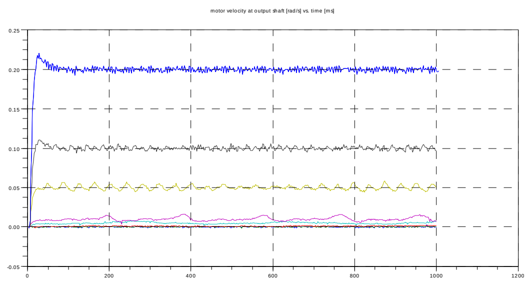

Fig. 10 Motor velocity step response

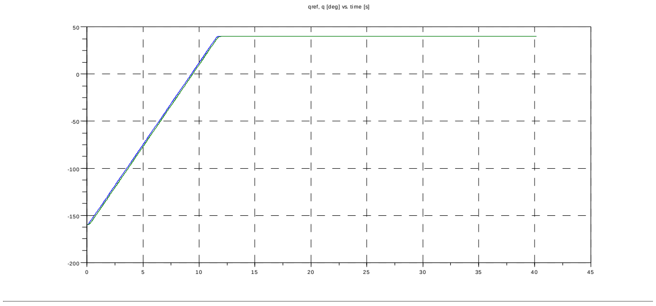

Fig. 11 Trajectory execution

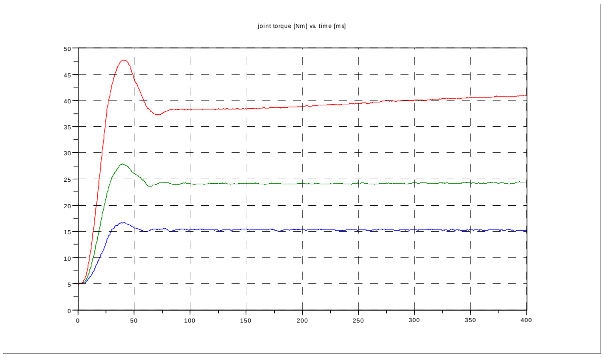

Fig. 12 Joint torque step response

The step responses show satisfactory performance for each control loop; an additional improvement can be expected when a more extensive tuning will be conducted for the seven arm joints in phase 3. By an appropriate utilisation of the motor and output position sensors, the joint can perform smooth and accurate trajectories through a wide velocity range, from a very low velocity of 6.3e- rad/s (practically there is no lower limit) to the required maximum velocity of 0.3 rad/s (if needed, the motor itself allows up to 0.5 rad/s).

The choice of implementing the torque measurement in a “highly” stiff output flange led to a robust mechanical design. The sensitivity of the strain gauge measurement system resulted anyway good for guaranteeing torque control loop performance. The impact test (conducted for testing the torque loop) showed a stable impact and no bouncing. The manual backdrive test (either in torque control mode or in brake release mode) showed that it is possible to easily move the joint by hand.

CONCLUSION

A prototype of DEXARM joint has been developed in phase 2 of the project.
The design has been based on the choice of high performance electro-mechanical components, customised where necessary to minimise mass and dimensions. The integration of the components in their structural case has been carefully designed, to minimise assembly misalignment, providing high accuracy and high stiffness.
The joint has been equipped with position and torque sensors, providing the needed sensory information for very good sinusoidal commutation and motor speed control, joint position control and joint torque control.
From the thermal points of view, the important power dissipative items have been directly connected to the outer case to reduce the thermal path resistance to the outer environment.
The complete joint integrates together the mechanics, electronics and control software. It provides a central hole for cable passing, with a cable enrichment and clamping system, to compensate for the joint rotation. Power, data, cabling and connector interfaces as required in the final robot arm configuration have been implemented and are operational.

The joint has been subject to an extensive test campaign. The functional performance has been verified in laboratory environment and under the specified operative thermal conditions, in thermal chamber.
The result is an integrated robotic joint with very good performance, in a design configuration that is complete and scalable into the three different joint sizes (shoulder, elbow, wrist), as needed to accomplish the development of the Dextrous Robot Arm.

REFERENCES

[1] A. Rusconi, P. Magnani, T. Grasso, G. Rossi, J.F. Gonzalez Lodoso, G. Magnani, “*DEXARM – a Dextrous Robot Arm for Space Applications*”, Proceedings of 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation - ASTRA 2004, ESA/ESTEC, Noordwijk (The Netherlands), November 2004.

[2] P.H.M. Schoonejans, R. Stott, R, F. Didot, A. Allegra, E. Pensavalle, C. Heemskerk, “*Eurobot: EVA-assistant robot for ISS, Moon and Mars*”, Proceedings of 8th ESA Workshop on Advanced Space Technologies for Robotics and Automation - ASTRA 2004, ESA/ESTEC, Noordwijk (The Netherlands), November 2004.

[3] G.Ferretti, G.Magnani, P.Rocco, A.Rusconi, L.Viganò, “*On the Use of Torque Sensors in a Space Robotics Application*”, IROS ’05 conference, Edmonton (Canada), August 2005.

[4] D. Camorali, G.Magnani, P.Rocco, A. Rusconi, *“Position/torque control of a space robotics arm”*, 4th IFAC Symposium on Mechatronic Systems, Heidelberg, Germany, 12-14 September 2006, pp. 283-288.