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DEXTROUS ROBOT ARM

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ABSTRACT

In the recent past, several proposed European missions (EuTEF, PAT, Eurobot, Aurora) have shown the need of a robot arm comparable in size, force and dexterity to a human arm. Therefore, Contraves Space AG has embarked on the development of a Dextrous Robot Arm (under a TRP programme) which could be used for diverse space robotics applications in which the manipulation/intervention tasks were originally conceived for humans. Beyond the classical design challenges 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. The result presented in this paper is a baseline design of a dextrous robot arm which ESA intends to complement with the ESA developed Common European Space A&R (CESAR) controller in order to serve future robotics missions.

INTRODUCTION AND MOTIVATION

The next generation of space robots for the International Space Station will be required to perform more dexterous tasks than their predecessors in order to perform maintenance on the ISS and reduce the need for costly and hazardous Extra-Vehicular Activity (EVA) [1]. The minimization of crew time in general and EVA time in particular, is an operational goal of all ISS Partners and a pre-requisite for long term manned space activities. Using robots in support of crew during EVA will considerably enhance efficiency of the astronauts, but development is necessary to ensure that aspects such as safety and reliable design are properly demonstrated before an operational system will exist. The objective of the Eurobot development programme (ESA) is to make a robot for use on the ISS, which will also constitute the base for future planetary missions (landing on the Moon or on Mars) and for other future human spaceflight scenarios.

The Dextrous Robot System comprehends a Dextrous Robot Arm (hereafter referred as DEXARMs) which could be used for diverse space robotics applications in which the manipulation/intervention tasks were originally conceived for humans. These applications include external and internal servicing of Space Station platforms as well as robotics for planetary exploration. Different End-Effectors will contribute to the versatility of the robot system, however the specific End-Effectors (EE) and the Tool Exchange Device (TED) are not part of this work.

The challenge of this development is to build a robot arm which is versatile and can handle high loads but which is small and compact. Additionally, it has to be compliant with the space requirements. A robot arm with 7 joints and the required dimensions allocates about 80% of the mass to the actuated joints. The conventional approach of putting together components cannot bring these resources to the required low levels of mass, volume and power consumption Thus, it is considered that the main focus is set to the development of a highly integrated mechatronic joint. The resource savings made into the joints and harness will allow the following design of lightweight limbs and supporting structures.

The first part of this paper addresses the key requirements of a dextrous robot arm. Then, the main components are analysed and a preliminary design of a joint is made. The last section concludes this work and gives a perspective to future works.

REQUIREMENTS

The key requirements were identified and are shortly discussed in the following sections. They mainly refer to the Statement of Work of the Dextrous Robot Arm [2].

General

The DEXARM will provide manipulation capabilities equal to or better than those of a human arm in EVA (Extra Vehicular Activity) suit. It will have 7 degrees of freedom, a total length of 1 meter and a horizontal reach of 0.86 cm (see Fig. 1). The system mass will be below 20 kg. The end-effector will move with a maximum linear speed of 0.1 m/s. Depending on the robot kinematic configuration and the maximum joint speed the gearbox ratio will be determined.

The DEXARM will retain its performance capability for 5 years without refurbishment or exchange. Its design will enable a total of 4380 hours operational use in orbit.

High applied loads

The DEXARM will be capable to exert a force of 200 N and a torque of 20 Nm at the tool flange. The force of 200 N represents 200 Nm at the shoulder, which is to be done actively, not with brakes. The maximum handling mass during Eurobot operations is 500 kg in 0-G.

The DEXARM will hold its pose, while unpowered, against its maximum payload of 10 kg in 1-G. This indicates that either the joints are not passively backdriveable or that brakes are needed. In powered state the DEXARM will hold its pose against a force of 400 N at the tool flange.

High pose accuracy

The unidirectional position accuracy is 0.3 mm and the unidirectional position repeatability is 0.03 mm at rated load and 0.1 m/s velocity on the inclined ISO test plane with all seven robot axes in motion. Regarding the working envelope this is equal to 5 arcsec and can as such not be met by a harmonic drives which is foreseen to use. However, this is irrelevant if a sensor with enough resolution and repeatability is located at the output of the harmonic drive because they have essentially 0 backlash.

Backdriveability

The DEXARM will allow EVA to back-drive its joints at any time by applying force to its tool flange or limbs. This will not require special tools and force used will be compatible with EVA capabilities. Joints will not be damaged by back-driving. This must be considered for the braking strategy, the gear ratio selection and the sensor characteristics.

Compact size

The thickness of the DEXARM elbow, wrist and limb in between will not exceed the corresponding dimensions of an EVA suit lower arm. The DEXARM will stow in a compact volume whose largest dimension is at most half of the largest dimension of its full-stretched configuration.

Summary

The main challenge from the technical point of view is the development of a high performance joint which incorporates several functions, usually contained in own subsystems, into a lightweight, low volume and low power consuming fully integrated mechatronic unit. Special attention will be paid to the scalability of the joint, since for a dextrous robot arm, depending on the location of the joint, higher or lower performance is required.

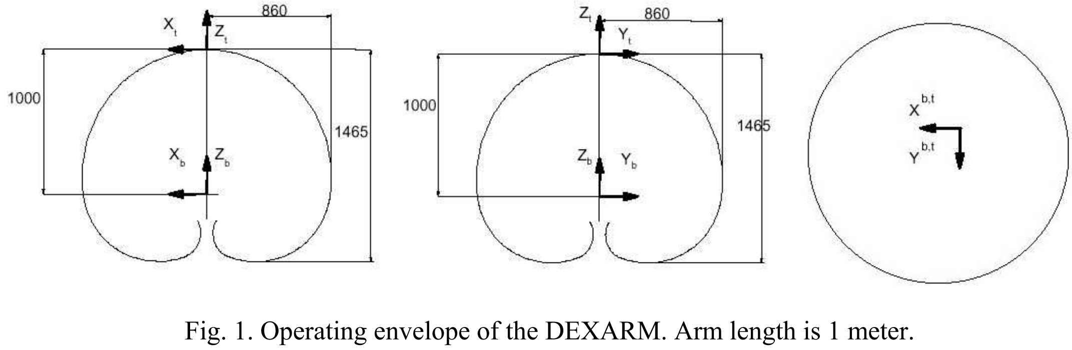

Fig. 1. Operating envelope of the DEXARM. Arm length is 1 meter.

DEXARM TOPOLOGY

The DEXARM (Fig. 2a) consists of:

- 3 joint assemblies (shoulder assembly, elbow assembly and wrist assembly)
- 2 limbs (upper limb, lower limb)
- 2 mounting flanges (base flange, tool flange)

6 degrees of freedom (DOF) are minimally required to operate a robot arm in 3 dimensional space requiring multi-directional approach to the position and orientation of the objects in the working volume. 3 degrees of freedom are required for translations in the x,y and z direction and 3 degrees of freedom are required for rotations around the x,y and z axes. Using 6 degrees of freedom allows a limited number of poses where the same position can be reached. There are however two clear advantages to have 7 degrees of freedom for the DEXARM:

Kinematic advantage: An infinite number of arm poses can be configured to reach the same position. The main advantage here is the ability of collision avoidance in a complex working volume.

Dynamic advantage: DEXARM must be able to do both operations requiring a stiff configuration for high torques and operations requiring a non-stiff configuration requiring low torques (for subtle/sensitive movements). Dependent on the operation at a certain position, DEXARM can be configured such that, choosing from the infinite amount of arm poses, the optimal arm pose is used for the operation.

It is a requirement to implement the Wrist Assembly with 3 DOFs. Thereby, it is possible to perform a large choice of tool movements (e.g. screwing) while the rest of the arm stands still. The 4 other DOFs can be allocated on different ways to the remaining two joint assemblies. Several combinations of Yaw (Y), Pitch (P) and Roll (R) can be selected. For example: Y-R—Y-R—Y-P-R for a robot with 2 DOFs at the Shoulder Assembly and 2 DOFs at the Elbow Assembly.

The arrangement of the DOFs determines the type and design of the joints in many ways. Economic aspects benefit from choosing a concept with several identical joints. On the other hand, joints which are scaled to the specific performance required, depending on their location, may lower the weight and increase the performance. Next, the complexity of a joint increases with the number of its DOFs (it is much easier to build a simple revolute joint than for example a spherical joint). Lastly, the joint configuration has an impact on the robot's performance (error propagation, acceleration, weight).

For the future work a 3-1-3 configuration (Fig. 2b) is proposed. It resembles the closest a human arm and will thus be easier and more intuitive to control remotely. Additionally, the inertia of the moving arm is diminished because three joints are mounted onto the Shoulder Assembly. A disadvantage is that any position errors at the shoulder will have bigger effects on the end-effector's position. The final configuration remains to be evaluated according to the aforementioned criterias.

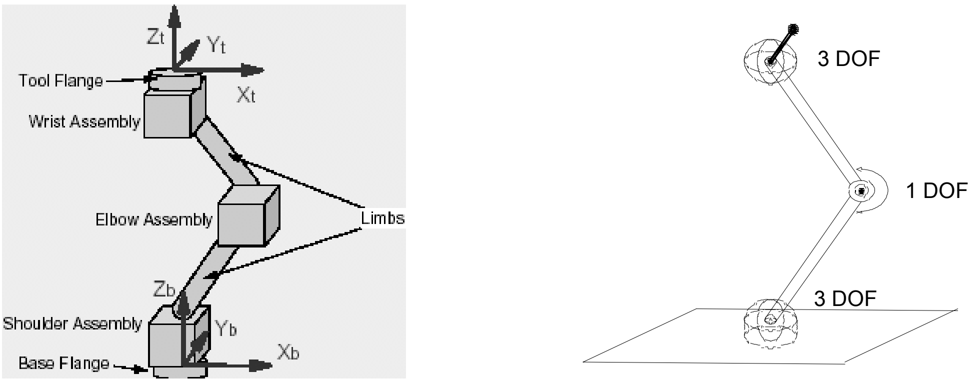

Fig. 2 a) Dextrous Arm

b) 3-1-3 Joint configuration

DEXARM JOINTS

To achieve the goal of an arm design with full joints instrumentation and harness having a total system mass of 20 kg, the conventional approach of combining components will not reduce the mass to the desired low level. A combination of a standard harmonic drive gear with a standard motor leads already to a mass of 3.25 kg per joint, which would result in 22.75 kg for the 7 joints, leaving a shortage of 2.75 kg to accommodate the remaining components as brakes, sensors, bearings, limbs, harnesses, etc.

A new approach of integrating all required joint functions into a single, specific component is considered to be the solution. The target mass derived from the above for the seven joints of the arm is 15 kg. This results in a joint mass of below 60% of the total mass of conventional, already mass optimized arm.

Concept

Different actuator components, which are mainly available on the market, were reviewed to reflect how main functions of a joint can be realized. It has been well recognized, that the functions have to be accommodated in a highly integrated joint.

Motor

It is essential that the power consumption is reduced to a minimum in order to save the resources of the robotic system or the planetary exploration vehicles. A high torque motor with low RPM is required to limit the power consumption. As a goal the power consumption shall be below 200 Watts. The motors which are considered to be suitable for such an application are stepper motors and synchronous motors.

In terms of working speed, stepper motors are relatively slow compared to permanent magnet synchronous motors, called Brushless DC motors or “Torque Motors”. In terms of torque/volume ratio or torque/weight performances, the hybrid stepper motors are very efficient, however they require small mechanical airgap values (typically below 0.1 mm), which impose tight mechanical tolerances on the related mechanical parts. In contrast, permanent magnet synchronous motors normally have airgap values close to 1 mm. For peak torque overload during a short time, brushless DC motors have a significant capability, while stepper motors are generally much more limited. The detent torque of a brushless DC motor does not have a “clean torque behaviour” which can be used to keep the motor in position when unpowered. The torque/copper-loss ratio (i.e. motor constant) for stepper motors is usually higher than for brushless DC motors.

For low speed applications, the efficiency of hybrid stepper motors is significantly better than the one obtained with a permanent magnet synchronous motor with similar overall dimensions. Brushless DC motors require a position sensor for the electric commutation. The drive electronic for stepper motors is in general simple. Only when a closed loop configuration with an encoder is required, the drive electronic complexity is about the same as for permanent magnet synchronous motors. Regarding the generation of mechanical vibrations or acoustic noise, the permanent magnet synchronous motors are of advantages over the stepper motors.

Gearbox

Conventional planetary gears accommodate the sun gear in the middle of the unit, not allowing the feed through of any cables as required for the usage in a robot joint and are therefore not suitable for the required application. Special epicyclical planetary gears exhibit the required cable feed through possibility, however the torque capability, the size and the weight do not match the requirements. In addition planetary gears exhibit some backlash, whereas harmonic drives, due to their nature, exhibit nearly no backlash.

Bearings

Only rolling element bearings are considered for this application as they provide low friction and wear combined with high stiffness. The options are related to the type and arrangement of bearings (Table 1). Standard conical roller bearings have not been considered because all the models found were excessively heavy.

Table 1. Bearing comparison

#	Option	Comments
1	Crossed roller bearing	Good stiffness, some clearance (can not be pre-loaded)
2	4-point ball bearing	Reduced stiffness, some clearance (can not be pre-loaded)
3	Double-row conical ball bearing	Good stiffness, some clearance (can not be pre-loaded)
4	2 conical ball bearings, mounted face-to-face	Good stiffness, can be pre-loaded (complex integration)
5	2 conical ball bearings, mounted at some distance	High stiffness, can be pre-loaded, increased design complexity

The solutions have been assessed and compared with respect to the most important aspects. Considering mass, size, assembly complexity, stiffness and clearance two conical ball bearing mounted fact to face are the favourite solution. However this depends on the actual stiffness which is difficult to assess and on the feasibility of a pre-loaded pair of bearings within the joint design.

Brake

Conventional electromagnetic brakes are of large volume and high mass. Although the efficiency is higher when not combined with the motor function, they exhibit a huge disadvantage in the brake-moment/mass ratio. Conventional type brakes are available on the market whereas piezo-electric brakes are customized items.

Angle position sensor

To measure the rotor position either an encoder or a resolver can be used. Encoders are available in a broad variety of accuracy and are much more accurate than resolvers. Resolvers are more suitable to measure the rotor positions of motors for their commutation. Encoders are available for “quasi absolute” angular measurements using a reference mark , or for “absolute” angular measurements with the same number of tracks on the disc as bits are required. For the dextrous joint angle measurement accuracy, resolvers are considered to be not suitable.

Angular encoders provide sufficient fine accuracy to cover the required angular position accuracy of 5 arc seconds with a factor of 10 to comply with the required pose accuracy. Several different mechanical configurations are available to accommodate mounting configurations, such as hollow through shaft.

Torque sensor

Torque measurements are required in order to enable controlled backdriveability.

Different solutions have been assessed and compared with respect to the most important aspects in Table 2. A piezo torque sensor on the output axis obtains the highest rating but other solutions are not far off. However, it must be considered that option 1 is probably not acceptable due to the impossibility to measure small moments and option 5 involves higher levels which would have to agree on supplying this service. For the DEXARM options 2 and 4 seem to be appropriate.

Table 2. Torque measuring principles

#	Option	Comments
1	Sensing based on motor current measurements	Nearly impossible due to very high gear ratio and back-driving moment
2	Piezoelectric torque sensor on output axis	Max moment critical with 400 N sustained force at 0.9 m lever arm
3	Dynamometer built with several (3 or 4) piezoelectric shear sensors	Complex electronics needed to compute moment
4	Strain gauge measurement applied on structural elements of the output axis	Complex electronics needed to compute moment
5	Strain gauge measurements applied on limbs	Moments must be computed at arm or system level and fed back to the joint controller

DEXARM LIMBS

The main loadcases under consideration are stiffness (>100 Hz fully stretched) and thermal behaviour (-80 to 60 °C). Design goal is to minimise weight while maximising stiffness and minimising thermal expansion.

The limbs have slightly differing requirements depending on their position in the robot arm. This in fact points to the need for a separate trade-off when defining the laminate lay-ups for a composite tube.

Dimensions

The geometry envelope of the limbs is given by two constraints, the maximum reach of the DEXARM (1000 mm in stretched configuration) and the requirement that it does not exceed the outer circumferential envelope of an EVA suit lower arm (which has minimum internal circumference 322 mm according to NASA STD-3000).

The length of each limb depends on the system architecture and the number of limbs it requires and will lie between 120-150 mm for an arm with 6 limbs and 400 to 500 mm for a 2 limb configuration. The maximum diameter based on the internal circumference and taking into account the thickness of the space suit is in the range of 120 mm.

Cross section

In discussing limbs it is usual to assume the use of axisymmetric circular cross sections. However, it is beneficial to study in particular the use of elliptical or polyhedral cross sections which can yield higher specific bending stiffness as compared to circular cross sections.

By using tangency restraints and requiring the areas to be equivalent a comparison between thin annuli and regular polygon sections is possible. Given that for a regular section the torsional moment of inertia is the addition of the two principal moments, the bending and torsional stiffness ratios when compared to a circular cross section are identical. The best performance is thus that of the triangle, but the side length exceeds the admissible dimensions. Triangular shapes are also very difficult to manufacture by either filament winding or pultrusion, though they could be made by joining stringers with hand laminated sidewalls (thin laminates or sandwich structures).

The second highest stiffness (32% higher than that of a circular cross section) is that of the square. This section has several advantages: it occupies the same space as the circular section but flat walls result in easier stacking of units on top of each other, hinges are easier to locate as a planar contact surface is available. A square section can be fabricated using filament winding and/or pultrusion provided the corners have an adequate radius. On the negative side the cross section is not shear stable so that end reinforcements are required and at very thin gauges the side walls will buckle when compression loaded.

As in the case of regular polyhedra the stiffness of circumscribed ellipses (aspect ratio < 1.0) is lower than that of circumscribing ellipses. However the fact that one of the axis has considerable higher inertia than the other can be used to ease rotation and maximize stiffness/weight ratios. In fact the lower human arm cross section is an ellipse which changes axes in going from the elbow to the wrist.

Geometry

Several geometrical aspects can be considered:

- Tapered vs. untapered beams
- Single tube vs. multi-tube bundles
- Curved vs. straight beams

The most attractive design is given by a so called tri-tube cross section, which implies a structural redundance, i.e. in case of failure of any one member the other two could carry the load. The multi-tube configurations yield considerable higher bending stiffness at the cost of torsional stiffness. Due to this they are only suitable for the lower arm. Moreover, they comprise added complexity of intermediate flanges and multiple bonds at the joints.

Material

To fulfill the requirements of position accuracy, loads and system weight the limb material must be selected carefully. The relevant evaluation criterias are the stiffness/mass ratio and the E-modulus/density ratio. According to the specific requirements the following materials come into consideration:

- Silicon carbide and nitride, boron
- Aluminium metal matrix composites
- Epoxy Carbon and Epoxy PBO

Epoxy-carbon fibre combine a relatively low density (1.4..1.8 g/cm^3), a high E-modulus (200..240 GPa) and a low thermal expansion coefficient (- 0.1..1.0) with a moderate material price.

PRELIMINARY DESIGN OF JOINT

In order to achieve a technically feasible solution in a short time, it is very 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 which can be adapted with minor changes to the purpose of the DEXARM project.

Based on the preceding studies, the decision was taken to focus on the design of a rotational joint able to cope with the most demanding force requirements and later to scale it down to smaller sizes needed for a "scaled-joint" version of the arm. Three types of joints with scaled load carrying capability (shoulder>elbow>wrist, similar to a human arm) are currently considered as a baseline. However there is no final decision on this aspect and a "symmetric" version with identical (maximum strength) joints is still considered as an option.

A preliminary design of the joint is depicted in Fig. 3. A DC brushless motor is driving the output housing via a Harmonic Drive. The housings are connected with two angular bearings and sealed with a slipring to protect the inside from very fine dust. A passive brake on the motor shaft holds the position if the motor is switched off or if there is a complete power loss. The brake is preloaded with springs and an electro magnetic coil keeps the brake open during operation of the DEXARM. Torque loads are measured with strain gauges applied on the output axis. All electrical signal and power cables go through a cable drum allowing the joint being rotated without applying too much stress on the cables at low temperatures. The end stop system with a moving lock provides more than 360° rotation. Angular feedback will be given by an encoder. All parts can be disassembled at any time by using bolts and ring-nuts. Bonding processes and higher integration of sub-units can be implemented in later design stages to reduce the overall mass.

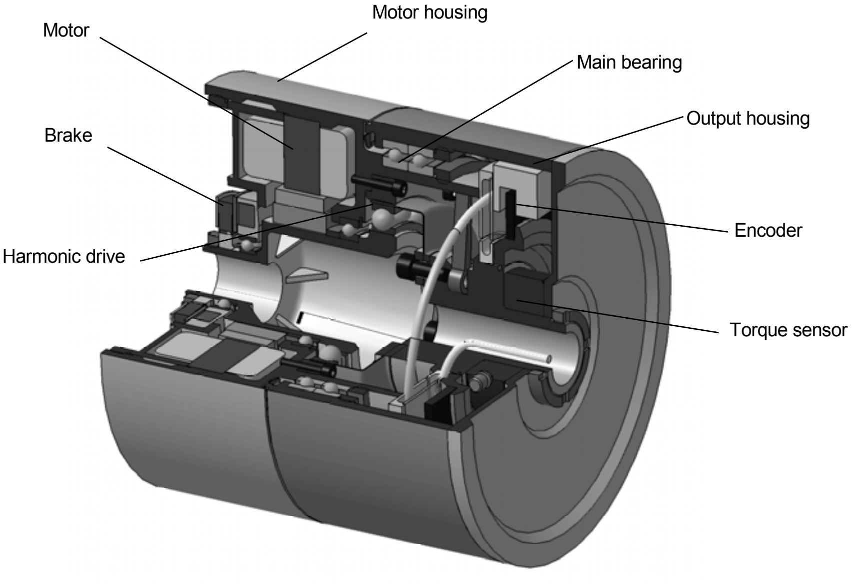

Fig. 3. Joint assembly

CONCLUSION AND FUTURE WORK

In this work the topology, the joints and the limbs of a dextrous robot arm have been analysed. The requirements have been reviewed and the main components of a highly integrated joint have been evaluated. Based on these results a preliminary design of a high torque joint has been conceptualised. Some improvements are to be expected from further optimisation in the following development phases.

In the next work, the joint configuration of the DEXARM has to be further investigated. The results will show whether a specific and scalable joint or a universal joint needs to be developed. Subsequently, it will be possible to make a detailed analysis of the system performance. This will finally provide the basis for a detailed design of the DEXARM.

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