

DLR's Dynamic Actuator Modules for Robotic Space Applications

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Abstract

Based on our long-term goal to develop “robonauts” for space and the experiences our research department accumulated in space robotics, this article describes recent design and development results at DLR's Robotics and Mechatronics Center. Herein, we focus on lightweight robot arms, articulated hands and highly integrated actuation modules for space applications. We show how the development process started with fully sensorized, highly dynamic joint modules with state feedback control and led to seven degree of freedom (DOF) torque-controlled robot arms that enable innovative Cartesian impedance controllers. Further, we present two space robotics examples that are based on such modular actuation units. The first one is the ROKVISS experiment which has been launched towards the ISS in 2004 and returned to earth in 2011. The second is the Dextrous Robot Hand, DEXHAND, which we developed on contract with ESA. These two projects underline the strong interest to transfer our knowledge and experience from terrestrial robotic developments to innovative space technology.

Introduction

Currently, many operations in space, such as maintenance or new module assembly, have to be carried out by astronauts and expose them to a hazardous environment. These missions are associated with high risks and costs. While robotic systems are not yet ready to replace humans in space, they may provide an excellent support for astronauts. Supported by telemanipulation concepts, robots could be used for many of the Extra Vehicular Activities (EVA). Herein, robotic perception and partial autonomy could strongly simplify tasks for the astronauts. Further, methods like force feedback allow operators haptic interaction at distant locations. Besides near earth orbital activities, we believe that autonomous and semi-autonomous robotic systems will take an important role in planetary exploration scenarios.

In order to bring teleoperated systems to the International Space Station (ISS), the European Space Agency (ESA) is currently investigating different scenarios. We think that humanoid robots, like our terrestrial technology demonstrator “Justin”, (Figure 1) could fulfill ESA's development goals within this context. Since the ISS is designed for humans, sending up robots with hands and arms is an obvious option that also NASA follows with its Robonaut [1]. In the case of a telerobotic scenario, humanoid robots simplify the mapping from the operator to the robotic system.

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Figure 1: Teleoperator using a head-mounted display to get 3D visualization and lightweight Robots (LWRs) as haptic input device with force feedback and "Justin" in telerobotic operation

This results in an intuitive operation that minimizes learning time as well as user fatigue and improves execution speed. Upon those arguments, ESA decided to develop an EVA capable hand/arm system. Based on the experiences of our lab with space robotics projects like ROTEX and ROKVISS, ESA assigned the development of the space-qualifiable hand to the DLR Robotics and Mechatronics Center (RMC).

Since space robotics applications require highly integrated, lightweight systems with low power consumption and high performance, DLR's robotic actuation technology and our longtime experience with a space robotic system may provide interesting solutions for future missions. Throughout this article we present our robotic drive train technology and its development process as well as two space related application examples. The next section) of this paper discusses the design of the DLR drive train unit including the in-house developed permanent magnet synchronous motors.

Furthermore, it describes how a terrestrial seven DOF arm is built based on these actuation units. A later section presents ROKVISS, our robotics component verification experiment that was operated at the outer surface of the ISS from 2004 to 2010. The interesting fact of this experiment is that we used a mixture of space qualified and off-the-shelf components and achieved very reliable long-term operation in space. Receiving the robot back allows us to collect valuable data about the effects of the space environment on the system. Furthermore, this paper describes the development of the EVA qualifiable Dexterous Robotic Hand, DEXHAND, for the ESA. All presented results are based on the Critical Design Review (CDR) status, giving an overview of the technical decisions with respect to the mechanical design.

DLR Drive Train

Developing actuators for dynamic and sensitive robotic systems is a challenging task. The broad range of applications and the intended interaction with the environment require characteristics that differ from common actuation scenarios in industry. The same robot, for example, has to deliver high torques at low speed in one application while it has to provide high dynamics in another. Since robotic actuators are usually attached to the moving structure, they also need to be small and lightweight. In order to reduce positioning errors and to avoid disturbances during reversing motions all gears should be free of backlash. Thus, the requirements for robotic drive trains are manifold. The most important ones are summarized in the following list:

- high torques at low speed or stand still
- low weight
- small sizes
- high dynamics
- high efficiency / low losses

- backlash free gearing
- sensor feedback (position and force-torque)

In the end of the 1990th no commercially available actuators could sufficiently fulfill those needs. Thus, at our institute, permanent magnet synchronous motors were developed that match the requirements. Being combined with very low backlash Harmonic Drive (HD) gears, they constitute high performance robotic actuation units. These units provide high dynamics and high link side torques due to low inertia parts and the high reduction ratios of the HD gears. Further, their low number of components reduces the probability of failure.

In the following, we present the development of our lightweight robotic arms with a focus on our modular actuation units. We begin at the motor stage and progress via the highly integrated actuation modules towards the complete robot.

The DLR brushless Motors

The key components of the DLR drive train concept are the permanent magnet synchronous motors developed at our institute. The so-called “Innen-Läufer-Motor” (ILM: German for “inside rotating motor”) is well suited for highly dynamic tasks involving frequently reversing motions. For maximum performance, all of our motors are sized to comply with available HD gear dimensions.

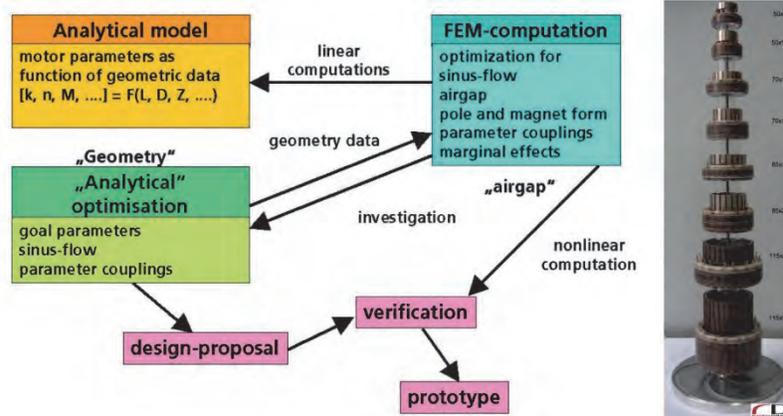


Figure 2: Concurrent engineering for the actuator design and the RoboDrive variations

During the two year development process we strictly followed a concurrent engineering and optimization process (see Figure 2) to achieve high dynamics combined with low losses and low weight. The complete design is based on extensive multi-physics simulations, considering electromagnetic, mechanical and thermal effects. In the final design short copper paths, very dense and optimized windings, strong neodymium rotor magnets and low inertia rotating parts are the main source of the high dynamics. Furthermore, the ILMs consist of a high number of pole pairs (ILM 25 and ILM 38 have 7 pole pairs all others have 10), which allow very accurate positioning and reduce motor ripples. Using wires with a large cross-sectional area allows the motor to handle large currents with low losses and thus, to produce very large torques at low angular velocities. To give a performance example, the torque/current constant of the ILM 25 (stator diameter of 25 mm) is $0.008 \text{ N}\cdot\text{m}/\text{A}$. The motor uses approximately 12.5 A (without saturation effect) to provide a torque of 100 mN-m.

The corresponding HD gears with 1:100 reduction ratio (HFUC8) for example has a nominal torque of 2.4 N-m, a repeatable torque of 4.8 N-m and a momentary peak torque of 9 N-m. The limiting factors for the motor torques are thermal constraints related to the passive cooling. In case of active cooling the torque output of our motors could be even increased. At the time of development the motors achieved a 50% reduction of weight and losses with respect to commercially available units with comparable torque

ratings. Currently, our motors are becoming the state of the art for high performance robotic drives and are commercialized by the company RoboDrive [2].

The DLR Actuator Units

As already mentioned, our motors are developed to comply with the ratings of Harmonic Drive gears. Together with those they form the core of our highly integrated actuation units. Aside those core parts, the units include power, data acquisition, motor control and communication electronics in a very dense package.

The amount of wires has been drastically reduced to two power (one for electronics and one for the motors) two communication lines (SERCOS is a ring) and one emergency stop. Due to the large hollow shaft of the motors these lines can be easily guided through a robot joint and thus remain inside the robot. Furthermore, the actuation units comprise a large set of sensors enabling sophisticated impedance and admittance controllers with underlying high performance torque or position control loops. These sensors are motor side position sensors for commutation and relative position measurement as well as link side absolute position and joint torque sensors (see Figure 3).

Aside the high performance, low weight and low losses, two properties of our actuation units are very interesting for space applications. First, the high torque capacity of the motors allows applying short and very strong “kicks” that could free the unit in case of cold welding within the bearings or the HD stage. Of course, in this case the power electronics has to be designed to supply large currents for a short time.

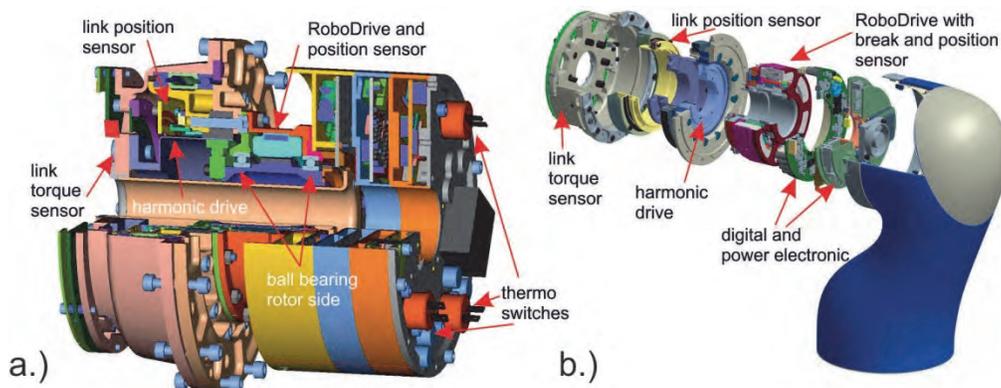


Figure 3: DLR drive train concept a.) ROKVISS unit - ILM70 - HFUC25, b.) Joint module of the LWR III

The second advantage is that the low number of mechanical components reduces the probability of failure (see Figure 4). In the following, the mechanical components of one joint unit are listed:

- stator
- rotor with magnets
- rotor bearing
- HD wave generator (WG)
- HD flex spline (FS)
- HD circular spline (CS)
- output bearing.

Within these components the rotor bearing and the WG bearing are the most crucial elements since the associated friction has to be overcome by the motor torque directly.



Figure 4: DLR drive train concept a.) DEXHAND unit CAD, b.) DEXHAND unit photo, c.) ROKVISS unit photo

In summary, the design of our actuation units allows highly dynamic and powerful operation as well as precise control in fine manipulation tasks. An example for the usage of this drive train concept within a space application is the joints of our ROKVISS experiment that is described in more detail later.

The DLR modular Arm

Developing, building and controlling lightweight robotic arms for a large variety of applications are a research focus at the DLR Robotics and Mechatronics Center (RMC). Starting with the Lightweight Robot I (LWR I) presented in 1994 via the LWR II of 1999 to the current model LWR III from 2003, we gained a lot of experience within this field. Due to the success within the research community and an initial market demand for such technology, in 2006 the KUKA GmbH started to commercialize the LWR III. A first small batch series was mainly provided to different research institutions.



Figure 5: a.) LWR III, b.) LWR as a KUKA product, c.) modular robot system "Justin" with 54 DOF

Currently, around hundred units are sold and the car manufacturer Daimler sees high potential for a factory-wide deployment of the LWRs. For them, especially attractive is the possibility of switching in-between torque-based and position-based control concepts. This is very promising for the solution of challenging assembly tasks.

Besides the innovative impedance and admittance control algorithms developed for our lightweight robots, its modular joint-link concept is one of the reasons for its success. Hereby, the underlying modular assembly system with only a few basic components concerning joint mechanics, electronics and links allows composing completely different configurations in a short time. Thus with three different single degree of freedom (DOF) robot joints and a two DOF wrist joint, different kinematic configurations can be easily assembled. For example, in addition to the symmetric version an asymmetric version (Figure 6) can be built. This is particularly interesting for space applications where the arm needs to be folded for stowing.

Again the design process for the joint and link modules followed a concurrent engineering process including kinematic and dynamic simulations as well as an FEM analysis. Supported by a link component library with variable parameters, virtual prototypes could be assembled, tested and optimized. One special result of this process is the ball-shaped two axis wrist joint (see Figure 7). This joint imitates the human wrist but achieves much higher mobility. Its short distance between the wrist pitch axis and the tool-center-point (TCP), helps to reduce the motion of the lower robot joints in case of changes of the TCP orientation. Furthermore, the wrist design enables two kinematic configurations, a common configuration with roll-pitch-roll axis and optional a roll-pitch-pitch configuration. To reconfigure the joint the short standard flange simply has to be replaced with an extended 90° bend flange. Another advantage of the wrist is that its cardan joint avoids singularities in an extended position and the reduced joint mass allows carrying larger payloads.

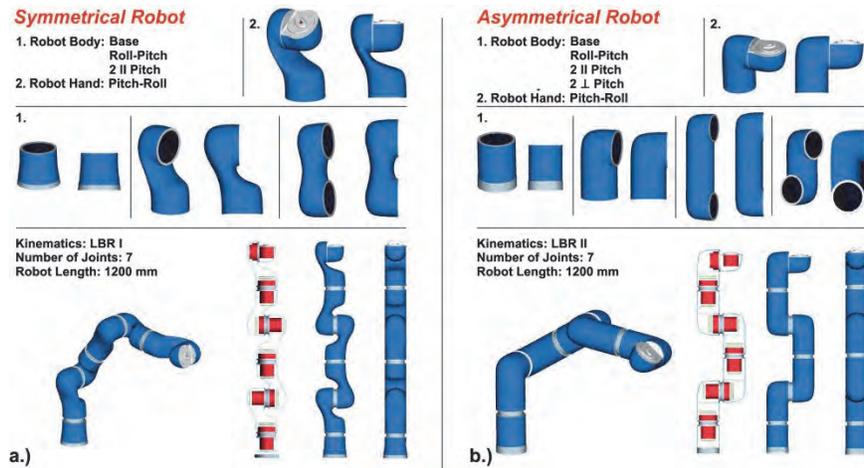


Figure 6: a.) symmetric LWR modules ,b.) unsymmetric LWR modules

The DLR lightweight robots are very well suited for a large variety of service robotics applications with their modular assembly, kinematic redundancy (7 DOF), the torque controlled joints, the low inertia and a load to weight ratio of nearly 1:1,. Some examples at our institute are the humanoid “Justin”, the three arm co-worker scenario, several single arm manipulation tasks as well as the bi-manual input station for robotic experiments. The concept of highly integrated modular actuation units is further improved for the new DLR hand arm system as well as the DEXHAND. With their low power consumption and the above mentioned features our drive trains and complete robots provide interesting capabilities for future space missions [3].

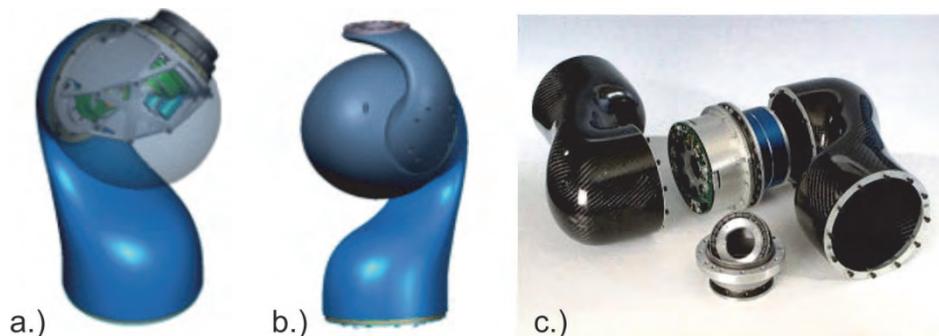


Figure 7: LWR cardanic hand module joint a.) roll-pitch-roll configuration, b.) roll-pitch-pitch configuration c.) LWR joint modules

ROKVISS

The German space robotic project ROKVISS (German: "Roboter Komponenten Verifikation auf der ISS") has just been finished. The system has been returned to earth early 2011 and the hardware is now subject to detailed analysis and advanced tests.

ROKVISS (see Figure 8) aims at the space qualification of DLR's LWR modules (modified for a space environment) with a reduced setup of a 2 DOF robot arm on the ISS. With this experiment DLR could prove the concept can use partly components-off-the-shelf (COTS) within a very tight and highly integrated mechatronic device based on the modular joint concept discussed previously.

After more than five years of successful operation and without any failure the innovative mechanical and electronic concept seems very promising for the use in space projects. Those projects are in the wide range of future robonaut applications as well as planetary robotic missions. Indeed what we are still missing in space are fast signal transmissions. One relay satellite could provide signal round trip delays of 0.5 seconds within a coverage times of around 40 minutes. This allows even haptic feedback, which is a major idea of our advanced telerobot control strategy using visual and haptic feedback [4].

ROKVISS was also a telerobotic demonstrator with real-time stereo-video transmission and tactile feedback. The telerobot success was the second major achievement of ROKVISS, besides the component verification. We believe that realistic telerobotics probably combined with partial or full autonomy will be needed in future space robotic applications [5-7].



Figure 8: ROKVISS photo of the experiment mounted on the ISS

The following subsection deals with the mechanical design and the detailed structure of the ROKVISS robot describes the friction analysis and shows preliminary results.

Mechanical System Design

In Figure 8a the overall ROKVISS is shown, while Figure 8b shows the joints as described in the previous section. Figure 8c shows ROKVISS in its position outside the ISS at the Zvezda service module.

The ROKVISS experiment consists of a small robot with two torque-controlled joints, mounted on a Universal Workplate (UWP). Each joint module consists of a power supply, a controller board, a power converter, the drive train and a torque sensor. Inside the robot there are 2 joint modules, a stereo camera, an illumination system, an earth observation camera and a power supply. A mechanical contour device is mounted on the UWP for verifying the robot's functions and performance (see Figures 8a and 8c).

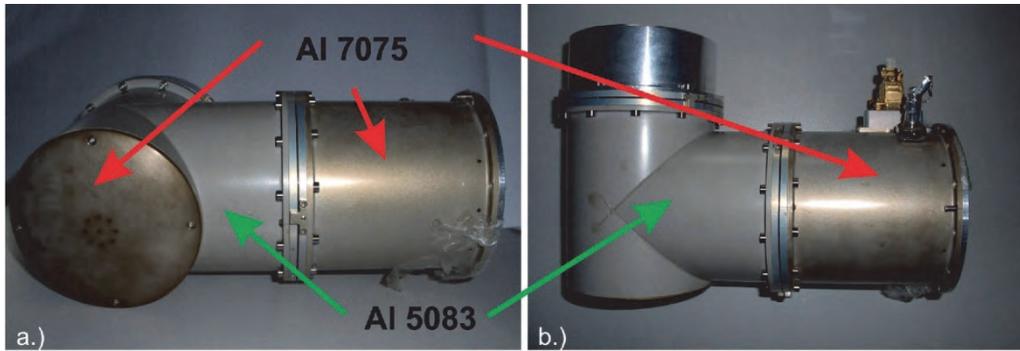


Figure 9: ROKVISS FM modules with color changes on the surface after return to earth

These two robot joints have been extensively tested and the joint parameters have been identified by repetitively performing predefined robot tasks in an automatic mode, or based on direct operator interaction. The automatic mode is necessary due to the fact that communication constraints limit the direct link experiment time to windows of only up to seven minutes when the ISS passes over the tracking station German Space Operations Center (GSOC). Figure 9 shows the returned two joint modules. After five years of operation on ISS differences on surface with its anodic treatment (LN9368 I 2101) of the two different aluminum alloys (Al 7075 I Al 5083) are obvious [8, 9].

Friction Analyses

The preliminary results of the on-orbit identification show that the total friction for joint 1 in space increased by about 50% compared to the friction on ground, taken at 20°C, under normal atmospheric pressure (Figure 10). However, only a small further degradation of the parameters has been observed so far during the mission. This friction change will be analyzed in the upcoming tests to determine if the lubricant (Braycote 601) and/or the guidance condition influenced this effect. The temperature dependency of the parameters is close to the range of identification uncertainty (Figure 10) [10].

Conclusion for the Friction Identification

The friction in the two joints increased initially, already at the first experiment in space compared to the values measured on ground, but remained rather constant afterwards. All the controllers were robust with respect to these changes. The friction changes of joint 1 and joint 2 are different. Friction in joint 1 has the same structure as on ground, but values increased by 50%. The friction in joint 2 shows no more significant viscous friction and the total increase is lower than 20%. Since the same lubricant was used for both joints (Braycote 601), further experiments are planned in order to explain the different behavior.

To provide a better fit of measured and simulation data, a nonlinear (third order polynomial) function is required. However, due to the higher number of optimization parameters, their variance over different experiments is greater. A trajectory with a higher number of distinct velocities is needed in order to reduce the variance of the results.

Stiffness Identification

The main sources of elasticity in the joints are the flex splines of the HDs and the torque sensors. The elasticity is identified by contacting a rigid surface with the tip of the robot and by commanding a slowly changing force to the joints. Since the torque is measured after the gear-box, the stiffness can be easily identified with the available torque and position signal. The model torque is computed as a product of position increment and stiffness. The stiffness for joint 2 has a value around $4900 \text{ N}\cdot\text{m}/\text{rad}$ in space.

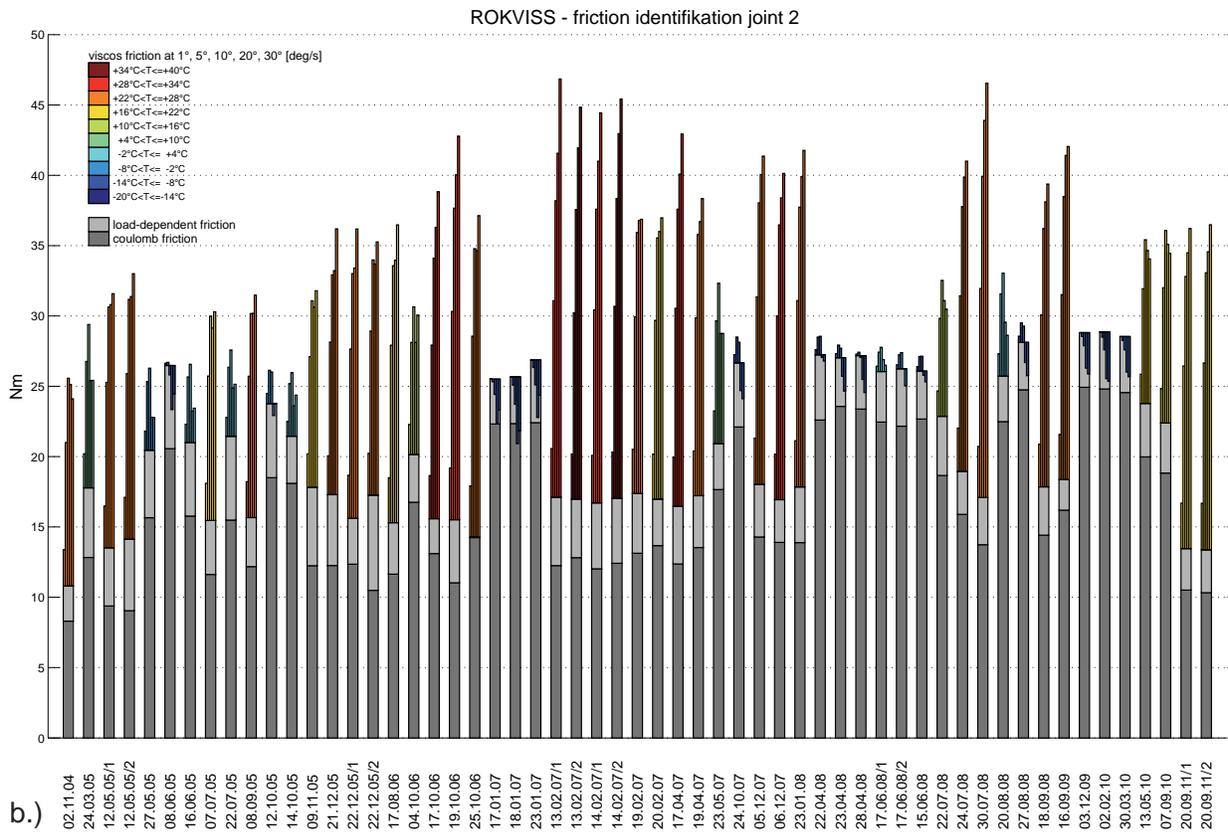
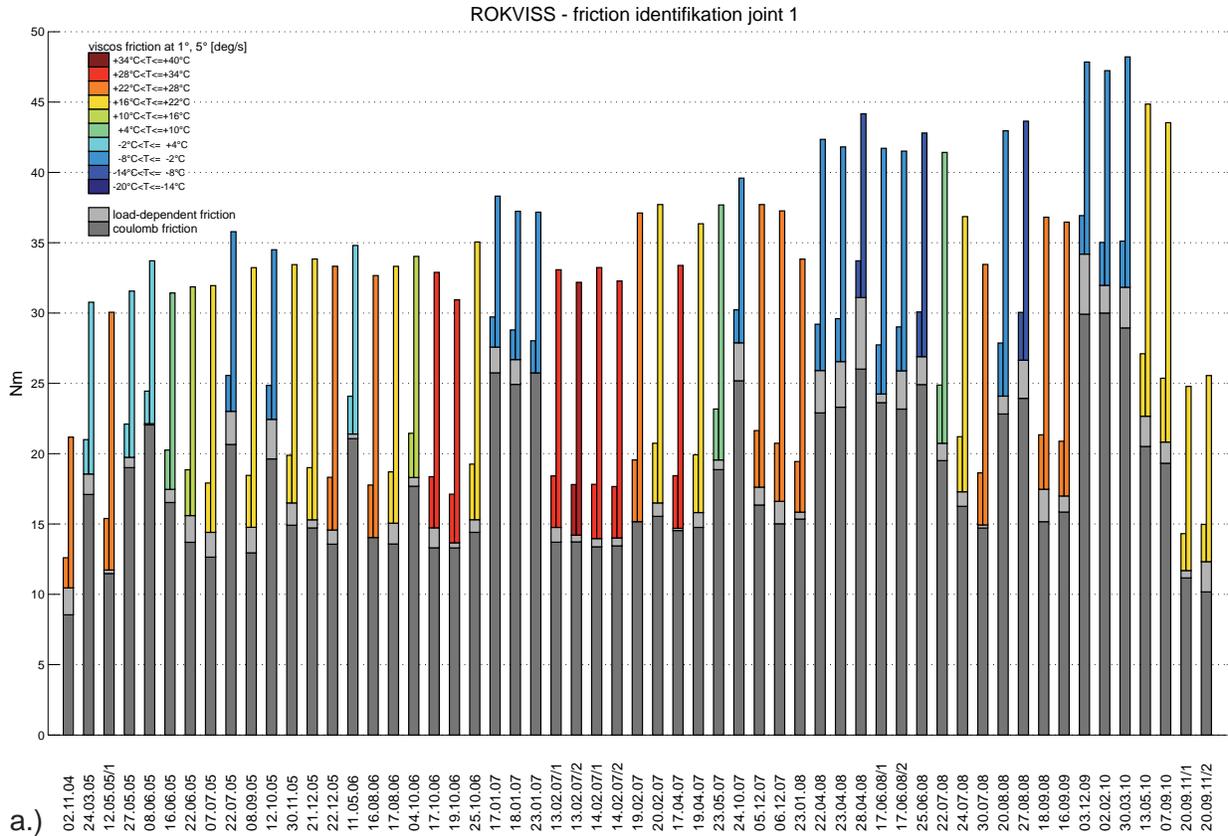


Figure 10: Friction analysis of the FM joints (a. Joint one, b. Joint two)

No significant differences between the stiffness values on the ground and in space are observed. Still, a change of about 15% can be observed. However, this deviation is within the range of the load dependent stiffness variation and the controllers are designed to be robust with respect to such uncertainties.

Conclusions

Though the ROKVISS mission was planned for one year, already after 8 months of operation the main goals of the mission were achieved. The hardware proved to work reliably under space conditions. The dynamical parameters of the joints, although somewhat different than on ground, show a small variation over time and with temperature. The controller structures proved to be robust with respect to these variations and to the used COTS elements. Within the cooperation with the Russian Institute for Robotics and Cybernetics in St. Petersburg (RTC) the mission of ROKVISS has been extended step by step up to end 2010. Then the collective decision has been taken to bring the main parts of ROKVISS down to earth. Currently we are in close cooperation with the RTC to accomplish tests and analysis of these modules. Initially, complete segment tests are planned to identify the behavior and especially understand the correlation between conditions on ISS, thermal vacuum chamber in the test facility and the conditions in the laboratory environment. With this experience we may gain the competence to build "Justin" for space application.

DEXHAND

The development of a torque controlled multi-fingered hand is also a domain in which the DLR has a long history [11–14]. The DEXHAND is designed to be able to perform a set of generic space oriented tasks. For example, the removal of a multi layered insulation (MLI) cover or the manipulation of a handle. This section presents how the design concept and the architecture of the hand are selected based on the hand capability requirements. As discussed in the previous sections, the DEXHAND is in line with the DLR overall goal to develop a complex two handed system for space application such as EVA assistance or substitution of astronauts [15, 16].

The first part that follows presents the main requirements for the system and explains how the general concepts have been selected and the overall architecture is described. The second part "reveals" the mechanical structure, the tendon actuation system and the torque sensor implementation. The fourth part gives an overview of the control system, controller architecture and the software distribution.

Requirements and Concept

The design of the DEXHAND is driven by its required capabilities. Some constraints are purely technical: operating temperature, maximum fingertip forces, joint velocity, but others are functional, such as grasping and operating a pistol grip tool (a space version of an electric drill). The desired capabilities must be translated into technical requirements that result in a trade-off between system complexity, capabilities, reliability, volume, weight and cost. Finally top level functional requirements have been defined, such as the DEXHAND shall be able to grasp the following EVA tools and to support their operations: Pliers, Scissors, Hammer, Tether, Scoop, Cutter, Allen Wrench et cetera.

Successful operation of the tools implies force closure of the grasp with respect to the preferably form closure which should be achieved. In the robotic community, hands are ranging from the simplest grippers to the most advanced biomimetic devices. The design space (i.e., the possible design solutions) of hands is extremely large, therefore, the first part of the project was to select a concept that would fit to the initial requirements. Examples of parameters that must be selected are:

- number of fingers
- number of degrees of freedom (DOF) per finger
- number of actuated DOFs
- placement of the fingers in the hand
- shape of the fingertips

- size of the fingers
- etc...

Certainly, each finger DOF brings more capabilities but increases the number of parts. The use of multiple small actuators instead of one large actuator, increases the capabilities to distribute power losses, might provide redundancy, and usually provides a better form factor. However, the raw power density is reduced. The control complexity and the number of sensors must also be increased in order to take advantage of the available degrees of freedom.

The principle parameters are selected based on the manipulation experience gathered with the DLR Hand II and DLR/HIT hand. A parameter refinement is done by simulating grasps with each object of the EVA tool list. For example, in order to perform trigger actuation of the pistol grip tool, while maintaining tool stability, it appears that at least three fingers are required. For fine manipulation, the shape of the fingertips is playing a key role. Several shapes are compared with respect to rolling, maximum load and the ability to pick up small objects. The DEXHAND is using a variable curvature with a flat end fingertip shape.

Finally, the DEXHAND development differs from the hand developments at DLR. This time the modularization borderline changes (see Section 1.2). For the LWR III the border of the modularization was at joint level. The Hand II (as well as DLR/HIT hand) modularization borderline is based on fingers. While the DEXHAND and as well the Hand Arm System (HaSy [14]) are based on motor modules as previously discussed.

Overall Architecture

The DEXHAND system is developed for use with a robotic arm (Dexarm) designed and realized by Selex Galileo. The hand has 12 actuated DOFs, distributed in 4 fingers with 3 degrees of freedom each. Figure 11 presents the latest state of the CAD model of one Finger and Figure 12 shows two photos of the DEXHAND prototype with housings and without. The actuation system is based on geared motors followed by a tendon transmission system (see first section). The motors are controlled using a combination of a DSP, FPGA and motor controllers. Joint torque measurements are available and realized with full bridge strain gauge sensors. Multiple temperature sensors are available to protect the system against overheating and freezing. The control system of the hand is able to run entirely inside the hand. The DEXHAND is required to communicate over a CAN bus with a common VxWorks communication controller. The communication to control the Dexarm is routed as well through a real-time VxWorks system. It will allow the hand and the arm controllers to be tightly synchronized in the future.

In the DEXHAND, modular fingers are used in order to increase the system reliability. It also improves the cost efficiency of the project. However, based on a kinematic analysis and the experience from the DLR Hand II, a special finger is used for the thumb. As shown in [17], the thumb deserves a special treatment in order to increase the hand dexterity. For example, in order to properly oppose to the other fingers the thumb should have at least twice the maximum fingertip force. The DEXHAND fingers are design to actively produce a fingertip force of 25 N (for the stretched finger) while withstanding 100 N passively.

Mechanical Design

The transmission system is using polymer Dyneema tendons and harmonic drives in order to bring the motor torque to the joints. The concept keeps the extremities (the fingers) with radiation uncritical electronics. The shielding strategy consists in housing the whole electronic system in an aluminum shell with at least 2 mm thickness.

This leads to a fully electro-magnetic interference (EMI) sealed hand body containing:- the drives, the power electronics and the communication electronics. The only exceptions are the torque sensors, based on strain gauges, and some temperature sensors, which have to be placed in the fingers. The design successfully encases all electronic systems in its protective housing.

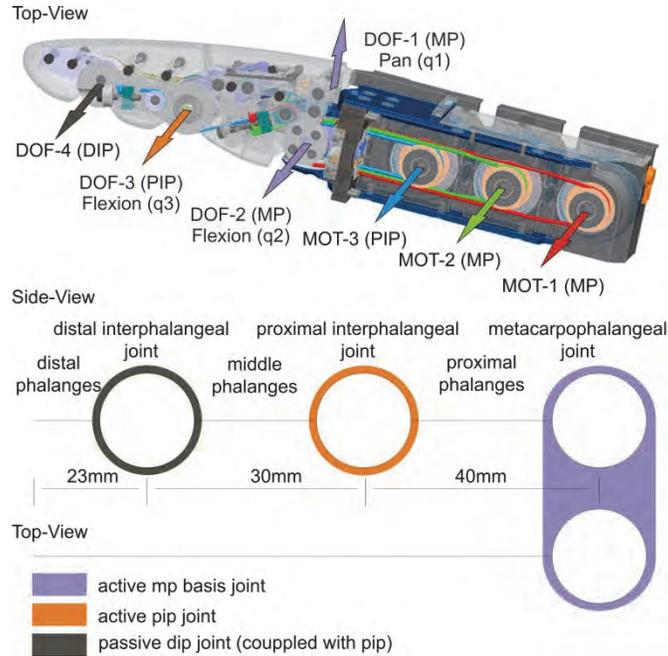


Figure 11: Actuation principle of the DEXHAND fingers

The cardanic metacarpophalangeal (MP) base joint is driven by two motors. Due to the coupling of the tendons in the MP joint the two motor torques can be used together for one DOF of the base joint. This aspect opens the possibility of using the same motors for the base joint and the proximal inter-phalangeal (PIP) joint. Indeed, due to the difference of lever length (pulley radius), the required torques are scaled dependent to each joint. The PIP joint has a fixed coupling with the distal inter-phalangeal joint (DIP) with a ratio of 1:1. In Figure 11 the section lengths, joint positions and definitions are shown.

The coupling matrix P , which relates motor velocity θ with joint velocity q is:

$$\dot{\theta} = P \dot{q} \quad (1)$$

$$P = \frac{1}{r_p} \begin{pmatrix} r_1 & r_2 & 0 \\ -r_1 & r_2 & 0 \\ r_{13} & r_{23} & r_3 \end{pmatrix} \quad (2)$$

Where r_p is the motor pulley radii, r_1 , r_2 and r_3 , are the joint pulley radii, and r_{13} and r_{23} are the pulley radius of the PIP tendons in the base. Given that the coupling matrix is not configuration dependent, the relationship can be integrated in:

$$\theta = Pq \quad (3)$$

The motor unit for DEXHAND has been developed based on the DLR / RoboDrive (see section1) [2] ILM 25 motor including the gear of a harmonic drive HFUC8 with a transmission ratio of 100:1. The whole unit fits into a cylinder of 27-mm diameter and a length of 17.5 mm with a weight of 46 g (see section 1 Figure 4). The unit provides a continuous torque of 2.4 N-m with peaks up to 9 N-m which is the maximum peak torque of the gearing. In the DEXHAND, the motor has been electronically limited to 2 Nm for power reasons. Each actuated joint has a reference mark in the middle of its motion range. These reference marks are composed of a small magnet and a Hall-effect sensor located in the actuated joint. The joint torque measurement is implemented using a sensing body and full bridge strain gauges sensors (Figure 12). The torque sensors are all physically located in the proximal finger link. Therefore, the sensor for the PIP/DIP-joints measures the reaction torque of the coupling tendons.

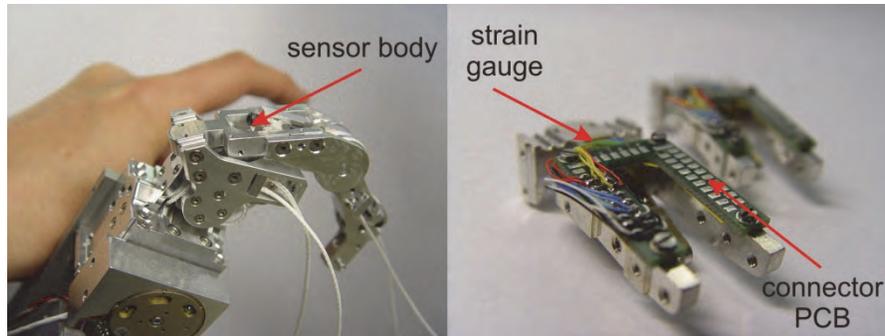


Figure 12: a.) Finger without housing, b.) Strain gauge sensor body

All sensors, except one of the reference sensors of the MP joint, are located and mounted in one mechanical part. This part also contains the pull relief of the wires, as well as the shield connection of the cable from the fingers to the electronics in the palm. This simplifies the assembly and the maintenance of the finger. Special care was taken in the design of the sensor body in order to prevent temperature drift. The force measurements obtained in a thermal chamber from -50° to $+70^{\circ}$ confirmed the measurement stability. The palm structure consists of 11 main segments. These segments are massive aluminum parts to improve heat transfer and increase the thermal inertia. The modules of the DEXHAND are four different ensembles representing the ring-, middle-, index- and thumb finger actuation units. A unit includes the tendon guidance from the motor pulleys to the MP and DIP joint. The palm surface mainly consists of the outer shell parts. Furthermore, all parts are designed without sharp edges. They are optimized for ideal thermal allocation and minimum resistivity (Figure 13 shows the hand without the palm grasp pads).

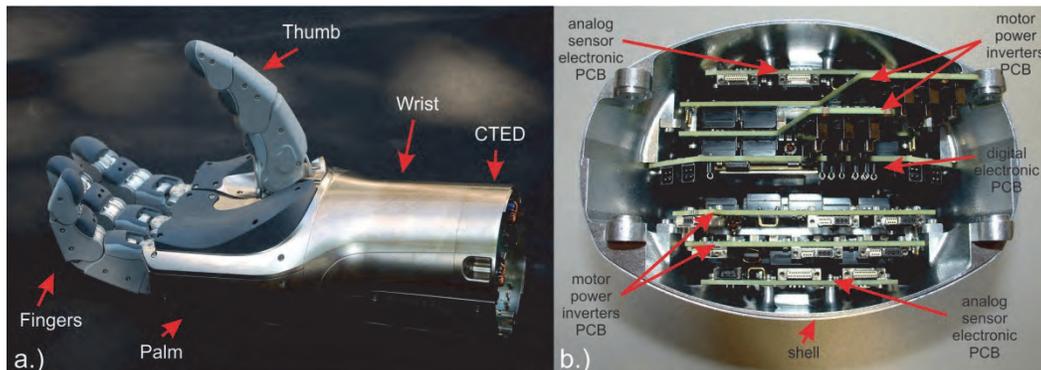


Figure 13: a.) Section view of DEXHAND with its components, b.) PCB placement in the wrist

The wrist houses all electronic parts. This includes the analog, the digital and the power circuit boards. The electronic boards are coupled to the palm assembly with connectors. The housing of the DEXHAND is composed of 2-mm aluminum shells. It is fully closed to provide good EM compatibility. During electro static discharge (ESD) tests with 4-kV impulse at the fingertip and palm structure no failure has been detected. The final DEXHAND design is presented in Figure 13a. Furthermore the compact and also fully integrated housing of the electronic inside the wrist is shown in Figure 13b.

Software and Control

As presented in the previous section, the hand comprises a DSP and a FPGA. The FPGA is used for low level, high speed functional blocks. In the DSP, functional blocks such as calibration tables, impedance control loop, communication, and safety systems are implemented. The controller itself is an impedance controller running at 1 kHz.

The communication to the system is done via a CAN bus, on which no hard real-time data is allowed. The commands to the system are always asynchronous. In order to establish telerobotic scenario, a VxWorks

real-time system is used to establish the data exchange between the data glove data source and the DEXHAND. Moreover, the system is used to monitor the communication bus and to provide a TCP/IP communication interface from any standard operating system.

Conclusion

After more than 20 years of torque-controlled lightweight robot development the third generation becomes a useful product now, where we have tried to use all present day available simulation and computational technologies to approach the technical limits. Taking into account its weight of 13-14 kg, its typical power consumption of little more than 100 watts, its load capability of around 8 kg, its motion speed based on maximal joint speeds of 180 deg /sec, it is probably one of the lightest robots that have been built so far. It is the basis for DLR's future space robot developments

The presented ROKVISS project has proven the capability of using the lightweight robot and motor unit concepts for space application. The experience acquired with the ROKVISS project influenced many decisions. We believe that upcoming tests and results from analyzing the returned hardware will even further improve the DLR space developments.

Furthermore this paper presented an overview of the DEXHAND project with its 12 motor units, its tendon driven actuation principal and its overall mass of 3 kg. The fingers proved to be capable of applying 25 N at the fingertip, and can withstand 100 N impact loads.

It should be noted that the biggest issue in terms of thermal control of DEXHAND are the digital electronic circuits, the power inverters and not the motors. Indeed, they have very little dissipation capabilities. The EM compatibility issue is mainly solved by using a thick enclosing aluminum shell, for the radiation issues only space qualified parts are used. The used commercial parts are qualified with TID tests. The control system runs entirely in the DEXHAND, complying with the very low communication bandwidth requirements.

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