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Design and development of a joint for the Dextrous Robot Arm

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ABSTRACT

The Dextrous Robot Arm (DEXARM) is a robotic arm which can be used for various Space robotics applications in which the manipulation/intervention tasks were originally conceived for humans. These applications are typically:

- external or internal servicing of Space Station platforms
- robotics for planetary exploration.

DEXARM's first application is planned to be serving as an arm of the Eurobot robotic system. The Eurobot system concept requires a robotic arm with 7 DoF (Degrees of Freedom) including a spherical wrist. The overall dimensions and the loading capability are similar to a human arm. This paper concentrates on the development of the joints, as their integration and packaging is the most crucial point for the development of the arm.

INTRODUCTION

The International Space Station (ISS) requires Extravehicular Activity tasks in order to support several activities, including the upcoming ISS assembly missions, maintenance, servicing, and repair of the ISS and other large space structures, maintenance, servicing, and repair of ISS payloads and experiments, removal and replacement of Orbital Replaceable Units (ORU), and for contingency operations.

A robotic system complimentary in capability to an EVA crew member would benefit all of these aspects of ISS extravehicular operations. Such a system would decrease the workload on an EVA crew member, thereby increasing the overall safety of the ISS crew and saving valuable consumables (O2 and N2) and crew time. A robotic system comparable in size and capability, including anthropomorphic arms, would fulfill these support needs.

For planetary missions (Moon, Mars) it is equally important to have a robotic system or a robotic arm to do EVA-type work when no human crew is being flown yet, or cooperative work in a later stage when there is crew. The robotic arm will be prepared for such interplanetary missions as well.

These topics are being followed up by the EUROBOT project, where a robot with anthropomorphic arms is being developed. The EUROBOT system concept requires a robotic arm with 7 DoF (Degrees of Freedom). The overall dimensions and the loading capability are similar to a human arm, as shown in Fig. 1.

Fig. 1 DEXARM overall view

The three main areas of development have been so far:

1. the limbs
2. the joints
3. the joint control and
4. system level design

The limbs function is to form the mechanical and thermal connection between the joints. They are planned to be realised of a CFRP (Carbon Fibre Re-enforced Plastics) structure due to its light weight and high – and tunable – stiffness and strength properties paired with the possibility to design very different shapes. CFRP has been utilised on many space projects and thus very thorough material databases are available.

The mechanically most complex parts of the arm are the joints. They have to incorporate high load capacity on a minimal space, accompanied by additional functions such as braking, power/signal transfer lines and manual actuations (e.g. If the robot stops functioning and the arm needs to be manually reset to another position). In addition, in order to minimise the complexity of the central control unit, local drive electronics and sensors are inevitable. The design, development and testing of one joint within the DEXARM project will be presented in more detail in this paper.

An appropriate control electronics is required to move the arm. This electronics can be broken down into Command Interface, Processing & Logic, Motor Driver and Sensor Interface, as shown in Fig. 2. Each of these main functions is integrated on its own CCA (Control Circuit Assembly) that will be mounted at the "fix" part of the joint and will be hidden within the limb in the final design. For the DEXARM Project, CSEM has integrated and tested very successfully the control electronics, together with a sophisticated graphical user interface for the testing.

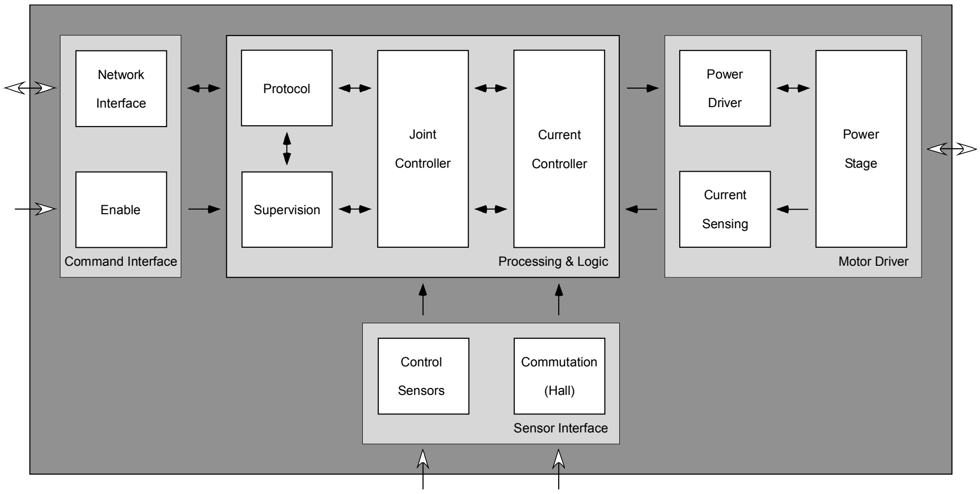

Fig. 2 DEXARM controller overview

Of course, the system level design of the arm is most crucial. Operation ranges, force deduction to limb and joint level, stowage and many further aspects need to be verified and designed properly. The presented concept in Fig. 1 evolved out of thorough investigations that was done in cooperation with Dutch Space. The following baseline parameters evolved from this work.

Tab. 1 DEXARM main performance parameters

Work range (stretched / sideways)	> 1.00 m / 0.86 m	Unidirectional pose accuracy	< 1.0 mm
Peak holding force	> 400 N	Unidirectional pose repeatability	< 0.4 mm
Peak moving force	> 200 N	Multi-directional pose accuracy variation	< 1.0 mm
Continuous moving force	> 100 N	Linear end-effector speed (arm used as a leg in walking configuration)	< 0.1 m/s
Static compliance	> 1.0E5 N/m	Frequency to receive position, velocity or torque setpoints	100 Hz
Overall positioning accuracy (in 0-G) within the operating temperature range	< 2.0 mm	Mass	< 27 kg

A further outcome from the system level considerations was to inherit only three sizes of joints into the arm in order to minimise design, development, manufacturing, assembly and testing efforts and thus costs, as shown in Fig. 3. The following sizes are taken:

Tab. 2 DEXARM joint sizes

	Large	Medium	Small
Location	Shoulder (Roll – Pitch)	Elbow (Roll – Pitch)	Wrist (Roll – Pitch – Roll)
Size (Outer Diameter / Length [mm])*	128 / 143	114 / 117	114 / 108
Peak Torque [Nm]	238	157	72

* without electromagnetic brake since it is planned to substitute them for the flight models by other means

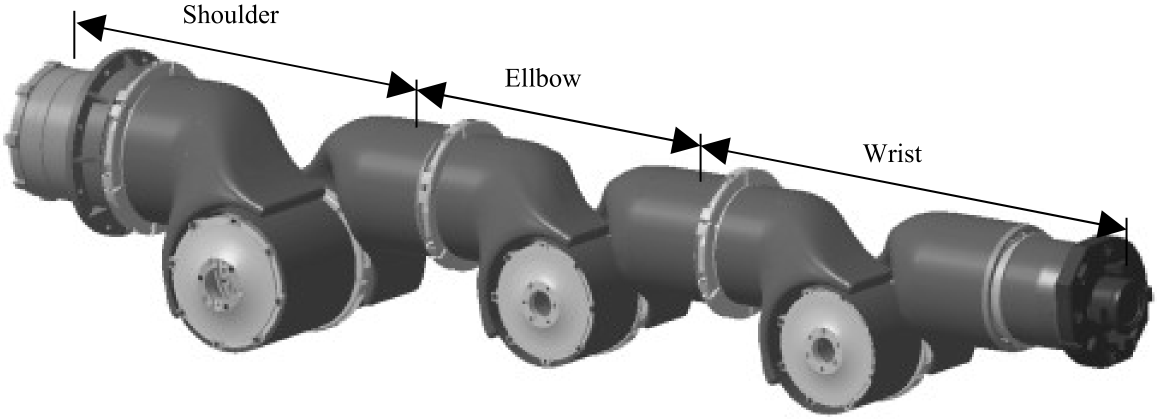

Fig. 3 DEXARM components and location of the joints

As the large joints are the most demanding ones in terms of required torque and stiffness to size ratio, Contraves Space decided to detail out fully the large joint and manufacture a full scale EM (Engineering Model) of this joint. The next section gives an overview on this joint design, followed by a section on the verification logic and the testing of this joint.

DEXARM JOINT DESIGN

Design Overview

The design of the joints is based on a modular concept, that allows to manufacture and test the joints separately from the limbs. Hence, each joint is integrated into its own housing, with clearly defined mechanical, thermal and electrical interfaces.

The joint features a frameless brushless DC-motor, a brake, a compact Harmonic Drive, a lightweight electric encoder on the output axis, a torque sensor and a hard stop system.

The hollow shaft design enables the feedthrough of the main bus systems. The central helical harness includes a power and signal bus and also routes the signal cables of the torque sensor to the joint controller. Therefore, no slipring or cable drum is required.

The brushless DC-motor includes hall sensors for monitoring the rotor position. The motor drives the Harmonic Drive gearbox with a gear ratio of 1:160. The Harmonic Drive rotates the Output Shaft and the motor can be blocked by the passive brake on the outer side.

On the Output Shaft, strain gauges are applied which are used for torque measurement. The Encoder Support contains a hard stop system with an extended joint range of up to 400 deg. It also holds the electric encoder. At this location the flexibility of the Harmonic Drive and of the thin-walled section of the Output Shaft will be compensated; due to the fact that the encoder rotor is attached to the very stiff structure of the Coupling Disc and the Output Housing, the position measurement done by the encoder takes the main deflection of the joint into account and is thus very accurate.

The torque is transmitted by the Coupling Disc to the Output Housing. On the Output Housing an interface is provided to mount a limb, located directly above the main bearings. The other limb will be attached to an interface situated on the Motor Housing.

The joint control electronics is not shown in the figure. It will be mounted to the flange of the brake housing.

As mentioned above, the large joint has been selected to be designed, manufactured and tested as a EM in the initial study phases. In order to be able to develop the three different joint sizes in an effective manner and in a short schedule, the design of the largest joint relies on components that are available in different sizes. This ensures the scalability which is necessary to get a mass-optimised system.

A view on the overall design is given in Fig. 4.

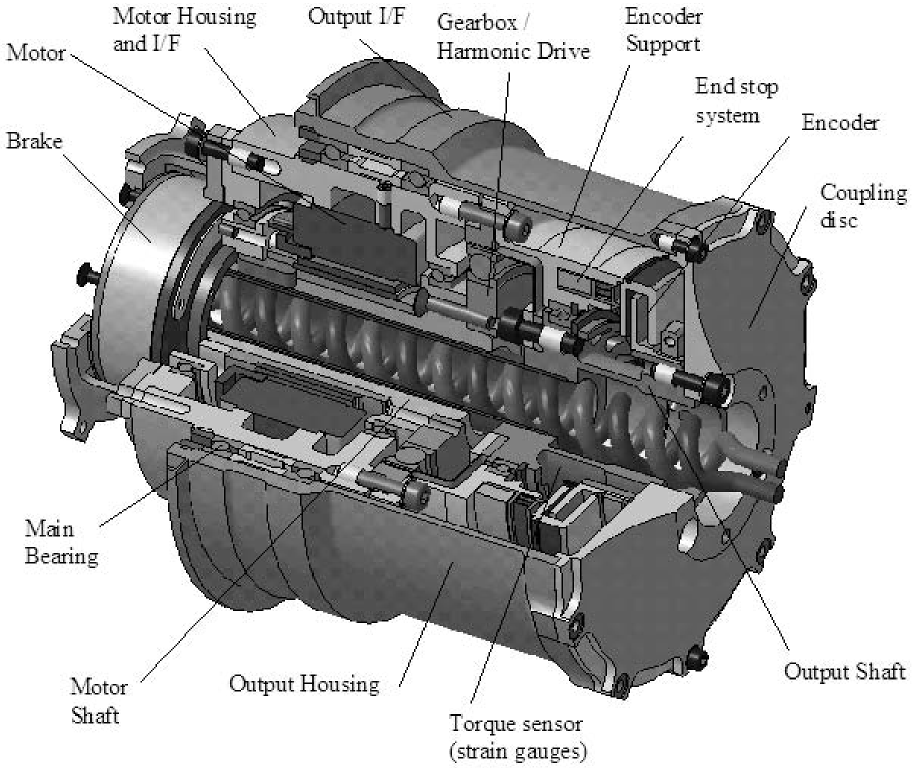

Fig. 4 DEXARM large joint cut view

Selection of the components

In order to achieve a technically feasible solution in a short time and cost effective manner, it was important to rely on known components and technologies. The establishment of a design baseline for the drive units was therefore focused on selecting components available on the market. As far as possible, components and suppliers have been selected, who have heritage with space compatible designs or are willing to enter this field.

The following components/features are implemented into the joint design:

- *Motor:* A brushless DC motor is selected from Kollmorgen motors. Maccon (its supplier) has extensive space heritage (e.g. EuMetSat, Biolab, PATS, LCTSX, MHS, FY-3). The selected motors have a driving torque range compliant with the peak torques mentioned above.

- *Gearbox*: Harmonic Drive does also have space heritage. Examples for recent space projects using Harmonic Drive gears are Mars Explorer, ISS JEM and SADM's (Solar Array Drive Mechanisms, e.g. SARA 21 and SEPTA series, that have been recently taken over by Contraves Space). A 160:1 gear ratio is used.
- *Bearings*: Kaydon ball bearings were used in various space projects. Examples are: Mars Rover, Apollo 15 Lunar Rover, Hubble Telescope, Canadian Robot Arm. The bearing size is adapted to the need.
- *Encoder*: The encoder is based on a capacitive measuring technique and has a simple and robust design. These encoders are available in MIL standards. Netzerprecision – which is the only supplier of this type of encoder – is interested in a space qualification program. Considering the close collaboration of Netzerprecision with Contraves Space, the design and qualification of a space compatible encoder is feasible at a later stage.
- *Joint Control Electronics*: The current boards of the EM are commercial standard. However, known electronics manufacturing companies can be selected for the space compatible version later on. The joint control electronics consists of four CCAs as discussed previously. They are attached to the brake interface.
- *Brakes*: A passive brake from Kendrion is used on the joint EM that has been already built. It automatically engages in case of power failures. Its power consumption was reduced to a very low value of approx. 1 W by modifying the gap between brake body and disc. The brake is coupled to the motor shaft. It is located on the outside of the joint. The joint design allows to leave the brake away without changing the internal joint design. The brake is mainly planned to be used for the on-ground models, where the earth gravity in combination with external loads is too dominant when the arm is stopped..
- *End Stops*: The end stop system mechanically limits the operating range of the joint. Thanks to its design it enables an extra large range of approx. 400°. A joint rotation range of above 360° is considered useful for roll joints in order to diminish singularities. The end stop system also includes an end switch system that enables the unique position information in the extended range in combination with the encoder. A single-turn encoder can not deliver this information by itself.
- *Torque sensors*: The joint features an integrated torque sensor based on strain gauges. A full bridge configuration compensates (homogenous) temperature variations on the axis as well as bending, axial and radial loads. The required mass and volume are very low. Measurements performed with the PT joint have shown that this sensor is accurate and linear on a range up to the maximum holding torque of 400 Nm.
- *Torque sensor interface electronics*: To achieve a high quality torque measurement, the strain gauge signals should be amplified before they are routed through the joint to the joint controller. On the other side, the amplifier should not enlarge the joint dimensions. Hence, a tight integration is necessary. For this purpose a torque sensor interface was developed that was integrated in the output shaft/coupling disc. It has a diameter of only 30 mm (see Fig. 7). The strain gauge wires are routed through the output shaft onto the amplifier PCB. On the PCB a full-bridge circuit is established. On the EM, the torque signal lines are then routed through the hollow shaft of the joint
- *High-Stiffness overall design*: A high mechanical stiffness of the joint has been achieved by the following design features:
    - Highly preloaded main bearings
    - Output I/F directly connected above the main bearings to provide a direct load path (i.e. only the rotary torque output is transmitted by the output axis).
    - Motor Housing I/F and Output I/F are located side-by-side, thus only low bending moments will be induce
    - Mass/stiffness optimised structure (e.g. coupling disc)
- *Hollow shaft*: The joint provides a hollow shaft which can be used for the feed-through of the main harness (system power and data bus). The central harness of the joint has a helical or a double helical design in order to minimise torsional stress of the cables. Thus, no bulky slip-rings or cable drums are required.
- *I/O Interfaces and Harness*: On joint level, an input and an output interface for the power and data bus is required. The input side is situated at the joint controller. The harness is split up there. The required cables for the joint controller are separated and led to the control electronics. The other part of the harness is routed through the hollow shaft of the joint, as discussed above. On the output side, which is located at the Coupling Disc, the helical harness ends. It is also connected to the torque sensor interface there.

The next few figures show some hardware pictures of the large joint that was built as a EM model at Contraves Space.

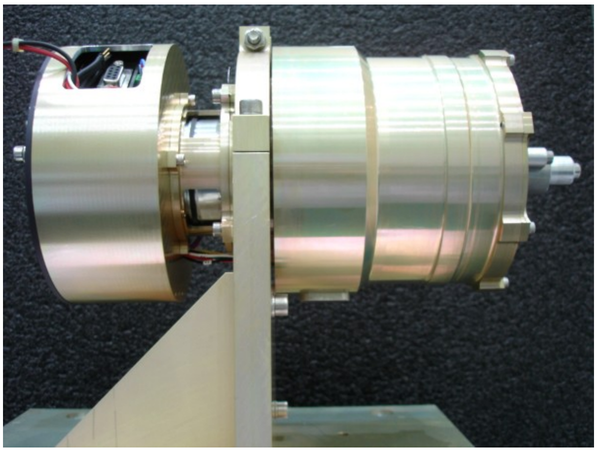

Fig. 5 DEXARM large joint EM overall view

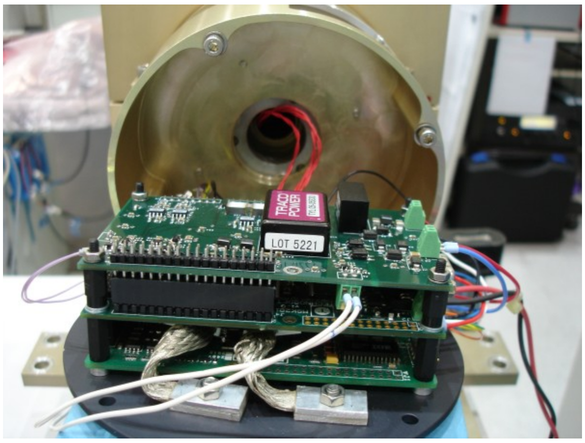

Fig. 6 DEXARM large joint EM overall view

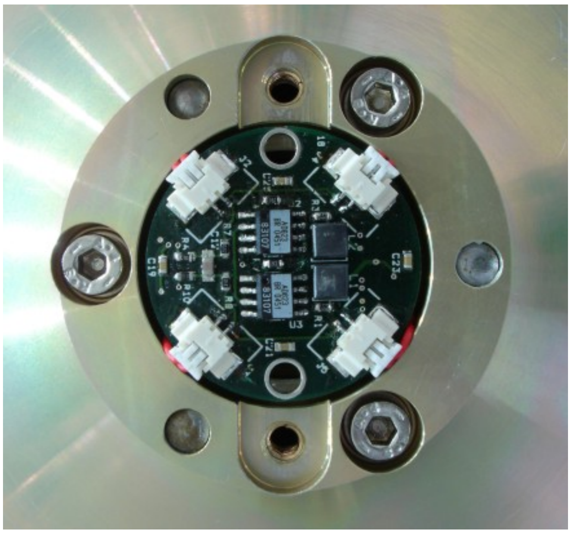

Fig. 7 DEXARM torque sensor interface

Fig. 8 DEXARM torque sensors

DEXARM JOINT VERIFICATION AND TEST RESULTS

The verification of the joint performances is done in two steps. During detail design a number of analyses have been performed to find the optimal structure paired with feasible component sizes. Once the joint has been built, performance parameters have been verified by testing. These topics are presented within this section.

Analyses

Functional Analyses

Functional Analyses have been performed and proved the design feasible for the following load cases. These load cases were reduced from arm system level analyses to joint level forces and torque needs.

1. Moving payload: This load case represents a task where DEXARM has to move the maximum applicable payload (500 kg in 0-G, 10 kg in 1-G). The acceleration is low (0.2 rad/s^2).
2. Applying force: This load case represents a task where DEXARM has to apply the maximum force (200 N in 0-G, 100 N in 1-G), e.g. in order to insert an object. The maximum payload is used, and the acceleration is virtually zero.

3. Walking: This load case represents a task where DEXARM is used as a leg with medium acceleration. The payload is 180 kg; this mass has been derived from the Eurobot specification which indicates a total mass of 200 kg, decreased by 20 kg of the relevant arm. In 1-G a payload of 5 kg has been assumed.
4. Using tools: This load case represents a task where DEXARM has to handle with tools. It is assumed that the tools have a small mass (0.5 kg in 1-G, 5.0 kg in 0-G) and that the robot moves with high acceleration (0.2 rad/s^2 and 5 rad/s^2 in 1-G and 0-G respectively). A maximum torque of 60 Nm has to be applied.

Note that the factors of safety were applied according to the ECSS standards for the on-orbit predictions, but some reductions were applied for the 1-g earth testing in order not to jeopardise the mass requirements.

Structural Analyses

A structural analysis was performed for the large joint based on a sophisticated FEM (finite element model) as shown in Fig. 9.

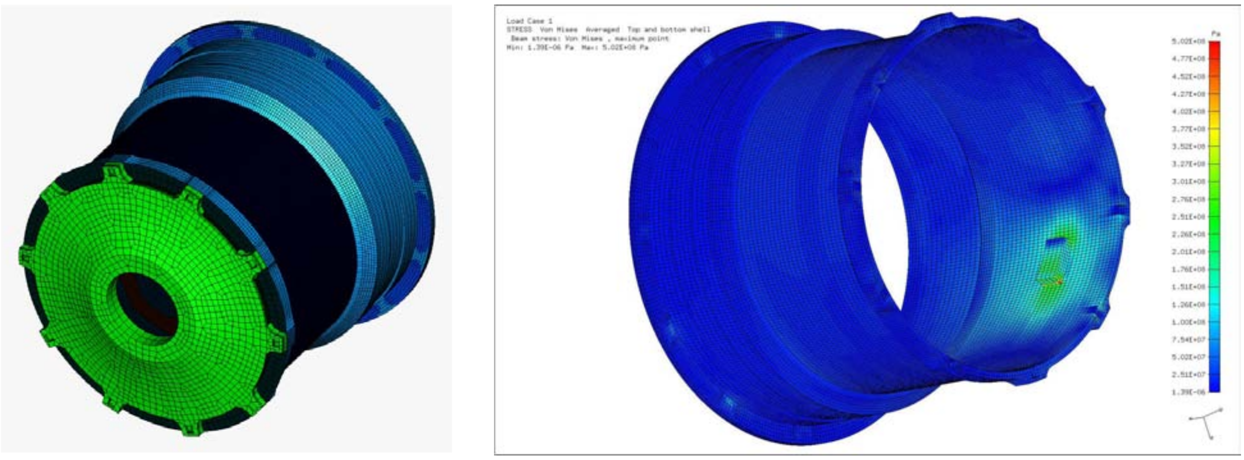

Fig. 9 DEXARM FEM

Using this FEM, stiffness and strength analyses were performed with load cases that were derived from arm level requirements as discussed above. In addition, thermo-elastic load cases were studied. Applying standard safety factors as recommended in the ECSS norms, all safety margins are proved to be positive.

Specific emphasis has been put on the evaluation of the performance of the bearings in order to find a good compromise between pre-load required to fulfill the stiffness requirements and lifetime of the joint.

Tests

The joint was subjected to extensive functional testing performed on the Contraves Space test bed as shown in Fig. 10.

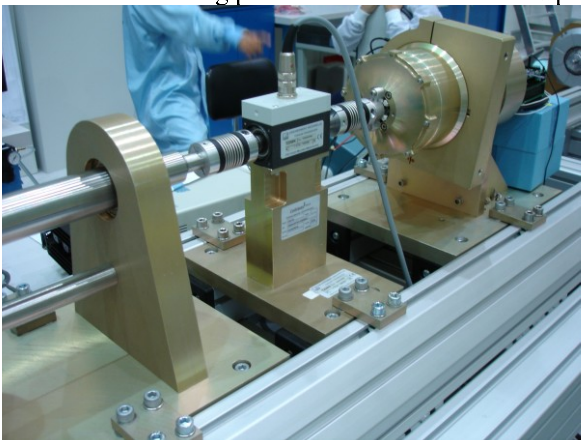

Fig. 10 DEXARM joint testing on the functional test bed

The specified functionality as well as the main performance ratings of the joint could be achieved. No damage occurred during the tests. The following list gives a summary of the performed tests and their outcome:

- Position accuracy: +/- 2.5 mrad
- Joint range: approx. 393°
- Continous torque: 193 Nm for 15 min
- Peak torque: 270 Nm for 120 ms
- Max. holding torque: 400 Nm
- Maximum speed: 0.44 rad/s
- Controller position accuracy: error ≤ 0.1 mrad
- Controller velocity accuracy: error ≤ 2 mrad/s
- Controller torque accuracy: error ≤ 2 Nm
- Well-controlled step response behaviour

The controller mass and dimensions are not considered since it is recommended to implement the electronics in a custom multi-chip and hybrid modules design for the final version of DEXARM. This will allow saving considerable space and mass.

The position accuracy did not provide the expected performance. It is worse than the required +/- 0.25 mrad. The capabilities of the internal encoder should enable a higher accuracy. An extensive test was performed then; it showed that the error is of systematic nature. It is assumed that this error can be partly eliminated and partly modelled in software. With the acquired knowledge it seems quite feasible to increase the position accuracy to the required value of 0.25 mrad.

CONCLUSIONS

The paper presented the design and verification of the DEXARM joint. It could be shown, that a very compact joint design is feasible and that the joint fulfills the major requirements. However, some further work is to be done in order to

- further optimise the mass
- optimise the controller behaviour and thus increase the positional accuracy
- substitute the brake

An noticeable point was the development process. It started with an extensive requirement review phase in order to ensure a consolidated design phase. However, this could not be fully achieved because major details came out later in the project which have a big impact on the design. E.g. the brake system was thought to be essential in the beginning, but when the actuator design was finalised it was found that the brake is only needed for ground testing and can be omitted for flight.

Hence, for further projects it could be summarised as a lesson learned, that the project must be able to adapt to changing information and it must be possible to omitt or include details, that were not identified in their full extent during the initial requirement consolidation phase – no matter how long that was.

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REFERENCES

[1] S. Schuler et.al.: “Dextrous Robot Arm Summary Report”, DEX-CSAG-AD-106, 13.12.2005